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Electronics Science

Final

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Institute of
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CONTRA COSTA COLLEGE

LOS ANGELES TRADE-TECH

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I. GENERAL INFORMATION

1a. *Center Information*

Date submitted	December 5, 2013
Reporting period	March 1, 2013 – February 28, 2014
Name of the Center	Center for Energy Efficient Electronics Science (E^3S)
Name of the Center Director	Eli Yablonovitch
Lead University	University of California, Berkeley
Contact Information	
Address	267M Cory Hall Berkeley, CA 94720-1770
Phone Number	510-642-6821
Fax Number	510-666-3409
Email Address of Center Director	eliy@eecs.berkeley.edu
Center URL	https://www.e3s-center.org

Participating Institutions

Below are the names of participating institutions, their roles, and (for each institution) the name of the contact person and their contact information at that institution.

Institution Name	Massachusetts Institute of Technology Dimitri Antoniadis
Address	60 Vassar St. 39-427 Cambridge, MA 02139
Phone Number	617-253-4693
Fax Number	617-324-5341
Email Address of Center Director	daa@mtl.mit.edu
Role of Institution at Center	MIT is a lead research, education, and outreach partner.

Institution Name	Stanford University H.-S. Philip Wong
Address	420 Via Palou Stanford, CA 94305
Phone Number	650-725-0982
Fax Number	650-725-7731
Email Address of Center Director	hspwong@stanford.edu
Role of Institution at Center	Stanford is a lead research, education, and outreach partner.

Institution Name	The University of Texas at El Paso David Zubia
Address	500 West University Ave, El Paso, TX, 79968
Phone Number	915-747-6970
Fax Number	915-747-7871
Email Address of Center Director	dzubia@utep.edu
Role of Institution at Center	The University of Texas at El Paso is a research, education, and outreach partner to encourage greater minority participation in engineering.

Institution Name	Contra Costa College Seti Sidharta
Address	2600 Mission Bell Drive San Pablo, CA 94806
Phone Number	510-235-7800 x 4527
Fax Number	510-236-6768
Email Address of Center Director	ssidharta@contracosta.edu
Role of Institution at Center	Contra Costa College is an education and outreach partner to encourage greater minority participation in engineering.

Institution Name	Los Angeles Trade-Technical College (LATTC) Martin Diaz
Address	500 West Washington Blvd. K-423b Los Angeles, CA 90015-4181
Phone Number	213-763-7302
Fax Number	213-763-5393
Email Address of Center Director	DiazM@lattc.edu
Role of Institution at Center	LATTC is an education and outreach partner to encourage greater minority participation in engineering.

1b. *Biographical Information of New Faculty*

Please see Appendix A for biographical information on three new faculty members. One was added to the Center during Period 4 and two will be added in Period 5.

1c. *Primary Contact Person*

Below is the name and contact information for the primary person to contact with any questions regarding this report.

Name of the Individual	Josephine Yuen
Center Role	Executive Director
Address	552 Sutardja Dai Hall, Berkeley, CA 94720
Phone Number	510-664-4439
Fax Number	510-664-4113
Email Address	joyuen@eecs.berkeley.edu

2. *Context Statement*

Information processing equipment, including all computers, consumer electronics, telephony, office equipment, network equipment, data centers and servers, and supercomputers, consume a significant amount of electricity, growing with time, both on an absolute basis as well as a fraction of the total [1]. Rapid growth of energy consumption for information processing is a direct result of the spectacular success of the information technology industry largely fueled by the exponential growth in electronics functionality enabled by Moore's law scaling of integrated circuit (IC) devices.

Energy efficiency and power consumption in circuits and devices are emerging as the key problems in Electronics Science. This includes both the need to reduce the power consumption in the rapidly growing number of large data centers, as well as to satisfy our demand for greater digital functionality in smart portable devices. Another issue is the recognition that the energy consumption of an IC imposes its own limit on scaling. As more and more transistors are packed onto a chip with fixed dimensions of a few tens of mm^2, the power dissipated during dynamic operation of transistors as well as the standby power dissipated even when transistors are not in operation tends to grow almost linearly with the number of transistors (which itself grows exponentially). There is a fundamental limit to the amount of power dissipation that can be tolerated in an IC due to limits in heat extraction.

The confluence of these trends is of critical importance. The rapid growth in the demand for information processing within the economy is driving increasing demands for electricity production. Even reaching the limits of current projections may be prevented by the power density of increasingly complex chips. These issues imply a possible slowdown or halt to the growth of information processing capability.

In spite of this, the basic element of electronics, the transistor, still requires an operating voltage of ~1Volt, much in excess of what is fundamentally necessary. If we had a switching device that is much more sensitive than a conventional transistor, an integrated circuit could function with only a few milli-Volts. Since energy consumption in electronics is proportional to the square of operating voltage, the energy used to manipulate a single bit of information is today as much as 10^6 times greater than needed in an ideal system.

There are many elements that enter into the energy requirements of an information processing system. The Center for E^{3}S is concentrating on two fundamental core components in processing digital information: the digital logic switch and the short-medium range communication of information between logic elements. We seek to enable the development of technology that can approach the most fundamental limits of the energy consumption required to process information [2]. This goal represents a potential reduction from current energy levels, per operation, by 6 orders of magnitude.

The new switch is targeted to have the following specifications:

- Steepness (or sensitivity): ~1mV/decade, allowing switches with a swing of only few milli-volts.
- On/Off current ratio: 10^6:1
- Current Density or Conductance Density (for miniaturization): 1 mS/μm; i.e., a 1μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in mS/μm of conductance versus the traditional requirement of milli-Amps/μm, reflecting the Center's target operating voltage of significantly less than the 1 Volt.)

For optical interconnects to be a low power consumption alternative, the Center's high level goal is to achieve close to quantum limit detection (20 photons/bit) and atto-Joule/bit communication (~10 aJ/bit), when including the receiver system.

The Center's focus on achieving energy efficient devices with ultra-low operating voltage is novel. This goal requires a broad-based effort aimed at making ground-breaking and fundamental advances in physics, chemistry, materials, and nano-device research. The key mission of the Center for E^{3}S is to open a new energy efficiency frontier in information technology by developing the enabling transformative science and technology. As a Science and Technology Center, the foremost goal in the Center for E^{3}S is the elucidation of these basic scientific issues to lay a solid foundation upon which technology development can be based and device fabrication and optimization activities can follow. The focus on establishing the fundamental understanding of the science for achieving devices operating close to the fundamental limits is thus far ahead of industry.

The research program of the Center for E^{3}S comprises four Themes:

I. Nanoelectronics with a focus on solid state millivolt switching

II. Nanomechanics with a focus on reliable, ultra-low voltage operation in solid state relays

III. Nanophotonics focused on few-photon communication

IV. Nanomagnetics that is current actuated and potentially more efficient than today's switches

Themes I, II and IV are each pursuing a different approach to electronic switching. Theme III addresses optical communication that is gradually replacing wires for longer interconnects in digital systems, both intra-chip and chip-to-chip.

Overarching these four Themes is the System Integration research, where the outcomes include a common set of metrics for each of the themes and a systems perspective that will enable future ultra-low energy information systems to be actually built and would actually matter. In addition, there are Theme specific collaborations as each Theme is guided by a circuit/systems perspective. The System Integration research will ensure that the component research outcomes of the Center will be effective in enabling future ultra-low energy information systems.

Nanotechnology offers the potential for continuing the exponential growth in capabilities beyond the energy-imposed scaling limits of current CMOS technology. Achieving this promise requires researchers from several basic disciplines (physics, nanomaterials, nanodevices) to work in a coordinated matrix fashion, as the underlying principles governing the radically new approaches are elucidated. It also requires a partnership of researchers from multiple institutions. At the inception of the Center in 2010, researchers from UC Berkeley, MIT, Stanford and Tuskegee University joined forces to accelerate the new fundamental science that can lead to a radically lower power successor to conventional technology. However, because research, by its nature, is neither straight forward nor prescriptive, we can expect that the research team, and as a consequence the member institutions, will change over time. To put reporting of the state of the Center for E^{3}S in perspective, we are summarizing here the aggregate changes in faculty participation by member institution as the Center ends Period 4 and enters Period 5; further details on faculty changes are given in the sections on Center Management and Plans for Period 5.

	UC Berkeley	MIT	Stanford	Tuskegee	UTEP	FIU
Period 2	11	6	1	1		
Period 3	12	7	1	2		
Period 4	12	7	1		1	
Period 5	11	7	1		1	1

While the research thrusts have stayed the same, the Center's research program, in its third year (Period 4), is beginning to see changes and consolidation in approaches within each Theme, as we make advancements in our understanding of the technical challenges.

Theme I: Tunnel FETs (TFETs) continue to be a key approach in the Nanoelectronics Theme. Even though the concept has been in research for several years, TFET experimental results have continued to be disappointing, in spite of simulation predictions of phenomenal device performance. The lack of a sound scientific foundation has impeded achieving promising results. The Center is the first concerted effort to focus on the elucidation of the physics of the sharpness of energy bandgaps both theoretically and experimentally.

In Period 4, comprehensive analysis of our own data and published historical device data indicated that the band edges observed in tunnel diodes are significantly less sharp than those reported for the intrinsic optical absorption edges. Even the optical band edges would fall short of the goals of the Center. The observed lack of steepness in experimental devices can be attributed to device inhomogeneity, arising from many causes including doping inhomogeneity. Simulations of turn-on characteristics of Tunnel FETs and experimental data on diodes made from well-controlled epitaxial materials further supported this conclusion. E^3S researchers will continue on device demonstration experiments in single quantum channel devices to overcome inhomogeneity and to answer how sharp the electrical transitions can fundamentally be. Preliminary efforts to surmount device inhomogeneity will begin before the end of this reporting period.

Theme II: The Nanomechanics Theme focuses efforts on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of conventional transistors. Prior research on micro/nano-electro-mechanical (M/NEM) switches concentrated on achieving functional devices with good yield and reliability (to enable integrated circuit demonstrations) and on theoretical studies of their scaling behavior. The Center was the first to pursue experimental investigations in scaling the contact area size to nm^2 and to achieve a mechanical relay with sub 0.1 Volt switching.

Theme II researchers have also been concerned with stiction, which is caused by surface adhesion forces on the contacting surfaces. This affects reliability and causes hysteresis. In the past 18 months, Theme II researchers learned from their experimental and simulation data that surface adhesion forces continue to be important at the nano-scale. Surface adhesion is a fundamental limiter toward millivolt switching that will need to be overcome. The Center's aggressive goals have pushed Theme II researchers as a team to innovate new approaches to overcome this fundamental barrier. The cross-university discussions and collaborations under E^3S have elucidated basic requirements and experimental pathways for these approaches. Our research in nano-relays controlled by an organic "squishable" film is beginning to show a pathway to avoid surface adhesion. In Period 4, feasibility of the "Squitch" concept was demonstrated in a two-terminal device. Another approach to breaking the surface adhesion limit that calls for a sub-nanometer gap is also being pursued. These device feasibility investigations are complemented by studies on the materials science of surface adhesion.

Theme III: The Nanophotonics Theme's target on nanoscale ultra-efficient active optical components for on-chip application differs from the optoelectronics industry efforts which have concentrated on longer distances and higher energy. The strategy is consolidated to include two elements: i) coupling of optical antennas to nanoscale devices to make spontaneous emission faster than stimulated emission at the nanoscale, and ii) to provide for ultra-sensitive photo-receivers by direct integration of detector and the first transistor, to minimize capacitance in a form of photo-transistor. In Period 4, the research program made progress in applying this strategy. In addition, Period 4 has seen additional emphasis in mode-matching optical antennas to Silicon photonic waveguides.

Theme IV: Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that can approach the Landauer limit [2] or perhaps even surpass it via reversible logic as predicted by Bennett [3]. This Theme has the most fundamental science character, but new material and conceptual breakthroughs are suggesting that applications might arrive sooner than expected. Our initial approach included a mix of projects that investigate the experimental technical foundation of spin-based computing. The effort is to learn more about spin dynamics, particularly at room temperature, as well as to demonstrate a basic low energy magnetic switching functionality based on voltage control of magnets. In Period 3, Theme IV researchers began to consider new approaches as the spin Hall effect began to emerge. In Period 4, new Theme IV projects based on current-control of magnetic switching were initiated. This change from voltage control to current control is also leading to changes in the research team composition in the coming Periods.

The Center's mission also includes education and broadening participation. The four research partner institutions are joined by two community colleges, Contra Costa College (CCC) and Los Angeles Trade-Technical College (LATTC), in this effort. Our goals are to educate a diverse generation of scientists, engineers, and technicians to be the future leaders, researchers, educators, and workers in the new electronics science and technology. We aim to foster understanding by society of the energy challenge faced in information technology and to promote the application of the Center's research outcomes as the foundation for technological solutions in low energy consumption electronic systems.

The graduate students and postdocs of the Center are trained through formal course work, research, and a variety of venues when the Center's research directions and results, as well as the applicable research of others outside the Center, are discussed and shared. For professional development, they participate in the many programs and activities organized by the Center. There are activities specifically designed for them to develop leadership and mentoring skills as they contribute to programs that are designed to benefit undergraduates and high school students.

The Center develops and manages most of its undergraduates programs. We place a strong emphasis on recruiting students from groups that are underrepresented in the technical disciplines of the Center. The Center's key diversity effort is its Transfer-to-Excellence program, which enables higher transfer rate of California community college students to STEM baccalaureate programs a key focus of its diversity efforts, as the student bodies of these colleges have larger representations of women, people from racial groups underrepresented in STEM fields, students who are the first generation to attend college, and veterans.

At its inception, the Center leveraged established high school programs at its partner research institutions to add value. In Period 2 we re-examined our strategy and concluded that the focus should be with programs that have a broad national reach. The phase-out of participation from high school programs with local or limited reach is taking place over two years. Instead, E^{3}S resources are being transitioned to develop educational content for MOSTEC, an MIT developed online community of high school students that can provide educational experiences for over 100 students per year from all over the nation.

To integrate the programmatic endeavors with research, the Center has defined online education to be important part of its strategy. At the inception of the Center, **E. Yablonovitch**, Center Director**,** developed and taught EE 290: Advanced Topics in Solid State Devices as an online course for E^{3}S members and a non-E^{3}S audience to learn about technical topics relevant to low energy devices, topics that we refer to as E^{3}S topics. The course is taught at UC Berkeley and offered to members at all institutions through videoconferencing and online posting of course material. The Center's education strategy is to build a library of online courses that will reach a broader audience, including researchers, scientists, and engineers, undergraduate and graduate students at other colleges and universities, and pre-college students and teachers.

Knowledge transfer is another important part of the Center's mission. The Center's goals are to establish industry and education partnerships as venues for introducing new and more efficient electronics technologies and to prepare workers at all levels to participate in the new opportunities. The Center has an Industrial Research Board made up of representatives from leading electronics and information technology companies, whose role is to guide the Center's research directions towards practical, and ultimately commercially successful outcomes. We expect that it will be through the semiconductor industry that the Center's research successes will eventually be transferred into low power electronics applications. During the life of the Center, researchers in academia are also knowledge transfer partners. As the Center's research results lead to changes in directions and approaches, it is critical that the

Center's sharing of knowledge will lead to a community of like-minded research peers who together can accelerate the achievement of the goal of millivolt switching and few-photon communications.

The preparation of the next generation of scientists, engineers and technicians is also a community endeavor. We leverage the expertise and resources partners to deliver on the Center's promise to prepare a new diverse generation of STEM workers. We contribute to the field of engineering and science education through publications and presentations on what we learn in the design, execution and evaluation of our programs.

The Center for E^3S, which is led by **E. Yablonovitch** of UC Berkeley, Center Director and Principal Investigator of the NSF Award, was started in October 2010. At the preparation of this Period 4 Annual Report, the Center has completed approximately 38 months of full operation.

Summary of the State of the Center

At the highest level, the status of the Center can be viewed through the metrics given in the Center's Strategic Plan. The metrics were established to help track our performance in the various areas that make up our mission. Effective management is critical for a healthy research climate within the Center as well as for successful partnerships.

Objective	Metric	Targets	Results		
			Period 2	Period 3	Period 4
Research	Multi-PI projects	Period 2: 30% Period 5: 75%	44%	67% (14)	55% (12)
	Multi-Institutional projects	Period 2: 10% Period 5: 30%	4%	10% (2)	9% (2)
	Unplanned research projects	Period 3: 1 Period 4: 3 Period 5: 0	3	4	1
	New joint research funding opportunities	Period 3: 1 Period 4: 3 Period 5: 0	n/a	1	1
	Publications with authors from multiple institutions	Period 3: 12 Period 4: 3 Period 5: 5	0	1	1
	Publications with authors from multiple departments	Period 4: 2 Period 5: 4	0	0	1
Education	Center graduates completed E^3S training	Period 3: 50% Period 4: 50% Period 5: 50%	n/a	3 (17%)	7 (35%)
	Students and postdocs participating in education and diversity programs	Period 3: 60% Period 4: 70% Period 5: 75%	52%	48 (52%)	41 (69%)
	Students and postdocs	Period 3: 15%	11%	11 (19%)	20 (34%)

	serving in leadership roles in the Center	Period 4: 20% Period 5: 25%			
Diversity	Women in the Center's research programs	Period 3: 5% increase Period 4: 30% Period 5: 30%	13 (22%)	15 (25%)	13 (19%)
	Underrepresented minorities in the Center's research programs	Period 3: 15% increase Period 4: 5% Period 5: 10%	2 (2%)	1 (2%)	5 (7%)
	Participants from groups underrepresented in STEM in the Center's Diversity programs	Period 3: Baseline Period 4: 80% Period 5: 80%	n/a	93 (82%)	Women: 37 (44%) URM: 58 (68%) Total: 73 (86%)
	Pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline Period 4: 70% Period 5: 70%	n/a	31 (68%)	98 (75%)
	Community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Period 3: 5% Period 4: 80% Period 5: 80%	n/a	3 (100%)	6 (100%)
	Undergraduates who pursue advanced degree in science and engineering	Period 3: 5% Period 4: 30% Period 5: 35%	n/a	0 (0%)	5 (38%)
Knowledge Transfer	Website hits & unique visitors	Period 3: 20% increase Period 4: 10% Period 5: 10%	Website Hits: 11,354 Unique Visitors: 6,123	Website Hits: 140% (27,298) Unique Visitors: 167% (16,338)	Website Hits: 42% (38,800) Unique Visitors: 40% (22,809)
	Contacts with industry: • General • Industry Presentations	Period 3: 36 Yearly: 2	66 4	20 2	42 6
	Research collaboration with industry	Period 4: 1 Period 5: 2	0	1	1

	Center publications	Per Year: 18	17	16	20 plus 2 in press and 10 under review/ submitted
Knowledge Transfer	External citations of publications	Period 3: 10 Period 4: 100 Period 5: 100	15	178	393
	Patent disclosures • Disclosure/Provisional • Patent Application Filed	Period 3: 3 Period 4: 3 Period 5: 5 Period 4: 0 Period 5: 3	1 0	0 0	1 0
	Students hired into relevant industries	Period 5: 50% Period 10: 50%	Students: 0% Postdocs: 100% (1)	Students: 64% (7) Postdocs: 33% (2)	Students: 16% (2) Postdocs: 20% (2)
	Technology development attributable to Center's research	Period 10: 1	n/a	n/a	n/a
	External articles on Center	Period 3: 100% increase Period 4: 3 Period 5: 5	1	0	0
Center Management	Centerwide communications	• 1 newsletter • Annual Retreat • Annual NSF Review • Updated Website	None August 29-30, 2011 None Continuously	June 2012 August 21-22, 2012 January 9-10, 2012 Continuously	June 2013 August 26-27, 2013 January 9-10, 2014 Continuously
	Annual Surveys: • Students /Postdocs	3 or higher on Likert Scale	Average: 3.9±0.2	Average: 4.0±0.3	Average: 4.2±0.2
	• Co-PIs		No survey in Period 2	Leadership: 4.46 Collaboration 3.25	Leadership: 4.7±0.5 Collaboration not available
	• External Advisory Board		Strategic Plan: 4.18 Center Status: 4.01	Strategic Plan: 4.07 Center Status: 3.96	Strategic Plan: 4.6 Center Status: 4.6

	Authorship disputes	20% decrease annually	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale
	Plagiarism		0	0	0
	Assessment of goals, objectives, and outcomes – Strategic Plan Review	Yearly	January 5, 2012	December 19, 2012	December 17, 2013

Research

Center's Faculty: In Period 4 (March 2013 through February 2014), the Center has 21 faculty researchers at four partner institutions. These researchers bring expertise in materials synthesis, device physics and processing, and theory and modeling. They are:

- *UC Berkeley*: Elad Alon, Jeffrey Bokor, Connie Chang-Hasnain, Chenming Hu, Ali Javey, Tsu-Jae King Liu, Ramamoorthy Ramesh, Sayeef Salahuddin, Irfan Siddiqi, Junqiao Wu, Ming C. Wu, and Eli Yablonovitch
- *MIT*: Dimitri Antoniadis, Vladimir Bulović, Jésus del Alamo, Eugene Fitzgerald, Judy Hoyt, Jeffrey Lang, and Timothy Swager
- *Stanford University*: H.-S. Philip Wong
- *The University of Texas at El Paso:* David Zubia

Research in Period 4:

The introduction of this executive summary has provided a high level overview of the Center's four Themes and the System Integration effort, including the new directions and changes. In-depth discussion of the five areas of research is found in Section II – Research in the main body of this annual report. Below is an expanded summary that details the key advancements of each area of research in the current Period 4.

- *Theme I* - Nanoelectronics: Theme I comprises **E. Yablonovitch,** Theme Leader, **C. Hu**, **A. Javey** and **S. Salahuddin** from *Berkeley*; and **D. Antoniadis**, **E. Fitzgerald**, **J. Hoyt** and **J. del Alamo** from *MIT*. Tunnel Field Effect Transistors (FET) as the milli-volt alternative to the conventional FET has been a key focus. There are two mechanisms to obtain a steep subthreshold swing in a TFET: (i) electrostatically changing the tunneling barrier thickness and (ii) the Energy Filtering or Density-of-States overlap mechanism, whereby the current can abruptly turn on when the conduction band and valence band align. Energy Filtering, which has been advocated by the Center, requires a steep abrupt band edge for the density of states. Determining the steepness of the semiconductor band edge has been a key scientific and practical goal of Theme I. In Period 4, Theme I researchers made major strides in elucidating observed band edge sharpness in current-voltage spectroscopy.
  - The **Yablonovitch** group *(Berkeley)* systematically analyzed experimental data on TFETs, available in the open literature and within the Center. Devices that rely on electrostatically changing the tunneling barrier thickness suffer a fundamental tradeoff between current density and steepness and will never achieve a steep turn on at high current densities. Our conclusion is based on a simple theoretical understanding, which is also supported by experimental data. The best subthreshold swings steeper than 60mV/decade occur at I_{on} around 1nA/µm, while current

drive in the range of 1mA/μm is the goal [4]. The Energy Filtering or Density-of-States switching mechanism that the Center has advocated requires a steep band edge density of states to abruptly turn on when the conduction band and valence band begin to overlap. We have introduced a new approach that allows us to analyze a variety of published and fabricated tunnel diodes for band edge steepness. The somber conclusion is that device spatial inhomogeneity results in a band edge steepness of 90mV/decade or worse. This understanding supports the need for atomically controlled device designs, or single quantum channel designs, which can reveal the true fundamental band-edge steepness.

  - The simulations of **D. Antoniadis** and **J. Hoyt** *(MIT)* have also confirmed that inhomogeneity due to thickness variations results in a poor subthreshold swing, as the observed swing results from a composite of different thresholds corresponding to the thickness varations. These turn on at different biases and lead to a net gradual turn on.

  - In elucidating factors that contribute to homogeneity, the controlled material growth research of the **E. Fitzgerald** group *(MIT*) identified the various materials defects present and how to control them. The observation of density-of-states switching in the Type III diodes made from materials grew in a controlled manner and the characterization of the steepness have identified the effect of these materials defects on the steepness of the switching action. For InAs/GaSb, controlling the misfit dislocation at the interface has demonstrated more abrupt switching. The quality of the interface was improved by beginning the growth with InAs versus GaSb. Annealing has shown to improve the sharpness of switching, likely due to the annealing of point defects in the structure. We have also successfully demonstrated some control over the band alignment by using alloying, for example, the use of the InAs/AlGaSb.

  - The understanding of the need to avoid the spatial inhomogeneity aligns with the research of **J. del Alamo**'s group *(MIT)* that has been pursuing Superlattice Nanowire FETs (SLS NW-FETs) that will limit the area of the tunneling junction, eventually down to a single quantum channel. In Period 4, his team achieved the first experimental feasibility of a InGaAs Vertical Nanowire FET,which has served as demonstration vehicle and process development driver. The fabricated nanowire transistor is allowing us to investigate important issues such as interface quality, electrostatics and ohmic contacts before proceeding to superlattice contacts.

  - Alternatively, spatial inhomogenieties can be addressed by semiconductors built from new layered materials, such as the chalcogenides. Thus, the group led by **A. Javey** *(Berkeley)* has continued to explore the fundamental physics and electron transport across the interface of 2-D to 2-D van der Waals pn-junctions by mixing and matching 2-D III-Vs and/or 2-D layered chalcogenides. In Period 4, Chalcogenide heterostructures built from single layer MoS_2 and a single layer of WSe_2 were analyzed and strong interlayer quantum coupling was found between the adjacent single layers. We discovered Type II band alignment, that is direct in reciprocal space, but indirect in real space, between the conduction band in the n-MoS_2 layer to the valence band in p-WSe_2.

- *Theme II - Nanomechanics*: In Period 4, Theme II has multi-disciplinary participation from three institutions. Led by **T.-J. King Liu** *(*EECS, *Berkeley)*, the Theme II research team includes **V. Bulovic** and **J. Lang** (EECS, *MIT*), **T. Swager** (Chemistry, *MIT*), **H.-S. P. Wong** (EECS, *Stanford*), and **J. Wu** (MSE, *Berkeley*), and **J. Bokor** (EECS, *Berkeley*).

  - With zero off-state leakage and abrupt (zero sub-threshold swing) on/off switching behavior, mechanical relays offer the promise of aggressive supply voltage scaling for ultra-low active energy consumption (projected to be <1 aJ/op). From the inception of the Center, the researchers in Theme II have recognized the need to scale the mechanical switch to nanometer-scale dimensions and address issues such as surface adhesion and wear in order to realize relay-based integrated circuits (ICs) that operate not only with good energy efficiency but also with good reliability ($>10^{14}$ On/Off cycles). Earlier theoretical studies undertaken by **T.-J. King Liu** *(Berkeley)*and her research group *(Berkeley)* on scaling projected that sub-10 milli-Volt operation should be achievable with nanoscale contact areas/dimples if the contact adhesion would scale down proportionately with the area of the contact dimple regions. During Period 4 the group of **T.-J. King Liu** obtained experimental results indicating that the minimum contact adhesive force will be ~1 nN for ultimately scaled contacts (1 nm^2 contact area), which would make it difficult to reduce the switching energy to the 1aJ range. That is, a relay which operates by making and breaking physical contact between contacting electrodes will be difficult to scale aggressively to ~10mV operating voltage and sub-micron actuation area. The problem of surface adhesion, alternatively known as stiction, can be mitigated by decreasing the surface energy between the surfaces that serve as the source and drain.

  - In Period 4, there were two device feasibility projects that focused on demonstrating milli-volt operation through device designs that switch through tunneling, i.e., a switching mechanism with a current flow through a very narrow gap without the source and drain actually touching.
  - Most noteworthy is the experimental progress found in the multidisciplinary collaboration of **V. Bulovic**, **J. Lang** and **T. Swager** *(MIT)***.** They use of compressible organic thin film between the source and drain electrodes that provides localized spring restoring force to alleviate direct contact stiction; an approach that was initiated at the end of Period 2. The project's Period 4 highlight is the proof of concept in a two-terminal squitch based on laterally-moving cantilevers. A device with a self-assembled layer of fluorinated decanethiol molecules between the source and drain demonstrated repeatable switch operation. In this two-terminal switch, an approximate 10^5 on-off ratio was achieved within a 1.5 V range. The lower actuation voltage observed in the presence of the molecular layer suggests the possibility of self-assembly of a smaller switching gap than that initially fabricated. While low voltage switching has yet to be demonstrated, the device data is a clear demonstration of feasibility of the approach. The thin self-assembled compressible molecular layer has: (1) alleviated the problem of stiction by preventing direct contact; (2) helped to self-define the nanometer-scale squitch gap; and (3) permitted tunneling across the gap. The proof of concept was done with a thin film of self-assembled fluorinated decanethiol, which best-fit theoretical modeling estimates to have a Young's modulus of approximately 0.24 GPa. Organic compounds with optimal mechanical and electron-transport properties have now been synthesized for molecular thin films with a Young's modulus lower than approximately 10MPa to enable sub 1Volt switching. Among the materials most recently engineered for this purpose are P3HT-based polymers that enable self-assembly of thin molecular films having piezoresistive properties in addition to the ability to support the electromechanical modulation of tunneling current.

- *Theme III – Nanophotonics:* From the inception of the Center, **M.C. Wu, C. Chang-Hasnain** and **E. Yablonovitch** *(all Berkeley)* have been the researchers in Theme III. **E. Alon** *(Berkeley)* has collaborated to provide system analysis of optical interconnects. New to Theme III in Period 4 is **D. Zubia** *(UTEP)*, who joined the Center in this reporting period. The focus of this Theme has continued to be the fundamental physical and technological investigation of the nanophotonic components. During Period 4, progress has been made on emitter and receiver projects, and the research has broadened to include the integration of the components on silicon photonic waveguides. Improvements in the underlying III-V growth technology for III-V nanophototransistors have also been demonstrated.
  - The research on Spontaneous Hyper Emission (SHE) nanoLEDs has two components: (i) integration to an InP waveguide; and (ii) electrically pumped nanoLED.

        i. Mode-matching of the antenna LED to InP ridge waveguides has been demonstrated using multi-element antenna (Yagi-Uda) structures [5] [6].

        ii. Progress has also been made towards realizing an electrically pumped nanoLED that is assisted by an optical antenna. Previously, we have reported that under optical excitation we have demonstrated 35× enhancement of the spontaneous emission rate. The electrically pumped design is similar to a FIN-FET except the channel is replaced by III-V emitter, the gate metal is replaced by optical antenna, and the source/drain is replaced by electron and hole injectors. We have developed the nanofabrication process for electrically pumping the antenna-enhanced LED and have preliminary test results demonstrating successful current injection and electroluminescence.

    - This light emitter research needs to be complemented by ultra-high sensitivity phototransistors to ensure a low energy communications channel. Two different materials systems; (i) Ge/Si and (ii) III-V have been investigated for the low-capacitance, high-sensitivity phototransistor.

        i. A single crystal germanium gate Photo-MOSFET with 18 A/W responsivity and speeds up to 2.5 GHz with potential improvement with future scaling was achieved.

        ii. The research towards a nanophototransistor shifted to the use of InP, away from InGaAs, as the photodetector was shown to have large dark currents. The InP nanopillars have shown much brighter photoluminescence and higher internal quantum efficiency compared to InGaAs based nanopillars, which makes it a much more promising material system for realizing the highly sensitive nanophototransistor (BJT) onto silicon substrate. To make InP based BJT possible, we have developed a regrowth technique for growing layers of InP materials onto the tip of the InP nanopillar. With the regrowth method, we have shown that the dark current of a p-i-n photodetector built using the regrowth method can be dramatically reduced to ~100fA range (or µA/cm^2) level. This can lead to better detector performance in both sensitivity and signal-to-noise ratio.

    - The **C. Chang-Hasnain** *(Berkeley)* group has also demonstrated selective area growth of InP nanopillar on silicon substrate in collaboration with **D. Zubia** *(UTEP)*. By using a 100 nm thick silicon dioxide with ~ 300-400 nm diameter holes, the growth location of the nanopillar can be precisely controlled. Initial results show that the InP nanopillar would only grow within the openings of the silicon dioxide mask with a 66% yield. The silicon dioxide mask not only serves as a growth mask, but also serves as an electrical isolation layer to prevent the doped nanopillar shells from touching the substrate. This helps lower the dark current to improve detector sensitivity and signal-to-noise ratio. Towards establishing a fundamental understanding of the selective growth process, the **Zubia** group has begun to develop a new mathematical formulation for strain partitioning, accounting for compliance in the substrates [7].

- *Theme IV - Nanomagnetics*: Since the start of the Center, the E^{3}S researchers in the Nanomagnetics team was up made of faculty from different disciplines (electrical engineering, materials science and physics): **J Bokor**, Theme Leader, **R. Ramesh**, **S. Salahuddin** and **I. Siddiqi** *(all Berkeley)*. The Center considers this Theme to have the longest time horizon of the Center's research themes, given the prospect of building practical devices that can approach the Landauer limit [2], or perhaps even surpass it via reversible logic as predicted by Bennett [8]. Thus, the initial approach has been to undertake a mix of projects that enhance the experimental technical foundation for logic and to learn more about spin dynamics particularly at room temperature as well as projects to demonstrate millivolt magnetic switching. As a result of the new breakthroughs in the Spin-Hall effect, Theme IV is now pursuing current control of magnetic switching versus voltage control, the approach in place since the start of the Center. In Period 4, two new projects were added to Theme IV: (i) magnetic switching based on the Spin Hall effect (SHE) and (ii) ultra-fast magnetic switching.

  - Conventional magnetic switching is governed by precessional dynamics that sets a minimum switching time of ~100ps, but to have practical application in logic, a switching speed in the range of a few psec would be far more attractive. Building on prior work, [8] [9], **J. Bokor** *(Berkeley)* is pursuing a concept of magnetic switching via rapid magnetic phase transitions. These can be driven as rapid equilibrium heating or by a highly non-equilibrium process that is created by selectively 'heating' only the electrons with an ultrafast source. It is during the transient high electronic temperature phase that the Curie temperature of the ferromagnet is momentarily exceeded, and a rapid demagnetization on a sub-psec time scale results [10]. During Period 4, the effort has been on refining the underlying concepts and to plan research details for addressing ultrafast magnetic switching. Equipment and partnerships are being put in place to enable this study.
  - Aided by fruitful discussions within Theme IV, **S. Salahuddin** *(Berkeley)* identified the possibility of replacing the magnetic field based clocking mechanism of conventional nanomagnetic logic schemes using a Spin Hall Effect (SHE), a term that was first coined by J.E. Hirsch in 1999 [11]. The basic physics hinges on the spin-orbit coupling that results from the electrons flowing in a material experiencing a pseudo-magnetic field. As these electrons collide with impurities in the material, they scatter in preferential directions based on their spin polarizations. As a consequence, a non-equilibrium spin polarization builds up along the edges of the material. Recent research in SHE revealed dramatic results. A particularly exciting work is a recent demonstration by two groups (Grenoble and Cornell) that an unpolarized current flowing in a metal with large spin orbit coupling can switch the magnetization of a ferromagnet sitting right on top of it [12] [13]. This means that the generated surface/interface spin density is sufficient to contribute enough angular momentum to the ferromagnet so as to completely reverse its magnetization. In fact, it is now clear that there is a significant 'gain' in the spin accumulation coming from Spin Hall Effect owing to the continuous repolarization of the charge current along the length of the wire.

    The initial work on Spin Hall Effect (SHE) performed by the **Salahuddin** group was funded from other sources. Once the opportunity for nanomagnetic logic was identified, the Salahuddin team leveraged all these funding sources, including E^{3}S, to demonstrate a SHE clocked nanomagnetic logic. Thus, this project, though not identified as part of the Period 4 plan of the Center in last year's annual report, is being reported in this Period 4 annual report.

    The Saluhuddin lab *(Berkeley)* has made exciting progress. Experiments on a simple 3-dot NML chain have demonstrated experimentally a nanomagnetic logic circuit where the clocking does not involve any application of magnetic field. When a current pulse was applied to this system, Hall resistance measurements showed that the 3-dot chain indeed goes to a 2up-1 down state or a 2down-1 up state. When this is done with an input magnet whose magnetization is not affected by the clock pulse, the 3 dot circuit goes to a dipole coupled state as determined by the input magnet. Importantly, the current needed for the logic operation was shown to be almost 3 orders of magnitude lower compared to previous demonstration of on-chip nanomagnetic logic. This logically translates to a more than 4 orders of magnitude reduction in energy dissipation as compared to state of the art. Projecting from the experimental data, operation below 100 mV is envisioned.

- *System Integration Research*: **E. Alon** and his team *(Berkeley)* pursued Theme specific analysis for each of the four Themes in Period 4. For Theme I, with the generalized framework that was developed in Period 3 for analysis of I_{on}/I_{off} that accounts for variability, we achieve the ability to numerically predict the required level of variability for an alternative switching device with sharper steepness characteristics to achieve a given level of energy consumption relative to the conventional MOSFET. For Theme II, the collaboration with **T.-J. King-Liu** on relay-based microcontroller circuits has included novel circuit approaches and joint experimental efforts. For Theme III, an analysis of the energy limitations of photonic receivers showed that limitations on the minimum swing at the output of the receiver – and not SNR limitations – typically set the minimum required energy consumption for the entire link. For Theme IV, an initial study on utilizing magnetics-based devices for analog applications identified devices that switched along their easy axis as being unsuitable in most analog applications because they have no region of linear small-signal gain – they instead can only be flipped between distinct states (similar to a relay). However, switching along the hard axis can result in linear small signal gain.

Education and Diversity

The leadership of the Center for E^3S has made a concerted effort to develop education programs that integrate and leverage our research. In its effort to develop a new generation of Ph.D. and M.S.-level scientists and engineers, the Center adapted a model of vertical integration, where our education programs: 1) integrate research with educational activities; 2) enhance interaction and mentoring among undergraduates, graduate students, postdoctoral researchers, and faculty members; and 3) broaden the educational experiences of its students and postdoctoral associates to prepare them for a wide range of career opportunities. To meet these goals, the Center for E^3S offers ongoing training on energy efficient electronics topics and professional development opportunities for its students and postdocs. Detailed description is given in Section III, Education of this Annual Report.

The goal of the diversity programs of the Center for E^3S is to increase the number of students from historically underrepresented groups in engineering who attend university and graduate programs in technical disciplines that will contribute to low energy electronics. While the Center seeks to ensure that the composition of center participants reflects the diversity of the US, with a particular focus on underrepresented racial/ethnic backgrounds, women, and people with disabilities, there is increasing recognition that the more tangible goal is to attain a diversity profile that is better than a comparable benchmark. In Period 3, we introduced the use of benchmark data as part of goal setting. This change does not detract from the Center’s critical focus to enhance the diversity of the Center’s participants, especially given the Center’s existing demographics. We do so through pipeline programs that develop students from underrepresented groups to have sustained interest and to excel in STEM, presented in this Annual Report’s Section VI, Diversity. Accordingly, many of the Center’s educational programs also have a strong diversity focus. The diversity activities being pursued involve and/or impact many levels: postdocs, graduate students, undergraduate students, and high school students.

At the beginning of this reporting period, Period 4, the Center had 161 students and postdoctoral researchers that have been trained in our Center under the supervision of E^3S faculty. Twice since the inception of the Center, **E. Yablonovitch**, Center Director, developed and taught EE 290: Advanced Topics in Solid State Devices as an online course covering the topics of the Center for E^3S members. Over one-third of our graduate students and postdoc have completed this course. Approximately 50% of the Center’s students and postdoctoral researchers are participants in the Center’s education, leadership, diversity, and outreach programs, serving as mentors, course instructors, outreach leaders, or lab tour guides. The Center also has 29 alumni that are pursuing careers in academic, industry, national research laboratories, or startups.

For our diversity programs, 76% (224) of the 296 students whom E^3S has hosted, directly or through partnering programs, are from underrepresented groups, including women, ethnic minorities, and veterans. Thirty-four percent (100) of the students are pursuing an E^3S-related major (i.e., electrical engineering, material science and engineering, physics, or chemistry). For the Transfer-to-Excellence programs (TTE), which provide community college students a research or course experience at Berkeley, 100% (9) of the participants have transferred to a 4-year institution. Seventy-eight percent (7) of these students are current undergraduate students at Berkeley, where two are recipients of the Regents' and Chancellor's Scholarship, the most prestigious scholarship awarded by the University of California, Berkeley, to entering undergraduates. The other two students are enrolled at University of California, Los Angeles and San Diego. For our upper division E^3S Research Experiences for Undergraduates program (E^3S REU), 24% (7 of 29) of the Center's past E^3S summer researchers have completed their B.S. degree, and 76% are still enrolled. Among this group of graduates, 57% are pursuing a Ph.D. at Berkeley, and two are currently graduate students in the Center.

New in Period 4 is an emphasis of developing educational content that relates to the scope and mission of the Center. This emphasis builds on the online course, Advanced Topics in Solid State Devices (EE 290) of **E. Yablonovitch,** Center Director, developed for E^3S members and expanded to a non-E^3S audience to learn about technical topics relevant to low energy devices, topics that we refer to as E^3S topics. The Center's education strategy to integrate research and education is to build a library of online courses of energy efficient electronics science that will reach a broader audience, including other researchers, scientists, and engineers, undergraduate and graduate students at other colleges and universities, and pre-college students and teachers. In Period 4, **T.-J. King Liu** and **J. del Alamo** have developed online teaching materials. The 2013 summer programs also yielded online educational materials developed by **W. Phillips**, E^3S Teacher Fellow, and **A. Ragsdale,** who taught the Hands-On Practical Electronics Workshop. In Period 4, **E. Fitzgerald** offered an online course in Innovation and Commercialization (MITx:3.086x Innovation and Commercialization) that supports the Center's goal of training the next generation of scientist and engineers to understand innovation and entrepreneurship.

Many established education efforts for training and for professional development of the Center's students and postdocs have continued to be embedded in Center activities.

- The Fourth Annual Retreat included research presentations, review of Center's progress, discussions of competitive research, education and outreach overview, online education, and poster presentations;
- In addition the Third Annual Graduate Student and Postdoc Retreat allowed the participants to share research and learn from each other; and
- The E^3S Research Seminars series and Journal Club held a total of 15 sessions in 2013;

Other training included:

- A career workshop featuring panelists who have worked or are working in industry, academia, and national labs. **C. Chang-Hasnain** *(Berkeley)* **E. Fitzgerald** *(MIT*), **H.-S. P. Wong** *(Stanford)*, and **D. Olynick** *(LBNL)* all spoke on the different career tracks they had taken and offered advice on how to prepare for these careers;
- Project management and mentor training conducted by **S. Artis** for mentors in summer research programs for undergraduates;
- Diversity training conducted by **D. Masterson,** a partner at UC Berkeley, for mentors in summer research programs for undergraduates; and
- Ethics training conducted by **S. Artis** as part of the New Member Orientation at the Graduate Student and Postdoc Retreat.

Leadership opportunities included:

- Organizing the Research Seminar series, the Journal Club and activities of the Graduate Student and Postdoc Council;
- Participation at the STC Director's Meeting as Student or Postdoc Representatives of the Center;
- Serving as leaders on laboratory tours, Cal Day, and Bay Area Science Festival;
- Serving as poster reviewers for the Center's Research Experiences for Undergraduates Poster Session;
- Mentoring undergraduate students doing research at the Center; and

- Serving on the selection committee for applicants to undergraduate summer research program.

In the previous Period 3, the Center focused on implementing our diversity programs and monitoring the outcomes of the programs. In the current Period 4, this reporting period, the Center has focused on streamlining our diversity programs to better align with the Center's vision and goals for enhancing diversity in the field of low-energy electronic devices and cultivating a diverse pool of applicants for our programs. The Center also hired a program manager to share in the management of the Center's pipeline programs, which included two new programs established in Period 4.

- E^{3}S Internship (ETERN), a program for undergraduate students at the member institutions to do research throughout the academic year (20 weeks) with the Center's faculty, expanded to include 9 undergraduates hosted by E^{3}S faculty at Berkeley and MIT. In addition, new in Period 4 was an international internship pilot where one ETERN spent 8 weeks doing research at the École Polytechnique Fédérale de Lausanne, Switzerland.
- E^{3}S Research Experiences for Undergraduates program (E^{3}S REU) at *Berkeley* and *MIT* had 13 rising juniors and seniors. The students conducted 9 weeks of research, each hosted by an E^{3}S faculty (**E. Alon, J. Bokor, E. Fitzgerald, A. Javey, T.-J. King Liu, S. Salahuddin, I. Siddiqi, T. Swager, M.C. Wu,** and **E. Yablonovitch**). In addition, the students participated in enrichment activities, including ethics training and a leadership day where the undergraduates were panelists sharing their experience as undergraduate researchers with lower-division undergraduates and community college students.
- The Transfer-to-Excellence (TTE) program's goal is to inspire California community college students to pursue baccalaureate STEM degrees through research (TTE REU) or cross-enrollment (TTE X-Enroll) at Berkeley. This population has with many students from underrepresented minority groups, student who are first generation to attend college, and students from low-income families. The TTE REU had 7 participants who participated in an 8-week research experience hosted by E^{3}S co-PIs, **T.-J. King Liu, A. Javey, E. Yablonovitch, C. Chang-Hasnain,** and **J. Wu,** and E^{3}S Education Affiliates **A. C. Arias** and **X. Zhang,** and mentored by their graduate students and postdocs. We are developing a network of Education Affiliates, who are faculty outside the Center but are interested in contributing to the Center's Education and Diversity programs. New in Period 4 was the implementation of a 1-week bootcamp on the fundamentals of electronic devices. The Center hosted one TTE X-Enroll student from Berkeley City College. An additional critical program element is year-long transfer advising and support that continues even after the participants' completion of the summer programs. These services are delivered through partners at Berkeley.
- E^{3}S Hands On Practical Electronics Summer Research Workshop (E^{3}S HOPE SRW) hosted 10 lower-division undergraduates, including 2 community college students, for 1week of intense lectures on electronics, hands-on build projects, lab tours, and research presentations. This is a bridge program to stimulate interest in research. New in Period 4 was the recording of the lectures from this program that will be added to the Center's online course library.
- E^{3}S Teachers Fellows Program (formerly Research Experiences for Teachers - E^{3}S RET) hosted two community college faculty members. **W. Phillips**, an instructor in the Electronic Systems Technology Program at Chabot College, hosted by **E. Yablonovitch**, developed curriculum on power and fuel cells for his electronics technician courses. **M. Wong**, a physics, engineering, and astronomy instructor in the Contra Costa Community College District, completed a 10 week research project in the laboratory of **S. Salahuddin.**

The Center's pre-college programs are targeting rising high school seniors. The Center has leveraged the existing partnership and infrastructure at the member institutions.

- Minority Introduction to Engineering and Science (MITES) program; and
- MIT Online Science, Technology, and Engineering Community (MOSTEC).

The pre-college programs promote student's early interest in science and engineering careers, particularly among female and students from underrepresented groups. Emphasis is placed on introducing electronics courses and research experiences in science and engineering to high school students of diverse backgrounds. As a result, the Center envisions pre-college participants as individuals who will enhance the pipeline for a future diverse generation of scientists, engineers, and technicians.

The E^{3}S impact on the two MIT programs includes funding the electronics elective for 12 high school students in the MITES program. In addition, we are one of the founding sponsors of MOSTEC, an online enrichment program for high school seniors that includes an electronics workshop. MOSTEC, now in its third year, also provides a weeklong conference at MIT and assists the participant during the college application process. The Center hosted 41 of students in MOSTEC.

In addition to the operational programs, the Center has focused on active recruitment of a diverse pool of applicants. **S. Artis** and **L. Marlor** recruited this fall for the Center's diversity programs. Targeting upper division undergraduates, they attended 2 diversity and graduate fair conferences and conducted graduate preparation workshops and information sessions at 11 universities. For the Center's community college programs, **S. Artis** and **L. Marlor** presented at 1 conference and 5 information sessions at community colleges.

Knowledge Transfer

The Knowledge Transfer goals of the Center for E^{3}S are to establish industry/education partnerships as venues for introducing new and more efficient electronics technologies and ways to prepare workers at all levels to participate in the new opportunities. As such, Knowledge Transfer includes the transfer of new-found knowledge that is relevant to the Center's research as well as programmatic activities. We think of Knowledge Transfer as cross-fertilization that goes in both directions, up and down the food chain from fundamental research to technology development and ultimately commercialization.

While the Center has placed great emphasis on its relationship with industry as targets for knowledge transfer, there is also a strong recognition of the importance of researchers in academia as knowledge transfer partners. As the Center's research results lead to new research directions, it is critical that other researchers in the same technology domain participate in the pursuit of similar approaches so that a community of like-minded researchers can accelerate towards the goal of ultra-low energy electronic devices.

Key knowledge transfer highlights in the first nine months of Period 4 are as follows:

- The Center was the lead organizer of the 3rd Berkeley Symposium on Energy Efficient Electronic Systems with **E. Yablonovitch** and **J. Bokor** as the co-chairs of the organizing committee and IEEE Electron Device Society as a technical co-sponsor;
- 20 papers on the Center's research were published in peer-reviewed journals, 2 additional are in press and 10 papers are submitted/under review.
- 28 peer-reviewed papers on the Center's research were presented at professional meetings that have published or will publish the abstracts of the talks.
- 2 peer-reviewed papers on learnings and best practices from the Center's programmatic activities were presented at two education conferences that have published proceedings.
- **S. Artis** was conference committee chair of the 2013 Annual Women in Engineering Proactive Network (WEPAN) Conference, where as a panelist, she presented on early engagement of undergraduates in research.

The Center's researchers and staff also used smaller venues for knowledge exchange:

- E^{3}S Theme Leaders presented Center's research programs at Intel (Hillsboro, OR) to Intel's Component Research scientific leadership and its engineers.

- E^{3}S faculty and students, orally and in a poster session, presented the Center's research directions and results at the 2013 annual retreat that included representatives of all 5 industry partners and at the annual meeting of the E3S External Advisory Board which included individuals from academia and industry.
- **S. Artis** discussed diversity recruitment partnerships at the Education and Diversity workshop of the 2013 STC Director's Meeting.

External Partnerships

Nearly all elements of the Center for E^{3}S have partners to help achieve the goals. Even before the Center's inception, industry partnerships were formed, and the Center continues to view industry partnerships as the cornerstone in the execution of E^{3}S' two-way knowledge transfer strategy. The Center's researchers have formal and informal partners as they pursue their scientific investigations. The education and diversity programs leverage the experience and resources of campus partners to deliver programs at the member institutions. The Center continues to execute and enhance its partnership strategy to enable successful achievement of all its goals.

In Period 4, the Center for E^{3}S has continued to strengthen its partnership with industry through the five member companies, Applied Materials, Hewlett-Packard, IBM, Intel and Lam Research. Intel has continued to have a research development relationship with the Center through **M.C. Wu**, leader of Theme III. In Period 4, the representative of all member companies participated in at least one Center function. Newly emerging is IBM's interest to provide characterization support to Theme II's squitch research project.

E^{3}S researchers have worked with colleagues affiliated with academia in and outside the U.S. to achieve their research objectives. These mainly informal partnerships are for material growth and characterization. **C. Hu** *(Berkeley)* is hosting a graduate student from National Chiao Tung University (NCTU), Taiwan. This is part of a collaboration on tunneling FET research with the NCTU group that is funded by Taiwan's I-Rice program. One research group in Switzerland, with whom we collaborated in organizing two knowledge transfer events in 2012, hosted an ETERN from E^{3}S for 8-weeks of research in this past summer. In Period 4, we used the 3rd Berkeley Symposium on Energy Efficient Electronic Systems to engage other research centers working in the same domain, just as was done when the Center organized the 2nd Berkeley Symposium.

The Center's education and diversity programs have continued to leverage the expertise and resources of campus partners. Our MIT partners have enabled E^{3}S to deliver electronics training for a high school online community (MOSTEC) and to support REU interns at the laboratories of E^{3}S MIT faculty. At UC Berkeley, collaboration with other summer internship programs on campus has provided the participants with more substantive experiences and the possibility to be part of a large community. In Period 4, we developed new partners at UC Berkeley to enhance diversity recruitment and support the transfer of community college students who are alumni of the Center's programs.

The success of our programmatic activities also relies on partners who are outside the center's member institutions. For the Transfer-to-Excellence program for community college students, we have continued to partner with MESA for recruitment and UCLA's CCCP to provide transfer support to the Center's community college alumni when they return to southern California. We are partnering with two other STCs on REU recruitment for the 2014 summer programs.

Center Management

The Center has continued to measure the effectiveness in its leaders primarily through two perception surveys of the faculty, postdocs and graduate students. Of key interest is the Center's leadership ability to instill what it espouses as values into the Center: inclusiveness, teamwork, open and timely communications, agility, focus on performance, and ethical conduct.

- Student and Postdoc Survey: Period 4 is the third year that the Center has surveyed its graduate students and postdocs. Graduate students and postdocs were surveyed on the climate of the Center in terms of the first five stated values of the leadership team. Overall, survey results indicate that the students and postdocs' agree (Likert score = 4.1±0.2) the Center is living up to its values. The Period 4 aggregate result is similar to the results of the two previous reporting periods: Period 3 = 4.0±0.3; Period 2 = 3.9±0.2.
- Co-PIs Perception of the Center's Collaboration, Ethics, and Leadership Team: A Survey of E^{3}S faculty's perception was administered for the second time in Period 4. The first survey only addressed collaboration and ethical conduct, and the Period 4 survey was expanded to include questions on the behavior of the Leadership Team. Unfortunately, faculty participation in this period's survey was not statistically sufficient to allow conclusions on collaboration, but results on Ethics and perception of the Leadership Team can be reported**.**

  The survey on the Leadership Team addresses the Leadership team's practice of the values promised in the Strategic Plan and the provision of technical leadership in relationship to the Center and each faculty respondent.

Promoting an inclusiveness environment	4.8
Promoting teamwork	4.7
Communicating in an open and timely manner	4.7
Making decision in the Center's interest	4.3
Recognizing a co-PI's performance	4.8
Promoting strong ethics	4.9
Providing technical leadership	4.9

- The Center's Strategic Plan calls for assessing whether the Center members are behaving ethically, in terms of plagiarism and sharing of credits when working together. Until now, we have not received any direct complaints of plagiarism nor are there authorship disputes. Nevertheless, we have taken a proactive approach by including survey questions to understand the graduate students' and postdocs' view of the ethical climate of the Center. In Period 4, the section on ethics in both surveys was modified to bring further clarity, especially to allow followup by our external evaluator, should the answers call for intervention. We conclude from the data from both surveys that there are no unethical situations in the Center.

A key Center Management initiative in Period 4 has been the integration of the new research group at The University of Texas at El Paso *(UTEP)*, led by **D. Zubia**. The solution was to ramp up the new faculty's acquaintance with the Center's faculty and activities. This was accomplished through a two-month residence at Berkeley by **D. Zubia** and a UTEP graduate student during which they successfully collaborated with **C. Chang-Hasnain** on the Selective Growth of InP Nanopillar. In addition, **T.-J. King Liu** and **E. Alon** each hosted a junior from UTEP in last summer's REU program.

The E^{3}S Executive Committee continues to provide management oversight as well as planning and making decisions for the Center. From the annual survey data, we learned that graduate students and postdocs of the Center agree that the Center's leadership has been effective and agile in decision making; Likert average rating of 4.2. They also agree that the Center's leadership has focused on performance; Likert rating of 4.1. The committee's work has mainly been done through regular meetings, which are pre-announced with agendas. These processes were shared previously in the Period 2 annual report. Six Executive Committee meetings were scheduled in Period 4, held via teleconferencing.

The primary sources of external advice and guidance for the Center for E^3S are two groups: the External Advisory Board and the Industrial Research Board, both of which met in Period 4.

- The E^3S External Advisory Board experienced the following changes: (i) appointment of a new chairperson as the founding chairperson stepped down after a 2-year term; (ii) appointments of 4 new members, including two individuals who have strong expertise and interest in education and diversity; and (iii) resignation of two members. The Period 4 committee is given in Section VII – Center Management of the Annual Report.
- The Center for E^3S is fortunate to have received strong support from four leaders in the semiconductor industry, even before it was founded. In Period 3, we expanded the Industrial Research Board to reflect the addition of a new industry member. The Period 4 board's membership changed as the executive liaison at two member companies left their employers. Representatives of all five member companies attended the Center's 2013 Annual Retreat in August. The Retreat provided time for the Industrial Research Board to meet with the Center's Executive Committee. The industry representatives provided input on the technical presentations that preceded the Board meeting and shared how their companies are planning for the need of lower energy device technologies.

Center Output

Publications		
	Peer Reviewed Journal Publications	20
	Peer Reviewed Journal Publications – In Press	2
	Peer Reviewed Journal Publications –Under Review/Submitted	10
	Peer Reviewed Conference Proceedings	10
	Books and Books Chapters (In Press)	2
	Non-Peer Reviewed Publications	4
Conference Presentations (Talks and Posters)		37
Other Dissemination Activities (including Invited Talks)		21
Awards and Honors		14
Ph.D. and M.S. Graduates		12
Postdoc Alumnus		10
Patents Disclosures		1

PLANS FOR PERIOD 5

Research: The Center's four Themes and the System Integration research effort will continue, but changes are expected in Period 5 that will contribute towards new technical directions for the Center in its 2nd five years.

- Research Directions

System Integration: The principal goal continues to be the exploration of the implications of actual communication and computation circuits/systems on the design, optimization, and requirements of the emerging device technologies being explored in the Center. We further aim to develop circuit techniques that utilize the characteristics of these emerging devices as well as eventually carry out experimental demonstrations of the proposed circuits/systems.

The number of research projects that require circuit and systems analysis is expected in increase in Period 5. To accelerate progress the System Integration research team is growing in Period 5.

Theme I: The Period 5 work plan reflects a year of transition, as the Theme I's technical direction consolidates. Most projects that have been initiated in past periods will continue and evolve around the four approaches: the bilayer switch, nanowire tunnel FETs, monolayer semiconductors, and the systematic study of controlled growth on diode switching performance. To enable a tighter focus among researchers, the Negative Capacitance project will not be pursued. The goal is to go beyond spatial inhomogeneity to determine the intrinsic band edge steepness that will limit Tunnel switch performance.

In view of the need for structural perfection at the quantum level, in Period 5 we will recruit new research partners who could contribute toward bottom-up fabrication of chemically perfect device structures.

Theme II: Theme II will continue to focus on device approaches and materials studies to overcome the fundamental energy-efficiency limit of a mechanical switch set by contact surface adhesion. A laterally actuated relay design with sub-lithographic contact gaps will be developed for use as a vehicle to investigate these approaches as well as to allow the investigation of energy-efficient systems. The two approaches will be pursued are the squitch and the tunnel switch. Materials studies to ameliorate surface adhesion will focus on low adhesion 2D and 1D materials.

Period 5 will see additional efforts to plan for a circuit demonstration of millivolt switching relays.

Theme III: This Theme is continuing on the same direction towards few-photon optical communications, using previously articulated antenna enhanced LED transmitters and ultra-sensitive photo-receiver concepts. Consideration of different device design options for integrated photo-receivers has coalesced around the bipolar photo-transistor concept. Advancements in device performance will be accompanied by additional efforts toward optical mode-matching for waveguide integration. Period 5 should see additional results from an effective collaboration between Berkeley and UTEP as part of this Theme, as well as the availability of epitaxial materials grown within the Center for Theme III emitters and photo-receivers.

Theme IV: The transition of research projects to the concept of current controlled switching of nano-magnets followed by magneto-resistively controlled currents with net current gain and fan-out will be complete. At the same time, new concepts have emerged toward phase-transition picosecond magnetic switching. On the other hand, the project on electric field controlled magnetic switching will not continue owing to the promise of the spin Hall effect toward low voltage current controlled switching.

Research Faculty

Adding Florida International University (FIU) as fourth subaward institution will enable a new faculty, **S. Khizroev**, to be part of Theme IV. **S. Salahuddin** *(Berkeley)* will focus on Theme IV research objectives and will not participate in Theme I. Changes in Theme IV are also leading to two Berkeley faculty, **R. Ramesh** and **S. Siddiqi**, not continuing with the Center in Period 5.

To expand research investigations with circuit and systems implications and in anticipation of a circuit demonstration in Theme II, **V. Stojanovic** *(Berkeley)* will join the Center and collaborate with **E. Alon** *(Berkeley)* and the Theme leaders to accelerate the projects that require circuit/systems analysis.

- Programmatic Activities

In Period 5, we do not expect changes in direction in the Programmatic Activities. We will mainly continue the previously communicated strategies, continue with the established programs, and make changes as call for by the strategies. Below, we highlight changes that we are expecting in Period 5.

Education: In Period 5, the Center for E^{3}S will continue to expand the E^{3}S online library of educational modules, and develop a comprehensive access strategy. We will continue to use the iLab of MIT as an online laboratory platform. The pilot that illustrates issues of energy flow, storage, and dissipation in a digital inverter during switching, developed in Period 4, will be offered to the high school seniors in the MIT Online Science Technology Engineering Community (MOSTEC). The Center plans to develop additional experiments for MOSTEC, should the pilot be well received. With our community college partners, we will assess the applicability of iLab as a resource to enhance engineering and technician courses at community colleges.

The Center will also design a weeklong E^{3}S Summer School for undergraduates. Potential topics for the course would be: Quantum Mechanics, Optical Devices, Memory, MEMS, Nanoelectronics, Material Growth, Spintronics, and Innovation. These topics will be covered through classroom lectures and lab tours. Additionally, the summer school will include a day focused on graduate admission and preparing for graduate school. The secondary goal of this program is to attract underrepresented students to the Center. Therefore, we will collaborate with minority serving institutions to advertise this program.

To provide additional advice and guidance on education and diversity strategies and programs, the Center will begin having Education and Diversity Advisory Board meetings every spring. The Center has identified members with interests and experience to advise on education, particularly online education, and diversity. These members will have their first meeting in April of Period 5.

Knowledge Transfer: The second objective in the Center's Knowledge Transfer goals calls for engaging government stakeholders on energy efficient electronics research. This begins with engaging the general public, a direction that will command more of the Center's attention in Period 5. We will do so through science demonstrations at public outreach events. Dissemination of educational videos that are made by E^{3}S members, also part of the Center's education plans, will also further knowledge transfer. We expect that such dissemination will begin in Period 5.

In Period 5, as the research direction and programmatic endeavors of the past 4 years delivered definitive results, we look forward to additional peer-reviewed publications and conference presentations.

External Partnerships: The Center will work to increase its technical engagement with industry members in Period 5. In particular, there are two opportunities at IBM: the characterization of the organic films for the Squitch project with IBM Watson Research Center through P. Solomon and the provision of III-V material on insulator for Tunnel FETs (Theme I, MIT) by L. Czornomaz of IBM Zurich Research Laboratory.

We are seeking international partners to provide research experiences for the Center's ETERNs. We will do so through Center alumni outside the U.S. As the Center accelerates its online education and outreach activities, partnering with experts in online teaching platforms and multimedia tools will help jump start the Center's efforts.

We will apply additional efforts to expand industry membership, particularly to include mid-size companies.

Diversity: In Period 5, the Center will continue to target recruitment efforts to attract a pool of diverse students to our programs and expand our public outreach activities across the E^{3}S institutions. For recruitment, the Center will continue to visit and inform minority serving institutions and colleges and universities that do not have research opportunities for undergraduate students of E^{3}S opportunities. The Center will also continue to offer information sessions, attend diversity conferences, and host webinar series.

New in Period 5 will be E^{3}S Outreach Kits to increase students' interest in science and engineering. The Center is planning to develop a suite of outreach activities that can be used across E^{3}S institutions to engage students from underrepresented groups in areas of energy efficient electronics science.

II. RESEARCH

1a. Goals and Objectives

The transistor suffers from a serious drawback, in that it requires a powering voltage close to 1Volt (>>kT/q=26 milli Volts) to operate well. On the other hand, the wires of an electronic circuit could operate, with tolerable signal-to-noise ratio, at voltages as low as a few milli-Volts. Owing to this excess voltage, the energy per bit-function in digital electronics is currently ~10^6 times higher than it need be.

At a high level, the new switch is targeted to have the following specifications:

- Steepness (or sensitivity): ~1mV/decade, allowing switches with a swing of only few milli-volts.
- On/Off current ratio: 10^6:1
- Current Density or Conductance Density (for miniaturization): 1 mS/μm; i.e., a 1μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in mSiemens/μm of conductance versus the traditional requirement of 1 milli-Amp/μm, reflecting the Center's target operating voltage of significantly less than the 1 Volt.)

Power consumption by electrical interconnects, used for both off and on-chip communication, have also been increasing. Today, off-chip electrical interconnects use ~1 pJ/bit of energy to communicate, while the energy for on-chip interconnect is ~100fJ/bit. Optical interconnects have the potential to be a low power consumption alternate and the Center' high level goal of the optical interconnects is to achieve close to quantum limit detection (20 photons/bit) and atto-Joule/bit communication (~20 aJ/bit), when including the receiver system.

For Nanomagnetics, the Center's most futuristic Theme, the goal is to achieve spintronic devices that will operate as close as possible to the fundamental limit of energy dissipation of *k*Tln2 that Landauer has predicted theoretically [2].

While these high level goals and objectives serve as a technical vision, the Center also is continuing to define more detailed circuit/system-level requirements for future, low-energy switching devices that will serve to guide the Center's research program. The definition of these requirements – as well as the justification for the steepness, on/off ratio, and conductance density requirements listed earlier – is itself a series of research projects that is part of the "System Integration" research of the Center. The System Integration efforts will also explore optimized circuit/device co-design strategies; and eventually, support experimental demonstrations of the novel devices in complete circuits

Details of the Center's research goals and objectives are given below in the context of the Center's research in Period 4 (Section II.*2a*).

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Integrative Research	Multi-PI Projects	Yearly	Period 2: 30% Period 5: 75%
	Multi-Institutional Projects	Yearly	Period 2: 10% Period 5: 30%
	Unplanned research projects	Yearly after Period 2	Period 3: 1 Period 4: 3 Period 5: 0
	New joint research funding opportunities	Beginning in Period 3	Period 3: 1 Period 4: 2 Period 5: 2
	Publications with authors from multiple	Yearly	Period 3: 12

	institutions	beginning in Period 2	Period 4: 3 Period 5: 5
	Publications with authors from multiple departments	Yearly	Period 4: 2 Period 5: 4

1c. Problems Encountered

Theme I:

The research towards realizing a nanowire Tunnel FET in **J. del Alamo**'s laboratory at MIT encountered significant process development challenges in Period 4 before achieving the first device milestone, namely the demonstration of a nanowire MOSFET. This has hampered progress on developing the theory behind the approach. In addition, the upcoming milestone of studying the density of states of a superlattice-source transistor will require the application of a low temperature source for Ballistic-Electron-Emission Microscopy (BEEM). Despite exhaustive search, a suitable tool has yet to be located.

Theme II:

The Period 4 work plan called for prototype device demonstrations of sub 1 volt switching within the three key projects of the Theme. Progress toward this goal has been slowed by various technological challenges.

- At Berkeley, the group of **T.-J. King Liu** was pursuing an out-of-plane-actuated switch design for the Tunneling Relay prototype device with sub-nanometer contact gaps. This approach has proven to be impractical due to process variations within the university research lab environment which make the control of thin-film residual stress and strain gradient impossible. The King-Liu group therefore has designed a laterally actuated relay which is anticipated to be demonstrated at the beginning the next reporting period.
- At Stanford, the group of **H.S.P. Wong** was studying graphene as a structural material. Surface adhesive force prevented the three-terminal prototype device designed in the last Period from properly functioning. The issue was attributed to insufficient structural stiffness (spring restoring force) of the extremely thin structure. The Wong group therefore has modified their approach to use graphene/graphitic layers coalesced with metal to controllably increase structural stiffness. Material synthesis methods and process integration are in development.
- At MIT, **J. Lang**'s team experimented with a number of molecular coating integration approaches to arrive at a viable squitch fabrication process. A successful proof of concept was achieved for the squitch. Further work will focus on newer organic films, engineered to have sufficiently low stiffness for sub-1 Volt squitch operation.

Theme III:

Unexpected down time from collaborators and long lead time from vendors led to a very long wait for the III-V epitaxial wafers needed for the nanoLED project undertaken in the laboratory of **M.C. Wu** (Berkeley). The Wu lab has reached out to the G. Fitzgerald group (MIT) on growth of the epitaxial InP and InGaAs wafers. We are hopeful that collaboration within the Center for epitaxial materials will ease the III-V material supply needed in Period 5.

The laboratory of **C. Chang-Hasnain** *(Berkeley)* had planned the III-V phototransistor to be based on InGaAs. Experimentation revealed two issues: i) To compensate for the uncertainty of the doping concentration, the device needs a thicker base region, which will lead to higher capacitance and thus, a slower and less sensitive device; ii) A complicated etching step must be used to remove undesirable polycrystalline materials that if left unremoved, would result in large leakage current. These factors led to an InP material system, which does not have a deposited polycrystalline layer, and thus, should give devices with reduced leakage current and higher sensitivity. Additional efforts have been applied to validate the p-n junction of the InP device and thus, delayed achieving the first BJT phototransistor results.

Theme IV:

The last annual report (Period 3) indicated that the project, Electric Field Control of Nanomagnets in $BiFeO_3$ heterostructures, was encountering delays in achieving millivolt switching. To mitigate risk, we initiated a parallel approach for electric field control of a magnetostrictive ferromagnetic material on piezoelectrics. Unfortunately, in Period 4, materials development of this composite material system also has proceeded slowly, deterring progress towards demonstration of switching of nanamagnets at reduced voltage.

The development of an rf SQUID magnetometer for studying spin dynamics is now in its third year. Recently, the instrument has reached a level of development when spins at a relatively high density and at milli K have been detected. The long development process has prevented the instrument to establish a contributing role in a Center focused on room temperature spintronics.

2a. Research Thrusts in Period 4

In the current reporting period, Period 4, the research focus of the Center for E^3S has remained the same as in previous reporting periods. The most challenging aspect of energy efficiency in electronic devices is internal communication in processors. Indeed the main function of the electronic switch is to drive signal currents and voltages along the internal wire in an integrated circuit; these wires are often referred to as interconnects. Through four distinct themes, the Center is researching different approaches to electronic switching and communication at the chip level. The four themes have been with the Center since inception.

I. Nanoelectronics with a focus on solid state millivolt switching
II. Nanomechanics with a focus on reliable, ultra-low voltage operation in solid state relays
III. Nanophotonics focused on few-photon communication
IV. Nanomagnetics that has the potential of approaching the theoretical limit.

Themes I, II and IV are each pursuing a different approach to electronic switching. Theme III addresses optical communication that is gradually replacing wires for longer interconnects in digital systems, both intra-chip and chip-to-chip.

Over-arching these four Themes is the System Integration research, where the outcomes will include a common set of metrics for each of the themes and a systems perspective that will enable future ultra-low energy information systems to be built and integrated using elements of each of these approaches. In addition, there are Theme specific collaborations as each Theme is guided by a circuit/systems perspective. The System Integration research will ensure that the component research outcomes of the Center will be effective in enabling future ultra-low energy information systems.

While the research thrusts have stayed the same, the Center's research program, in its third year (Period 4), is beginning to see changes and consolidation in approaches within each Theme, as we make advancements in our understanding of the technical challenges.

Theme I: Tunnel FETs (TFETs) continues to be a key approach in the Nanoelectronics Theme. Even though the concept has been in research for several years, TFET experiment results have been disappointing, and simulation predicting phenomenal device performance, but experiment faring far worse. The lack of a sound scientific foundation has impeded achieving promising results. The Center is the first concerted effort to focus on the elucidation of the physics of the sharpness of energy bandgaps both theoretically and experimentally.

In Period 4, comprehensive analysis of the Center's own data and published historical device data indicated that the band edges observed in tunnel diodes are significantly less sharp than those reported for the intrinsic optical absorption edges. Even the optical band edges would fall short of the goals of the Center. The observed lack of steepness in experimental devices can be attributed to device inhomogenity, arising from many causes including doping inhomogeneity. Simulations of turn-on characteristics of Tunnel FETs and experimental data on diodes made from well-controlled epitaxial materials further supported this conclusion. The E^{3}S researchers will continue on device demonstration experiments in single quantum channel devices, to overcome inhomogeneity, and to answer how sharp the electrical transitions can fundamentally be. Preliminary efforts to surmount device inhomogenity will begin before the end of this reporting period.

Theme II: The Nanomechanics Theme focuses efforts on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of conventional transistors. Prior research on micro/nano-electro-mechanical (M/NEM) switches concentrated on achieving functional devices with good yield and reliability (to enable integrated circuit demonstrations), and on theoretical studies of their scaling behavior. The Center was the first to pursue experimental investigations in scaling the contact area size to nm^2, and to achieve a mechanical relay with sub 0.1 Volt switching.

Theme II researchers have also been concerned with stiction, which is caused by surface adhesion forces on the contacting surfaces. This affects reliability and causes hysteresis. In the past 18 months, Theme II researchers learned from their experimental and simulation data that surface adhesion forces continue to be important at the nano-scale. Surface adhesion is a fundamental limiter toward millivolt switching that will need to be overcome. The Center's aggressive goals have pushed Theme II researchers as a team to innovate new approaches to overcome this fundamental barrier. The cross-university discussions and collaborations under E^{3}S have elucidated basic requirements and experimental pathways for these approaches. Our research in nano-relays, controlled by an organic "squishable" film is beginning to show a pathway to avoid surface adhesion. In Period 4, feasibility of the "Squitch" concept was demonstrated in a two-terminal device. Another approach to breaking the surface adhesion limit that calls for a sub-nanometer gap is also being pursued. These device feasibility investigations are complemented by studies on the materials science of surface adhesion.

Theme III: The Nanophotonics Theme's target on nanoscale ultra-efficient active optical components for on-chip application differs from the optoelectronics industry efforts which have concentrated on longer distances, and higher energy. The strategy is consolidated to include two elements: i) coupling of optical antennas to nanoscale devices to make spontaneous emission faster than stimulated emission at the nanoscale, and ii) to provide for ultra-sensitive photo-receivers by direct integration of detector and the first transistor, to minimize capacitance in a form of photo-transistor. In Period 4, the research program made progress in applying this strategy. In addition, Period 4 has seen additional emphasis in mode-matching optical antennas to Silicon photonic waveguides.

Theme IV: Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that can approach the Landauer limit [2], or perhaps even surpass it via reversible logic as predicted by Bennett [3]. This Theme has the most fundamental science character, but new material and conceptual breakthroughs are suggesting that applications might arrive sooner than expected. Our initial approach included a mix of projects that investigate the experimental technical foundation of spin-based computing. The effort is to learn more about spin dynamics, particularly at room temperature as well as to demonstrate a basic low energy magnetic switching functionality based on voltage control of magnets. In Period 3, Theme IV researchers began to consider new approaches as the spin Hall effect began to emerge. In Period 4, new Theme IV projects based on current-control of magnetic switching were initiated. This change from voltage control to current control is also leading to changes in the research team composition in the coming Periods.

Also, new in Period 4 is that the member institutions where the Center's research program is taking place have changed. Tuskegee withdrew from the Center at the end of Period 3, while The University of Texas at El Paso (UTEP) officially became part of the Center in mid 2013. This change enabled **D. Zubia** to be the newest E^{3}S faculty, who joined Theme III, undertaking research that is relevant to Nanophotonics. The changes in member institutions are discussed in Section VII – Center Management. The biosketech of **D. Zubia** is given in Appendix A.

Thus, in Period 4, the Center's research is pursued by 21 faculty researchers.

- UC Berkeley: Elad Alon, Jeffrey Bokor, Connie Chang-Hasnain, Chenming Hu, Ali Javey, Tsu-Jae King Liu, Ramamorthy Ramesh, Sayeef Salahuddin, Irfan Siddiqi, Junqiao Wu, Ming C. Wu, and Eli Yablonovitch
- MIT: Dimitri Antoniadis, Vladimir Bulović, Jésus del Alamo, Eugene Fitzgerald, Judy Hoyt, Jeffrey Lang and Timothy Swager
- Stanford: H.-S. Philip Wong
- UTEP: David Zubia

Together, they bring electrical engineering, materials science, physics and chemistry expertise to the Center (Figure 1).

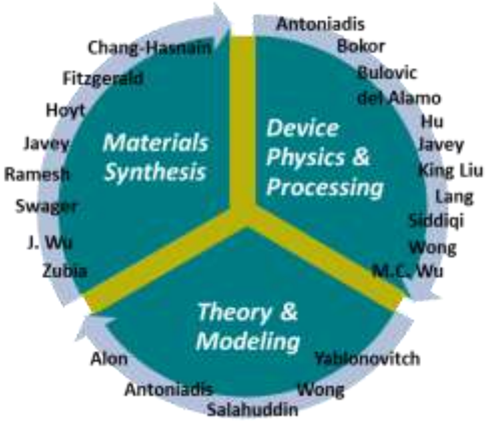

Figure 1: Scientific and Engineering Expertise of E^{3}S Faculty Funded in Period 4

The following table, giving the faculty participation in the five research areas of the Center, is provided as a guide to the following narratives of this Section – Research Thrusts.

Institution	Faculty	System Integration	Theme I	Theme II	Theme III	Theme IV
UC Berkeley	Alon	*x*	*x*	*x*	*x*	*x*
	Bokor	*x*		*x*		*x*
	Chang-Hasnain				*x*	
	Hu		*x*			
	Javey		*x*			
	King Liu	*x*		*x*		

	Ramesh					*x*
	Salahuddin		*x*			*x*
	Siddiqi					*x*
	J. Wu			*x*		
	M.C. Wu	*x*			*x*	
	Yablonovitch		*x*		*x*	
MIT	Antoniadis		*x*			
	Bulović			*x*		
	del Alamo		*x*			
	Fitzgerald		*x*			
	Hoyt		*x*			
	Lang					
	Swager			*x*		
Stanford	Wong			*x*		
UTEP	Zubia				*x*	

The Center's four research Themes and the System Integration effort are made up of multiple projects addressing different aspects and/or utilizing different approaches that will help the Center make progress toward its goals. The faculty and their research groups are taking advantage of the collaborative environment offered by the Center. Most projects involve multiple research groups. Moreover, as the Center and in particular, the Themes, are evolving into a community/communities, informal collaborations also abound.

Theme meetings are evolving to be an important enabler of team science. Faculty members have reported that they highly value Theme meetings where colleagues share issues and approaches, and vet each other's ideas. By comparing and discussing the evolving approaches of the teams in the same Theme, some researchers have reported that they develop new understandings of the fundamentals and thus, have been able to evolve their approaches more rapidly. These interactions are building and enhancing the foundation for team science.

In Period 4, specific examples of collaborations within the Center are given to illustrate the team science in action at the Center for E^{3}S.

- Several E^{3}S faculty acknowledged the role of **E. Yablonovitch**, Center Director, in the direction and outcomes of their research. Examples include the study of band edge sharpness of single layer chalcogenides in Theme I, the research focus on scaling (versus reliability) of mechanical switches in Theme II, and the recently adopted technical directions of Theme IV.
- Research on the bilayer tunnel transistor has been taking place at Berkeley and MIT. While the experimental details are different, the two teams collaborated on the device simulation. The on-current regime was studied in the **E. Yablonovitch** group at Berkeley, while the off-current and parasitic mechanisms was studied by MIT advised by **J. Hoyt** and **D. Antoniadis**. The fusion of these different foci has allowed better modeling of tunneling transistor characteristics. Joint publications have resulted from this collaboration.
- To analyze the switching steepness in a diode, the **E. Fitzgerald** group at MIT is applying the analytical method developed at **E. Yablonovitch** group at Berkeley for analysis of tunneling FET's.
- The development of the squitch at MIT achieved a key device milestone in Period 4. The interactions among Theme II researchers have been central to the development of this switching approach that avoids stiction in relays. The Center members, who are experts in the traditional design of high-performance digital circuits, particularly those at UC Berkeley, have provided the challenging static

and switching metrics that have driven the design process pursued by the squitch team. The squitch researchers reported that "realistically, none of these interactions, and more importantly the development of the squitch in the first place, would have happened without the Center."

- The hosting of **D. Zubia** (*UTEP*) and the graduate student by **C. Chang-Hasnain** in her laboratory in Berkeley supported the integration of the new members into the Center and resulted in significant improvement in nanopillar growth yield.

E^3S seminars and annual retreats are additional venues for students and postdocs to get to know each other and each other's research. In the annual survey, the graduate students and postdocs have indicated that their research has been benefited from the collaborative environment (Figure 2).

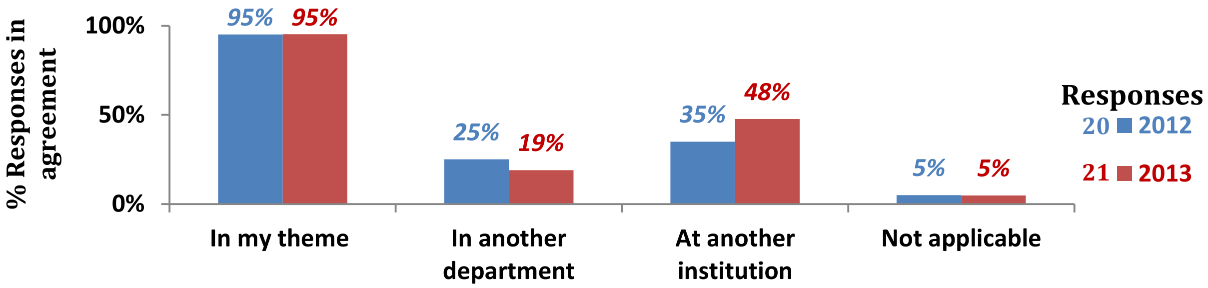

Figure 2: The respondents' research has been helped by discussions, inputs, and collaborations with/from others.

2ai. System Integration Research

In Period 4, the System Integration effort, led by **E. Alon** (*Berkeley)*, sought to complete the generalized analytical framework for the effects of variability and device steepness. In addition, he has worked closely with all four Theme Leaders at Berkeley on projects that have direct impact on their Themes:

- Apply the new, generalized variability analysis framework to provide numerical requirements for specific device designs of relevance to MOSFET alternatives.
- Investigate and optimize the system-level performance, area, and energy design space addressable by ultimately scaled relay-based integrated circuits.
- Develop new receiver circuit topologies enabling ultimately low-energy photonic links.
- Explore the opportunities provided by magnetics-based devices as the front-ends for communication applications, even though the I_{on}/I_{off} of magnetic devices are low.

Details of these System Integration projects are given below.

- Building on efforts of prior reporting period, the comprehensive expansion of the optimal Ion/Ioff analysis to include the effects of variability and how it interacts with the devices' local steepness characteristics was completed in Period 4.

  A key result of this analysis is that it allows us to numerically predict the required level of variability for an alternative switching device with sharper steepness characteristics to achieve the same level of energy consumption as a MOSFET. Figure 3 below shows this numerical prediction for various levels of MOSFET variability.

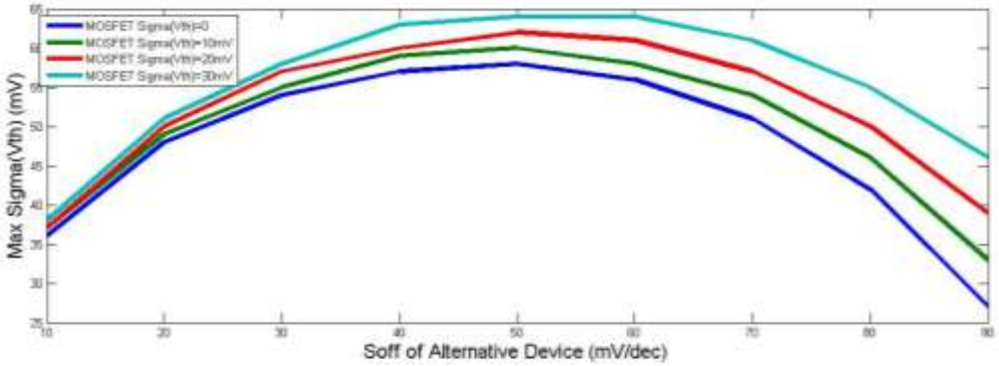

Figure 3: Plot of the maximum allowed threshold voltage standard (σ_{Vth}) allowed for an alternative device to achieve the same minimum energy consumption as a MOSFET (with an assumed S_{off} of ~100mV/dec) under several levels of MOSFET threshold variability.

- The collaboration between **E. Alon** and **T.-J. King-Liu** on relay-based circuits has included experimental efforts. During Period 4, we designed and taped out a complete relay-based microcontroller that addressed several issues that hindered the functionality of our earlier designs. Specifically, plasma-induced charging during the etch of our interconnect layers was identified to cause dielectric shorts-in our earlier circuits (i.e., the so-called antenna effect); the new design therefore took steps to limit the maximum length of any individual wire segment. Testing of this design continues, with early indications that these specific issues have been successfully addressed.

  We have developed an initial design flow that will allow us to fully utilize the timing-, area-, and power-driven capabilities of commercial CAD tools for synthesis and place-and-route. The key challenge is that commercial tools assume CMOS circuit implementations of the standard cells which do not suit the characteristics of relays very well, but we have identified a mechanism to automatically create new "standard cells" based on the intermediate results of the logical synthesis.

- We have completed an analysis of the energy limitations of photonic receivers showing that limitations on the minimum swing at the output of the receiver – and not SNR limitations – typically set the minimum required energy consumption for the entire link (Figure 4).

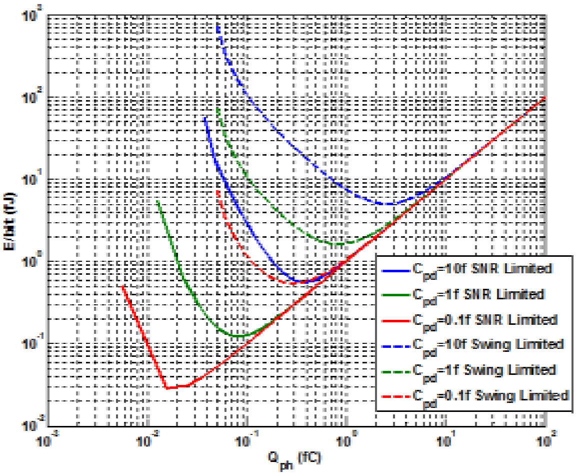

Figure 4: Optimal energy/bit (E/bit) versus transmitted photon charge (Q_{ph}) for swing-limited vs. SNR-limited photonic links.

- We have completed an initial study on utilizing magnetics-based devices for analog applications. Devices which are switched along their easy axis were identified as being unsuitable in most analog applications because they have no region of linear small-signal gain – they instead can only be flipped between distinct states (similar to a relay). However, switching along the hard axis can result in linear small signal gain, and hence we have developed a preliminary small signal model to predict the achievable gain of the device as a function of the device/material parameters.

2aii. Theme I: Nanoelectronics *Theme Leader:* **E. Yablonovitch** *(UC Berkeley)*

In Theme I, the approach is to continue to use a solid-state switch, but with a new switching mechanism, that can operate at a drastically lower voltage than conventional transistors. A main concept involves changing the fundamental switching mechanism from modulating the height of a barrier as in all conventional transistors, to modulating the tunneling current through a barrier. All conventional transistors are thermally activated and respond according to the Boltzmann factor. Tunnel Field Effect Transistors (TFET's) have the potential to be a more sensitive switch, responding more steeply than kT/q, or with a subthreshold swing of less than 60mV/decade (i.e., ln{10}kT/q, where kT/q=26 mV is the thermal voltage at room temperature).

The recognition that TFETs have the potential to be an alternative to ordinary transistors is not new, given the body of prior TFET research. There have been many attempts to experimentally implement a TFET, but the results have been disappointing, with simulation predicting phenomenal results but experiment faring far worse [14] [4]. While there have been reports of steep subthreshold current versus voltage slope, or reports of good On/Off current ratio, or reports of good tunnel conductance, the goal of achieving all three simultaneously, as spelled out in Research Goals and Objectives (Section II.*1a*), has been elusive. In most cases the switching mechanism has been tunnel barrier thickness modulation which is not expected to result in high conductance density while simultaneously satisfying the other two requirements.

The inception of the Center allowed the Theme I Research team to focus on a different mechanism, "Density of States" switching, or an "Energy Filtering" switch, which has the potential to achieve all three requirements simultaneously. As we learned more, the Center's concept to achieve this potential has continued to evolve (Figure 5).

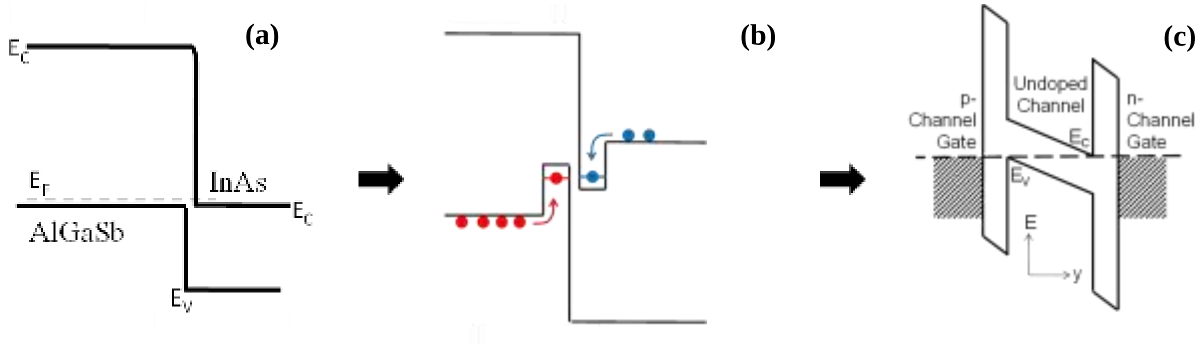

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Figure 5: a) Type III Heterojunction; b) 2D-2D Quantum Well Heterojunction; c) Bilayer Switch

Theme I has continued to increase the scientific understanding of the underlying physics. In this reporting period, Period 4, **E. Yablonovitch**'s group *(Berkeley)* have systematically analyzed data on tunneling structures, available in the open literature and in the Center, to determine what limits their performance and what needs to be done. There are two mechanisms to obtain a steep subthreshold response in a TFET. All of the best results to date have relied on electrostatically changing the tunneling barrier thickness. Unfortunately this has only given subthreshold swings steeper than 60 mV/decade at I_{on} at around 1 nA/um, while we want the I_{on} to be at 1 mA/um. We have proven that devices that rely on this mechanism have a fundamental tradeoff between current density and steepness and will never achieve a steep turn on at high current densities. The Center has focused on the second mechanism for obtaining steepness, the density of state mechanism, also called the “Energy Filtering” mechanism. The current can abruptly turn on when the conduction band and valence band align. However, this requires a steep band edge density of states. To measure the band edge density of states we introduced a new method for analyzing backward and Esaki diodes. This has allowed us to measure the band edge steepness in a variety of published tunnel diodes. Our analysis has found that the heavy doping required to enable a thin tunneling barrier ruins the band edges and resulted in a band edge voltage swing of 90 mV/decade or worse. This understanding supports the need for double gate devices such as the bilayer that the Center proposed in Period 3, as it eliminates doping from the tunneling junction (Figure 5c). But the inherent problem is not the heavy doping, but rather the inherent inhomogeneity associated with doping. This spatial inhomogeneity results in a spatial spread of threshold voltages, ruining the prospects for the steep response. We will deal with inhomogeneity by emphasizing a small area single quantum channel device, which will eliminate the spatial inhomogeneity issue, and we hope will reveal for the first time the true inherent steepness of band edges. This is both of fundamental and practical importance.

In this reporting period, Period 4, the research groups of **E. Yablonovitch** *(Berkeley)* and **D. Antoniadi**s and **J. Hoyt** *(MIT)* have worked collaboratively on device simulation, but with parallel paths to achieve experimental proof of concept for bilayer TFETs. The Berkeley group chose InAs as the active material for its direct gap and low electron effective mass which aid in improving the on-state conductance of the TFET. For the purpose of studying device physics, the MIT group is fabricating a Si/Ge heterostructure based bilayer that leverages their extensive experience in a well-developed materials technology to provide better experimental control for material quality and dielectric interfaces and thus maximizes the potential for a steeper band edge. The emphasis will be on small area devices to reveal the inherent band-edge sharpness, or devices that can be cooled to very low temperatures without contact freeze-out to at least reveal the threshold energy distributions of a multi-channel device.

The simulations of **D. Antoniadis** and **J. Hoyt** *(MIT)* have confirmed that inhomogeneity due to thickness variations results in a very poor subthreshold swing. Figure 6 illustrates how the observed subthreshold swing is a composite of different thresholds turn on at different biases and smear out the gradual turn on. The understanding of the need to avoid the spatial inhomogeneity aligns with the research of **J. del Alamo**’s group *(MIT)* that provides very small devices, allowing allow only a single quantum channel to the tunnel junction. Alternatively, spatial inhomogeneity can be addressed with semiconductor built from materials that naturally occur as an integral number of molecular layers and thus, the group led by **A. Javey** *(Berkeley)* has continued to research monolayer semiconductors.

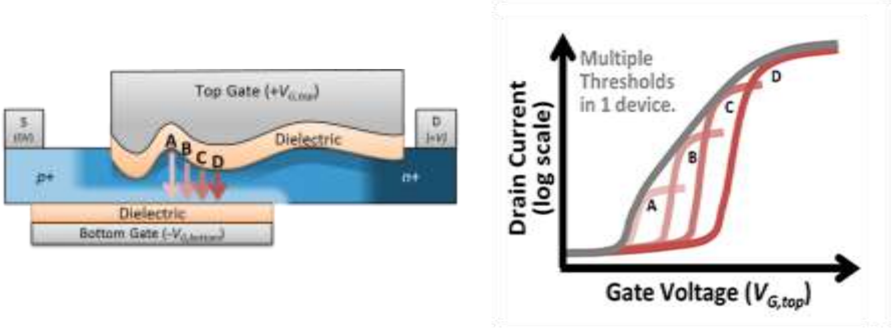

Figure 6: Thickness Variability Leads to Multiple Thresholds

Material imperfections from non-ideal interfaces are sources of undesirable traps [15] [16] [17]. The group of **E. Fitzgerald** *(MIT)* has been researching the impact of material growth conditions on the band edge steepness of InAs/GaSb tunneling diodes. The Fitzgerald group is also addressing the need for very sharp interfaces in epitaxial materials for the rest of Theme I.

As we previously predicted [18], quantum confinement in the tunneling direction can increase the on-state conductance by a factor of 10-100. Thus pn-junction dimensionality has emerged as a new and fundamental criterion for this most venerable solid state component. The Center has two efforts, started in Period 3 and continued in Period 4, on demonstrating InAs/ GaSb TFETs to exhibit a steep turn on and a high on-state conductivity at the same time. One effort is led by **C. Hu** *(Berkeley)* and in collaboration with A. Javey, while the other effort is jointly led by **D. Antoniadis** and **J. Hoyt** *(MIT)*, but these appear to reveal more about the spatial inhomogeneity of threshold voltages, rather than the fundamental information that is needed for low voltage switching.

Another effort continued from previous reporting periods is the experimental proof of concept of using negative capacitance to achieve low energy MOSFET by **S. Salahuddin** *(Berkeley)*. This is an alternative concept to TFETs, pursued since the inception of the Center, as the strategy has been to research more than one approach to solid state switches.

The following sections provide the status of the Theme I research efforts summarized above.

- *Understanding TFET Data*

  The best reported subthreshold swings have been measured at a current density of around a nA/um and get significantly worse as the current increases. The **Yablonovitch** research group *(Berkeley)* sought to understand the issues by systematically analyzing what contributes to the subthreshold swing voltage of a TFET. The subthreshold swing voltage (SS) is given by the following model [19].

  $$SS = \frac{1}{\eta_{el}} \times \left(\frac{1}{S_{tunnel}} + \frac{\eta_{conf}}{S_{DOS}} \right)^{-1} \qquad (1)$$

  η_{el} is the electrostatic gate efficiency. η_{conf} is the quantum confinement efficiency and comes from energy level shifts the occur when the quantum well shape changes with bias. S_{tunnel} represents the steepness in mV/decade that comes from changing the thickness of the tunneling barrier. S_{DOS} is the steepness of the joint density of states (DOS) and represents the rate at which the joint DOS fall off as the band edges are misaligned in mV/decade.

  Either a steep S_{DOS} or S_{tunnel} is needed to get a steep subthreshold swing. First we consider tunneling barrier width modulation, S_{tunnel}. To do this we consider a simple model for the tunneling probability as a function of electric field, F: $T(F) = \exp(-\alpha / F)$ where α is a device dependent constant. Using this we can find S_{tunnel} for the lateral and bilayer tunneling junctions:

  $$S_{Barrier} \approx \left| \frac{d\phi_s}{d\log(T)} \right| = \left| \frac{1}{\log(T)} \times \frac{F}{d\vec{F}(\phi_s)/d\phi_s} \right| = \left| \frac{\phi_s}{\log(T)} \right| \qquad (2)$$

  $\emptyset_s$ is the potential across the tunneling junction and is set by the tunneling barrier height. This simple model clearly shows why all experimental results to date can only show a steep turn on at low currents. As T decreases, S_{tunnel} also decreases. For a T=1%, we need $\emptyset_S < 120$ meV to have S_{tunnel}<60 mV/decade. However, the minimum $\emptyset_S$ will be set by the band edge DOS. If we want 5 decades of on/off ratio, the band edge DOS must be suppressed by 5 orders of magnitude. That means that a 120 meV barrier must have a band edge steepness of 24 meV/decade. Consequently, a sharp band edge DOS is needed to get a steep subthreshold swing at high current densities.

  Accordingly, we consider the band edge steepness, S_{DOS}. From optical absorption measurements we get a lower limit on S_{DOS} of 17 meV/decade in intrinsic bulk GaAs [20]. In practice, heavy doping destroys that band edge and gives an optical S_{DOS} worse than 60 mV/decade [21]. Therefore, doping must be eliminated from the tunneling junction. This can be done with a bilayer or with a modified lateral structure as shown in Figure 7.

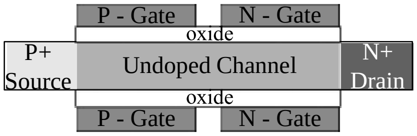

Figure 7: A lateral tunneling device with both an N and a P gate is shown. The double gate structure eliminates doping from the channel.

To electrically measure S_{DOS} in tunneling diodes, The **Yablonovitch** group has introduced a new method to analyze tunneling diodes. The absolute conductance, I/V versus bias voltage V in a tunneling diode should be interpreted. The absolute conductance is proportional to the tunneling joint density of states. This is discussed in detail in [21]. In a TFET the gate controls the channel resistance by changing the tunneling density of states, while the source drain bias determines the Fermi levels and thus the current level. Since the resistance change is most relevant, we need to look at the resistance or absolute conductance in a tunneling diode.

Consider the current-voltage characteristics of an InAs/AlSb/$Al_{0.12}Ga_{0.88}As$ heterojunction backward diode [22]. The I-V curves are in Figure 8(a) and the absolute conductance is in Figure 9(b). Since the conductance is proportional to tunneling joint density of states, we can measure the inverse of the semilog slope of the conductance, called the semilog conductance swing voltage, to find the steepness of the tunneling joint density of states in mV/decade. This is indicated by the inverse slope of the diagonal line in Figure I-4(b). As shown in the figure, the semilog swing voltage of the smoothly varying absolute conductance is 98 mV/decade and it measures the tunneling joint density of states. It has one of the lowest tunneling joint density of states measured which is likely due to the fact that it has one of lowest doping levels of $1.4\times10^{17}/cm^3$ near the tunneling junction.

In Figure 8(c-d), a germanium backward diode [23] is considered. This has the steepest semilog conductance swing voltage of 92 mV/decade that we could find. Next, In 8(e-f), we show the current and conductance for an InAs homojunction diode at two different doping levels ($N_A = 1.8\times10^{19}$; $N_D = 3\times10^{18}$ and 1×10^{19}) [24]. When the n-side doping is increased from $3\times10^{18}/cm^3$ to $1\times10^{19}/cm^3$ the absolute conductance I/V swing drastically increases from180 mV/decade to 570 mV/decade and clearly illustrates the dangers of smearing a band-edge by doping too heavily.

In Figure 8(g-h), we analyze the I_D-V_D characteristics of an $In_{0.53}Ga_{0.47}As$ TFET that has a poor gate oxide [25]. The measured subthreshold swing voltage is 216 mV/decade. The measured I_D-V_D semilog conductance swing voltage is 165 mV/decade. Since the I_D-V_D characteristic is not limited by the gate oxide, it reflects the junction’s steeper intrinsic tunneling properties. This shows the value of using the semilog conductance swing voltage to analyze a TFETs potential performance when the gate oxide has poor quality.

In TFETs, subthreshold swing voltages less than 60 mV/decade have been measured, but the best diodes only show swings worse than 90 mV/decade. This is because the steep swings have only been measured at extremely low current densities of a nA/um. These low current densities have been obscured by trap assisted tunneling and the forward bias current in diodes.

Overall, we see that we must have a steep band edge density of states to get a steep subthreshold swing at high current densities. Consequently, we must eliminate doping and preserve the material quality in the tunneling junction to get a steep density of states turn on.

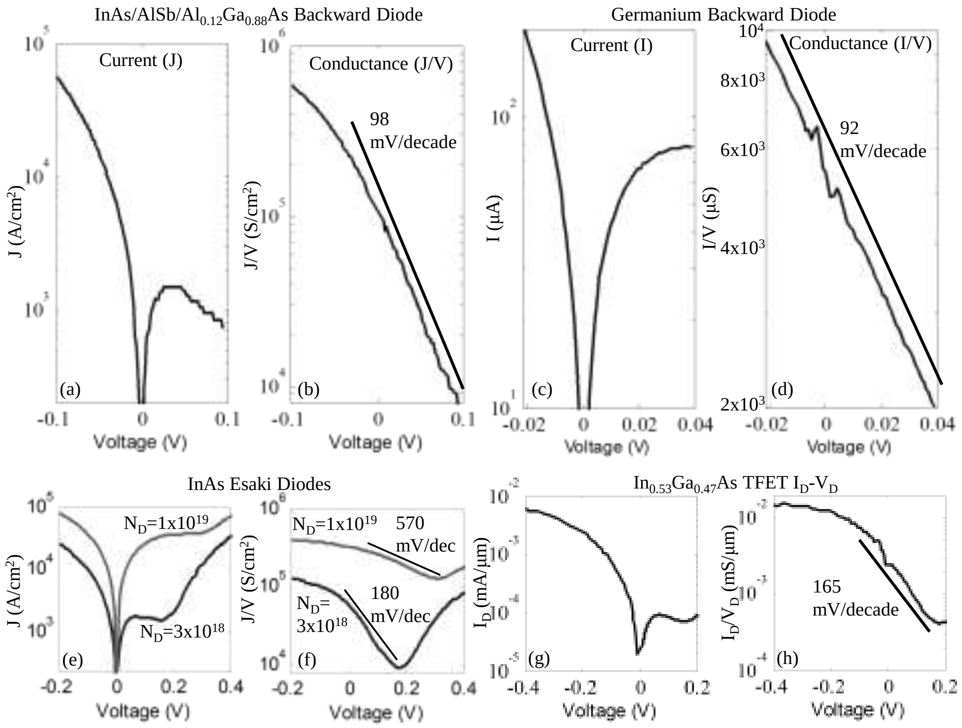

Figure 8: (a-b) The current and conductance for an $InAs/AlSb/Al_{0.12}Ga_{0.88}As$ heterojunction diode [22], (c-d) a Germanium diode [23], (e-f) and InAs diodes [24] are plotted. At V=0, the current diverges on a log plot and so the logarithmic slope is meaningless. The conductance is proportional to the tunneling density of states. (g) The I_D versus V_D and (h) $G=I_D/V_D$ versus V_D for an $In_{53}Ga_{0.47}As$ TFET is plotted [25]. The measured subthreshold swing voltage is 216 mV/decade, while the semilog conductance swing voltage is 165 mV/decade. Since the I_D-V_D characteristic is not limited by the gate oxide, it reflects the junction's steeper intrinsic tunneling properties.

- *Bilayer TFETs*

  The researcher groups of **E. Yablonovitch** *(Berkeley)* and **D. Antoniaids** and **J. Hoyt** *(MIT)* collaborated to complete the second phase modeling and simulation analysis of the electrostatically doped electron/hole 2D-to-2D ("bilayer") tunneling device structure. The simulation analysis addressed the tradeoff between gate efficiency and on-state current to find the optimal device design.

  - *InAs Based Bilayer - Towards Experimental Proof of Concept*

    For our first proof-of-concept demonstration of the bilayer TFET, the team at Berkeley has chosen InAs as the active material for its direct gap and low electron effective mass which aid in improving the on-state conductance of the TFET. A cross-sectional diagram of the InAs bilayer TFET is given in Figure 9.

    The simulation analysis found that an InAs homojunction bilayer provided the best tradeoff between gate efficiency, on-state conductance and complexity. This device is being fabricated using the XOI processes of the A. Javey group which will allow for the vertical double gating of InAs films [26].

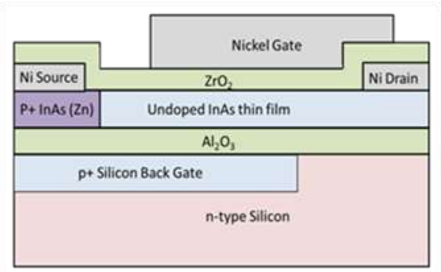

Figure 9: Cross-sectional diagram of the InAs Bilayer TFET in fabrication at Berkeley

Processed silicon substrates which enable the localized back-gating of the transferred InAs films have been fabricated and characterized. Initial device results are expected at the end of this calendar year.

- *Si/Ge Heterostructure Based Bilayer - Towards Understanding Device Physics*

  To help elucidate the device physics, the team led by **D. Antoniadis** and **J. Hoyt** *(MIT)* chose a material system with which they have extensive experience and will give a reasonable energy gap of $E_{G,eff}$ = 185meV. A cross-sectional diagram of the Si/Ge bilayer TFET is given in Figure 10a. Using a well-established fabrication procedure will reduce gate interface traps, defect states and spatial inhomogeneity that has limited the subthreshold swing of previous experimental efforts.

  The simulation showed that a thicker body and smaller effective band gap will reduce the applied voltage or workfunction difference required for eigenstate alignment (Figure 10b). Consequently, the strained-Si/strained-Ge heterostructure is an ideal candidate to do this. The simulation work also analyzed the impact of thickness variation on the turn-on voltage. A thicker body results in a thicker tunneling barrier and thus a lower tunneling current. However, decreasing body thickness increases quantization and the voltage required for band alignment. Furthermore, thickness fluctuations result in severe threshold voltage variations that will smear out the turn on if the body is too thin. Consequently, the body thickness was optimized to find the best tradeoff between thickness fluctuations, on current and workfunction difference.

  Fabrication of the s-Si/s-Ge electron/hole bilayer (3Gate) TFETs will begin in the last months of this reporting period.

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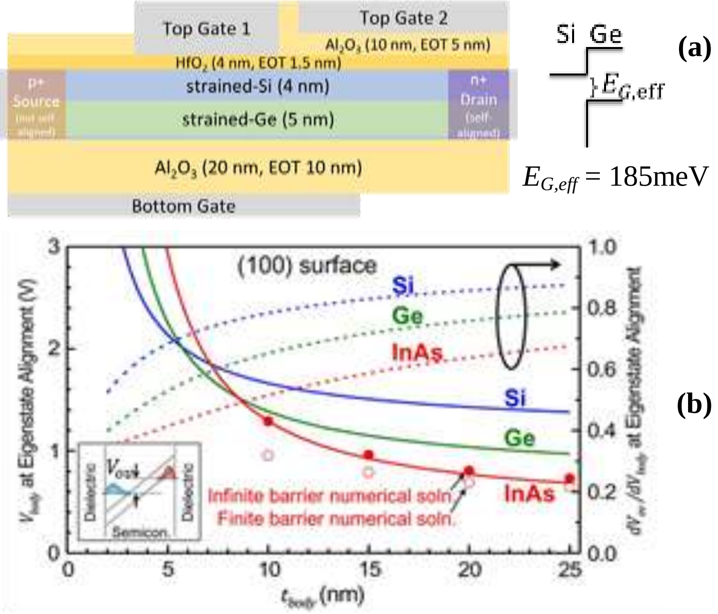


Figure 10:

a) Cross-sectional diagram of the Si/Ge Bilayer TFET under investigation at MIT;

b) Impact of semiconductor body thickness on voltage required for eigenstate alignment

- *Superlattice Nanowire FETs – Towards Experimental Proof of Concept*

  In alignment with the understanding of the need for very small device, thereby limiting the tunnel junction and avoid spatial inhomogeneity, is the Superlattice Nanowire FETs (SLS NW-FETs) research of the **del Alamo** group (*MIT)* with the goal of achieving the first experimental demonstration and enhancing the fundamental understanding of the switching mechanism. A top-down fabrication approach has been pursued. Bottom-up fabrication techniques are not considered to be manufacturable as Au particles are used as seeds or highly specialized epitaxial processes are utilized. Bottom up techniques also may not be able to implementthe SLS-MOSFET. Top-down techniques allow one to use commercial epitaxial heterostructures that are widely available and of very high quality and then through etching, a nanowire is formed. The top-down fabrication approach is expected to more flexible and less expensive.

The initial focus of Period 4 has been to demonstrate a MOSFET; i.e. an InGaAs Vertical Nanowire FET without a superlattice. The biggest challenge is the need for an etching technology for In-containing compounds that allows the creation of high-aspect ratio structures in the nanometer scale. We have successfully established this technology that involves Reactive Ion Etching (RIE) and is followed by controlled digital etch. Figure 11(a) shows an InGaAs nanowire after RIE with a diameter (D) of 30 nm and an aspect ratio of 10. Such an etching technology is critical to realize the quantum confinement required to demonstrate the SLS NW-FET, according to our simulation. We have also developed an integrated process to fabricate wrap-around-gate vertical nanowire field-effect transistors in III-V heterostructures. A D= 30 nm device wrapped around by Tungsten gate metal is shown in Figure 11(b). This is the first top-down fabrication approach for vertical nanowire III-V transistors ever demonstrated. This process can be readily adopted to the fabrication of SLS NW-FET without significant modifications.

Using the newly developed processes, we have successfully fabricated InGaAs Vertical Nanowire MOSFETs with a wrap-around gate by our new top-down approach. We have successfully demonstrated 30-50 nm diameter MOSFETs. The output characteristics of a D= 30 nm transistor are shown in Figure 12. They demonstrated excellent saturation at low V_{ds} with R_{on} = 759 Ω·µm. A peak g_m of 280 µS/µm is extracted at V_{ds}=0.5 V. A subthreshold swing of 145 mV/dec at 0.05 V and 200 mV/dec at 0.5 V are obtained. We have also observed a marked improvement in the electrical characteristics as a result of digital etch. In terms of a balance between short-channel effects and transport, these devices are as good as the best vertical nanowire transistors fabricated by bottom-up techniques [27] [28].

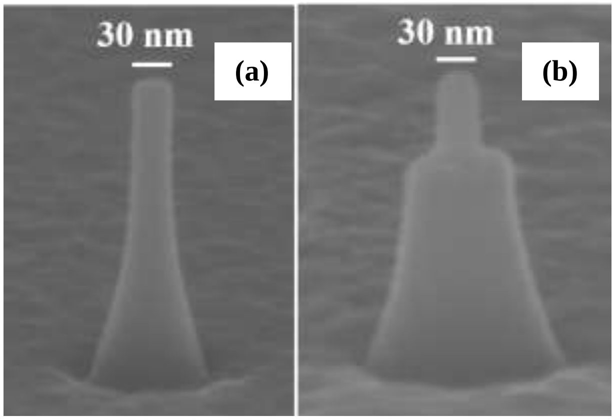


Figure 11: a) D=30mm InGaAs nanowire with an aspect ratio greater than 10; b) D= 30 nm device wrapped around by W gate. The top region is exposed for ohmic contact formation.

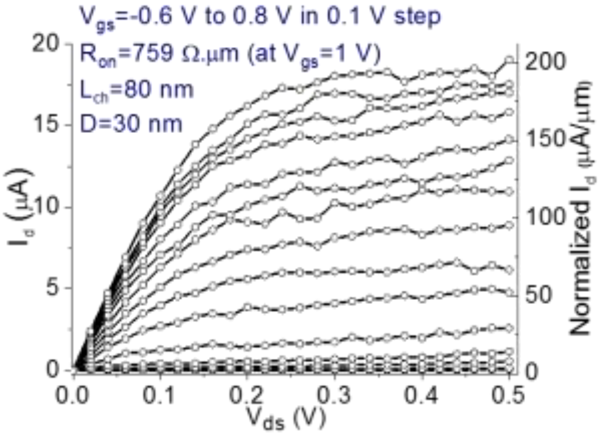


Figure 12: Output characteristics of a D=30mm InGaAs single NW MOSFET with 4.5 nm Al2O3 as the gate dielectric and L_{ch}=80 nm.

This nanowire MOSFET has been a demonstration vehicle and process development driver. Without the complication of the superlattice, the fabricated nanowire transistors are allowing us to investigate important issues such as interface quality, electrostatics and ohmic contacts.

Before the end of Period 4, we will initiate the fabrication of InGaAs-based Nanowire Tunnel FETs using the new nanowire fabrication process. This new goal is in support of the previously discussed theoretical insights in Theme I that have established the need for very small devices to minimize the averaging of electrical characteristics that softens the minimum subthreshold swing that can be obtained.

- *Monolayer Semiconductors*

A. Javey and his research group (*Berkeley)* are investigating monolayer semiconductors to address the need for atomically flat thickness for reproducible threshold voltage and also spatial homogeneity. In Period 4, the first goal has been to explore the fundamental physics and electron transport across the interface of 2-D to 2-D van der Waals junctions by mixing and matching 2-D III-Vs and/or 2-D layered chalcogenides. To enable the study of chalcogenide heterojunction, a dry transfer method was developed to stack together two layers of chalcogenides of micro-scale thickness. Chalcogenide heterostructures built from single layer MoS_2 and WSe_2 were optically analyzed and strong interlayer coupling was found between the two single layers stacked; see Figure 13. The type II band alignment is optically direct in reciprocal space, but is spatially indirect in real space between the conduction band in the n-MoS_2 layer to the valence band in p-WSe_2. A giant internal electric field found in between these two layers is attributed to the direct band gap nature of the hetero-bilayer.

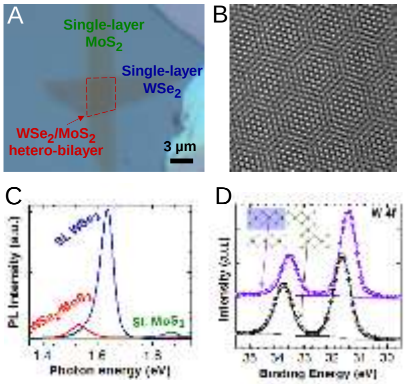


Figure 13: (A) Optical microscope image of a WSe_2/MoS_2 hetero-bilayer on a Si/SiO_2 (260 nm) substrate fabricated using a transfer approach; (B) High resolution TEM images of the hetero-bilayer, showing the resulting Moiré pattern; (C) PL spectra of single-layer WSe_2, MoS_2, and the hetero-bilayer in A; (D) XPS Comparison of W 4f core level doublet from WSe_2 and WSe_2/MoS_2 indicating a shift of 220 mV to lower binding energy, corresponding to a negative net charge on the WSe_2 top layer.

The **Javey** group also studied the doping of few-layers metal chalcogenides because it has not yet been well explored [29]. This is particularly important given that metal chalcogenide FETs reported so far are often limited by Schottky barriers (SBs) at the metal / semiconductor interfaces [30] [31] [32] [33]. Therefore electrical properties are hindered by the contact resistances rather than intrinsic material properties. To be able to push chalcogenide FETs to their performance limits and also reveal their intrinsic electronic transport properties. In the last period, Period 3, we reported the use of NO_2 molecules as effective p-dopants for monolayer and few-layer WSe_2 [30]. In this doping scheme, NO_2 molecules are absorbed on the surface of WSe_2, resulting in surface electron transfer from WSe_2 to NO_2 given the strong oxidizing nature of NO_2 molecules. This method of doping preserves the material quality and will help enable steep subthreshold swings in monolayer TFETs. Building on this concept, here we report the first degenerate n-doping of MoS_2 and WSe2. Specifically, we use potassium as an efficient surface n-dopant and achieve a high electron sheet density of ∼1.0×10^{13} cm^{-2} in MoS_2 and 2.5×10^{12} cm^{-2} for WSe_2 (Figure 14). We also for the first time demonstrate few-layer WSe_2 n-FETs with electron mobility of ∼110 $cm^2/V.s$ by selectively n-doping the metal contact regions with K.

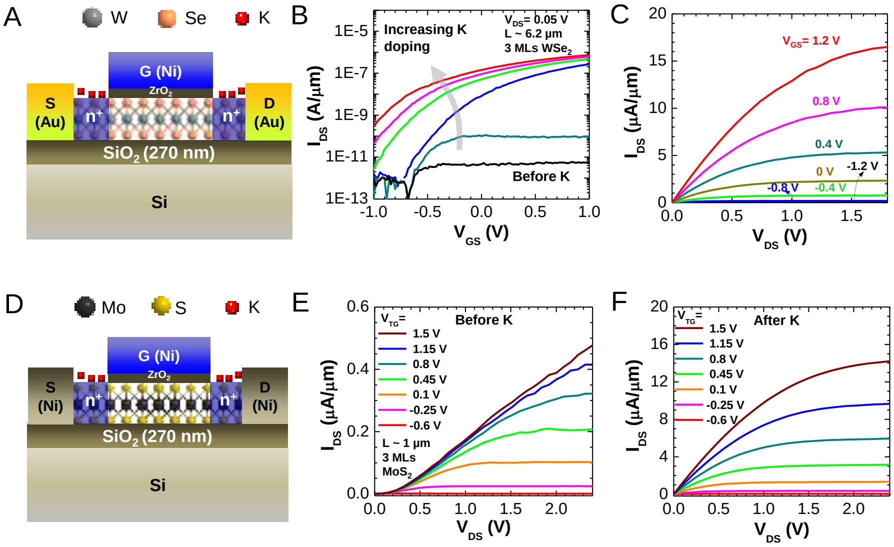


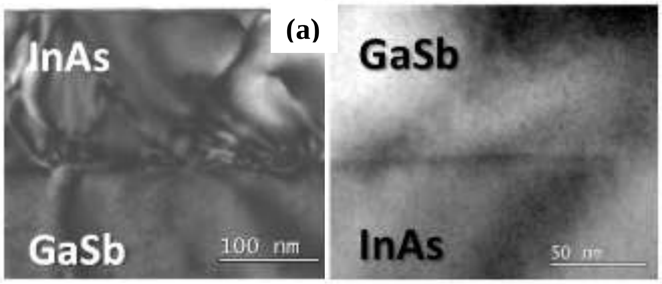
Figure 14: (A) Schematic of a top-gated few-layer WSe_2 n-FET, with chemically n-doped S/D contacts by K exposure. (B) Transfer characteristics of a 3-layer WSe_2 device (L~6.2 µm) as a function of K exposure time. The black curve is before doping, while the other curves from bottom to top are after 1, 20, 40, 70, and 120 min doping. (C) Output characteristics of the device in B after 120 min doping. (D) Schematic of a top-gated few-layer MoS_2 n-FET, with chemically n-doped S/D contacts by K exposure. (E, F) Output characteristics of a device (thickness of 3-layers, L~1 µm) before and after K doping respectively.

- *Understanding the Impact of Material Growth on Device Performance*

The **E. Fitzgerald** group *(MIT)* has focused on studying the impact of material growth on device attributes as a means to understand the physics of tunneling in Type-III InAs/GaSb semiconductor heterojunctions. Recognizing that the steepness of switching is limited by fundamental issues arising from the materials structure, phonon effects, or electrostatics immediately at the interface, we see the potential to control these effects, meaning that the ability to tailor the materials for the physics of density-of-states switching that would enable extremely sharp-switching devices.

We have successfully observed density-of-states switching in type-III heterostructures, measured its steepness, identified the various materials defects present and how to control them, and have elucidated the effect of these materials defects on the steepness of the switching action.

In this reporting period, we have identified misfit dislocations as an important leakage source in these structures, in that the trap states associated with these dislocations can lead to defect-assisted leakage mechanisms. Growing InAs on GaSb at standard MOCVD temperatures leads to immediate relaxation, which we believe is due to intermixing and the strain buildup from intermediate compositions. We can control this by lowering the temperature at the beginning of InAs growth, growing in the reverse order, or straining the GaSb underlayer. Figure 15a shows TEM images of various structures, while Figure 15b shows their corresponding conductance-voltage curves with conductance slopes shown, indicating an increase in steepness with a lower dislocation density.



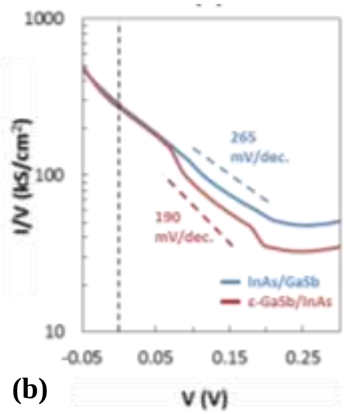


Figure 15: a) TEM comparison of InAs grown on GaSb versus GaSb on InAs; b) Comparison of conductance slope for both structures

We also have identified the effect of annealing, which improves the sharpness of switching, likely due to the annealing of point defects in the structure, as shown in Figure 16.

Another important question that needs to be addressed is what the actual band overlap should be in order to maximize sharpness and potentially minimize defect effects. We have successfully demonstrated control over the band alignment by using alloying, for example, the use of the InAs/AlGaSb as shown in Figure 17. We can use this system to explore the tunneling in a range of broken and staggered gap sizes.

Our optimization of materials properties and electrical sharpness is applicable to the Theme I research projects at Berkeley and MIT. Initially, we plan to examine these structures in a three-terminal geometry through collaboration with J. Hoyt and D. Antoniadis (MIT).

Finally, we are exploring an alternative to relying on the intrinsic materials structure to obtain a sharp change in density of states, and are examining the potential to induce density-of-states sharpness using engineered periodic structures via the use of minigaps due to formation of sub-bands. This is being done as part of a new collaboration with J. del Alamo. We have demonstrated extremely fine control of period thickness in InAlAs/InGaAs superlattices grown via MOCVD down to 1 nm in period, as shown in Figure 18. We plan to study the sharpness of density of states in these structures as a function of period thickness and materials properties. This material growth research on superlattices in the Fitzgerald group will contribute to the next planned step in the del Alamo group of fabricating a nanowire TFET with a superlattice design, as discussed previously.

Before the end of Period 4, material growth research to study of effect of broken gap size versus electrical characteristics for InGaAs/GaASb and AlGaSb diodes. We are also expecting preliminary results of effect of AlSb barrier thickness and electrical characterization of Ge/InAs heterojunctions.

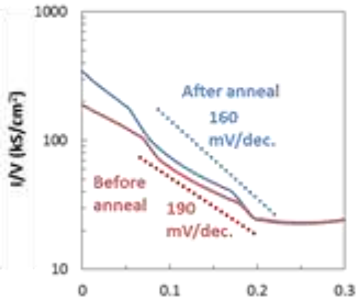


Figure 17: Comparison of GaSb/InAs conductance slope before and after 7 minute 600^{0}C anneal

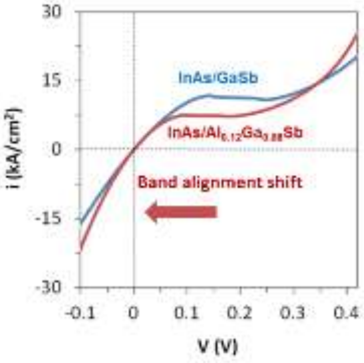


Figure 16: Shift in band alignment (seen by peak-voltage shift) due to alloying of Al into GaSb

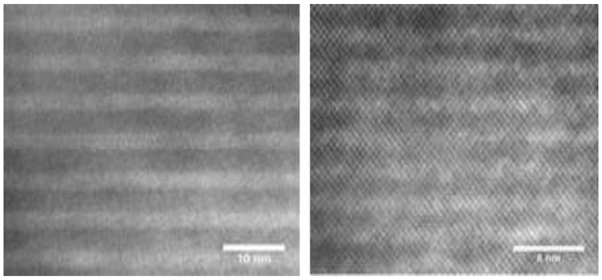


Figure 18: InAlAs/InGaAs superlattices with 3 nm (left) and 1 nm (right) periods

- *Experimental Demonstration of Type III InAs/AlSb/GaSb TFETs*

  This is the continuation of research activities on InAs/ /GaSb TFETs that were initiated at Berkeley and MIT in the previous reporting periods. In the previous reporting period, Period 3, we reported diode results, the first step towards demonstrating TFETs. The approach takes accounts for the understanding on p-n junction dimensionality and quantum confinement. In Period 4, the research efforts were focused on demonstrating TFETs.

  - *InAs/AlSb/GaSb with 3D-2D Tunneling and a Superlattice Quantum Well Source*

    The research of C**. Hu**, in collaboration with **A. Javey**, *(both Berkeley)*, has focused on efforts in epi-layer structures design, device structure design and device fabrication processes. The GaSb structure that has a normal-to-gate 3D to 2D tunneling takes into The InAs layer is designed to be sub-10 nm to enable spatial confinement and thus, a sharp turn-on device characteristic. The 2nm AlSb layer is inserted to provide a free band movement between the InAs layer and GaSb layer to reduce the device off-state current.

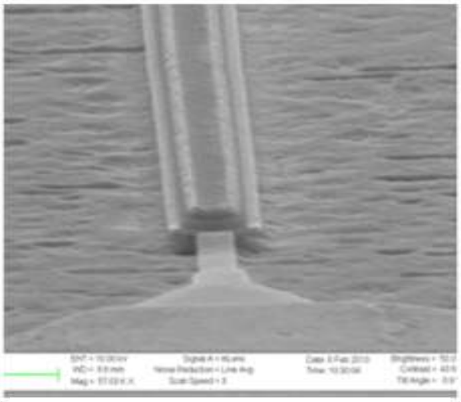


Figure 19: Mesa Supported by HSQ

Development of new processes has continued in Period 4. Successes included new processes for T-shape gate, self-aligned drain metal process and selective wet etching of GaSb without attacking the InAs layer. A process to use hydrogen silsesquioxane (HSQ) as a mechanical support (Figure 19) and a gate last process have also been established and utilized (Figure 20).

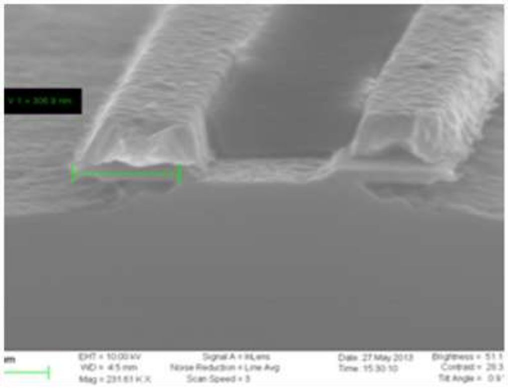


Figure 20: Test Structure for Gate Last Process showing non-collapsed Drain Wings

TFETs have been characterized at room temperature and low temperatures. At room temperature, the TFET has I_{on} of 139 μA/μm, I_{on}/I_{off} of 10^3 and a subthreshold slope (S_{min}) of 111 mV/decade. TFETs with a record on-current density of 0.17mA/μm^2 at room temperature have been achieved. To understand the impact of doping and material defects, low temperature measurements on subthreshold slope have been conducted, showing a swing of 46mV/dec at 100K (Figure 21).

The high room temperate subthreshold slope is attributed high interface trap density (D_{it}) which can be solved with gate last process and a post deposition annealing. The gate coupling ratio is also low, a problem that is solvable by designing a different device configuration. A gate-all-around process is expected to improve the gate coupling ratio. In the remaining months of this reporting period, we will begin to address these problems by investigating a new device gate all around design.

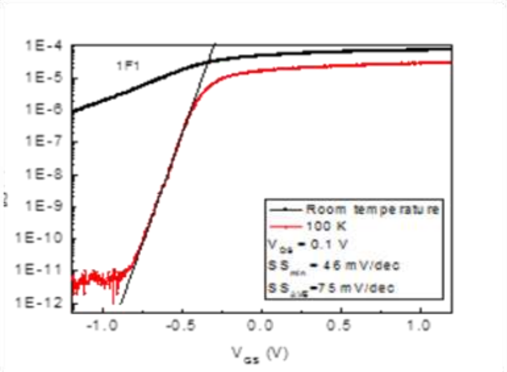


Figure 21: Subthreshold Slope Measurement at 100K

- *Ultrathin InGaAs/GaAsSb TFET*

The research groups of **J. Hoyt** and **D. Antoniadis** *(MIT)* fabricated and characterized vertical quantum-well (QW) tunnel-FETs based on an ultrathin $In_{0.53}Ga_{0.47}As/GaA_{0.5}Sb_{0.5}$ staggered gap (type-II) heterostructure lattice matched to InP. Area-dependent QW-to-QW tunneling current is demonstrated. Devices with HfO_2 high-k gate dielectric (EOT ~ 1.3 nm) exhibit minimum subthreshold swings of 140 mV/decade at 300 K, with an ON-current density of 0.5 $\mu A/\mu m^2$ at V_{DD} = 0.5 V (Figure 22). The low ON-current density is attributed to the strong quantization in the ultrathin InGaAs layer, which is expected to increase the tunneling barrier by ∼150 meV relative to the bulk $E_{g\text{-}eff}$ of 270 meV. Sharp negative differential resistance is observed in the output characteristics. For the first time, gate-tunable backward diode characteristics are demonstrated in this material system, with peak curvature coefficient of $30V^{-1}$ near V_{DS} = 0V.

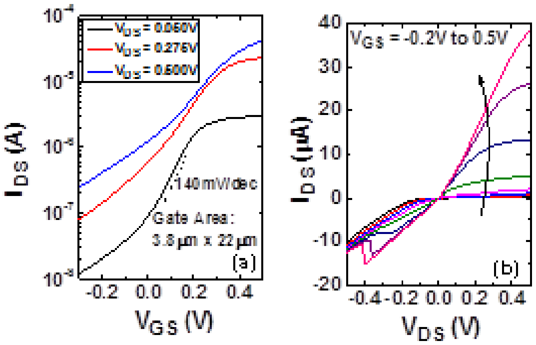


Figure 22: Transfer and output characteristics of the InGaAs/GaAsSb TFET. Negative differential resistance is observed and subthreshold swing of 140mV/dec is measured at 300K.

- *Negative Capacitance Field Effect Transistors*

S. Salahuddin (*Berkeley)* is continuing to investigate the use of ferroelectric gates to achieve steep-subthreshold swing in a MOSFET, a concept that he has pioneered [5]. In this Reporting Period 3, we developed a time dependent experimental scheme that shows how the unstable negative capacitance region can be accessed in an isolated ferroelectric capacitor and prescribed this scheme, as describe below, as a canonical test for negative capacitance in any arbitrary system.

A 60 nm $Pb(Zr_{0.2}Ti_{0.8})O_3$ sample was connected to a voltage pulse source through a 100 kΩ resistor. The transient voltage across the ferroelectric was measured using an oscilloscope. Figure 23a shows the experimental setup. Figure 23b shows the voltage and current transients in the circuit upon the application of a voltage pulse of 2 V magnitude and 40 µs duration. We note in Figure 23b that after the 2 V → 0 V transition of the source voltage, the voltage across the ferroelectric (V_{FE}) switches to a negative value. On the other hand, the current in the loop does not switch in its direction. In a classical series network of a resistor and a capacitor, after the source voltage transitions to zero, the current direction in the loop switches its direction while the voltage across of the capacitor retains the same sign as before. The counter-intuitive observation in our time dependent experiment with the isolated ferroelectric capacitor can be explained using the Landau model of ferroelectrics. This confirms that this phenomenon is a classic signature of negative capacitance in ferroelectrics.

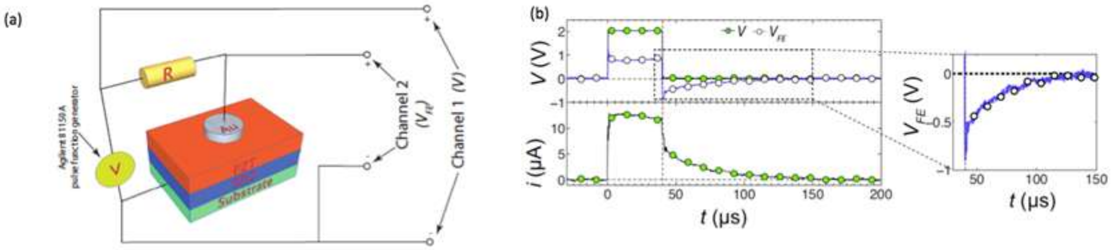


Figure 23: a) The experimental setup; b) Voltage and current transients in the circuit upon the application of a voltage pulse of 2 V magnitude and 40 μs duration.

In collaboration with C. Hu *(Berkeley)*, we fabricated our first negative capacitance transistors based on a SOI technology. After almost two years of process integration work, we have been able to measure three terminal characteristics. Characterization of these MOSFET is expected to continue until the end of Reporting Period 4.

2aiii. Theme II: Nanomechanics *Theme Leader:* **T.-J. King Liu** *(Berkeley)*

With zero off-state leakage and abrupt (zero sub-threshold swing) on/off switching behavior, mechanical relays offer the promise of aggressive supply voltage scaling for ultra-low active energy consumption (projected to be <1 aJ/op). From the inception of the Center, the researchers in Theme II have recognized the need to scale the mechanical switch to nanometer-scale dimensions and address issues such as surface adhesion and wear, in order to realize relay-based integrated circuits (ICs) that operate not only with good energy efficiency but also with good reliability (>10^{14} on/off cycles). Earlier theoretical studies undertaken by **T.-J. King Liu** and her group *(Berkeley)* on scaling projected that sub-10 milli-Volt operation should be achievable with nanoscale contact areas/dimples, if contact adhesion scales down proportionately with the area of the contact dimple regions. During this Reporting Period 4 they presented experimental results indicating that the minimum contact adhesive force will be ~1 nN for ultimately scaled contacts (1 nm^2 contact area), which would make it difficult to reduce the switching energy to less than 1 aJ. That is, a relay which operates by making and breaking physical contact between contacting electrodes will be difficult to scale aggressively to sub-10mV operating voltage and sub-micron actuation area.

The issue of surface adhesion, alternatively known as stiction, can be viewed from the following perspective. Actuation of a mechanical structure brings the source and drain electrodes into contact with each other resulting in solid-solid surface adhesion. This problem can be mitigated by decreasing the surface energy (Figure 24).

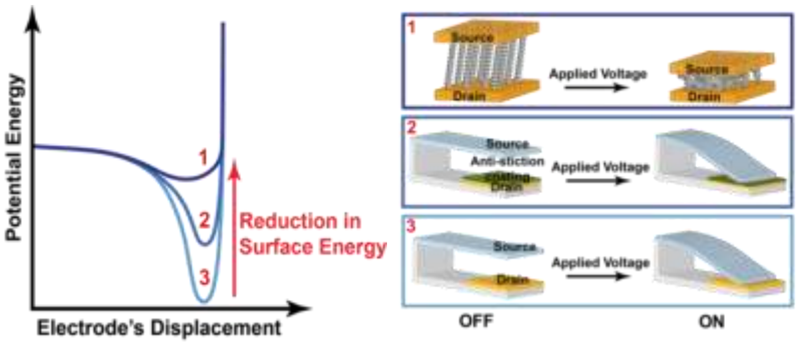


Figure 25: Illustration of methods to reduce surface energy in a mechanically contacting switch

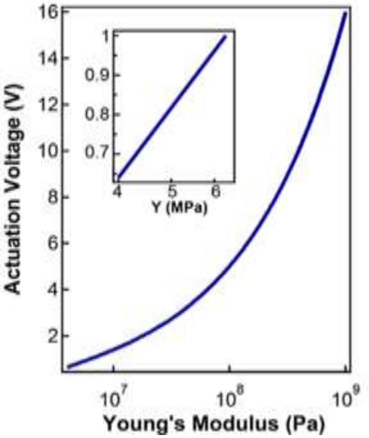


Figure 24: Actuation voltage for molecular films of different stiffness

The multidisciplinary collaboration of **V. Bulovic**, **J. Lang** and **T. Swager** *(all, MIT)* has continued to focus on the use of a compressible organic thin film between the source and drain electrodes that provides localized spring restoring force to alleviate stiction (Case 1, Figure 24). This approach, referred to as the "squitch", was initiated towards the end of Period 2 and has continued in this Reporting Period 4. In addition, since this is a non-contacting switchthat only modulates tunneling current, surface wear is also avoided. In Period 4, we refined our earlier theoretical study that was based on the Simmons Model to account for van der Waals forces, and concluded that a molecular thin film with a Young's modulus lower than 6.4 MPa is required to enable sub-1Volt squitch operation (Figure 25) [34]. The primary objectives of the squitch research have been the development of high-yield fabrication processes for two- and three-terminal squitches, and the experimental demonstration and characterization of the electromechanically-modulated tunneling switching mechanism upon which those squitches rely. To this end, the Period 4 efforts have focused on: (1) materials engineering of the molecular thin films that will occupy the squitch gaps; (2) the fabrication of two- and three-terminal squitches in both vertically- and laterally-actuated geometries; and (3) the characterization of squitch electromechanical properties.

While the squitch avoids the issue of contact adhesive force, it does so at the cost of non-zero off-state leakage current which may be unacceptable for some ultra-low-power (low activity factor) electronics applications. Thus, the research groups of **T.-J. King Liu** (*Berkeley*) and **H.-S.P. Wong** (*Stanford*) have been investigating anti-stiction coatings to mitigate contact adhesive force (Case 2, Figure 24). The focus is on materials with low Hamaker's constant, such as 2D materials with weak van der Waal interactions. This work is expected to elucidate surface science and enable sub-0.1V mechanical switch operation.

To mitigate risk, Theme II initiated the study of other approaches to overcome the fundamental energy-efficiency limit of a mechanical switch. The group of **J. Bokor** (*Berkeley*) is exploring the use of nanomagnets as a means to ameliorate stiction in metallic relays. The group of **J. Wu** *(Berkeley)* is assessing the feasibility of low-voltage switching by modulating the pressure applied to thin piezoresistive materials, VO_2 and MoS_2. In Period 4, a stress-induced phase transition in VO_2 has been characterized for sub-nanometer displacements. Similarly, the tunneling resistance across a few layers of MoS_2 modulated by relatively low compression force has been studied.

Details of the aforementioned Theme II research efforts are provided below:

- *Squitch*

  This project is a multidisciplinary collaboration between the groups of **V. Bulovic**, **J. Lang** and **T. Swager** *(all MIT)*. In this Reporting Period 4, this collaboration grew to include the group of **T.-J. King Liu** (*Berkeley*) to leverage the improved switch design developed at Berkeley.

  Device Proof of Concept: The project's highlight is the proof of concept in a two-terminal squitch based on laterally-moving cantilevers. These devices are fabricated using electron-beam lithography as shown in Figure 26. This approach is advantageous in that it permits the simultaneous fabrication of all electrodes prior to the introduction of the organic layer. This avoids damage to the molecular layer otherwise experienced in vertically-actuated devices when forming the top electrode. This approach appears to permit the most repeatable and controlled fabrication of nanometer-scale gaps. An example of a laterally-moving squitch is shown in Figure 27. A similar squitch with a near-15-nm open gap, in the absence of any molecular layer and in the presence of a PMMA (polymethyl methacrylate) support layer, was closed with a 4-V excitation. However, despite successful actuation, the operation was not repeatable as shown in Figure 28a due to stiction; this was as expected. A second device of the same structure tested after vapor-phase self-assembly of fluorinated decanethiol molecules in the contact gap exhibited repeatable operation with current-voltage characteristic resembling that of quantum tunneling as shown in Figure 28. In this two-terminal switch, an approximate 10^5 on-off ratio was achieved within a 1.5 V range. The lower actuation voltage observed in the presence of the molecular layer suggests the possibility of forming a smaller switching gap than that initially fabricated through the self-assembly process. It is believed that the cantilever collapses onto the opposing electrodes with the molecules being sandwiched in between. Figure 29 compares the experimental results to the Simmons theory of tunneling. In this analysis, the Simmons model is also modified to account for the change in tunneling gap due to electromechanical compression of the molecular layer while switching. Using the modified model (green curve as opposed to red), a close fit is acquired between the experiment and theory that suggests a 27% compression of the molecular layer. The best-fit theoretical model suggests a Young's modulus of approximately 0.24 GPa for fluorinated decanethiol, which is consistent with the results reported in the literature for alkanethiols of similar molecular structure. In summary, it is important to emphasize that the thin self-assembled compressible molecular layer has: (1) alleviated the problem of stiction; (2) helped define the nanometer-scale squitch gap; and (3) permitted tunneling across the gap. Thus, we have demonstrated the key benefits of the molecular thin film.

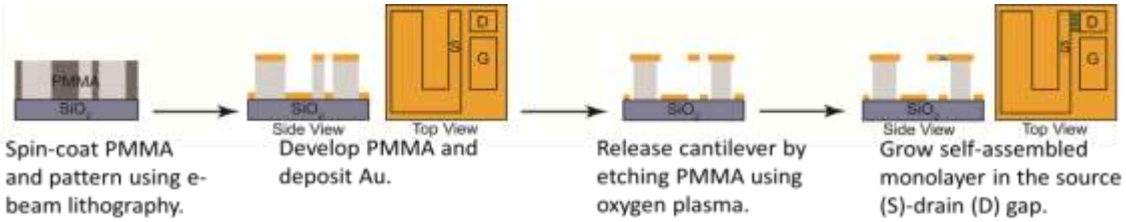


Figure 26: Fabrication process flow for three-terminal laterally-actuated squitches. Note that, for clarity, the self-assembled monolayer is shown to occupy only the source-drain gap in the right-most figure. In reality, it assembles over the entirety of the exposed gold surfaces.

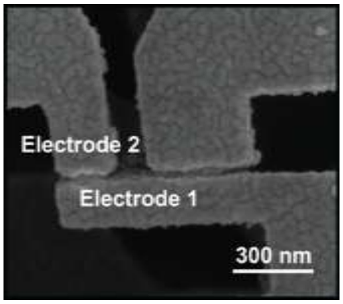


Figure 27: Scanning electron micrograph of an example tunneling squitch with gold electrodes and a PMMA support layer. The micrograph was acquired prior to the self-assembly of Fluorinated Decanethiol.

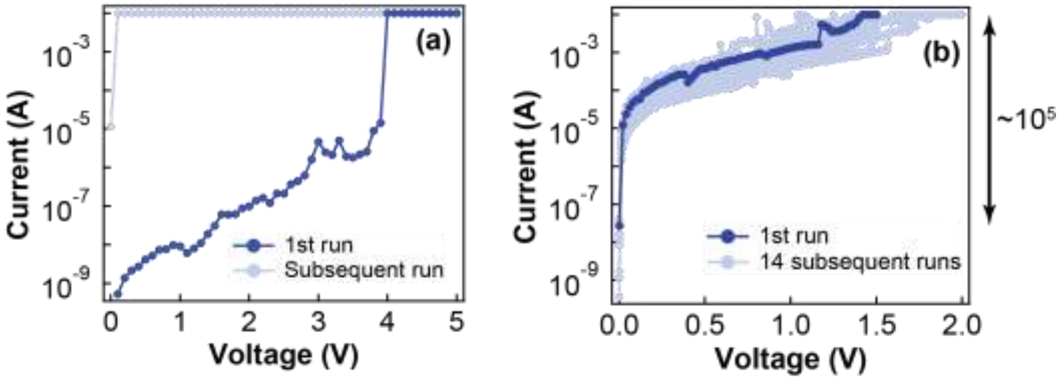


Figure 28: a) I-V charateristics of the two-terminal lateral squitch in the absence of a decanethiol molecular layer showing device failure due to stiction after the first sweep; and b) I-V characteristics of the device after the self-assembly of a Decanethiol molecular layer showing repeatable operation.

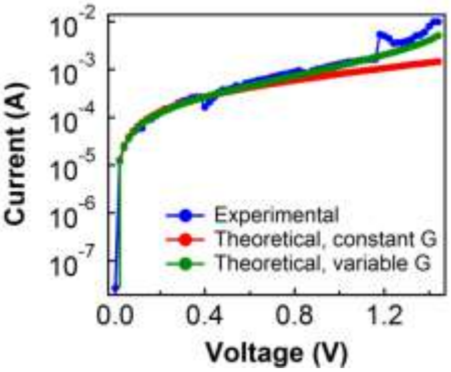


Figure 29: Experimental I-V characteristics of the two-terminal squitch (blue) compared to the theoretical characteristics based on the Simmons model of tunneling considering a constant tunneling gap (red) vs. a variable tunneling gap (green). The better fit of the variable-gap theory (green) to the experimental data (blue) indicates compression of the Fluorinated Decanethiol layer

Device Fabrication Processes: This proof of concept in a device has been made possible by extensive experimentation to develop a method for device fabrication.

We investigated a common method of fabricating vertical metal-organic-metal tunneling junctions by thermally evaporating a metallic top electrode onto a self-assembled, nanometer-scale, active organic layer, even previous experience has shown that there can be significant device failure manifested as electrical shorts, likely due to metallic filaments extending through the thin sparse organic layer. To prevent this, we deposited conducting organic buffer layers over the active organic layer prior to the evaporation of the top metal electrode. We improved yield by achieving more complete molecular films within the device active area of smaller dimensions.

Transfer printing was also explored to prevent the shorting observed during the thermal evaporation of the top electrode. We first utilized a thin gold film evaporated on a transfer pad of polydimethyl siloxane coated with a release layer. To eliminate the use of solvents to remove the release layer, we next developed a transfer process in which a near-1-µm-thick parylene carrier membrane was used to transfer the top electrode. Unfortunately, the parylene and the evaporated Au also formed wrinkles that did not permit the formation of a proper metal-organic-metal junction due to the presence of air gaps, and the surface roughness complicated the detection of nano-scale motion.

Our third squitch fabrication process, developed to eliminate both electrode shorting and wrinkling, employs graphene (or graphene oxide) as the top electrode. Our past experience with graphene led to our development to have graphene flakes and the separately-self-assembled organic layer be oppositely charged on their mating surfaces. This is expected to electrostatically encourage the desired self-assembly. Preliminary experiments have also encountered difficulties.

We now have identified the thermal evaporation process flow as the most likely to yield working devices. This approach is currently used as our main method to fabricate squitches used for characterizing the electromechanical response of various molecular films, and to confirm the presence of electromechanically-modulated tunneling.

Self-Assembly Process: vapor phase self-assembly may not be feasible for longer molecules which will require solution processing. Dissolution of PMMA in some solvents limits our material choices. To overcome this challenge, we developed an alternative fabrication method, replacing the PMMA support layer with hydrogen silsesquioxane (HSQ). The fabrication process flow is shown in Figure 30. An example device fabricated in the form of a doubly-clamped beam is shown in Figure 31. In the HSQ-based devices, multiple electrodes have been included. To mitigate stiction during initial electrode fabrication, larger gaps can be patterned. After fabrication, the additional electrodes included can be used to facilitate the formation of a nano-scale gap through application of a voltage that causes permanent stiction of the beam and one of the side electrodes. The remaining electrodes will then be used to manipulate the gap to control the tunneling current.

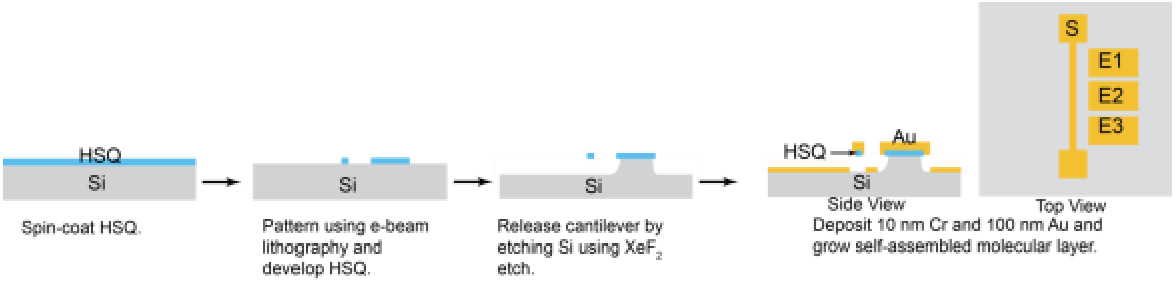


Figure 30: Fabrication process for lateral squitches based on HSQ support layer

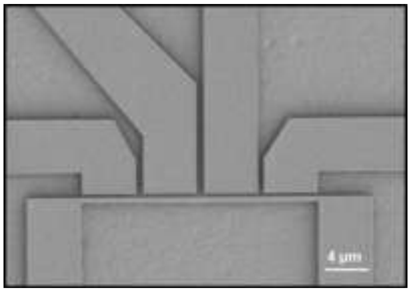


Figure 31: Example Squitch fabricated with an HSQ support layer in the form of a doubly-clamped beam (source) and having four additional electrodes to facilitate the formation and manipulation of a nanoscale switching gap.

To explore the hypothesis that the fabrication process promotes the formation of a nanoscale gap through the collapse of the beam or cantilever onto the opposing electrodes, the test structure shown in Figure 32 was fabricated using the process flow shown in Figure 30. It is expected that the beam will collapse onto the electrodes forming the smaller beam-electrode gap due to the presence of larger surface attraction forces. As expected, the electrical measurements presented in Figure 11 show the collapse of the beam onto the electrodes forming the smaller gap, leading to a current-voltage relation characteristic of electromechanically-modulated squitch switching. Additional experiments are currently underway to further explore and confirm this observation.

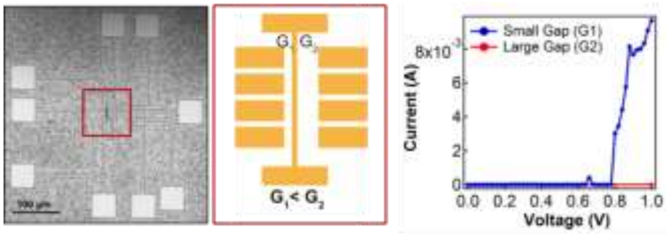


Figure 32: A clamped beam fabricated with electrodes on both sides having gaps G1 and G2 such that G1 < G2. Through vapor phase growth of a fluorinated decanethiol self-assembled molecular layer, the beam collapses towards the electrodes forming the smaller gap (G1) leading to I-V characteristics expected of a tunneling electromechanical squitch.

HSQ devices have the potential of high leakage current through the HSQ support layer affecting device reliability. For demonstration of three terminal squitches, our current research is focused on optimizing the use of a SOI wafer in place of the silicon substrate such that a 3-µm thick thermal oxide layer allows electrical isolation of device components from the bulk silicon to prevent leakage h. A schematic of this device structure is shown in Figure 33.

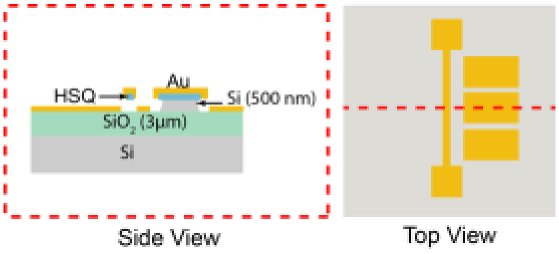


Figure 33: Schematic representation of a lateral Squitch based on HSQ support layer and SOI substrate.

Multi-Component Organic Materials Engineering: The device proof of concept was done with a thin film of fluorinated decanethiol, estimated to have a Young's modulus of approximately 0.24 GPa, a substantially lower than ~10 MPa required to enable sub-1-V squitch switching. Organic compounds with optimal mechanical and electron-transport properties were synthesized for molecular thin films with a Young's modulus lower than approximately 10 MPa to enable sub-1-V squitch switching. Among the materials most recently engineered for this purpose are P3HT-based polymers that enable self-assembly of thin molecular films having piezoresistive properties in addition to the ability to support the electromechanical modulation of tunneling current. These new molecular films complement the polyethylene glycol and fluorinated alkanes films that were reported in Period 3.

To incorporate any of our thin molecular films into squitches, our main focus has been their self-assembly on gold electrode surfaces using thiol-chemistry. However, driven by our recent collaboration with the **King Liu** group at UC Berkeley, we have also worked towards identifying alternative chemistries to achieve self-assembly of squitch materials over a variety of electrode surfaces including tungsten and ruthenium. Additionally, to confirm the successful formation of molecular films, various techniques including AFM, Raman, FTIR, XPS and QCM-D measurements, have been utilized to characterize the molecular layer formation. Our results confirm successful self-assembly of thiol- (for MIT) and amine-terminated (for Berkeley) squitch materials on gold (for MIT) and tungsten (for Berkeley) surfaces, respectively.

- *Anti-Stiction Coatings*
  - Dielectric Coated Contacts

As mentioned in the introduction of this section on Theme II, the **T.-J. King Liu** group *(Berkeley)* previously presented experimental results from 6-terminal relays (designed for compact implementation of digital logic) with contact regions of various sizes (area ranging from 6um^2 down to 0.04um^2) that were fabricated to investigate the scaling behavior of contact adhesive force. The experimental results show that adhesive force reduces with the total area of the contact regions, but not linearly due to the non-planar surface of the dimpled electrode. During this reporting period, the group developed a model to explain these results (Figure 34), and it indicates that van der Waals force is the main cause of adhesion. In order to achieve switching energy in the aJ range, the contact region size must be scaled to below 10 nm and an ultra-thin dielectric coating such as TiO_2 (deposited by atomic layer deposition after structural release) with low Hamaker constant should be used. It should be noted that current conduction in the ON state occurs via tunneling for dielectric-coated contacts.

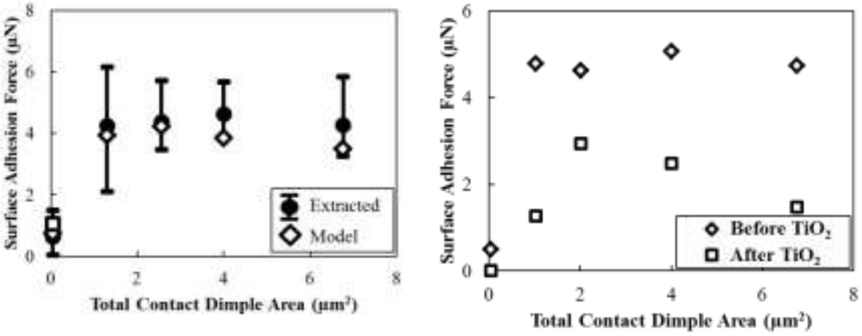
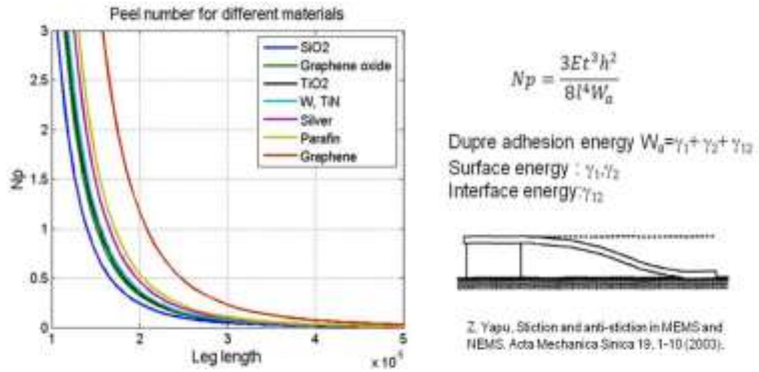


Figure 34: Contact adhesive force extracted from measurements of pull-in voltage and release voltage for logic relays of various contact dimple sizes: Comparison of experimental results vs. theoretical model (left) and comparison of contact adhesive force for relays with tungsten contacts vs. TiO_2-coated tungsten contacts (right).

- 2D Materials as Interfacial Materials

  Materials such as graphene and MoS_2 have with weak van der Waals (vdW) interactions, and thus, are good candidates for interfacial materials between contacts. Graphene is of particular interest due to its low surface energy, conductivity, barrier property, low cost, and thermal/chemical stability. The research group of **H.S.P. Wong** *(Stanford)* surveyed the literature and investigated the merit of 2D materials based contacts with low surface energy and low Hamaker's constant.



Z. Yapu, Stiction and anti-stiction in MEMS and NEMS. Acta Mechanica Sinica 19, 1-10 (2003).

Figure 35: Calculated peel number N_P of the shown cantilever structure made with different interfacial materials. E is Young's modulus, t is the thickness of the beam, h is the height of the beam, l is the length of the beam**Invalid source specified.**. Water was assumed to be the interfacial material that causes stiction. The surface energy of various materials was found from the

Figure 35 is a plot of peel number Np for cantilevers made with different materials interacting with water. The peel number, Np, is the ratio of elastic strain energy stored in the deformed microstructure to the work of adhesion between the microstructure and the substrate. If Np > 1, the restored elastic strain energy is greater than the work of adhesion, and the microstructure will not stick to the substrate. If Np < 1, the deformed microstructure does not have enough energy to overcome the adhesion between the beam and the substrate. Graphene exhibit the largest peel number (i.e. the least amount of capillary force) compared to many conventional materials used in MEMS with the same cantilever length. (The surface energy of each material is the experimental value taken from various literature sources [35] [36].) In addition, Graphene's Hamaker's constant which is a material dependent coefficient for van der Waals force (9 zJ (zepto-joule) for graphene / vacuum / graphene interface [36]) was also calculated to be an order of magnitude lower than most materials.

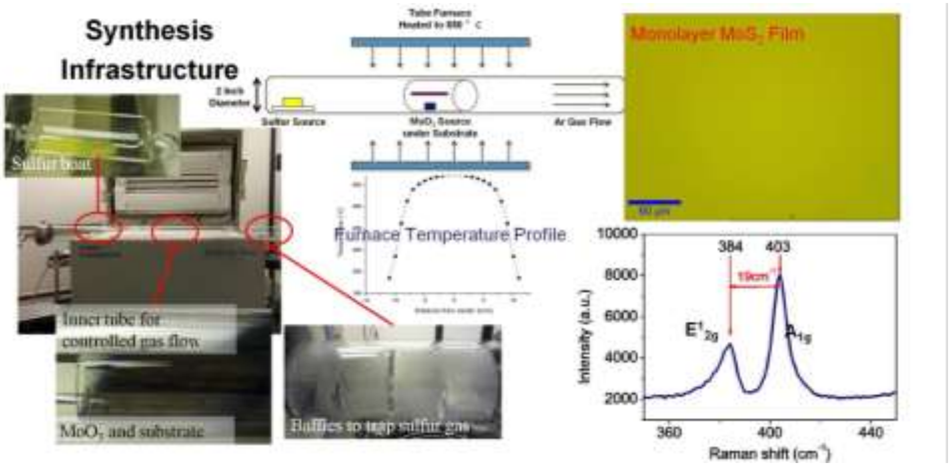


Figure 36: The synthesis infrastructure for MoS_2, an optical image of MoS_2 on SiO_2 substrate, and its Raman spectrum.

Most research on layered transition metal dichalcogenides (TMD) such as MoS_2, are still relying on mechanically exfoliated samples only a few μm^2 in size. To enable wafer-level fabrication of relays using layered materials as the interfacial layer, we developed an in-house 2-inch LPCVD method and successfully synthesized large area (> 1 cm^2) film of single layer MoS_2 on silicon dioxide substrate (Figure 36). We characterized the film using Raman spectroscopy and confirmed the uniformity and the number of layers obtained [37].

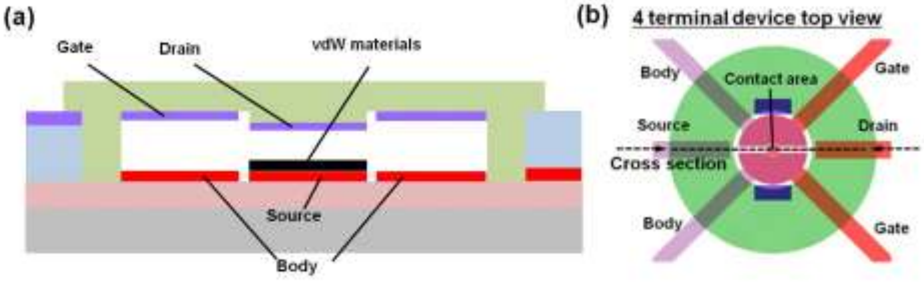


Figure 37: (a) NEM relay with van der Waals 2D materials (e.g. graphene, MoS_2) for low surface energy contact. (b) 4- terminal device top view

We have also continued on to design 4-terminal nanomechanical relays with vdW material contacts of varying area and actuating diaphragm size (Figure 37). One of the key challenges in fabricating the relay is the non-sticking nature of the 2D materials (i.e. the low surface energy of 2D material is a double-edged sword) – which is precisely the advantageous property we wish to exploit, but it also presents a fabrication challenge because of this property. Since there is only weak van der Waals interaction between the 2D material and the surface, 2D materials such as graphene tend to detach from the surface during the subsequent processes. There are several factors (surface energy, hydrophobicity, surface profile) that influence the adhesive quality of the films. Hence, we have characterized the transfer process of graphene to various target substrate materials with different process conditions. In Figure 38 (a-e), graphene tends to shrivel up or delaminate from untreated (or improperly treated) surfaces. Figure 38 (g-i) shows both single layer and multilayer graphene transferred to pre-treated surfaces of different materials with minimal tearing or delamination. Metals with high surface energy (Cr) tend to stick well with graphene while most oxides did not. Hydrophilic (or hydrophobic) nature of the surface had little effect on the adhesion. O_2 Plasma treatment helped with adhesion for hydrophobic nitride surfaces. However, plasma treatment on chromium worsened the adhesion probably due to partial oxidation of the metal surface.

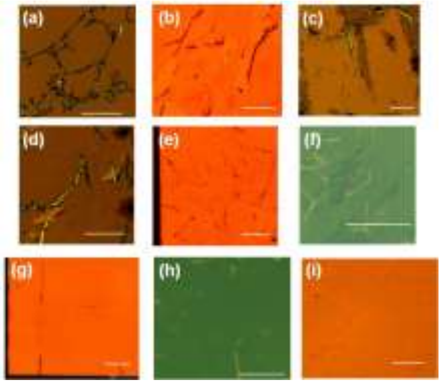


Figure 38: Optimization process for the transfer of single layer graphene (SLG) and multilayer graphene (MLG) films on various substrates with varying conditions. (scale bar: 30μm)
(a) SLG on bare SiO_2 with no treatment
(b) SLG on ALD Al_2O_3 with no treatment
(c) SLG on ALD Al_2O_3 with HMDS
(d) SLG on Al_2O_3 with plasma treatment
(e) SLG on metal(Cr) with plasma treatment
(f) SLG on nitride with HMDS treatment
(g) SLG on metal(Cr) with HMDS treatment
(h) SLG on Nitride with plasma treatment
(i) MLG on Nitride

The end of period goal is the fabrication of 4-terminal graphene relays. We will begin to experimentally study the relationship between the adhesive force, the hysteresis, the contact materials, and the contact area.

- *Tunneling Relay with Sub-Nanometer Gap*

  As shared in the section on Problems Encountered, the out-of-plane actuated design of the Tunneling Relay proposed in the last Period by the team of **T.-J. King Liu** (*Berkeley*) had many processing challenges. To minimize the operating voltage, the relay should be designed to operate in non-pull-in mode and have minimal contact area. The source and drain electrodes and channel are designed as sub-lithographic features formed by sidewall-spacer definition and there is a need for ultrathin and compliant structural materials. After spending many months to find solutions to process challenges at the nanofabrication labs at Berkeley and Stanford, we concluded that it is extremely difficult to achieve the out-of-plane actuated switches with well-controlled actuation and contact gaps (required to achieve non-pull-in mode operation) and precisely engineered contact geometry. Therefore we changed direction to investigate in-plane actuated switch designs with sub-lithographically defined contact regions.

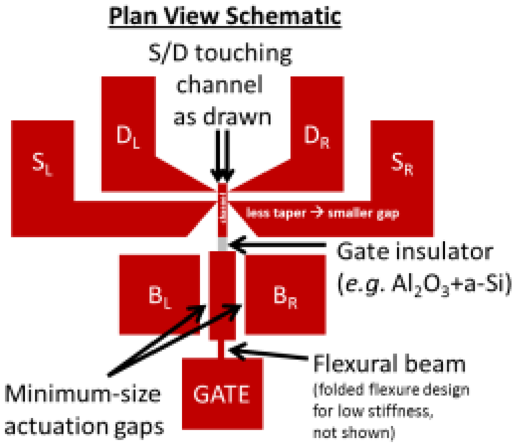
  

  Figure 39: Laterally actuated electro-mechanical switch design with minimum-sized actuation gaps and sub-lithographic contact gaps and contact area.

  In redesigning for the laterally actuated relay, we took the following into account (Figure 39). To achieve non-pull-in-mode operation, the contact gap size (g_c) must be much smaller than the actuation gap size (g_a). This is guaranteed if both g_c and g_a are defined lithographically, as in a laterally actuated switch design. To achieve low voltage operation without an inordinately large actuation area, g_a should be as small as possible, defined by the lithographic limit (0.25 μm for the DUV stepper in the nanofabrication lab at Berkeley). This means that g_c must be a sub-lithographic feature. If g_c is very small, then the spring-restoring force of the mechanical structure might be insufficient to pull the structure out of contact, *i.e.* the switch might be stuck on; therefore, an active turn-off design (employing electrostatic force to pull out the structure) is needed.

  We have commenced fabrication and will characterize laterally actuated relays employing sub-lithographic contact gaps for ultra-low-voltage operation, and electrostatic force for proper turn-off behavior. (We will use a combination of process “tricks” such as lithographic overexposure, over-etch and/or oxidation to form the contact gaps.) Preliminary FEM simulation results indicate that this approach will allow us to reach the goal of experimentally demonstrating sub-0.1 V switch operation. The demonstration is expected in early Period 5.

- *Exploratory Switching Concepts*

  - Incorporation of Nanomagnets in Micro-Mechanical Switches

    To address the issue of stiction, the group of **J. Bokor** *(Berkeley)* has been studying the applicability of magnets providing a restorative force. To test this concept, a process was developed and a suspended cantilever that has two layers of magnets and an air gap of 60nm in between was fabricated. A single layer of magnets was flipped, resulting in the cantilever being pulled down, which shows that the magnetic force is sufficient to actuate the cantilever.

- Non-Impacting Electromechanical Switching with Sub-Nanometer Displacement

Modulation of piezoresistance is another approach to mechanical switching. The group of **J. Wu** *(Berkeley)* has been investigating current conduction through a thin solid state material, either VO_2 or MoS_2, as a function of applied pressure.

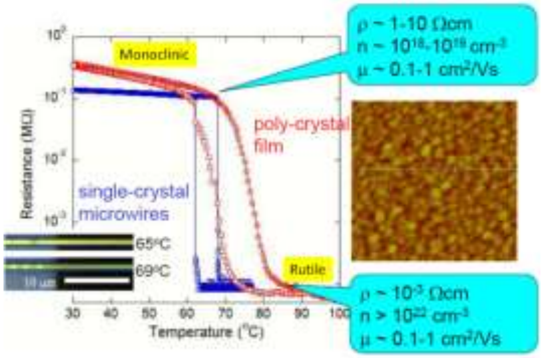


Figure 40: Resistance as a function of temperature (in a heating-cooling cycle) of a single-crystal VO_2 nanowire (blue) and a poly-crystal VO_2 thin film (red), both showing ~ 3 orders of magnitude change across the metal-insulator phase transition. The nanowire shows a sharp and abrupt change, indicating a single-domain transition, while the film shows a gradual change, indicating a multi-domain transition.

In the last annual report, we presented experimental data obtained by conductive AFM that showed a resistance change of >100x for a VO_2 film upon application of pressure by the AFM tip, indicating a stress driven Mott Insulator Transition at 30° C. However, besides a smaller resistance change than is desirable, additional studies on single-crystal microwires of VO_2 also raised concern of the possibility of hysteresis (Figure 40).

Using conductive AFM, we have experimentally demonstrated that the resistance between the AFM probe and the bottom electrode separated by a monolayer of MoS_2 can be reversibly reduced by up to 4 orders of magnitude (Figure 41). The resistance changes are reversible within the experimental sensitivity limited by instability factors such as thermal drift of the measurement setup. It should be pointed out that this large ON/OFF ratio cannot be explained solely by contact resistance change between the probe tip and MoS_2 sample, because the estimated contact area varies only by a factor of 10 in the applied pressure range. We note that the stress-induced resistance change is exponential, which is indicative of quantum tunneling process as the thickness of the monolayer MoS_2 (0.65 nm) is modulated by the tip force.

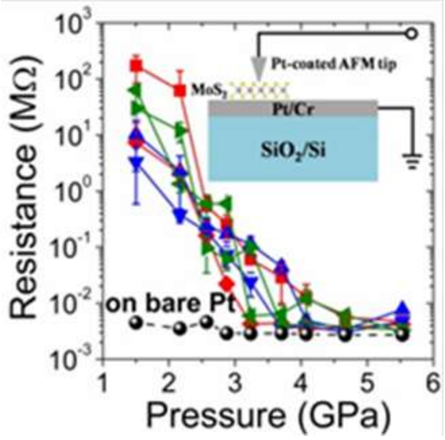


Figure 41: Resistance change when a monolayer MoS2 is being pressed with an AFM tip.

Figure 41 shows that the pressure required to effect the observed change in resistance is on the order of GPa, which is ~3 orders of magnitude higher than 6.4 MPa for organic films that we are seeking for sub-1 Volt operations in squitches (see the beginning of this Theme II section, 2aiii). We expect that similarly high pressure is required forVO_2, since an inorganic solid is significantly stiffer than an organic material.

2aiv. Theme III *Theme Leader:* **M.C. Wu** *(UC Berkeley)*

Today's optical communication consumes more energy than electrical interconnects for chip scale applications. State of the art optical communication used in fiber interconnect at board- and box-level has a sensitivity of ~10^5 photons/bit and consumes an energy of ~1 pJ/bit, involving discrete laser sources and Si photonics. By improving *both* energy efficiency and sensitivity by orders of magnitude in the emitters and detectors of an optical link, the Center's Theme III researchers are aiming to achieve the ultimate goal of approaching quantum-limited sensitivity (20 photons/bit) with an energy efficiency of 20 aJ/bit.

Theme III researchers have sought to establish the scientific understandings and eventually, the technology base to achieve the following:

- The optical sources that are highly efficient nano-emitters, ideally with no DC bias, and with high bandwidth (100Gbps); and
- The optical receivers with high sensitivity, enabled by ultra-low capacitance photodetector (< 100 aF) and intimate integration with transistor to minimize load capacitance.

In this reporting period, the focus of this Theme has continued to be the fundamental physical and technological investigation of the nanophotonic components, but the research has broadened to include the integration of the components on silicon photonic waveguides. Another change in Period 4 is the addition of a new faculty to the Theme III research team. From the inception of the Center, **M.C. Wu, C. Chang-Hasnain** and **E. Yablonovitch** *(all Berkeley)* have been the researchers in Theme III. **E. Alon** *(Berkeley)* has collaborated to provide system analysis of optical interconnects. New to Theme III is **D. Zubia** *(UTEP)*, who joined the Center in this reporting period.

All but one project of this reporting period are continuation of efforts from the previous reporting periods.

- System Analysis of Short-Distance Optical Interconnect: In collaboration with **M.C. Wu** and **E. Yablonovitch**, **E. Alon** has completed an analysis of the fundamental energy penalties (relative to SNR*kT) required for optimized receiver designs. This study is part of an effort on new receiver circuit topologies for enabling ultimately low-energy photonic links; see Section II.*2ai*.
- Spontaneous Hyper Emission (SHE) nanoLEDs: As introduced in the annual report of the last Reporting Period 3, LEDs, unlike lasers, is an optical emitter that does not require DC biasing (i.e., no threshold current). When coupled with optical antennas, the nanoLEDs have the potential to operate at a bandwidth greater than 100Gbps. In this Reporting Period 4, this project, led by **M.C. Wu,** in collaboration with **E. Yablonovitch**, has two goals.
  - Integrating nanoLEDs with silicon photonic waveguides. Conventional LEDs cannot be coupled efficiently to single mode waveguide due to spatial incoherence. The nanoLEDs are spatially coherent and its radiation pattern can be engineered by the optical antenna designs.
  - Electrical injection devices which call for (i) low-resistance electrical contacts to the nano emitter; (ii) confinement of carriers to the active region; (iii) design of optical antenna compatible with electrical contacts.
- Nano-Phototransistors with Ultralow Capacitance: The goal is to achieve highly sensitive receivers with the energy used to be in the order of 1fJ/bit by eliminating the capacitance of interconnect wires through integration of the photodiode and the transistor. We are pursuing nano-phototransistor using two classes of materials; germanium on silicon and III-V on silicon.
  - Photo-MOSFET with Ge Gate: The detector project that is led by **M.C. Wu,** in collaboration with **E. Yablonovitch** considered several research options for Period 4. One was to fabricate and characterize a germanium based nanophotodetector on silicon photonics in Period 4. However we soon realized that any wire used to connect the nanocavity diode to an external pre-amp would have capacitance that would dwarf the nanophotodiode, and thereby lose the sensitivity designed into the nanophotodetector. The only way to maintain this extreme sensitivity was by having the tightest possible integration between photodiode and pre-amp circuit, which would be a phototransistor. It is with this realization that we decided to pursue the phototransistor device.
  - III-V Nanopillar Based Nanophototransitor: Research in the group led by **Chang-Hasnain** in the last Reporting Period 3 investigated different device nanopillar structures for nanophotodetectors and concluded that a floating base bipolar junction phototransistor (BJT) design with the emitter, base and collector regions all integrated into the nanopillar is the best device design approach. The initial device work of this Period 4 was on InGaAs nanopillars, but based on the findings

presented in the earlier section, Problems Encountered (Section II.1c, this report), we shifted the research effort of the III-V BJT phototransitor from InGaAs based nanopillars to InP based nanopillars.

Selective-area growth of InP on Si(111): This is a new, previously unplanned, effort to support the nanopillar growth process that has wide applicability for III-V device structures and in particular, in this reporting period for growth of III-V phototransistors. **D. Zubia** *(UTEP)*, who joined the Center in this reporting period, and **C. Chang-Hasnain** *(Berkeley)* found synergy in the research of their respective group. The exploratory discussions led to a collaboration that demonstrated experimentally the feasibility and benefits of selective-area growth of InP nanopillars at Berkeley. This success is followed by the start of modeling efforts at UTEP on to understand the nucleation dynamics of InP selective growth.

Project status is detailed below, except for the system analysis project, which has been reported in the System Integration section of this report (Section II.*2ai*).

- *Spontaneous Hyper Emission (SHE) nanoLEDs*

Waveguide Coupled Device: During this period we demonstrated a nanoLED coupled to an InP waveguide [38]. The devices (Figure 42) consisted of InGaAsP ridges (40nm width, 37nm height, 150nm long) coupled to a gold arch-antenna (60nm wide, 250-400nm long). Multi-element antenna structures (Figure 42a) were also fabricated in a Yagi-Uda formation [5] [6]. The antenna structures were fabricated on top of a multi-mode InP waveguide. The waveguides were 320nm thick and varied in width between 500nm and 3um.

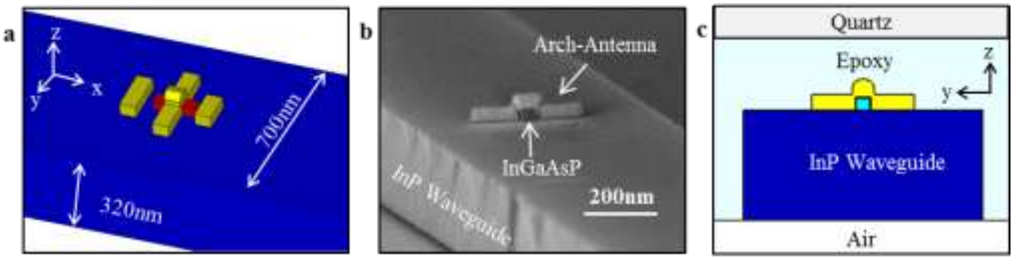


Figure 42: (a) Perspective view of Yagi-Uda antenna on top of InP waveguide. (b) SEM image of single-element antenna on InP waveguide before flip-chip bonding. (c) Front view of antenna structure with cut-plane through the center of the arch-antenna. Epoxy thickness not to scale.

As shown in Figure 43, coupling to an arch-antenna increases the amount of emitted light by ~10x. By integrating the amount of light coming out the end of the waveguide versus the amount of light coming directly from the region with the InGaAsP ridge, we can calculate that 50% of the total emitted light was coupled to the waveguide for single element devices and up to 70% for Yagi-Uda antennas. The Yagi-Uda antennas also exhibited directional emission with front-to-back emission ratios as large as 3:1.

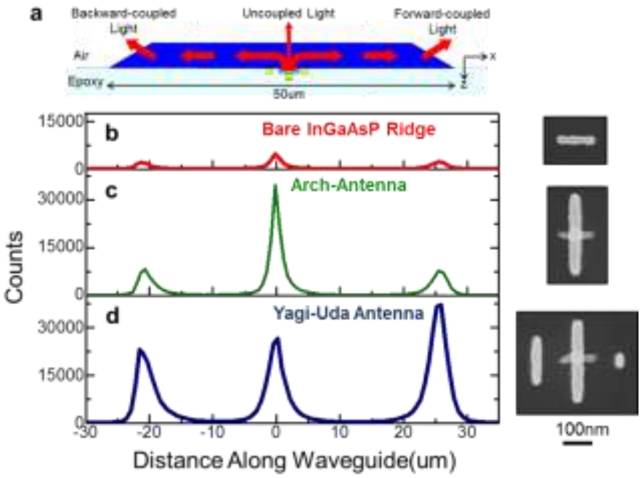


Figure 43: (a) Side view of Yagi-Uda antenna coupled to InP waveguide. The structure is flip-chip bonded to glass with epoxy, leaving the antenna fully embedded in epoxy. (b-d) Spatial image of light emitted from antenna-waveguide structures and corresponding SEM of device.

In order to use the nanoLED as a light emitter in an optical network, a process has to be developed for integrating the device onto a large-scale optical circuit. For this reason, we have developed an epitaxial layer lift-off process for transferring thin III/V layers to Si substrates. The III/V and Silicon can then be processed using standard Silicon patterning and processing tools to create wafer scale optical circuits with active material directly integrated on top. Figure 44 shows a SEM of a silicon chip with a thin InP/InGaAsP epitaxial layer that has been patterned into silicon photonics test structures. Subsequent pattering of the III/V layers will allow nanoLEDs to be integrated directly on the photonic circuits.

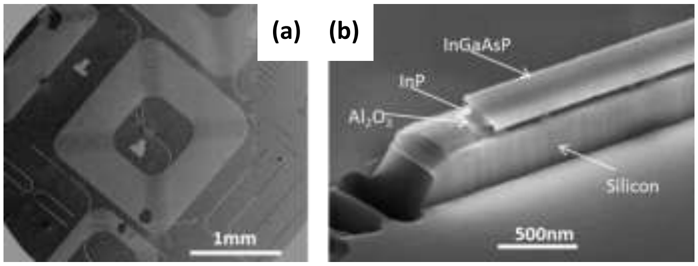


Figure 44: (a) SEM of photonic test structures consisting of a thin InP/InGaAsP layer on top of silicon. (b) Perspective SEM of a silicon waveguide with III/V sitting directly on top.

Our next step will be integrating our devices directly in a Silicon Photonics platform. This will allow for large scale manufacturing of low-power integrated optical circuits. Our research will focus on III/V integration techniques and device design to enable large coupling efficiencies to Silicon waveguides. We expect preliminary fabrication results with chip size photonic circuits towards the end of this reporting period.

Electrically Injected NanoLED: We have performed detailed design and simulation of electrically pumped nanoLEDs. The basic structure of the proposed nanoLED is similar to that of a FIN-FET except the channel is replaced by III-V emitter, the gate metal is replaced by optical antenna, and the source/drain are replaced by electron and hole injectors. Two different design approaches were identified and studied using device and electromagnetic modeling. The first approach (Figure 45a) utilizes a lateral current injection scheme in which carriers are injected from either end of an InGaAsP ridge (similar to a FinFET). The second approach (Figure 45b) employs vertical injection of carriers into an InP/InGaAsP double heterostructure ridge by using the antenna and substrate as electrodes. Electromagnetic simulation of the latter design was used to ensure that electrical leads can be connected to the antenna without perturbing the radiation mode (Figure 45c). Prior to ordering epitaxial wafers, device modeling was used to optimize design parameters such layer doping concentration and thickness. The epitaxial wafers have been recently received and device processing is underway.

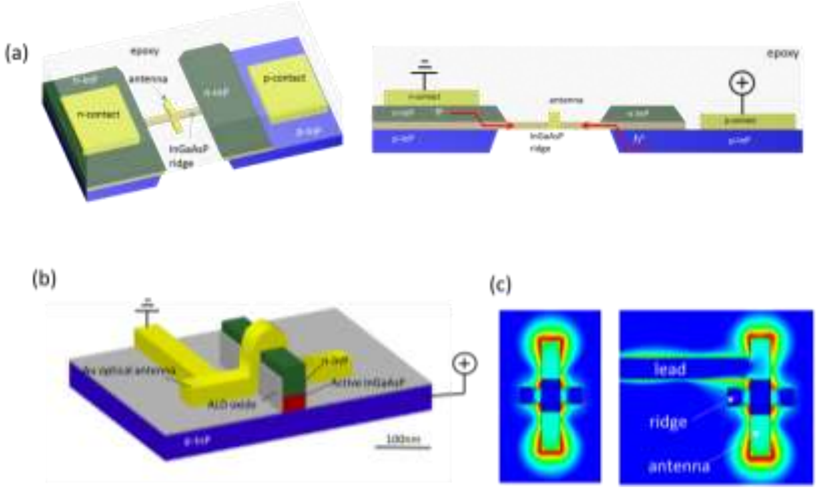


Figure 45: (a) Schematic of electrically injected nanoLED design utilizing lateral carrier injection into an InGaAsP ridge (b) Schematic of design utilizing vertical carrier injection into a InP/InGaAsP DH ridge. (c) Simulated plot of electrical magnitude showing minimal perturbation when electrical lead is connected to antenna.

We have developed the nanofabrication process for nano-FIN-LED and have preliminary test demonstrating successful current injection and electroluminescence. We have recently received a new shipment of epi material that will allow us to continue work towards a complete electrically injected nanoLED device. We expect improved performance from test structures using the new material by the middle of 2014.

- *Photo-MOSFET with Ge Gate*

  Process Development & Device Design: After a brief investigation and several trials during this period, the rapid melt growth (RMG) technique was determined to be ideal [39]. Using this technique, and the silicon photonics process already developed in the M.C. Wu lab, the second consideration was to modify and combine these two processes to create an integrated phototransistor on silicon waveguides. Our specific path was to use a germanium gated silicon MOSFET, where the silicon body of the device was also the same layer as the silicon photonics structures. This tightly integrated photo-MOSFET structure would minimize the overall capacitance of the photodiode and pre-amp circuit, which would ultimately allow the scaling of the capacitances that we have been advocating for the previous periods. Design of metal nanocavities and simulations for an optimal coupling of an extremely scaled photodiode on silicon waveguides, started in the previous reporting period, were completed. The 100 aF germanium device was simulated with 50% quantum efficiency.

  Device Results: A single crystal germanium gate Photo-MOSFET with 18 A/W responsivity and speeds up to 2.5 GHz with potential improvement with future scaling was achieved (Figure 46c). This was accomplished with a 1µm gate length device, which had total germanium dimensions of 1 µm x 8 µm with 350 nm of thickness (Figure 46a-b). A theoretical model of the germanium gate photo-MOSFET operation was developed. Extensive device simulations to confirm model with numerical simulations and data, and explore numerically the benefits of gate scaling with the photo-MOSFET were undertaken.

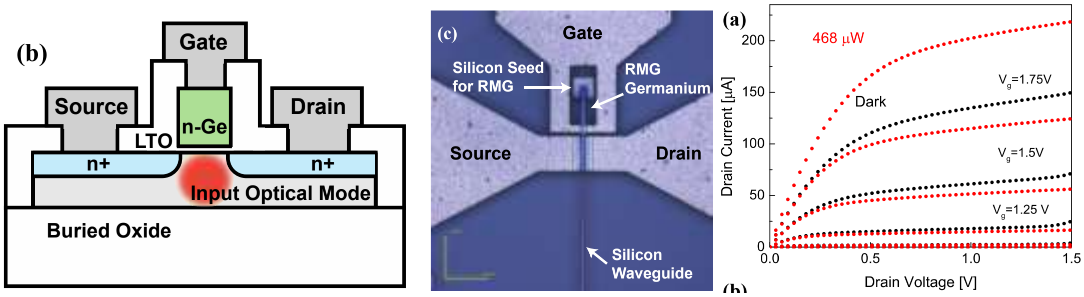
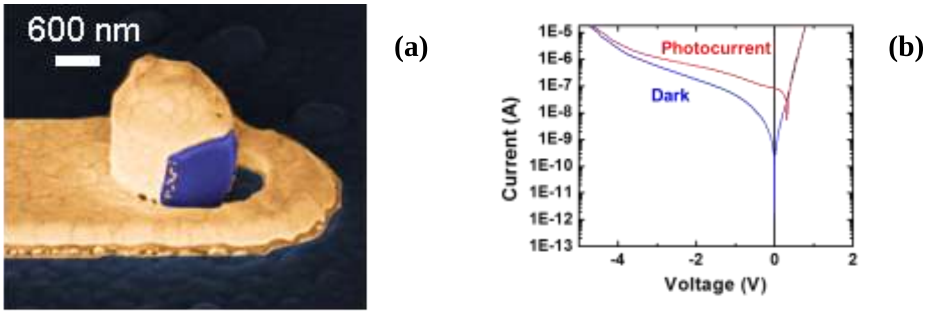


Figure 46: a) Schematic of the device is shown; b) microscopic image of the fabricated photoMOSFET; and c) Measured device characteristics.

Even though we shifted the focus on Photo-MOSFET, we continued efforts on germanium based nanophotodetector on silicon photonics, but with larger p-i-n diodes. We expect that before the end of this period, fabrication of such photodiodes on silicon waveguides will be completed and the devices characterized. While the devices will be relatively large (~1-10 fF), they will further the phototransistor research. The photodiodes will provide control samples to allow us to quantify the gain of the phototransistors, and will allow us to also more accurately quantify the germanium quality through dark current measurements.

- *III-V Nanopillar Based Nanophotodetector*

InGaAs APD: In this reporting period, the group led by **C. Chang-Hasnain** *(Berkeley)* first validated the quality of the p-n junction through demonstration in an APD. Figure 47a shows a SEM photo InGaAs nanopillar APD. The detector has only half of its surface covered in metal using angle evaporation, allowing incident beam to be detected. The I-V and multiplication characteristics are shown in Figures 47b and c, respectively. Figure 47d shows a rise time of 35 ps. This is the first time and the highest gain-bandwidth result for a single-pillar device. However, Figure 47b shows high dark currents, 10^{-9} A or higher. This reflects leakage which is traced to the undesired growth of a polycrystalline InGaAs layer on the silicon substrate that shorts out the emitter of the substrate. To remove this shunt path, a complicated etching step is required to remove the shunt path. Another complication is there is an uncertainty of the doping concentration which must be compensated by a thicker base region. A thicker base layer also means higher capacitance, which slows down the device and decreases the sensitivity. These factors led to the decision to migrate to an InP based materials system.



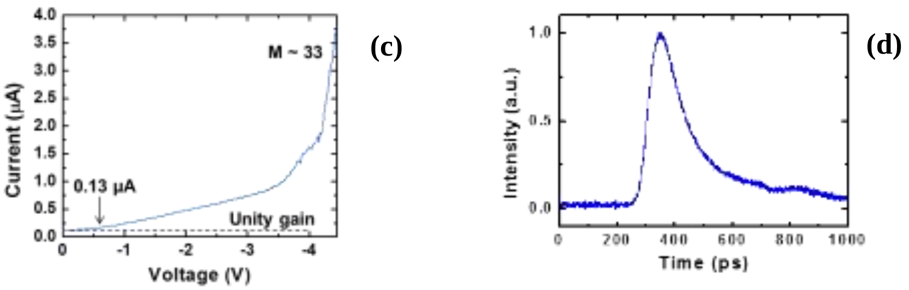


Figure 47: a) SEM photo of a single-pillar APD with half of its surface covered by contact metal, leaving the other half for photo detection; b) IV characteristics of InGaAs APD under dark and illumination; c) Multiplication factor as a function of reverse bias voltage for the InGaAs APD with a gain of 33; d) Short pulse response of APD, showing rise time of 35ps, equivalent of 9 GHz.

InP Nanopillar Photodetector with Ultra-Low Dark Current: The InP nanopillars show much brighter photoluminescence and higher internal quantum efficiency compared to InGaAs based nanopillars, which makes it a much more promising material system for realizing highly sensitive BJT onto silicon substrate (Figure 48a). The InP material system also allows for the building of more sensitive heterojunction bipolar junction transistor using lower bandgap, lattice matched $In_{0.53}Ga_{0.47}As$ for the base and collector regions. Using $In_{0.53}Ga_{0.47}As$ base and collector regions also allow the building of phototransistor that is sensitive to the silicon transparent, telecom wavelength at 1.55 µm. Thus far, we have also demonstrated 1.55 µm photoluminescence emission from InGaAs layer grown on the InP naonpillar (Figure 48b).

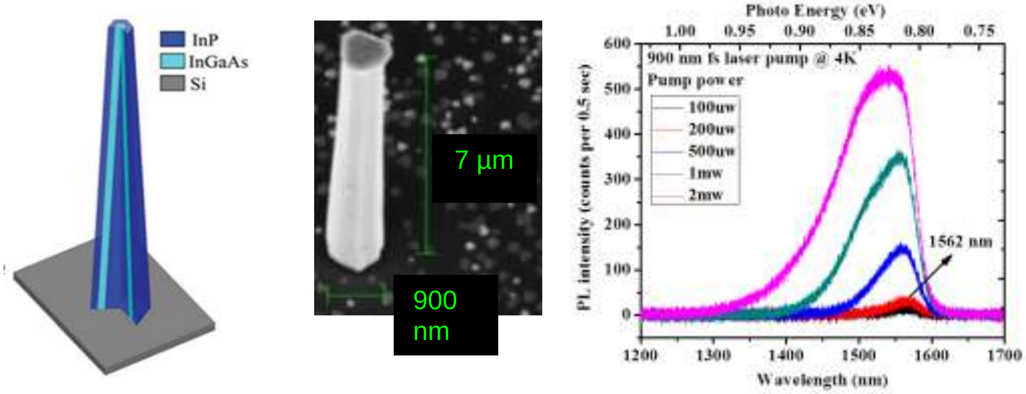


Figure 48: (a) Schematic and SEM image of InP nanopillar with lattice matched InGaAs layer grown inside the InP nanopillar; (b) Photoluminescence emission of InP nanopillar with InGaAs layer showing emission at 1.56 µm

To make InP based BJT possible, we have developed a regrowth technique for growing layers of InP materials onto the tip of the InP nanopillar (Figures 49 a and b). Such regrowth technique eliminates the need of a complicated and damaging etching step to isolate the Collector and Base regions of the BJT from the silicon substrate. The regrowth process begins with the growth of the core of the InP nanopillar in the MOCVD. After growth, a thin layer of silicon dioxide and amorphous silicon are deposited to cover the lower half of the nanopillar. These silicon dioxide and amorphous silicon layers prevent further InP growth on the lower part of the nanopillar, thus, regrowth of InP only occurs on the top portion of the nanopillar. The regrowth process also allows us to tailor the size and location of the Collector and Base region, allowing for more flexible design of the BJT. With the regrowth method, we showed that the dark current of a p-i-n photodetector built using the regrowth method can be dramatically reduced to ~100fA range (or µA/cm^2) level (Figure 49c). This can lead to better detector performance in both sensitivity and signal-to-noise ratio.

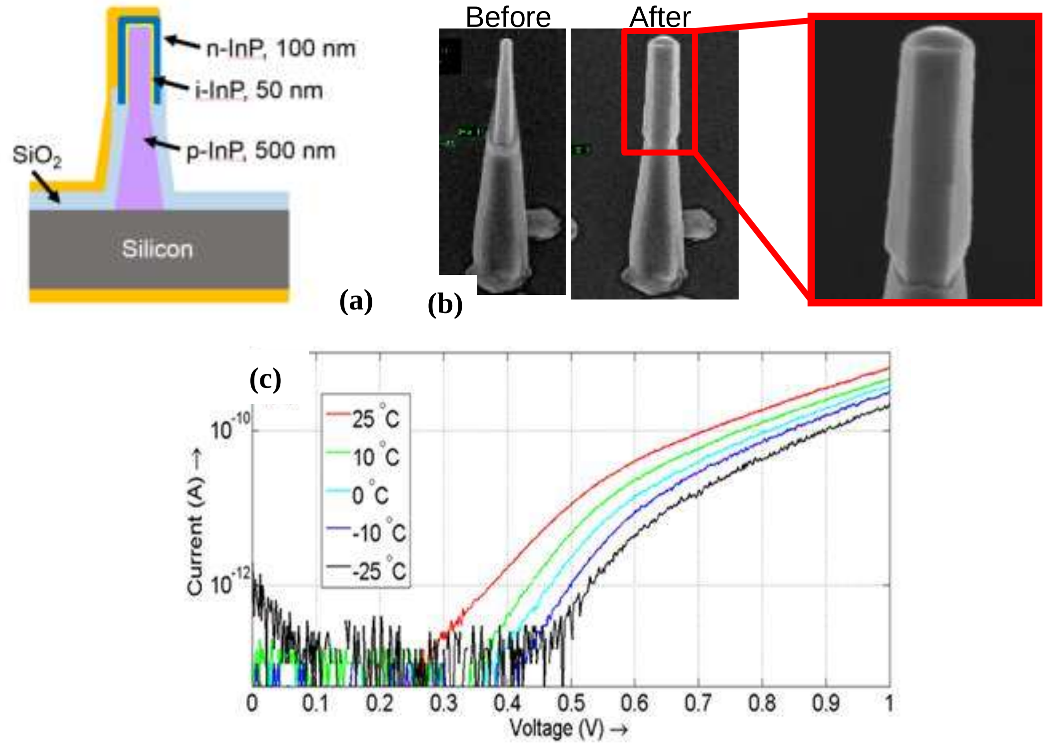


Figure 49: (a) Schematic of InP nanopillar with regrown layer; (b) SEM image of InP nanopillar before and after regrowth; (c) Dark IV of single InP nanopillar directly grown on silicon as a function of temperature, showing excellent dark current bellow 100 fA, or the noise limit.

The next step is a n-p-n structure and an BJT device. The work to demonstrate a BJT device is in progress. Preliminary device results are expected by the end of this reporting period.

- *Site Control of InP Nanopillar Growth*

The **Chang-Hasnain** group has also demonstrated selective area growth of InP nanopillar on silicon substrate in collaboration with **D. Zubia** *(UTEP)*. By using a 100 nm thick silicon dioxide with ~ 300-400 nm diameter holes, the growth location of the nanopillar can be precisely controlled (Figure 50a). Initial results show that the InP nanopillar would only grow within the openings of the silicon dioxide mask with a 66% yield (Figure 50b). The silicon dioxide mask not only serves as a growth mask, but also serves as an electrical isolation layer to prevent the doped nanopillar shells from touching the substrate. This helps lower the dark current to improve detector sensitivity and signal-to-noise ratio.

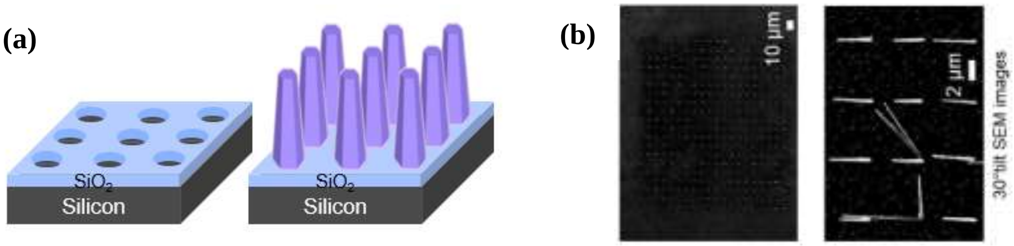


Figure 50: a) Schematic for selective area growth of InP nanopillars; b) SEM images of InP nanopillars grown with selective area growth.

Towards establishing a fundamental understanding of the selective growth process, the **Zubia** group has begun to develop a new mathematical formulation for strain partitioning in compliant substrates [7]. Modeling strain partitioning in nano-heterostructures is applicable to nano-needles and nanowires (Figure 51).

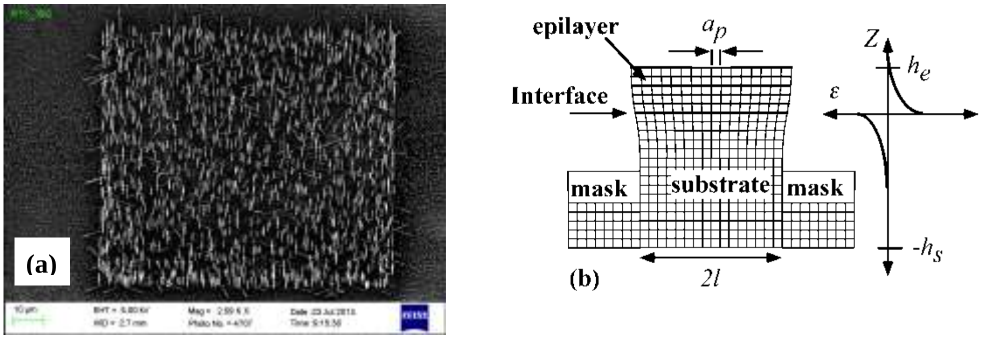


Figure 51: a) Selective-area growth of InP nanoneedles on patterned SiO_2/Si(111); b) Schematic representation of substrate compliancy in patterned substrates emphasizing strain decay away from the interface.

2av. Theme IV: Nanomagnetics *Theme Leader:* **J. Bokor** *(UC Berkeley)*

Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that can approach the Landauer limit [2], or perhaps even surpass it via reversible logic as predicted by Bennett [8]. This Theme has the most fundamental science character and longest time horizon of the Center's research themes, and so the initial approach has been to undertake a mix of projects that enhance the experimental technical foundation for computing and learn more about spin dynamics particularly at room temperature as well as projects to demonstrate a basic low energy magnetic switching functionality. While we have continued this approach, Period 4 has also been a transition year, as we re-examined the direction of this Theme. During Period 4, the Theme IV researchers at Berkeley are re-directing Theme IV research taking into account new advancements in the field of spintronics.

In the last reporting period, **J. Bokor** had begun to explore a key limiting factor for magnetic logic, the switching speed. In this Period, he has been refining the underlying concepts and research details for addressing ultrafast magnetic switching. Conventional magnetic switching is governed by precessional dynamics that sets a minimum switching time of ~100ps, but to have practical application in logic, a switching speed in the range of a few psec would be far more attractive. Building on prior work, [8] [9], the Bokor lab is pursuing a concept of magnetic switching via a highly non-equilibrium process that is created by selectively 'heating' only the electrons with an ultrafast source. It is during the transient high electronic temperature phase that the Curie temperature of the ferromagnet is exceeded, and a rapid demagnetization on a sub-psec time scale results [10]. It has recently been demonstrated that in rare-earth, transition-metal ferrimagnetic alloys that under these conditions, deterministic switching of magnetization direction can also be induced [9]. All previous experiments in this field have utilized fsec laser pulses to create the non-equilibrium high electron temperature phase. The approach being taken by the Bokor lab is to explore the initiation of this unique mode of magnetic switching using purely electrical voltage pulses.

Aided by fruitful discussions within Theme IV, **S. Salahuddin** *(Berkeley)* identified the possibility of replacing the magnetic field based clocking mechanism of conventional nanomagnetic logic schemes using a spin Hall effect. The initial work on spin Hall effect (SHE) by the Salahuddin group was funded by a gift from Intel and later, by the STARNET FAME center. Once the opportunity for nanomagnetic logic was identified, the Salahuddin team leveraged all these funding sources, including E^3S, to demonstrate SHE clocked nanomagnetic logic. Thus, this project, though not included in the Period 3 report as part of the Period 4 plan of the Center, is also reported as part of this Period 4 annual report.

The Center's emerging efforts in non-equilibrium magnetic dynamics has led to interactions between J. Bokor and S. Khizorev of Florida International University (FIU), whose recent publication in spin-transfer torque magnetization has attracted the Center's attention [40].

During this reporting period, the groups of **J. Bokor** and **I. Siddiqi** *(Berkeley)* have continued to pursue the goals of the fundamental studies that were initiated at the inception of the Center. Their respective research projects are:

- Experimental Verification of the Landauer Energy Limit; and
- Study of the classical spin dynamics using Diamond NV centers

The groups of **J. Bokor** and **R. Ramesh** *(Berkeley*) have continued their collaborations on low input voltage electric field control of magnetic switching with two materials systems that were initiated in past periods:

- $BiFeO_3$ single phase multiferroic heterostructures; and
- Composite multiferroic heterostructures

The following section reports on the new Theme IV projects.

- *Spin Hall Effect for Ultra Low Energy Magnetic Switching*

  The term spin Hall effect (SHE) was first coined in 1999 [11]. The first experimental demonstration SHE was observed in two dimensional GaAs [41]. The basic physics hinges on the spin-orbit coupling because of which the electrons flowing in a material experience a pseudo-magnetic field. As these electrons collide with impurities in the material, they scatter in preferential directions based on their spin polarizations. As a consequence, a non-equilibrium spin polarization builds up along the edges of the material. The prediction of this concept dates back to a 1971 work by Dyakonov and Perel [42]. Recent developments in SHE have gone beyond semiconductors as the primary material system of interest with dramatic results. A particularly exciting work is a recent demonstration by two groups (Grenoble and Cornell) that an unpolarized current flowing in a metal with large spin orbit coupling can switch the magnetization of a ferromagnet sitting right on top of it [12] [13]. This means that the generated surface/interface spin density is sufficient to contribute enough angular momentum to the ferromagnet so as to completely reverse its magnetization. This effect is thus huge compared to the small polarizations observed in GaAs. In fact, it is now clear that there is a significant 'gain' in the spin accumulation coming from Spin Hall Effect owing to the continuous repolarization of the charge current along the length of the wire. Salahuddin and his colleagues have recently shown that this gain allows one to do computation without having to use an external amplifier [43].

  S. Salahuddin and his group *(Berkeley)* have recently fabricated a simple 3-dot NML chain. Each dot has a radius of 200 nm with 30 nm spacing between dots. A Hall bar underneath is used to perform Anomalous Hall Effect measurements to measure magnetization of the 3-dot ensemble. When a current pulse was applied to this system, Hall resistance measurements showed that the 3-dot chain indeed goes to a 2up-1 down state or a 2down-1 up state. When this is done with an input magnet whose magnetization is not affected by the clock pulse, the 3 dot circuit goes to a dipole coupled state as determined by the input magnet (Figure 52). To the best of our knowledge this is the only experimental demonstration of a nanomagnetic logic circuit where the clocking does not involve any application of magnetic field.

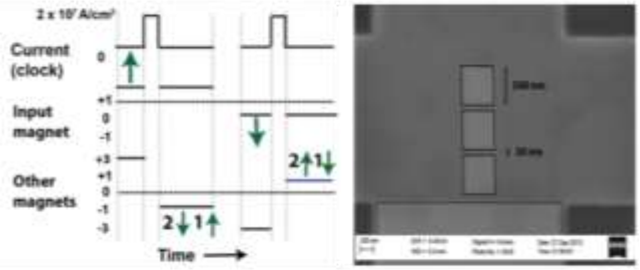


Figure 53: Information propagates across a chain of CoFeB magnets chain, clocked by the spin Hall current through Ta.

Importantly, the current needed for the logic operation was shown to be almost 3 orders of magnitude lower compared to previous demonstration of on-chip nanomagnetic logic. This logically translates to a more than 4 orders of magnitude reduction in energy dissipation as compared to state of the art (Figure 53) [44] [45] [46] [47] [48]. Projecting from the experimental data, operation below 100 mV is envisioned.

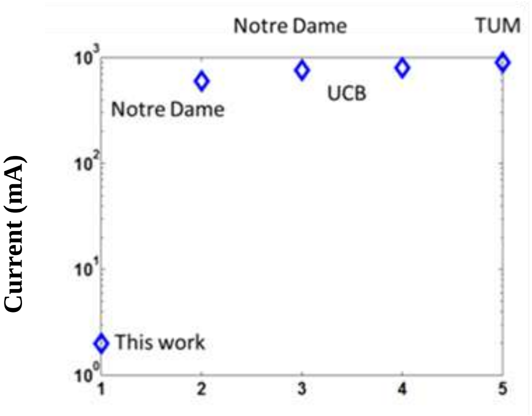


Figure 52: Comparions of Salahuddin's work on current need for logic operation with prior art**.**

- *Ultrafast Magnet Switching*

  This project takes advantage of non-equilibrium dynamics for ultra-fast demagnetization. **J. Bokor** and his team (*Berkeley)* have spent Period 4 detailing the experimental approach, setting up the laboratory and building collaborations so that the studies on the dynamics for ultrafast demagnetization can be initiated.

  The initial studies build on prior work that has shown that demagnetization in the psec time range can be enabled by hot electrons that are excited via direct heating with a short pulse laser [10]. The 'heating' is with a 60 fsec laser pulse that selectively heats ONLY the electrons. In a few psec, the excited electrons exchange energy and thermalize with the crystal lattice. The electrons are heated to a temperature of 1000-2000K! But since electrons are much lighter than the ions, after the electrons share energy with the lattice, the net temperature rise is only a few K. It is during the transient high electronic temperature phase that demagnetization and magnetic switching occurs. The dynamics of the magnetization will be studied by measuring the change of polarization on reflection from the magnet of a short probe pulse, using a Magneto-Optical Kerr Effect (MOKE) magnetometer.

  Ultimately the more practical approach is to inject hot electrons into the magnet by application of a short, low-voltage electrical pulse. Conventional CMOS scaling is projected to reach transistor speeds in the range of a few psec, so such electrical pulses will be available on-chip. In the near-term, Bokor's lab will use well-known optoelectronic techniques to generate psec electrical pulses and integrate with magnetic devices in suitable microwave stripline circuits [49]. The voltage pulse injects hot electrons into the magnet which will also be monitored on the psec time scale by MOKE.

  A new laser system suitable for use in this project was designed and specified. Collaboration with the group of D. Jena at U. of Notre Dame was initiated. This group will fabricate magnetic Schottky diodes for us on wide bandgap GaN substrates. To enable characterization of the electronic structure and electron energy loss processes at the Schottky barrier interfaces, an apparatus for carrying out ballistic emission electron microscopy (BEEM) has been designed and is under construction.

The following section provides the progress and status of the pre-existing projects.

- *Experimental Verification of the Landauer Energy Limit*

As neither one of the theoretical predictions of Landauer [2] and Bennett [3] on the thermodynamics limits of computation have been experimentally verified in a device**, J. Bokor** (*Berkeley)* has sought this experimental verification from the inception of the Center. In the previous periods, the group has found that the combined area of the hysteresis loops of a nanomagnet during bit erasure approaches Landauer's thermodynamic limit of *k*Tln(2) with high precision in the damped switching mode through micromagnetic simulation [50]. In addition, the first experimental measurement to verify the Landauer limit was carried out in the **Bokor** lab and reported last year, demonstrating results that are consistent with the predicted *k*Tln2 value, but the error bar was about 8*k*T.

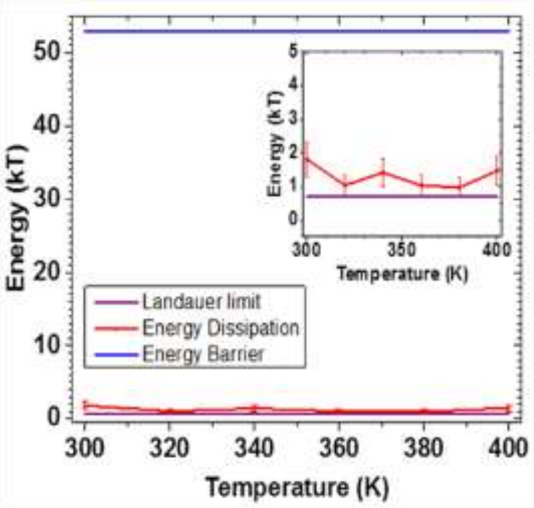


Figure 54: Experimental demonsration of the Landauer Limit to 0.5*k*T accuracy

In the past 12 months, we continue to reduce the measurement error by improving the signal/noise ratio in MOKE measurements of nanomagnet erasure. Figure 54 shows the improvement of measurement accuracy to 0.5KT; i.e. we obtained a value of 1.0 ± 0.5 *kT* at room temperature, consistent with the theoretical prediction. Nevertheless, careful analysis of this high precision experiment identified systematic variations in the results as a function of magnetic field parameters that should not be there. Using a combination of micromagnetic simulations and experimental study, we have identified likely origins of these effects. We are redesigning our sample and experimental apparatus to take these into account and hope to achieve further improvement in the measurement accuracy as a result.

- *Spin Dynamics Using Diamond NV Arrays*

Diamond NV center arrays were envisioned to be prime candidates for room temperature magnetic logic. In past reporting periods, **I. Siddiqi**'s group (*Berkeley)* had reported the development of a highly sensitive nanoSQUID to investigate mechanisms responsible for information loss in densely packed arrays. The nanobridge magnetometer's sensitivity is expected be sufficient to observe the spins of the Diamond NV centers that are dispersively coupled, and this could be accomplished with an ensemble of several hundred spins, as opposed to the requirement of other superconducting circuit systems of ~10^{17} spins.

In Period 4, we measured magnetic signals and relaxation of high density (~10^{18}/cm^3) P1 centers and NV centers implanted in diamond. Measurement temperatures were 15-350 mK. Although P1 and NV centers have been measured using electron spin resonance (ESR), the magnetic field of these impurities has never been directly measured before, making these results unique. We have also complemented these measurements with superconducting resonator measurements on the same samples.

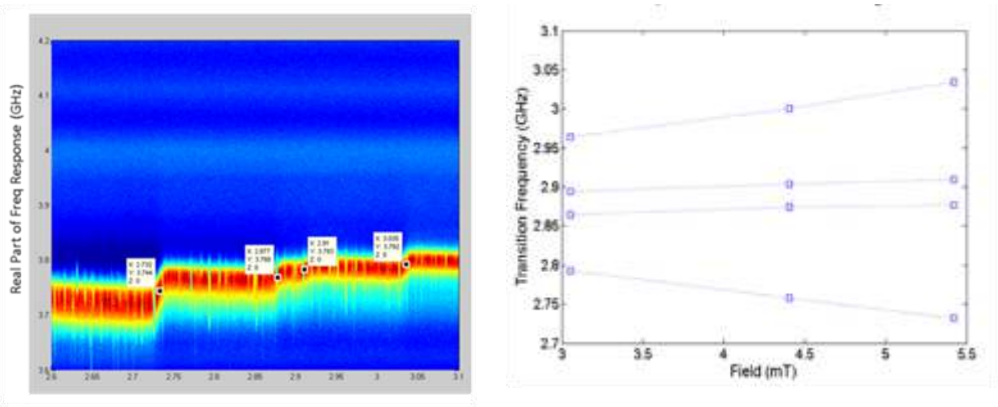


Figure 55: Transition frequencies for diamond P1 centers measured using the nanoSQUID magnetometer

To achieve these results, we developed a new capacitor dielectric layer (Al-Oxide) that allows for thinner oxide layer, and increases the versatility of our fabrication process. This has enabled us to fabricate smaller capacitor pads, thus improving the field tolerance of the nanobridge magnetometer beyond our published values.

With our current setup we are able to measure the P1 centers in diamond with the magnetometer, but are not able to directly detect NV centers because the magnetic signal from the centers cancels due to crystal symmetry. Magnetic field dependent spectroscopy results are shown in Figure 55. However, using a superconducting resonator, we are able to directly measure the NVs. Additionally we were able to study the unexpected off-resonant cross-coupling between NV and P1 centers present in of the diamond samples. When measuring several nanodiamonds, the crystal symmetry problem is reduced, and we still expecting to be able to measure NV nanodiamonds as proposed during the remaining of Period 4.

- *BFO Multiferroic Switching at Lower Voltage*

Having reported in Reporting Period 2 switching of nanomagnets at 7V [51] the near term goal of **R. Ramesh** and his research group (*Berkeley)* has been to demonstrate electric field control of magnetism in a CoFe-BFO heterostructure to below 1V during the current reporting period.

This happens in 2 steps. First, we have already demonstrated switching fields of ~50-70kV/cm, corresponding to switching voltages of 0.5-0.7V/100nm (Figure 56). These La-BFO films have been integrated on Si substrates. The top left part shows X-ray diffraction patterns attesting to the film quality, supported by the TEM image at the bottom. The right side figure shows the piezoelectric phase response showing the full switching around 50-70kV/cm.

The next step is to fabricate exchange coupled, CoFe-LBFO heterostructures, which has also been accomplished. The electric field control of this coupling is being studied using a combination of techniques. FMR studies have shown that the FMR signal in the CoFe layer can be successfully modulated with an electric field. The results of these studies are shown in Figure 57 for the case of CoFe/BFO interface. We are currently using this approach with the La-BFO multiferroic which should lead to a lower electric field (and voltage).

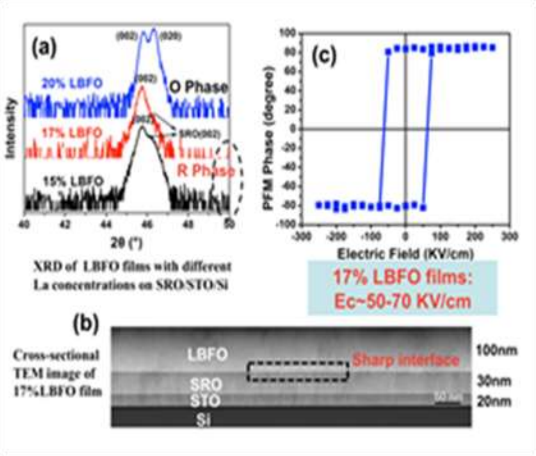


Figure 56: Switching observed in La-BFO films on Si substrates

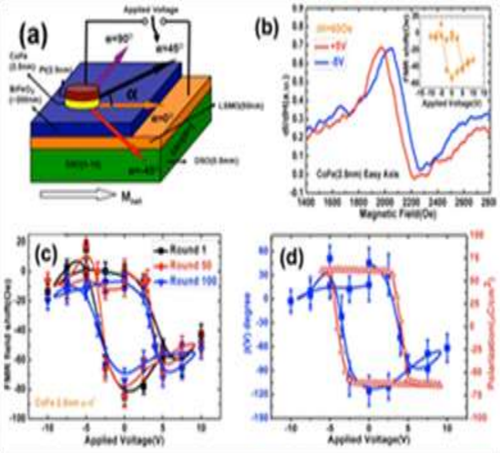


Figure 57: Electrical field control of CoFe-LBFO heterostructures.

- *PZT/Terfenol Composite Multiferroic*

The key goal for this project in the **Bokor** group (*Berkeley)* is establish a proof of concept with the fabrication and testing of composite magnetoelectric structures using thin-film piezoelectric materials (PZT or PMN-PT); see schematic of a sample in Figure 58. The key concept to be tested is the effects of "substrate clamping" on magnetic actuation.

Figure 58: Cross-sectional view of a composite magnetoelectric film

During this reporting period, composite magnetoelectric film stacks involving PZT or PMN-PT piezoelectrics have been grown. PZT and PMN-PT were deposited by pulsed laser deposition while the Terfenol D layer is deposited by sputtering.

High magnetostriction coefficient ferromagnet materials with Terfenol-D have been grown and their magnetic properties characterized (Figure 59). Polarization measurements confirm ferroelectric hysteresis. When Terfornol-D is poled, Hall Resistance hysteresis was observed.

While these initial results are promising, further work on the materials quality is needed to allow a definitive interpretation of the Anomalous Hall Effect measurements. Thus, significant efforts were applied to optimize deposition conditions to get a high magnetostriction coefficient for Terfenol-D as Terfenol-D magnetostriction properties are known to be extremely sensitive to alloy composition [52]. In particular, Terfenol-D composition is sensitive to sputtering parameters, like growth rate (power, argon pressure (Figure 60).

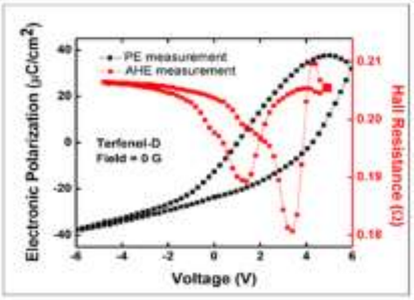


Figure 60: Characterization of ferromagnet materials with terfenol-D

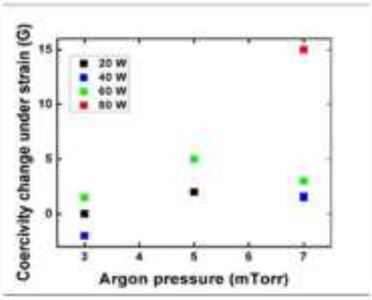


Figure 59: Ferromagneticity of Terfonol-D samples as a function of Argon pressure during sputtering

2b. *Performance Against Metrics*

Objective: Integrative Research

Metrics	Targets	Results		
		Period 2	Period 3	Period 4
Multi-PI Projects	Period 2: 30% Period 5: 75%	44%	67% (14)	55% (12)
Multi-Institutional Projects	Period 2: 10% Period 5: 30%	4%	10% (2)	9% (2)
Unplanned research projects	Period 3: 1 Period 4: 3 Period 5: 0	3	4	1
New joint research funding opportunities	Period 3: 1 proposal Period 4: 2 Period 5: 2	n/a	1	1
Publications with authors from multiple institutions	Period 3: 12 Period 4: 3 Period 5: 5	0	1	1
Publications with authors from multiple departments	Period 4: 2 Period 5: 4	0	0	1

2c. *Research in Period 5*

The Center's four Themes and the System Integration research effort will continue, but changes are expected in Period 5 that will contribute to the technical directions and foundation of the Center in its 2nd five years.

- Research Plans:

Theme I: The Period 5 work plan reflects a year of transition, as the Theme I's technical direction consolidates. Most projects that have been initiated in past periods will continue and evolve around the four approaches: the bilayer switch, nanowires tunneling structures, monolayer semiconductors and monitoring the inherent spatial inhomogeneity of larger devices by low temperature current/voltage spectroscopy. To enable a tighter focus among researchers, the Negative Capacitance project will not be pursued as part of Theme I, though it continues to garner considerable outside interest. The goal is to answer the fundamental and practical question of how sharp a bandedge could actually be, in spite of being hidden and obscured by doping and structural.

In view of the need for structural perfection at the quantum level, in Period 5, we will seek new research partners who could contribute toward bottom-up fabrication of chemically perfect device structures.

Theme II: Theme II will continue to focus on device approaches and materials studies to overcome the fundamental energy-efficiency limits of a mechanical switch.. A laterally actuated relay design with sub-lithographic contact gaps will be developed for use as a vehicle to investigate these approaches, as well as to allow the investigation of energy-efficient systems. The two approaches to be pursued are the squitch and the tunnel switch. Materials studies to ameliorate surface adhesion will include the molecular squitch concept, as well as low adhesion 2D and 1D.

Period 5 will see additional efforts to plan for a circuit demonstration of millivolt switching systems.

Theme III: This Theme is continuing on the same direction towards few-photon optical communications, using previously articulated antenna enhanced LED transmitters, and ultra-sensitive photo-receiver concepts. Consideration of different device design options for integrated photo-receivers has coalesced around the bipolar photo-transistor concept. Advancements in device performance will be accompanied by additional efforts toward optical mode-matching for waveguide integration. Period 5 should see additional results from an effective collaboration between Berkeley and UTEP as part of this Theme, as well as the availability of epitaxial materials grown within the Center for Theme III emitters and photo-receivers.

Theme IV: The transition of research projects to the concept of current controlled switching of nano-magnets followed by magneto-resistively controlled currents, with net current gain and fan-out will be complete. At the same time, new concepts have emerged toward phase-transition picosecond magnetic switching. On the other the project on electric fieldcontrolled magnetic switching will not continue owing to the promise of the spin-Hall effect toward low voltage current controlled switching.

System Integration: The number of research projects that require circuit and systems analysis is expected in increase in Period 5. To accelerate progress the System Integration research team is growing in Period 5.

- Faculty:

  Adding Florida International University (FIU) as fourth subaward institution will enable a new faculty, **S. Khizroev**, to be part of Theme IV. **S. Salahuddin** *(Berkeley)* will focus on Theme IV research objectives and will not participate in Theme I. Changes in Theme IV are also leading to two Berkeley faculty, **R. Ramesh** and **S. Siddiqi**, not continuing with the Center in Period 5.

  To expand research investigations with circuit and systems implications and in anticipation of a circuit demonstration in Theme II, **V. Stojanovic** *(Berkeley)* will join the Center and collaborate with **E. Alon** *(Berkeley)* and the Theme leaders to accelerate the projects that require circuit/systems analysis.

  The studies on epitaxial material growth undertaken in the laboratory of **E. Fitzgerald** *(MIT)* will expand beyond Theme I. The group will begin to investigate and grow III-V structures for Theme III's nanoLED project.

  The biosketches of the new faculty members, who are joining of the Center in Period 5, are given in Appendix A.

2ci. System Integration Research

The principal goal of this project is to explore the implications of actual communication and computation circuits/systems on the design, optimization, and requirements of the emerging device technologies being explored in the rest of the center. We further aim to develop circuit techniques that utilize the characteristics of these emerging devices as well as eventually carry out experimental demonstrations of the proposed circuits/systems. In Period 5, **E. Alon** and **V. Stojanovic** *(both Berkeley)* will be a team to collaborate with the Theme leaders on Theme specific investigations that require circuit/system analysis.

E. Alon will continue/expand our activities that were initiated in prior reporting periods.

- Explore the circuit and system-level opportunities offered by dense electro-mechanical memory (NEMory) devices integrated on top of CMOS. We will develop optimized interface circuitry and array organizations and utilize these designs to predict the energy/area/performance capabilities of the technology.
- Continue the development of circuit designs and demonstrations using relay technology. In particular, as the devices and fabrication process have become more mature, we will begin exploring squitch-based circuit designs, modeling, and analysis.
- Complete a general analysis of the minimum energy required by photonic links including all practical limitations and quantify the penalty these practical limits introduce beyond purely SNR-limited designs. We further plan to explore optimized photonic link designs based on the new emitter and receiver devices being developed in Theme 2.

V. Stojanovic will begin to quantify the benefits of the emerging device technologies in Theme II and IV at the circuit/system level as well as guidance to the device designers on which device design parameters are critical to improve at the system level. The first barrier is to create circuit-level device models for both technologies that are versatile-enough to capture the most important characteristics of the underlying devices yet simplified-enough to enable fast circuit-level simulation. The second barrier is to invent the circuit topologies that will get around or alleviate some of the challenges facing the underlying device technology (e.g. modest on/off ratios in Tunnel Magneto-Resistive devices, or long mechanical delays in relay devices). To address the first challenge, we will

- Create an updated set of behavioral models that capture the scaled, sub 0.1V relay device designs; and
- Create an initial set of behavioral models for modest on/off ratio TMR device.

The models will be followed by defining first-pass circuit topologies for TMR devices and scaled relay devices.

2cii. Theme I : Nanoelectronics *Theme Leader:* **E. Yablonovitch** *(UC Berkeley)*

Taking into account the research of Period 4 (simulation results, comprehensive analysis of TFET performance data, and data from diodes with controlled material growth), Theme I researchers have reach a preliminary conclusions that the difficulty in achieving abrupt switch is due to bandedge broadening by doping and materials inhomogeneity from like layer thickness and strain variations, and interfacial traps. In Period 5, the researchers will build on this conclusion with experimental data from device fabrication and characterization data. The data will come from device designs that are expected to show improved abruptness in switching and current or from device designs that are executed in well controlled material systems that will allow the elucidation of the science without extraneous factors.

In Period 5, Theme I research is coalescing around these underlying approaches:

- Bilayer TFET to take advantage of an undoped or very lowly doped channel and 2D-2D dimensionality
- Nanowires TFET to take advantage of very small geometries, thereby minimizing inhomogeneity
- Monolayer semiconductors to take advantage of chalcogenide layer compounds to take advantage of fewer interface states as well as less spatial inhomogeneity
- Controlled material growth to systematically understand the effects on the turn on characteristics of diodes

In parallel, **E. Yablonovitch** will lead an effort to explore paradigm changing concepts that will address the issue of material homogeniety. It is recognized that as these concepts are conceived, the Center is prepared to add researchers who can provide the necessary expertise for the Center to make progress in the new research directions.

To allow Theme I to have a tighter focus among the researchers, the Negative Capacitance project will no longer continue as part of Theme I in Period 5.

Below are additional details of the planned research that will be pursued by the current Theme I researchers.

- Bilayer: The laboratories of **E. Yablonovitch**, **J. Hoyt** and **D. Antoniadis** *(Berkeley and MIT)* are continuing the effort to fabricate and characterize the bilayer switch device. Having collaborated on simulation and modeling in Period 4, each group has designed its own bilayer device design in a different materials system.
  Berkeley: The InAs bilayer TFET with ultra-thin layers, fabricated in Period 4 using the layer transfer technique, will still be in characterization in the beginning of Period 5. The merit of this approach is the ability to study the turn-on function in a Type III device with very thin and undoped n-p junctions. Low temperature device characteristics will be obtained to help resolve the inherent material homogeniety that come with the device size. Several fabrication iterations of the device are expected in the normal course of device optimization.

  MIT: Fabrication of a new experimental device structure ("3Gate") that was designed to mitigate the impact of parasitic tunneling paths will continue into Period 5. This electrostatically doped electron/hole 2D-to-2D ("bilayer") tunneling device structure that will be fabricated using bond-and-etch back in strained-Si/strained-Ge, a materials system in which the MIT team has extensive experience. The relatively small Eg_{eff} (200 meV) is also an advantage. Even though Si/Ge is not a direct bandgap system, the merit of a well-controlled material system is the opportunity to assess of the improvements in turn-on steepness and current in a bilayer design, without the complications of a difficult-to-control material system. This assessment will help guide the future direction to pursue. Devices will be also be characterized at low temperature to resolve the multiple turn-on thresholds caused by device inhomogeniety that come with device size.

- Nanowires (NW) TFET: In Period 5, research into nanowire tunneling FETs that was initiated in Period 2 in the laboratory of **D. del Alamo** *(MIT)* will broaden to include more researchers at MIT and researchers at Berkeley.
  MIT: The laboratory of del Alamo will address the fabrication challenges as his team strive to realize a superlattice NanoWire gate-controlled Esaki diode as the next step. Issues include the need for a fabrication process that will result in more robust, reduce gate leakage current, reduce ON resistance, improve sidewall interfacial characteristics and to down-scale the nanowire diameter to ~20 nm. A key Period 5 milestone is the fabrication of nanowire structures with the goal of performing direct observations of the bandedge density of states. One anticipated difficulty will be the access to a Scanning Tunneling Microscope with bias and low temperature capabilities, a critical and necessary characterization tool.

  On the simulation front, the D. del Alamo, J. Hoyt and D. Antoniadis will collaborate towards building a self-consistent Poisson-Schrodinger 3D model capable of simulating the electrical characteristics of SLS-NW MOSFETs. We will start by building a 3D NW model and comparing the results with experimental devices. This will build the understanding necessary for the fabrication of Gate All Around-NW Tunnel FETs.

  The lab of Hoyt and Antoniadis will also begin to research on InGaAs/GaAsSb vertical nano-wire TFETs have the advantage of (a) direct bandgap, (b) effective bandgap at the heterointerface which can be tuned (by varying the alloy composition) between ~ 0 and 300meV, and (c) relatively small lattice mismatch which minimizes strain variations. We have proposed a new nanowire device structure which addresses issues identified in the prior structure. The tunnel junction is patterned into ~15nm-wide wires. Modelling efforts will guide the design of this device.

Berkeley: **C. Hu** will also pursue a pillar shaped structure with cylindrical gate as the next step towards revealing the bandedge sharpness in a single quantum channel. We will use a top-down approach, starting with high quality MBE substrate with proven junction quality and band alignment and creating the nanowire structure by etching. Collaboration on regrowth of InAs/AlSb/GaSb epilayer in sub-100nm holes will be established with National Chiao Tung University, Taiwan.

- Monolayer Semiconductors

  The **Javey** group *(Berkeley)* will continue research in chalcogenides monolayer semiconductors in Period 5. We will first perform device study of WSe_2/MoS_2 hetero-bilayer, enabled by selective electron/hole contacts. Then we will develop heterojunction TFETs based on WSe_2-$SnSe_2$ material system, which exhibits a Type III band offset. We will fabricate and characterize tunnel diodes and potentially TFETs based on WSe_2-$SnSe_2$. Few-layer h-BN will be used as an intermediate dielectric layer to allow the band to offset more efficiently with gating. Experimental work will be carried out along with device simulations.

  C. Hu will expand his TFET collaboration with Javey to include fabrication of WSe_2/MoS_2 tunnel diode and tunnel FET. These 2D semiconductors have far fewer interface states at the interface with gate dielectrics. They also afford the opportunity to create new thin body TFET structures.

- Controlled Materials Growth Studies: The **E. Fitzgerald** group will continue its materials growth research to understand limitations of interface sharpness toward electrical properties of backward diodes. One key focus will be on InGaAs/InAlAs superlattices, in support of the Superlattice Nanowire TFET research efforts of del Alamo. Some planned studies include the effect of AlSb barrier thickness and use of other barrier types in InAs/GaSb, the effect of band-alignment on tunnel properties via alloying and the effect of pn-junction dimensionality sub-threshold voltage swing.
  In Period 5, the **Fitzgerald** group will also initiate studies in InP-based materials for applications in Theme III's research in optical antenna enhanced nanoLEDs.

2ciii. Theme II: Nanomechanics *Theme Leader:* **T.-J. King Liu** *(UC Berkeley)*

In Period 5, Theme II will focus on approaches to overcome the fundamental energy-efficiency limit of a mechanical switch, set by contact surface adhesion. A laterally actuated relay design with sub-lithographic contact gaps will be developed for use as a vehicle to investigate these approaches, as well as to allow the investigation of energy-efficient systems. The two unique approaches being pursued in the Center under this Theme are the squitch and the van der Waals switch:

- *Squitch:* With no voltage applied the squitch is off, *i.e.* the separation between the conducting electrodes is relatively large (>4 nm). Electrostatic actuation is used to bring the conducting electrodes closer together (<2 nm separation) and thereby increase tunneling current by orders of magnitude. An intermediary molecular layer exerts a spring restoring force that counteracts the van der Waals force and thereby reduces the depth of the potential well (Figure 61).
- *van der Waals(vdW) Switch:* With no voltage applied the vdW switch is on, because the as-fabricated contact gap is extremely small (<1 nm) so that van der Waals force pulls the conducting electrodes into contact. Electrostatic actuation is used to separate the conducting electrodes, to turn off the switch (Figure 61).

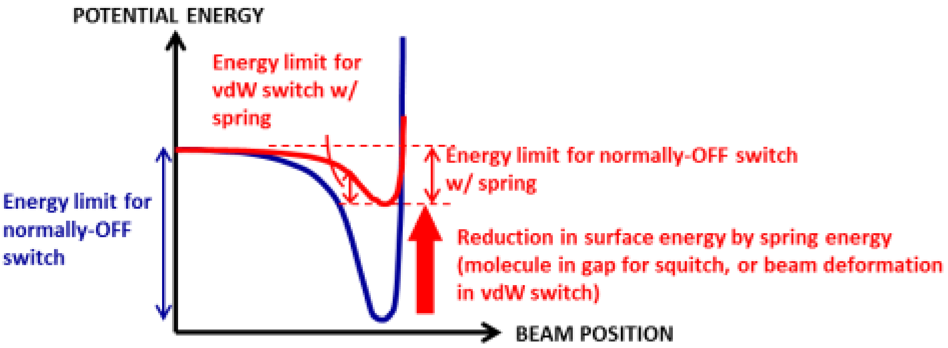


Figure 61: Schematic of the surface energy in a squitch and a van der Waals switch versus a conventional mechanical switch as a function of the gap between the source and drain

We will perform fundamental investigations of the piezoresistive properties of various candidate molecular layers for the squitch, and of the contact adhesion properties of two-dimensional (2-D) and one-dimensional (1-D) materials which potentially may be advantageous as atomically smooth surface coatings (with very predictable adhesive force) for the tunnel switch. The goal is to demonstrate at least 4 orders of magnitude change in current for a switching voltage of 100meV or less. As the relay design and fabrication process become more mature, we will begin exploring nanomechanical circuit designs to lay the foundation for an ultra-low-voltage system demonstration.

The exploratory concepts of a magnetically actuated switch and a solid-state switch with VO_2 or MoS_2 as a piezoresistive material will not continue in Period 5. The former will no longer be pursued because the need for low power in Theme IV mitigates against electro-magnetic actuation. The latter will no longer be pursued because the displacements and forces required to achieve at least 4 orders of magnitude change in resistance (of VO_2 or MoS_2) are too large to be practical for low-voltage operation.

More detailed descriptions of the future research activities under Theme II are provided below.

- *Squitch*

  The long-term goals for this project, a collaboration of **V. Bulović**, **J. Lang** and **T. Swager** *(MIT)*, include the demonstration of squitches with on/off conduction ratio exceeding 10^4, a switching energy less than 10 keV, a switching voltage near 0.1 V, and switching time approaching 1ns. The analyses and experimental results from previous years indicate that there exist no fundamental physical barriers to meeting these device performance goals. Rather, the significant challenges are the design and integration of sufficiently soft materials to hold apart the conducting electrodes, and the fabrication of squitches at the nanometer scale. Significant progress already has been made toward meeting these challenges. From a scientific perspective, we seek to understand the electromechanics of the squitch as it operates with nanometer-scale gaps containing a compressible molecular layer. We will develop molecular layers with more optimal properties, and will integrate multiple squitches into a single circuit (*e.g.* a 3-stage ring oscillator) to characterize device performance parameters such as gain, speed, switching energy, on:off conduction ratio, parasitic capacitance and so on. We will also develop molecules with different chemical terminations designed to adhere to the specific conducting electrode materials used in the laterally actuated relays with sub-lithographic contact gaps fabricated at UC Berkeley. (For example, we already have developed PEG-diamine and fluorous-decanamine molecular layers that will adhere to tungsten which has been used as the conducting electrode material in relays fabricated at UC Berkeley.)

- *van der Waal Switch*

The goal of this project, led by **T.-J. King Liu** *(Berkeley)*, is to develop and demonstrate a new MEM logic switch design that not only operates with less than 0.1 V swing in a conventional mode but also operates with even lower voltage swing in squitch and tunnel modes as described above. To achieve such ultra-low voltage operation without an inordinately large actuation area, the actuation gap will be defined by the lithographic limit (0.25 μm for the stepper in the UC Berkeley Marvell Nanolab) while the contact/tunneling gap will be defined by sub-lithographic techniques such as lithographic overexposure, overetch and/or sacrificial oxidation. Laterally actuated switches will be fabricated and characterized and then sent to MIT for molecular coating (to fill the contact gap) to form squitches. Operation of the fabricated switches in van der Waal mode will be investigated using millivolt ac signals across a range of frequencies.

- *Characterization of Low-Adhesion Contact Materials*

  Led by **H.-S. P. Wong** *(Stanford)*, this project will investigate the properties of low-dimensional materials (specifically graphene, MoS_2, and carbon nanotubes) as contacting electrode coatings. Graphene is a semi-metallic material while monolayer MoS_2 is a wide-bandgap (1.9 eV) semiconductor. Although the thicknesses of both materials are comparable (3Å for graphene, 7Å for MoS_2), their different band structures result in different transport (tunneling) characteristics. In addition, the atomic bonding configuration of graphene and MoS_2 are different, although both materials are van der Waal materials. Carbon nanotubes, on the other hand, have the same atomic bonding configuration as graphene but can be metallic or semiconducting depending on their chirality. The real contact area is also very different for 1-D *vs*. 2-D materials. We will explore the use of an integrated feedback circuit to stabilize the contact gap and thereby allow detailed characterization of tunneling current *vs*. voltage.

- *Demonstration of Low-Voltage Nanomechanical Integrated Systems*

  The principal goal of this project, led by the team of **E. Alon** and **V. Stojanović** (Berkeley), is to develop circuit design methodologies that leverage the unique characteristics of nanomechanical switches and to experimentally demonstrate energy-efficient integrated systems. We will to design and demonstrate a complete family of basic logic gates and combinational logic units, as well as memory cells, with the new switch designs described above. We will also investigate system-level opportunities enabled by the integration of nano-electro-mechanical memory devices on top of CMOS, developing optimized interface circuitry and memory array organizations and using these designs to predict the energy/area/performance capabilities of this dense non-volatile memory technology.

2civ. Theme III: Nanophotonics — *Theme Leader:* **M. C Wu** *(UC Berkeley)*

Theme III's focus will continue to be on optical emitters, photo-receivers and their integration into waveguides. Material growth projects pursued in support of device research will also continue.

- *Spontaneous Hyper Emission (SHE) nanoLEDs*

  Up until now, the research on SHE nanoLEDs in the **M.C. Wu** group *(Berkeley)* has been focused on making single devices. To demonstrate the true low-power signaling capability of these devices, they need to be integrated together into a photonic circuit. During Period 5 we plan to lay the groundwork needed to integrate these devices together into these large-scale circuits. To do this we will need to further develop the III/V on Silicon platform we have begun developing in Period 4 to enable the use of Silicon Photonics for long reach optical waveguides and devices. In addition, integrated nanoLEDs will need to be electrically injected to allow for direct modulation.

  Initially, these two problems will be addressed separately, with optically pumped nanoLEDs being used to test III-V/Silicon integration and individual electrically injected devices being made on normal InP substrates. For the second part of the Period we will use the experience we have acquired working on integration and electrical injection to integrate these two processes together. Electrically injected structures are inherently complex, so time will be needed to develop both a device and process design that can be successfully integrated into our Silicon platform.

- *Nano-Phototransistors with Ultralow Capacitance*

  Theme III will continue to pursue research in the nano-phototransistors based on the two classes of materials, germanium on silicon and III-V on silicon.

  - Germanium Nano-phototransistors
    There are two primary barriers to creating a low-energy photoreceiver: the large capacitance wire connecting photodiode to pre-amp and the difficulty in shrinking the capacitance of the photodiode without degrading the quantum efficiency. The research focus in Period 4 of creating a phototransistor that is essentially a tightly integrated photodiode/pre-amp system addresses the first issue. The approach of **M.C. Wu**’s group for the second issue involves optimizing a metal-optic cavity that naturally arises when scaling the device, which can be used to enhance absorption in very small volumes.

    In the current Period 4, we have learned that the overall signal of Photo-MOSFETs is not as strong as would be desired, even though there was gain and decent speed. Since the germanium gated photo-MOSFET operates much like a silicon MOSFET with an open circuit solar cell as the gate, the output photocurrent measured through the drain is proportional to the logarithm of the optical power input on the gate when the device is operated in the saturation region. A linear relationship between drain current and input optical power is present with the device is operated in the subthreshold region, but at the cost of lower overall output current. To resolve these fundamental trade-offs, we are planning to investigate bipolar transistors (BJT) as a more desirable alternative to a MOSFET based phototransistor, since in a BJT the output current should be linear with the input optical power in all regions of operation.

    Thus, in the next period, using the rapid melt growth technique integrated with silicon photonics that was developed in Period 4, the same mask and process, we will fabricate germanium p-i-n photodiodes, metal-semiconductor-metal (MSM) photodiodes, n-p-n bipolar phototransistors, and germanium body MOSFETs. Combined with theoretical models and device simulations we will explore which architecture is optimal for low-energy applications. We will also explore the actual fabrication of metal-nanocavity devices.

    The groups of **M.C. Wu** and **E. Yablonovitch** will work together to co-design an improved and optimized phototransistor. The team will leverage the fabrication experience in integrating germanium on silicon in the M.C. Wu group and the fundamental knowledge gained through modelling in the Yablonovitch group.

    Also important for optimizing a low-energy photoreceiver will be the understanding of how the receiver circuit is changed by having a phototransistor instead of a photodiode. We also plan to work closely with **Alon** group to refine their existing photoreceiver model for phototransistors to better understand how these differ from traditional photodiode/transistor photoreceivers.

  - III-V on Silicon Nano-phototransistors

    In Period 5, the **Chang-Hasnain** group will continue address the challenge that comes with the small capacitance need for a sensitive detector; the resultant need for small device dimensions sacrifices light absorption. The use of high quality InP nanopillar directly grown on silicon the high absorption coefficient of InP will enabloe very small bipolar phototransistor (BPT) to be able to absorb most of the light. Further enhancement can be achieved with the use of our newly developed regrowth method, which allows the creation of a large absorption region in the nanopillar core while maintaining a very small capacitance with a small carrier transport region in the regrown portion of the nanopillar. The regrowth method also prevents the shell from shorting to the substrate, further reducing the dark current and improving sensitivity. In Period 5, we will build sensitive InP BPT detectors using the regrowth method. Fabrication and characterization techniques to characterize the doping concentration will be developed. Then, we will use the regrowth method to fabricate BPT structures. Upon realizing working BJTs with the regrowth method, we will then develop doped InP nanopillars for the site control growth so that site controlled BJT detectors can be realized.

Increasing the yield of selective area growth can be a very difficult task without first knowing how the nanopillars nucleate. Dopants used during growing doped nanopillars with selective area growth can deter nucleations of nanopillars. We will use the growth nucleation model and design of experiment to mitigate this challenge. The nucleation model for nanopillars initiated in Period 4 by the **Zubia** group *(UTEP)* should enable a design of experiments to help fine tune the experimental growth condition to achieve higher yield for the site control growth undertaken in the **Chang-Hasnain** group *(Berkeley)*.

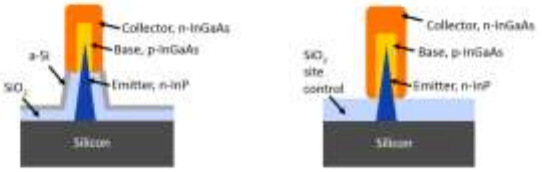


Figure 62: III-V nanopillar phototransistor fabricated by regrowth method (left) and by site-controlled selective-area growth (right).

- Selective-area growth of InP on Si(111)

  D. Zubia *(UTEP)* will investigate the selective-area growth of InP on Si(111) via the close-space sublimation method, in collaboration with **C. Chang-Hasnain** *(Berkeley)*. While this work will explore an alternative experimental pathway to achieving high quality InP nanoneedles and/or nanowires, the theoretical work will contribute to a broader understanding of growth kinetics and mechanics including growth selectivity, growth mode, and critical dimensions for low defect density. The work has the potential of contributing to materials growth of highly efficient devices such as phototransistors with ultra-low capacitance within the nanophotonics theme.

  The UTEP group has extensive experience with selective-area growth of CdTe on CdS for solar cell applications via the close-space sublimation (CSS) technique, a low cost, high throughput method technique, in which the distance between the source and substrate (~1 to 4 mm) is typically less than the mean-free path enabling efficient transfer of source material and pseudo-MBE mode growth at 0.1 to 10 Torr [53]. In 2013, the **Javey** group *(Berkeley)* reported the growth of InP nanowires using the CSS method [54]. Moreover, they also demonstrated the selective-area growth of InP on molybdenum. Together these two results illustrate the potential of growing the InP nanoneedles and/or nanowires on Si (111) via CSS for the first time.

  The research at UTEP will be coupled with the work on nanoneedle growth via MOCVD at Berkeley.

2cv. Theme IV: Nanomagnetics *Theme Leader:* **J. Bokor** *(UC Berkeley)*

Theme IV recognizes that the following research areas that are focused on spin control can offer a viable pathway to ultra-low energy magneto-resistive switching of electrical wires for logic.

- Spin Hall effect switching is about 100× more sensitive than Ampere’s Law for switching a magnet.

- Non-equilibrium and thermally induced magnetic phase transitions are much faster (picoseconds) than spin rotations, allowing access to higher operating speeds than had previously been considered for magnets.
- Magnetic Tunnel Junctions display adequate On/Off ratio for certain circuit applications, like always on communications channels.
- More general applications still call for the need for increased Magneto-Resistance ratio.

As Theme IV will continue to be the most futuristic Theme of the Center, the researchers will primarily be elucidating the physics and dynamics versus working towards near-term device demonstrations.

J. Bokor and **S. Salahuddin** *(both Berkeley)* continue in research in the first two areas. To help build a critical mass of researchers, the Center's Executive Committee solicited and accepted a proposal from **S. Khizroev** *(FIU)* to join the Center. As discussed in the introduction of the Theme IV reporting section, the Center finds synergy in the research direction of the **Khizroev** group [40]. The first author of the publication (J. Hong) has since joined the Bokor lab as a postdoctoral fellow of the Center.

We need to explore how magnetic devices can achieve significantly high MR (magnetoresistance on/off) ratio. This gap will be addressed in two ways:

- Solicit research proposals for increasing Magneto-Resistance ratio;
- Work with **V. Stojanovic** *(Berkeley)* for circuit/system analysis of pulse-powered circuits, and high activity factor circuits using modest MR on/off ratio devices.

Other previously reported Theme IV projects will not continue in the next Report Period 5 and when approved by NSF, **S. Khizroev** will join **J. Bokor** and **S. Salahuddin** to pursue research under Theme IV. Together, the three researchers will form the core of the Theme IV team and work with **V. Stojanovic** to understand how they can approach their research to have practical circuit applications.

The following is the work plan for Period 5.

- *Physics of Spin Hall Effect:*

  S. Salahuddin *(Berkeley)* will study the fundamental physics of interaction between spin current generated by spin Hall effect (SHE) and a nanomagnet within the context of power dissipation in magnetic switching specifically by looking into new materials, size scaling and dynamics. Our goal in this work will be to form a coherent understanding of the spin current generated by spin orbit interaction and its interaction with other magnetic entities. To pursue this goal we will combine synthesis of hetero-interfaces and magneto transport measurement with transport theory and magnetization dynamics calculations. While our current work on Ta/CoFeB heterostructures provides a solid starting point, we shall investigate other heavy metals such as Hf and conventional metals doped with heavy impurities such as Bi, Ir etc. We are already synthesizing some of these heterostructures.

  To illustrate the concept of switching based on SHE, we have recently shown that the spin Hall generated spin current can put a magnet in a metastable state. In a perpendicularly polarized MgO(1nm)/CoFeB(1nm)/Ta(10 nm) junction, when a current pulse is applied through the bottom Ta, the CoFeB goes to an in-plane direction due to the torque provided by the spin current. Notably, when the current is shut off, the magnet remains in this state (Figure 62a). This is surprising because the only two stable states for the magnet are either up or down. This metastable state is very robust and can be stable over many days. What is perhaps more intriguing is that the magnet cannot be placed to this metastable state by applying an in-plane field. We have done coupled spin transport-micromagnetic simulation and found that the spin current breaks the magnet into small up and down domains (Figure 62b), which on average gives a zero magnetization in the out of plane direction but can be robust against thermal noise and therefore stable. No such domain nucleation happens when an in-plane magnetic field is applied. This is an example of how the spin current makes it possible to access completely new magnetic states, otherwise not possible with a magnetic field.

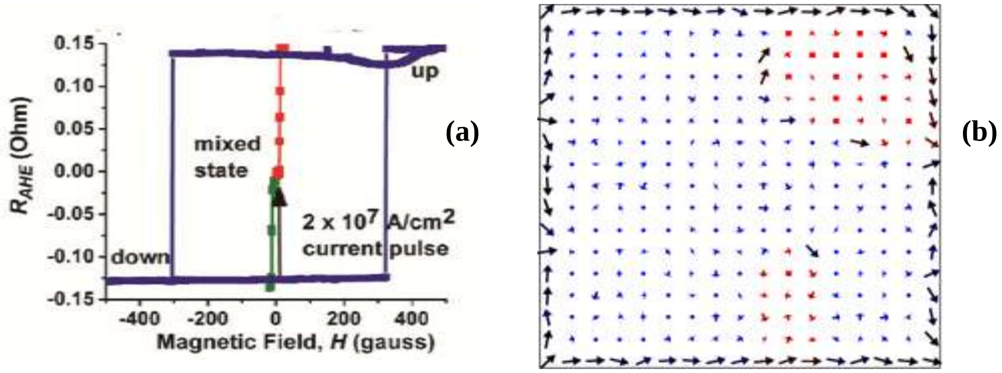


Figure 63: (a) Metastable state formation. After the current pulse is shut off, anomalous Hall resistance gives a resistance in between up and down. (b) Coupled spin transport-micromagnetic simulation showing a mixed state of up and down domains, otherwise not attainable by a magnetic field.

- *Dynamics of Ultrafast Magnet Switching*

Earlier, in the section, Research Thrusts of Period 4, we reported that the key effort of **J Bokor** for this project was the development of detailed plans for this executive of this research project. Next period will see the implementation of the plans. The key milestones are:

- Observation of basic demagnetization using the ultrafast MOKE magnetometer.
- Fabrication and test of picosecond electrical pulse generator using photoconducting GaAs switch.
- Integration of the electrical pulse generator with magnetic device and testing for demagnetization using MOKE.

- *Physics of Spin Switching in Sub-10-nm Spin-Transfer-Torque Magnetic*

Because **S. Khizroev** *(FIU)* will be a new faculty and the project's direction is new for the Center, we will provide background information to introduce the faculty and the approach.

Spin transfer torque (STT) magnetic tunneling junctions (MTJ) can enable non-volatile logic with near zero static power consumption, meeting a key challenge in further scaling of CMOS devices. In an STT-MTJ, consisting of two magnetic layers, spin-polarizing "hard" and data storage "free" layers, separated by a thin insulating film, the magnetic moment in the "free" layer can be reversed by driving a spin-polarized electric current through the junction. However, the relatively high current required to switch the spin orientations in these devices remains the main stumbling block. Assuming a linear scaling for the smallest reported density (~9 MA/cm2 for a 20-nm cell), the switching is still relatively energy-inefficient at this range of dimensions.

Previously, we conducted a preliminary experiment using a point-contact technique. We studied the STT effect in a MTJ, Ta/CoFeB/MgO/CoFeB/Ta, built on the tip of a nanoprobe in a direct contact with a copper substrate. With the contact resistance of the order of 185 kΩ, the measured magnetoresistance value was 29%. The average STT reversal current of only 95 nA indicated a switching current density of approximately 0.1MAcm^{-2} which is more than 30 times smaller than the smallest value reported for STT MTJs of larger dimensions. An atomistic-scale theory confirmed the experimental result which indicated at least an order of magnitude reduction of the spin damping in the sub-10-nm diameter range [40].

The main goal of Period 5 for this project is to understand the underlying physics of STT-MTJs in the previously poorly explored sub-10-nm range. A longer term important goal is to exploit the new physics to devise energy-efficient and thermally stable devices.

We hypothesized that we could achieve a substantially greater energy efficiency compared to that predicted according to the linear scaling if we could make the devices with effective cross-sectional dimensions of the order of 1 nm. In this region, the thermal reservoir, which usually absorbs the energy of excitations, becomes extremely small and is unable to absorb the energy resulting from the magnetic dynamics. The model of continuous crystalline lattice becomes invalid in this intermediate size range. A more suitable model would consider a material in the form of a cluster where the energy exchange between excitations is less effective than in a crystal. These factors lead to a rapid magnetization damping decrease, which implies less energy required for the switching (even at room temperature). Therefore the current density is expected to be substantially smaller than in the case of conventional linear scaling model. Besides the above hypothesis, recently our collaborator Prof. Bokor proposed another theory which explained the phenomenon by effectively “heating” up electrons and thus instantaneously reducing the switching current, like in the HAMR concept. Also, it is possible that both hypotheses can co-exist in this system.

We will test the theories by conducting a series of experiments on focused-ion-beam (FIB)-modified wafer-level STT-MTJ test structures with a characteristic cross-sectional dimension in the sub-10-nm range and then. We will build the junctions using optical lithography and then define the critical features using FIB.). We will use hundreds of the wafer-level FIB-modified test structures with a wide spread of the effective MTJ widths to conduct all the standard magnetic-field-dependent I-V tests and draw the dependence of the switching current on the effective width of the junction. In addition, we will work with our collaborators at the **Bokor** group *(Berkeley)* to use femtosecond sources to directly study the spin dynamics in the sub-10-nm junctions.

- *Circuit/System Analysis of Pulse-Powered Circuits, High Activity Factor Circuits Using Modest TMR On/Off Ratio Devices*

  This effort, to be undertaken in the group of **V. Stojanovic** *(Berkeley)*, will be reported in the System Integration section of this annual report. **J. Bokor** will be the key Theme IV interface on this System Integration project.

III. EDUCATION

1a. *Goals and Objectives*

Primary elements of the Center's education and human resource goals are:

- To train a new generation of Ph.D. and M.S.-level scientists and engineers who will:
    - be knowledgeable in the scientific approaches to low energy digital electronics systems;
    - understand that working in diverse teams optimizes creativity; and
    - understand the process of innovation, entrepreneurship and the transition of research results to commercially-viable products.
- To increase the number of students pursuing technical disciplines, contributing to an engaged, skilled and diverse technical workforce;
- To increase the number of students from historically underrepresented groups in engineering who attend university and graduate programs in technical disciplines that will contribute to low energy electronics; and
- To promote continued interest in the E^{3}S research areas among Center participants and alumni.

In its effort to develop a new generation of Ph.D. and M.S.-level scientists and engineers, the Center adopted a model of vertical integration, where our education programs: 1) integrate research with educational activities; 2) enhance interaction and mentoring among undergraduates, graduate students, postdoctoral researchers, and faculty members; and 3) broaden the educational experiences of its students and postdoctoral researchers to prepare them for a wide range of career opportunities.

1b. *Performance Metrics*

In the current strategic plan, the following indicators are used to measure the Center's Education performance:

Objective	Metrics	Frequency	Targets
Education	Number of Center graduates who have completed E^{3}S training	Yearly beginning in Period 3	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50%
	Number of students and postdocs participating in education and diversity programs	Yearly beginning in Period 3	Period 2: 5% Period 3: 60% Period 4: 70% Period 5: 75%
	Number of students and postdocs serving in leadership roles in the Center	Yearly beginning in Period 3	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25%

1c. *Problems Encountered*

Before its inception, the Center had proposed to develop a program to enhance the training of students who are aspiring to be electronic technicians through our community college partners, particularly Los Angeles Trade-Technical College (LATTC). Efforts in Period 3 to organize a needs analysis workshop involving LATTC and the Center's industry partners were unsuccessful. In Period 4, we chose a less ambitious approach by conducting informal interviews with the teaching staff of programs in two community colleges in northern California. We learned that the stronger community college technician training programs in California are narrowly focused to align with an employer. We have come across four programs that are "certified" by the Federal Aviation Administration (FAA). Teaching staff we met with informed us that many of the courses are completed online and the laboratory portion is taken on campus. They identified a need to have hands-on opportunity to troubleshoot systems. This applies to many disciplines, such as mechanical, electronics and software. Through multiple discussions with Chabot College, we identified an opportunity to enhance the curriculum of one electronics technician course. We responded by hosting a Chabot College instructor for 6 weeks this past summer (see 2c – the E^{3}S Teacher Fellows Program. Based on the input, we will also assess whether the iLab platform at MIT can be an effective online tool to enhance the technician curriculum.

New in Period 4 is an emphasis of developing educational content that relates to the scope and mission of the Center. The Center's education strategy is to build a library of online courses that will reach a broader audience, including other researchers, scientists, and engineers, undergraduate and graduate students at other colleges and universities, and pre-college students and teachers. The library is seeded with a course on Advanced Topics in Solid State Devices that **E. Yablonovitch,** Center Director, has developed and taught. The course was taught three times at UC Berkeley and offered to members at all institutions through videoconferencing technology and online posting of the course material.

In Period 4, **T.-J. King Liu** and **J. del Alamo** contributed online teaching materials. The 2013 summer programs also yielded online educational materials developed by **W. Phillips**, E^{3}S Teacher Fellow, and **A. Ragsdale,** who taught the Hands On Practical Electronics Workshop and Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU) bootcamp.

In Period 4, **G. Fitzgerald** offered an online course in Innovation and Commercialization (MITx:3.086x Innovation and Commercialization) that supports the Center's goal of training the next generation of scientist and engineers to understand innovation and entrepreneurship.

Meanwhile, our established education efforts to provide energy efficient electronics science and professional development training to the Center's students and postdocs have continued.

The recent 2013 survey of graduate students and postdocs identified the impact the Center's education programs on increasing the respondents' understanding of low energy consumption device science and technology (**Figure 64).**

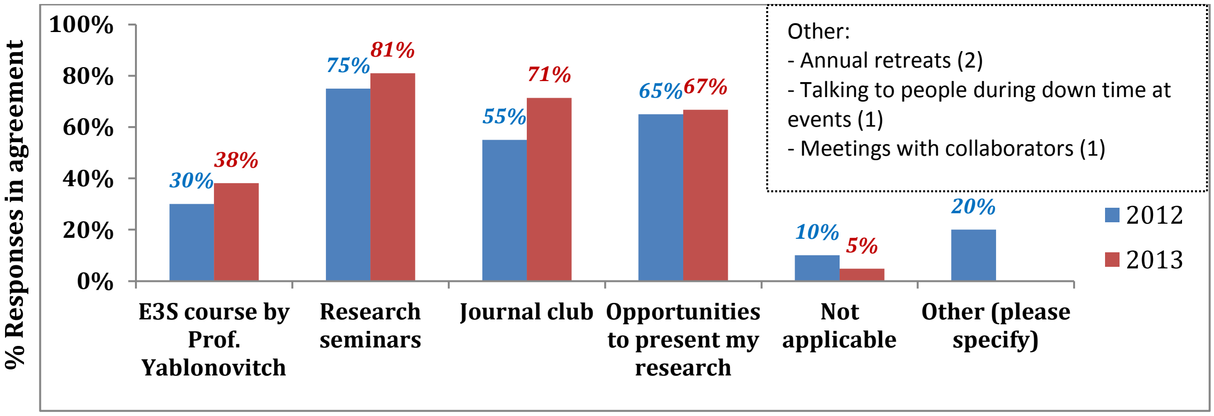


Figure 64: Graduate students and postdocs indicated the Center's educational activities are sharpening their understanding of low energy consumption device science and technology

The E^3S Professional Development Program (E^3S PDP), initiated in Period 3, continues to provide the framework to guide graduate students and postdocs to acquire a diverse and well-balanced development experience. By participating in the many activities of the Center, our members receive training in mentoring, project management, science communication, proposal writing, entrepreneurship, as well as in leadership development. New in Period 4 was a career panel that allowed the participants to learn about career pathways in academia, industry, and national laboratories. We also introduced diversity training for REU mentors.

In Period 4, the E^3S Internship (ETERN) program for early engagement of undergraduates in research has expanded in number and scope. We piloted an effort that enabled one ETERN to have an international internship. This fall semester, two ETERNs were part of the poster session at the External Advisory Board annual meeting, three presented posters at an E^3S Seminar, and two presented posters at the 2014 NSF Site Visit. We introduced professional development to these undergraduate center members through their engagement in the Center's outreach activities.

In Period 4, the Center also increased its educational outreach to the public.

In the following section, we report the program status for the following:

- Internal E^3S Educational Activities
- Professional Development Activities for Center members;
- External E^3S Educational Activities for general public and K-12; and
- Integration of Education and Research and the Center's philosophy.

Education efforts to cultivate a pipeline of students from secondary school to college and have strong emphasis on including female and students from underrepresented groups are presented in Section VI - Diversity.

2a. Internal Educational Activities

The internal educational activities that were initiated in previous reporting periods continued in Period 4. Seminars, journal club meetings, poster sessions, and the Center's Annual Retreat are all informal education venues for graduate students and postdocs. The research internship program, ETERN, for early engagement of undergraduates, expanded in Period 4 to include 9 interns doing research during academic terms at three member institutions. Also new is the development of online courses, which strengthens the Center's formal education activities.

Below, we will discuss each internal education activity.

Activity Name	Recorded Lectures - Why modern transistors cannot be operated with very small voltage.
Led by	**T.-J. King Liu** (Berkeley)
Intended Audience	For use by E^3S members in their courses and made available online for use by non-E^3S members
Approx Number of Attendees (if appl.)	n/a

These lectures will be used as modules to integrate energy-efficient electronic science research into existing undergraduate and graduate-level courses.

Activity Name	E^3S Research Seminars
Led by	**Y. Yang** (Berkeley), **J. Carter** (Berkeley) and **R. Iutzi** (MIT)
Intended Audience	Students and Postdocs
Approx Number of	Total – 71

Attendees (if appl.)	Undergraduate Students: 3 Berkeley Graduate Students: 30 Berkeley, 18 MIT, 4 UTEP Postdocs: 15 Berkeley, 3 MIT

The E^{3}S seminars serve as a vehicle to share the research being undertaken at the Center across research themes and member institutions, as well as an educational forum. The speakers are mainly graduate students and postdocs, who share the progress of their research. Occasionally, E^{3}S faculty present new projects, and industry partners have presented the research efforts in their company. One seminar in fall 2013 featured 3 ETERN students who had sufficient time in research to present. Period 4 is expected to conclude with 11 seminars; Appendix D gives a list of the scheduled seminars.

Activity Name	Journal Club
Led by	**Y. Yang** (Berkeley), **J. Carter** (Berkeley) and **R. Iutzi** (MIT)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 132 Undergraduate Students: 62 Berkeley Graduate Students: 39 Berkeley, 2 UTEP Postdocs: 16 Berkeley

The Journal Club typically meets four times in the summer, when we focus on learning and assessing research efforts external but relevant to the Center. In summer 2013, we focused on learning about synergies external to the Center. The topics included energy efficient memories, energy consumption considerations in wireless devices and the LEAST Center, a newly established multi-institutional post CMOS research center. Appendix D gives a list of the scheduled journal clubs.

Activity Name	Fourth Annual Retreat & Poster Session
Led by	**E. Yablonovitch** (Berkeley)
Intended Audience	Faculty, Staff, Students, Postdocs, Industry Partners & Programmatic Partners
Approx Number of Attendees (if appl.)	Total – 34 Graduate Students: 20 Berkeley, 5 MIT, 1 UTEP Postdocs: 5 Berkeley, 2 MIT, 1 Stanford

The Annual Retreat has continued to be a multi-purpose venue. One purpose is to educate graduate students and postdocs through two days of presentations and discussions. Part of the education is the opportunity to present one's research at a poster session attended by representatives of member companies. There were 19 posters at the 2013 Annual Retreat presented by 14 graduate students (8 Berkeley, 5 MIT, 1 UTEP) and 5 Berkeley postdocs. In addition, to illustrate the Center's online education strategy, **J. del Alamo** *(MIT)* made a presentation on the iLab platform and demonstrated this online laboratory with examples of energy flow, storage and dissipation in a digital inverter during switching. (See additional discussion of the Annual Retreat in Section VII. Management.)

Activity Name	Lightning Poster Presentation at the External Advisory Board Meeting
Led by	**L. Marlor** (Berkeley) and **J. Peng** (Berkeley)
Intended Audience	External Advisory Board
Approx Number of Attendees (if appl.)	Total – 16 Undergraduate Students: 2 Berkeley Graduate Students: 8 Berkeley, 1 MIT

	Postdocs: 4 Berkeley, 1 Stanford

Before the Poster Session at the 2013 External Advisory Board (EAB) meeting, each poster presenter gave a 2-minute talk of the poster. This new format was intended to further develop science communications skills of the Center's students and postdocs. The External Advisory Board members shared that the Lightning Poster Presentation and the Poster Session was the highlight of the meeting.

Activity Name	Third Annual Student and Postdoc Retreat
Led by	**S. Artis** (Berkeley) and Graduate Student and Postdoc Council (GSPC)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 21 Graduate Students: 11 Berkeley, 5 MIT, 1 UTEP Postdocs: 3 Berkeley, 1 MIT

In August, the Center hosted its 3rd Annual Student and Postdoc Retreat for graduate students and postdocs (Appendix E). Graduate students and postdocs spent the day in breakout sessions by research theme as well as a group session discussing their research projects and opportunities to collaborate. They also attended a panel about the career paths of faculty and researchers. A 30-minute new member orientation for new students and postdocs also took place. During the orientation, the students and postdoctoral researchers were introduced to Center's education and diversity programs and ethics training.

Activity Name	E^{3}S Internship (ETERN)
Led by	**S. Artis** (Berkeley) and **L. Marlor** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx Number of Attendees (if appl.)	Total – 9 Undergraduate Students: 6 Berkeley, 1 MIT, 2 UTEP

The ETERN program is an academic-year program for undergraduates at all of the Center's institutions. The primary goal is to attract students to energy efficient electronics science by providing research experiences to lower-level undergraduate students of member institutions, with the goal of enhancing the pipeline of students interested in graduate studies in the science and engineering disciplines of relevance to the Center. In Period 4, we had 9 participants. These students were advised by E^{3}S faculty and mentored by E^{3}S graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs such as research seminars and presenting posters at the EAB meeting. In Period 4, the Center piloted an international internship for one ETERN who spent 8 weeks doing research at the École Polytechnique Fédérale de Lausanne, one of the two Swiss Federal Institutes of Technology located in Lausanne, Switzerland; see Section V – External Partnership. The ETERN presented her summer research as a poster lightning talk and during the poster session at the EAB meeting.

2b. Professional Development Activities

The students and postdocs of the Center for E^{3}S can avail themselves to many professional development opportunities. In previous periods, we have already implemented training in ethics, project management, and mentoring and there are opportunities to review the summer programs applications. New in Period 4 were a career panel, diversity training and access to an online entrepreneurship course. The Center has also developed the E^{3}S Professional Development Program (E^{3}S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences.

Activity Name	E^3S Professional Development Program (E^3S PDP)
Led by	**S. Artis** (Berkeley) and Graduate Student and Postdoc Council (GSPC)
Intended Audience	All Graduate Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 31 Graduate Students: 19 Berkeley, 5 MIT, 1 Stanford Postdocs: 3 Berkeley, 3 MIT

Students and postdocs can develop professionally when they participate in the many programmatic activities of the Center. These programs offer different areas of development: leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship. The Center’s Professional Development Program is a framework to ensure a student or postdoc receives well-rounded professional experiences (Appendix F). For a certificate of completion, students and postdocs must complete: 1) at least one education activity in the area of outreach or mentoring; and 2) at least one education activity in three other training areas (leadership, teaching, proposal writing, science communication, and entrepreneurship). In Period 4, four students earned a certificate of completion, and 39 (61%) students and postdocs completed training in at least one of the training areas.

Activity Name	Ethics Training
Led by	**S. Artis** (Berkeley)
Intended Audience	New students and postdocs
Approx Number of Attendees (if appl.)	Total – 5 Graduate Students: 1 Berkeley, 2 MIT Postdocs: 1 Berkeley

At the 2013 Annual Student and Postdoc Retreat, **S. Artis** trained new students and postdocs on scientific ethics during the new member orientation. The ethics training covered the following topics: scientific standards, history of scientific ethics codes, types of research misconduct. After completing the ethics training, students and postdocs were sent an electronic copy of the book, *On Being a Scientist: Responsible Conduct in Research*, as an additional resource on scientific ethics.

Activity Name	Career Panel
Led by	**C. Chang-Hasnain** (Berkeley), **E. Fitzgerald** (MIT), **P. Wong** (Stanford), **D. Olynick** (LBNL)
Intended Audience	All Graduate Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 21 Graduate Students: 11 Berkeley, 5 MIT, 1 UTEP Postdocs: 3 Berkeley, 1 MIT

At the 2013 Annual Student and Postdoc Retreat, the Center hosted a career panel consisting of people who have worked in industry, academia, and national labs. **C. Chang-Hasnain, E. Fitzgerald, P. Wong**, and **D. Olynick** all spoke on the different career tracks they had taken and offered advice on how to prepare for these careers. Students also had the opportunity to ask the panel questions and learn more about the differences and similarities between the career paths.

Activity Name	Project Management and Mentor Training
Led by	**S. Artis** (Berkeley)
Intended Audience	Graduate Student and Postdoc mentors

Approx Number of Attendees (if appl.)	Total – 15 Graduate Students: 11 Berkeley Postdocs: 4 Berkeley

As part of the Center's objective to provide leadership experiences, graduate students and postdocs who served as mentors in the Center's summer undergraduate and precollege programs participated in project management and mentor training. Students and postdocs received 1 hour of mentoring and project management training and then over 360 hours of hands-on practice in mentoring, supervisory skills, communication, and leadership. The project management training provided an overview of project management and included the following topics: importance of project management, project management defined, and steps in project management. The mentor training provided an overview of how to be a mentor and included the following topics: what is/is not mentoring, impact of effective mentorship, and mentoring in action.

Activity Name	Diversity Training – Creating an Inclusive Learning Environment
Led by	**S. Artis** (Berkeley)
Intended Audience	Graduate Student and Postdoc mentors
Approx Number of Attendees (if appl.)	Total – 15 Graduate Students: 11 Berkeley Postdocs: 4 Berkeley

As part of the Center's objective to provide leadership experiences, graduate students and postdocs who served as mentors in the Center's summer undergraduate and precollege programs participated in an one-hour diversity training on creating an inclusive learning environment. The training, conducted by **D. Masterson**, one of Berkeley's Multicultural Education Program Diversity Facilitator, discussed strategies to make learning environments more active and inclusive, particularly when engaging with issues of human diversity.

Activity Name	E^3S Course – MITx:3.086x Innovation and Commercialization
Led by	**E. Fitzgerald** (MIT)
Intended Audience	All Center Members
Approx Number of Attendees (if appl.)	Total – 2 Graduate Students: 1 Berkeley, 1 UTEP

One of the Center's goals for its members is to understand the process of innovation, entrepreneurship and the transition of research results to commercially-viable products. In Fall 2013, **E. Fitzgerald,** a professor at MIT, offered MITx:3.086x Innovation and Commercialization, an online course that discusses innovation and commercialization from research to development to product in the market. The course presents a simple model for understanding the highly iterative process, in which you cycle repeatedly through many factors in the areas of Technology, Market and Implementation until the right pieces come together. **E. Fitzgerald** tells the story of his own major innovation, tracing it along the winding path into products we use every day. The course then proceeds to tell the larger story of how the vaunted American 'pipeline' for carrying this process has been pulled apart. This course was taught at MIT and offered to members at all institutions through edX, an online course system. Two E^3S graduate students, one from Berkeley and one from UTEP, took this class during Period 4.

Activity Name	REU Selection Committee
Led by	**S. Artis** (Berkeley)
Intended Audience	Postdocs as primary target

Approx Number of Attendees (if appl.)	Total – 17 Graduate Students: 6 Berkeley, 2 MIT Postdocs: 7 Berkeley, 2 MIT

Special emphasis is given to secure postdocs to serve on the selection committee for the E^{3}S Research Experience for Undergraduates. Given the substantial increase in the number of applications received, graduate students were also invited to participate in 2013. Each member of the selection committee reviews the application, personal statement, transcript, and letters of recommendations of ~6 applicants. Based on the review, the postdocs and graduate students provided a list of applicants that should be considered for placement in a summer research project.

Activity Name	REU Poster Review
Led by	**S. Artis** (Berkeley) and **L. Marlor** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx Number of Attendees (if appl.)	Total – 5 Graduate Students: 5 Berkeley

The Center hosted two REU programs, one for upper division undergraduates and another for community college students that was in conjunction with a REU site award. These programs concluded with a joint poster session of all REU participants. This offered a professional development opportunity for graduate students and postdocs to be reviewers. In Period 4, the five E^{3}S graduate students, 2 graduate students from our collaborator's center, and 3 community college representatives evaluated the posters based on the following criteria: presentation skills, poster layout, and content (problem, methods, results & understanding). One or two members of the review panel evaluated each student. At the conclusion of the poster session, assessments were anonymously shared with the REU intern to provide them feedback on their performance. All but one of the students received an evaluation of very good or okay.

Activity Name	Student Representatives at Science and Technology Center (STC) Director's Meeting
Led by	**S. Artis** (Berkeley)
Intended Audience	Student and Postdoc representatives from NSF-funded Science and Technology Center
Approx Number of Attendees (if appl.)	Total – 2 Graduate Students: 1 MIT, 1 UTEP

F. Niroui, a Ph.D. student at MIT, and **B. Aguirre**, a Ph.D. student at UTEP, served as student representatives at the STC Director's Meeting. F. Niroui shared a video on her E^{3}S research at the STC meeting. Both students participated in the student breakout sessions and STC mock up panel. This was a great opportunity for them to network with students from other STCs and to further cultivate their leadership skills as co-chairs on the Graduate Student and Postdoc Council.

2c. *External Educational Activities*

Activity Name	E^{3}S Teacher Fellows Program (formerly Research Experiences for Teachers - E^{3}S RET)
Led by	**J. Yuen** (Berkeley) and **S. Artis** (Berkeley)
Intended Audience	Community college professors
Approx Number of	Total: 2

Attendees (if appl.)	URM: n/a

With the Center’s focus on creating a pipeline of community college students to pursue a baccalaureate degree in science and engineering, it is imperative for the Center to engage community college faculty. These are individuals that can further integrate E^{3}S science and research findings into the community college curriculum, which will increase community college students’ awareness and knowledge about low-energy electronic devices. In Period 4, the Center hosted two community college faculty members in our E^{3}S Teacher Fellows Program (formerly E^{3}S Research Experiences for Teachers program - E^{3}S RET) for nine weeks.

W. Phillips, an instructor in the Electronic Systems Technology Program at Chabot College, was hosted by **Prof. E. Yablonovitch** and co-mentored by graduate students, **J. Chien and G. Scranton**. **W. Phillips** created new curriculum on power and fuel cells in his electronic technical course. The developed course content, upon completion, was applicable to three different courses at Chabot College and was integrated as modules in: ESYS 50: Introduction to Electronic Systems Technology, 56A: Electronic Power Systems I, and 56B: Electronic Power Systems II.

M. Wong, a physics, engineering, and astronomy instructor in the Contra Costa Community College District, completed a research project in the laboratory of **Prof. S. Salahuddin,** an E^{3}S EECS faculty, and was mentored by **D. Bhowmik,** a graduate student in the Salahuddin Group. To support the development of an education transfer plan, the E^{3}S teacher fellow joined a cohort of other in-service teachers who were also doing research at Berkeley through three other programs. This cohort was supported by a coach from Industry Initiatives for Science and Math Education (IISME), a non-profit consortium that seeks to transform teaching and learning through industry-education partnerships. The coach provided a process and met with the teacher fellows as they develop plans to adapt what they learned at Berkeley into their teaching. Upon return to the community college, **M. Wong** incorporated the application component of his research into his laboratory course.

Activity Name	Online Laboratory: Energy Balance of a Logic Inverter
Led by	**J. del Alamo** (MIT)
Intended Audience	High school and lower-division undergraduate students
Approx Number of Attendees (if appl.)	n/a

J. del Alamo developed a prototype to study the energy balance of a logic inverter using the iLab platform, an online laboratory that his group has built. This online laboratory allows pre-college and lower-division undergraduate students to remotely control the signal parameters and read off the currents and voltages through the circuit as it switches between its two logic states. Energy dissipation is visualized through an infrared camera, and waveforms can be collected and delivered to the student for computation of transients and energy balance. The prototype will be used for controlled educational experiments in MIT Online Science Technology Engineering Community (MOSTEC), one of the Center’s pre-college diversity program.

Activity Name	Online Lecture: Introduction to Energy-Efficient Electronics
Led by	**A. Ragsdale** (Stanford)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	n/a

A. Ragsdale, the graduate student instructor for the E^{3}S Hands On Practical Electronics Summer Research Workshop (E^{3}S HOPE SRW) and Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU) bootcamp, two diversity programs for undergraduate students, recorded lectures from the programs on circuit theory, network analysis, semiconductors and devices, and discrete and integrated circuits. These lectures will be used as modules to introduce high-school and lower-division undergraduate students, including community college students, to low-energy electronics. With both online modules, E^{3}S plans to augment the course content with supplemental readings and assignments to provide a comprehensive learning experience.

Activity Name	Cal Day
Led by	**J. Yuen** (Berkeley)
Intended Audience	High school seniors with admission offers from Berkeley and their families
Approx Number of Attendees (if appl.)	Total- 6 Undergraduate Students: 4 Berkeley Graduate Students- 2 Berkeley

Each April, UC Berkeley hosts a campus wide open house to attract high school seniors who have received admission offers. This yearly event also attracts the local community, school counselors and teachers visiting the campus with their students, and community college students aspiring to transfer. During Period 4, **J. Yuen** worked with 3 ETERNs and 1 graduate student to develop 3 demonstrations for Cal Day. The demonstrations were on graphene and 2D conducting material; lithography; and dye sensitized solar cells. Two other students, an undergraduate and one graduate student, joined to support the demonstrations on the day of the event; the E^{3}S demonstration was attended by ~65 people.

Activity Name	Bay Area Science Festival
Led by	**L. Marlor** (Berkeley)
Intended Audience	The Bay Area Community
Approx Number of Attendees (if appl.)	Total- 4 Undergraduate Students: 4 Berkeley

Each fall, a science festival is held at AT&T Park in San Francisco that showcases fun and exciting science to the general population. This year was the first year that E^{3}S participated in the event. **L. Marlor** led four ETERN students in demonstrating how 2D materials (graphene) conduct electricity. If the participant was old enough, the ETERNs would explain how the center is using 2D materials to tackle the energy efficiency problems faced in our current electronics. Approximately 28,000 people attended the fair, and of those, approximately 400 people participated in the E^{3}S demonstration.

2d. *Integration of Education and Research*

The Center's philosophy for its education programs is to rigorously use all opportunities to integrate its research and education activities. The Center also strives to implement vertical integration in all of our programs so students at all levels will be mentored and encouraged by people with more experience, with the goals of encouraging a greater number of students to complete graduate studies in E^{3}S majors. Below are tables that display the research and education components integrated in the different education and diversity activities.

- *Graduate and Post-Graduate Education Activities*

Activity	Research	Education

Annual Center Retreat	• Presentation of the research portfolio • Open discussions of research directions	• Education for the entire Center - Communication on the Center's values and management - Review of the research themes and projects • Education for Students & Postdocs • Poster Sessions by Students & Postdocs • Networking
Annual Student and Postdoc Retreat	• Presentation of the research projects • Open discussions of research collaboration	• Education for Students & Postdocs • Graduate Student and Postdoc Council meeting • Networking • Ethics training • Professional development training

- *Undergraduate and Pre-College Activities**

Activity	Research	Education
E^{3}S Undergraduate and Teacher Fellows Research Programs	• Research on energy efficient electronics science topics	• Graduate student as mentors: Education to enhance mentoring and project management skills of graduate students
Minority Introduction to Engineering and Science (MITES) MIT Online Science, Technology, & Engineering Community (MOSTEC)	• Application of energy efficient electronics science topics	• Graduate student as instructors: Education to enhance curriculum development and teaching skills of graduate students • Faculty lead webinars on research topics

*As we consider the main driver of the undergraduate and precollege education programs is to grow a diverse pipeline of students, these programs are discussed in greater detail in Section VII. Diversity.

Activity	Vertical Integration
E^{3}S Internship (ETERN)	• Undergraduates mentored by faculty, graduate students, & post-docs • ETERN students participate in outreach activities for pre-college students

The following is a specific example to illustrate how research and education are integrated using vertical integration.

In alignment with the goals of the E^{3}S program, the E^{3}S Internship (ETERN) has designed more components to integrate research into the education program. ETERNs are undergraduate students at any of E^{3}S universities. These participants are immersed into a 10-hour per week research experience during the fall and spring terms. While working on a research project throughout the semester, each ETERN is mentored by a faculty member as well as a graduate student or postdoctoral researcher. These students participate in group meetings and the Center's events. The vertical integration of this program does not stop in the research lab, as all ETERN students are expected to participate in one pre-college outreach event per year. During these outreach events, ETERNs have to explain technical concepts and their research projects to an audience that may not have a STEM background, thus enhancing their ability to communicate their science and research ideas to a broad audience.

In Period 4, the Center has expanded the ETERN program to offer a variety of professional development opportunities for students. Each student is now expected to be in the ETERN program for a total of 3 semesters. This extended length of time was added after realizing that one semester was too short for the students to fully realize a valuable lab experience. As the students progress through the semesters, they are expected to turn in a paper, a research poster, and finally present their research during an E^{3}S seminar. ETERNS are also expected to participate in Center events, in which graduate students and postdocs are invited. This year, two ETERN students presented posters at the Period 4 External Advisory Board (EAB) meeting and two ETERNs presented posters at the 2014 NAF Site Visit. These meetings also served as an opportunity for students to practice their networking skills.

2e. *Performance Against Metrics*

During this reporting period, the Center has compared the education programs against the Period 4 target. The table below displays this data and future metrics to measure education success.

Objective: Education

Metrics	Targets	Results		
		Period 2	Period 3	Period 4
Number of Center graduates who have completed E^{3}S training	Period 3: 50% Period 4: 50% Period 5: 50%	0	3 (17%)	7 (35%)
Number of students participating in education and diversity programs	Period 3: 60% Period 4: 70% Period 5: 75%	42 (52%)	48 (52%)	41 (69%)
Number of students and postdocs serving in leadership roles in the Center	Period 3: 15% Period 4: 20% Period 5: 25%	9 (11%)	11 (19%)	20 (34%)

2f. *Education Activities in Period 5*

In Period 5, E^{3}S will further develop its dissemination plan for online educational content. The Center will continue to expand its education content integrating the Center's research through E^{3}S Summer School and online lectures and laboratories. The vision for E^{3}S Summer School is an intense week-long program designed to introduce non-E^{3}S upper division undergraduate students to the fast-developing field of energy efficient electronics science. Potential topics for the course would be: quantum mechanics, optical devices, memory, MEMS, nanoelectronics, material growth, spintronics, and innovation. These topics will be covered through traditional lectures and lab tours. Additionally, the summer school will also include a day focused on graduate admission and preparing for graduate school. A companion goal of this program is to attract underrepresented students to the Center. Therefore, we will collaborate with minority serving institutions to advertise this program. In the future, we would like to grow this summer school into a certificate program, thus expanding to target a larger audience, including graduate students, postdocs, industrial researchers, and faculty members who want to learn more about the field of energy efficient electronics science. The Center will also develop online lectures and laboratories. Traditional courses from the E^{3}S Summer School will be recorded and edited to be made available as an online course through the Center's website. We will use the iLab platform to design online laboratories on energy-efficient electronics science for high school and lower-division undergraduate students, including community college students in engineering and technician programs.

To provide additional advice and guidance on education and diversity strategies and programs, the Center will begin having Education and Diversity Advisory Board meetings every spring. The Center has identified members with interests and experience to advise on education, particularly online education, and diversity. These members will have their first meeting in April of Period 5.

IV. KNOWLEDGE TRANSFER

1a. Goals and Objectives

The Knowledge Transfer goals of the Center for E^{3}S are to establish industry/education partnerships as venues for introducing new and more efficient electronics technologies and ways to prepare workers at all levels to participate in the new opportunities. As such, Knowledge Transfer includes the transfer of new-found knowledge that is relevant to the Center's research as well as programmatic activities. We think of Knowledge Transfer as cross-fertilization that goes in both directions, up and down the food chain. For Research, the scope will include device researchers at the leading electronics companies, circuit designers, CAD software writers, all the way to manufacturing workers in the semiconductor equipment industry. For Education and Diversity, the scope will include other educators and potential employers. Thus, opportunities will be created at all levels, from community college students up to Ph.D. graduates from research universities. Knowledge transfer is envisioned to be through the following channels:

- Strong liaisons with industry to make certain that the academic technical and programmatic directions will be practical, and lead to real success;
- Advice to policy makers at all levels of government on the implications for various device and education systems;
- Demonstration projects that test the devices and materials resulting from the Center's research projects, as well as enable formulation of novel practices for education and diversity;
- Meetings, summits, and workshops where results and knowledge gained through Center activities are shared; and
- Knowledgeable students who have been trained through research internships and entrepreneurial clubs.

1b. Performance Metrics

Objective	**Metrics**	**Frequency**	**Targets**
Knowledge Transfer	Website hits & unique visitors	Yearly	Period 2: Baseline Period 3: 20% increase
	Number of contacts with industry		
	General	Yearly	Period 2: 18 Period 3: 36
	Presentations by industry	Yearly	Yearly: 2
	Center publications	Yearly	Yearly: 18
	External citations of publications	Yearly	Period 3: 10 Period 5: 100
	Patent disclosures	Yearly	Period 3: 3 Period 5: 8
	Students hired into relevant industries	Yearly	Period 5: 50% Period 10: 100%
	Technology development attributable to Center's research	Yearly beginning in Period 10	Period 10: 1
	Number of external articles on the Center	Yearly beginning in Period 3	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase

1c. Problems Encountered

The Center continues to struggle with achieving 100% compliance in acknowledging NSF as funder in our publications. The Center will continue to send quarterly reminders to the E3S faculty, students and postdocs of their legal obligation to acknowledge NSF.

2a. Knowledge Transfer Activities

The Center's knowledge transfer is mainly information and knowledge exchanges with communities of peers through written materials, presentations and discussions. These exchanges are conducted through venues that enable the Center to share the knowledge and outcomes from either research or programmatic activities. Others venues allow the Center to learn information that are directly applicable to or put into context the Center's work. Many venues serve both purposes benefiting multiple parties.

Key knowledge transfer highlights in the first 9 months of Period 4 are as follows:

- The Center was the lead organizer of the 3rd Berkeley Symposium on Energy Efficient Electronic Systems with **E. Yablonovitch** and **J. Bokor** as the co-chair of the organizing committee;
- 20 papers on the Center's research were published in peer-reviewed journals, 2 additional are in press and 10 papers are submitted /under review.
- 28 peer-reviewed papers on the Center's research were presented at professional meetings that have published or will publish the abstracts of the talks.
- 2 peer-reviewed papers on learnings and best practices from the Center's programmatic activities were presented at two education conferences that have published proceedings.
- **S. Artis** was conference committee chair of the 2013 Annual Women in Engineering Proactive Network (WEPAN) Conference, where as a panelist, she presented on early engagement of undergraduates in research.

The Center's researchers and staff also used smaller venues for knowledge exchange:

- E^{3}S Theme Leaders presented Center's research programs to Intel's Component Research leadership and engineers.
- E^{3}S faculty and students, orally and in a poster session, presented the Center's research directions and results at the 2013 annual retreat that included representatives of all 5 industry partners.
- **S. Artis** discussed diversity recruitment partnerships at the Education and Diversity workshop of the 2013 STC Director's Meeting.

In the following sections, we report the Center's Knowledge Transfer activities in two categories: Research and Programmatic.

- Knowledge Transfer Related to Research:

  While the Center has placed great emphasis on its relationship with industry as venues for knowledge transfer, there is also a strong recognition of the importance of researchers in academia as knowledge transfer partners. As the Center's research results lead to new research directions, it is critical that other researchers in the same technology domain participate in the pursuit of similar approaches so that a community of like-minded researchers can accelerate towards the goal of ultra-low energy electronic devices.

  In Period 4, the key knowledge transfer venue of the Center was the 3rd Berkeley Symposium on Energy Efficient Electronic System, a biennial knowledge exchange forum of which the Center is the lead organizer.

3rd Berkeley Symposium on Energy Efficient Electronic Systems

Led by	**E. Yablonovitch, J Bokor, H.-S. P. Wong and E. Alon**	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	Stanford University	Palo Alto, CA

The 3rd Berkeley Symposium on Energy Efficient Electronic Systems offered technical sessions that range from devices to systems to provide researchers an integrated perspective of the challenges and advances in energy efficiency for information processing systems (Appendix G – Symposium Program). For the first time, the organizers welcomed IEEE Electron Devices Society as a technical co-sponsor. The Organizing Committee was co- chaired by **E. Yablonovitch** and **J. Bokor**, who together established the Symposium in 2009, before the Center was started. The organizing committee included two additional E^{3}S faculty members, **H.-S. P. Wong** and **E. Alon**. Participation from outside the Center was selected to allow the Center to build relationships with entities of relevance to the Center. Among the committee members were A. Seabaugh, Center for Low Energy Systems Technology (LEAST), a new post-CMOS research center that is funded by the Semiconductor Research Corporation and DARPA; G. Vandentop, Semiconductor Research Corporation; and J. Conway, DARPA. There was also participation by industry partners, H. Riel, IBM-Zurich, and C.-P. Chang, Applied Materials.

Of the 114 registered attendees, 24 were from industry and 47 were from academic institutions that are not a part of the Center. The program consisted of 30 presented papers, 6 of which were from industry and 17 were invited papers. The contributed talks and posters were selected through a peer-reviewed selection process. The Center contributed 6 talks and 7 posters.

The E^{3}S researchers also disseminated their research results through journal and talks at conferences.

Dissemination of the Center's Research Results in Peer-Reviewed Journals		
Led by	E^{3}S Faculty	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA

In the first 9 months of Period 4, the Center's faculty, students and collaborators have published 17 papers, all in peer-reviewed journals. Four papers from Berkeley are in press and 3 papers have been submitted for review, including a joint paper between Berkeley and MIT. One metric in the Strategic Plan is the number of citations of the Center's publications, which is 393 total from the Center's inception to date.

Dissemination of the Center's Research at Peer-Reviewed Conferences with Published Proceedings		
Led by	E^{3}S Faculty	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, CA

In Period 4, 28 contributed talks by researchers from Berkeley, MIT and Stanford were selected for presentations at professional meetings that subject the contributed papers through peer-reviews and that have and will be published in conference proceedings. Thirteen of these talks have been given or will be given at premier professional meetings, like Physical Society Meeting, CLEO, Materials Research Society Meeting, and IEEE International Electron Devices Meeting. Seven were presented at the 3rd Berkeley Symposium for Energy Efficient Electronic Systems, the biennial symposium of which the Center is the lead organizer. The 7 contributed papers underwent peer review by reviewers who were not associated with the Center, and for the first time, the Berkeley Symposium for Energy Efficient Electronic Systems is publishing its proceedings in IEEE Xplore, made possible due to the technical co-sponsorship of IEEE Electron Devices Society.

One key knowledge transfer focus for the Center is industry. We seek to share the Center's research with industry as well as learn from industry.

E^{3}S Annual Retreat		
Led by	**E. Yablonovitch** (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Palo Alto, CA
4.	The University of Texas at El Paso	El Paso, TX
5.	Contra Costa College	San Pablo, CA
6.	Los Angeles Trade Technical College	Los Angeles, CA

The Center also used its Annual Retreat to share the Center's direction and progress in research with its industry members. The attendees from industry were: A. Brand, Applied Materials; D. Hemker, Lam Research; P. Solomon, IBM; S. Williams, Hewlett Packard; and Ian Young, Intel. The industry members also attended a poster session that featured 20 posters by students and postdocs. One poster included results from a teacher fellow, who is as an instructor from Contra Costa College, a community college partner of the Center.

Research Presentations at Intel		
Led by	**E. Yablonovitch, T.-J. King Liu, J. Bokor, and J. Yuen** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

The E^{3}S leadership team attended a meeting at Intel to re-introduce the Center and provide a current view of the research programs to the leadership of Intel. Personnel changes at Intel necessitated the meeting. The visit started with a meeting with the leadership of Intel's Components Research, followed by presentations on three of the Center's research themes to a larger audience that included many engineers. (Additional details are given in Sections V & VII)

We also seek to learn from others who are doing research in the same domain or in domains relevant to our technology.

Seminars of Relevant Research External to the Center		
Led by	**A. Javey** (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

The Center utilizes an established venue to learn more about research that may have relevance to our research programs. In Period 4, we sponsored two speakers who gave seminars at Berkeley: Z. Zhong, U of Michigan, and K. Crozier, Harvard University. The sponsored talks, relevant to the Center's Themes I and III research, are one-way knowledge transfers to the Center. Typical attendance at the Solid State Seminars is ~40, some of whom are members of the Center at Berkeley.

Seminar by Center for Low Energy Systems Technology (LEAST)		
Led by	**J. Hoyt** *(MIT)* and **T.-J. King Liu** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA

Recognizing the synergy in goals between the newly established LEAST Center and the Center for E^3S, we invited its Director, A. Seabaugh, U of Notre Dame, to speak to the E^3S Journal Club.

- Knowledge Transfer Associated with Programmatic Activities

The Center considers knowledge transfer related to education and diversity to be an important mandate. As such, in Period 4, E^3S partnered with organizations to share best practices for REU programs and diversity. The Center also disseminated best practices through conference proceedings and presentations.

NSF STC Director's Education and Diversity Pre-Meeting Workshop		
Led by	**S. Artis, J. Yuen &** A. Tabor (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

The 2013 STC Directors' Meeting was preceded by an all-day Education and Diversity workshop. **S. Artis**, **J. Yuen**, and A. Tabor (*The Team for Research in Ubiquitous Secure Technology's (TRUST) Education Director*) served as co-presenters for the *Diversity Recruiting Partnerships* workshop (Appendix H: STC Education and Diversity Pre-Meeting Agenda**)** covering the following topics: Collaborating to Maximize Recruiting

Efforts, Diversity Metrics and Benchmarks, and Maximize the Impact of Collective STC Website. A result of this meeting was further collaborations among the STCs. S. Artis organized the STC REU Application Repository so STCs can share REU applications across centers. S. Artis and A. Tabor also facilitated the process to establish the LSAMP-STC REU Fellowship for LSAMP students at other universities. STCs will begin offering a slot to qualified LSAMP students in Period 5.

2013 Annual Women in Engineering Proactive Network (WEPAN) Conference Panel		
Led by	**S. Artis** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

S. Artis was as a presenter on the *Improving the Match Between Early College Students and Company Internships or Research Experiences for Undergraduates* panel at the 2013 Annual Women in Engineering Proactive Network (WEPAN) Conference in Atlanta, GA. S. Artis joined three other panelists, I. Gaeta, Intel, L. Snow-Solum, Rockwell Collins, and S. Hernandez, Cornell University, to discuss how corporations and universities can effectively utilize early college (freshman and sophomore) internships. S. Artis shared best practices and information on: 1) types of REU opportunities that work best for freshman and sophomore college students; 2) metrics REUs collect to show the return on investment (ROI) of these types of early college working experiences, and what constitutes success in terms of these metrics; and 3) key student attributes that universities look for in selecting students for REUs and early college internships.

Berkeley Multicultural Education Program Diversity Workshop		
Led by	**S. Artis** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

S. Artis co-facilitated Berkeley's *Looking In/ Looking Out: Exploring Workplace Diversity at Cal* workshop for Berkeley staff members. The workshop explores human diversity by reflecting on what makes individuals unique and how it affects one's worldview. Participants learn to: 1) reflect on who they are; 2) learn about others around them; 3) explore the impact of identity; 4) practice skills for interaction across difference; and 5) identify resources at Berkeley.

Presentations and Publications on Education Programs		
Led by	**S. Artis** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

S. Artis and the Center's external evaluator, C. Amelink, co-authored two peer-reviewed papers on the design, implementation, and evaluation of the Transfer-to-Excellence

Research Experiences for Undergraduates Program (TTE REU). The papers were presented at the 2013 American Society for Engineering Education Annual Conference & Exposition and the Eastern Educational Research Association Conference. Both papers have been published as part of the proceedings of the conferences; see Section VII – Centerwide Output.

E^3S Website		
Led by	**J. Yuen** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

The public pages of the Center's website are regularly updated to provide information about our programs and activities. There was a 40% rise in the number of unique visitors to the site in Period 4. Internal polls have indicated that the majority of internal users did not find the website useful as a communication tool (Section VI – Center Management) so we can only conclude that the yearly increase in traffic is from visitors external to the Center. Since we see a large increase in the month when applications for summer internships are due, we conclude that the yearly rise in website site traffic has been the result of interest in the Center's summer internship programs.

2b. *Outcomes*

The outcomes of the Center's knowledge transfer activities have been discussed in the previous section, as part of the description of each activity.

2c. *Performance Against Metrics*

Objective: Knowledge Transfer

Metrics	**Targets**	**Results**		
		Period 2	**Period 3**	**Period 4**
Website hits & unique visitors	Period 2: Baseline Period 3: 20% increase Period 4: 10% Period 5: 10%	Website Hits: 11,354 Unique Visitors: 6,123	Website Hits: 140% (27,298) Unique Visitors: 167% (16,338)	Website Hits: 42% (38,800) Unique Visitors: 40% (22,809)
Number of contacts with industry				
• General	Period 2: 18 Period 3: 36	66	20 Average: 43*	42 Average: 43*
• Presentations by industry	Yearly: 2	4	2	6

Number of research collaboration with industry	Period 4: 1 Period 5: 2	0	1	1
Center publications	Yearly: 18	17	16	20 plus 2 in press and 10 under review/ submitted
External citations of publications	Period 3: 10 Period 4: 100 Period 5: 100	15	178	393
Patent Disclosures	Period 3: 3 Period 4: 3 Period 5: 5	1	0	0
Students hired into relevant industries	Period 5: 50% Period 10: 50%	Postdocs: 100%	Students: 64% Postdocs: 33%	Students: 16% Postdocs: 20%
Technology development attributable to Center's research	Period 10: 1	n/a	n/a	n/a
Number of external articles on the Center	Period 4: 3 Period 5: 5	1 event	0 articles	0

*The number of industry contacts per period is dependent on the type of activities the Center chooses to organize for a given period. Period 2's result is largely influenced by a symposium that the Center organized, a symposium that takes place once every 18 months. Thus, we feel that the appropriate tracking methodology is a running average. Based on this methodology, the Center met its target in Period 3.

2d. Transfer Activities in Period 5

The second objective in the Center's Knowledge Transfer goals calls for engaging government stakeholders on energy efficient electronics research. This begins with engaging the general public, a direction that will command more of the Center's efforts in Period 5. We will do so through science demonstrations at public outreach events; see Section III.

Dissemination of educational videos that are made by E^{3}S members, also part of the Center's education plans, will also further knowledge transfer. We expect that such dissemination will begin in Period 5.

In Period 5, as the research direction and programmatic endeavors of the past 4 years delivered definitive results, we look forward to additional publications.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

A strategy of partnerships is one of the underpinnings of the Center's proposal to NSF. Nearly all elements of the Center for E^{3}S have partners to achieve the goals. Even before its inception, industry partnerships were formed, and the Center continues to view industry partnerships as the cornerstone in the execution of E^{3}S' two-way knowledge transfer strategy. The Center's researchers have formal and informal partners as they pursue their scientific investigations. The education and diversity programs leverage the experience and resources of campus partners to deliver programs both at the lead and subaward institutions. The Center continues to execute and enhance its partnership strategy to enable successful achievement of all its goals.

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Knowledge Transfer	Number of Contacts with Industry	Yearly	Period 2: 18 Period 3: 36 Period 4: 36

1c. Problems Encountered

In Period 4, there were changes in the key contacts for the Center at two of the Center's corporate partners, Intel and Applied Materials. The changes led to the need to establish relationships with the new corporate interfaces. The unplanned efforts delayed the Period 4 plan to recruit mid-size companies to join the Center.

2a. Activities in Period 4

The Center for E^{3}S has continued to strengthen its partnership with industry through the five member companies, Applied Materials, Hewlett-Packard, IBM, Intel and Lam Research. Intel has continued to have a research development relationship with the Center through **M.C. Wu** *(Berkeley)*, leader of Theme III. Activities in Period 4 included a visit to Intel by the Center's leadership team and representative of all member companies participated in at least one Center's function. Emerging is IBM's interest to provide characterization support to a Theme II research project.

E^{3}S researchers have worked with colleagues affiliated with academia in and outside the U.S. to achieve their research objectives. These mainly informal partnerships are for material growth and characterization. **C. Hu** *(Berkeley)* is hosting a graduate student from National Chiao Tung University (NCTU), Taiwan. This is part of a collaboration on tunneling FET research with the NCTU group that is funded by Taiwan's I-Rice program. One research group in Switzerland, with whom we collaborated in organizing two knowledge transfer events in 2012, hosted an ETERN from E^{3}S for 8-weeks of research in the past summer. In Period 4, we used the organizing of the 3rd Berkeley Symposium on Energy Efficient Electronic Systems to engage other research centers working in the same domain, just as was done when the Center organized the 2nd Berkeley Symposium.

The Center's education and diversity programs have continued to leverage the expertise and resources of campus partners. At MIT, partnerships have meant that the ability for E^{3}S to deliver electronics training for a high school online community (MOSTEC) and to support REU interns at the laboratories of E^{3}S MIT faculty. At UC Berkeley, collaboration with other summer internship programs on campus has provided the participants with more substantive experiences and to be part of a large community. In Period 4, we developed new partners at UC Berkeley to enhance diversity recruitment and support the transfer of community college students who are alumnae of the Center's programs.

The success of our programmatic activities also relies on partners who are outside the Center's member institutions. For the Transfer-to-Excellence program for community college students, we have continued to partner with MESA for recruitment and UCLA's CCCP for transfer support to the Center's community college alumni when they return to southern California. We are partnering with two other STCs on REU recruitment for the 2014 summer programs.

Given below are details of the Center's engagement in five different categories of partnership activities.

1. Industrial Partnerships:

   - Center's Industry Members: As mentioned in the Center Management section (Section VII), the Center uses an Industrial Research Board to advise on the Center's research direction. Companies who either had supported the Center's proposal before the inception of the Center or joined later by executing a member agreement are members of the Board. In late Period 4, the Center's executive contacts at Intel and Applied Materials changed, as the corporate executives left their employers. At Intel, the change eventually led to a meeting at Intel between E^{3}S leadership and M. Bayberry, Intel's corporate vice president of the Technology and Manufacturing Group and director of Components Research, I. Young, Intel Senior Fellow, Technology and Manufacturing Group and Director, Advanced Circuits and Technology Integration Industry Research Partnerships, and R. Chau, Intel Senior Fellow, Technology and Manufacturing Group and Director, Transistor Research and Nanotechnology. This meeting concluded with the designation of I. Young to be the E^{3}S interface.

     The Center's relationship with Applied Materials was rebuilt with the appointment of E. Yieh as the executive contact. This relationship was further strengthened as C.-P. Chang from Applied Materials' CTO office served as a member of the organizing committee of the 3rd Berkeley Symposium on Energy Efficient Electronic Systems.

     L. Sheet, of Lam Research, was scheduled to moderate one session on Nanoelectronics at the 3rd Berkeley Symposium on Energy Efficient Electronic Systems but could not participate due to illness.

   - Theme III has continued to use industry partnerships to complement the Center's research activities. (i) The research partnership with the Silicon Photonics group at Intel has continued with our contacts being: H.-F. Liu and B. Youssry. Through Intel's university programs on "Silicon Photonic Devices for High BW Low Power Optical Interconnects," **M.C. Wu** *(Berkeley)* has received matching support for the nano-photodetector project. The M.C. Wu group has regularly interacted with the researchers from Intel's Si photonics group. (ii) The SHE Nano-LED project has continued to use MOCVD grown III-V materials structure from L. Zhang of Bell Labs, Alcatel Lucent. Alcatel Lucent is not an industry member of the Center, but the Center is benefiting from M.C. Wu's long-term relationship with L. Zhang.

   - The progress on the Squitch project (Theme II) shared with corporate partners at this year's Annual Retreat attracted the interest of IBM. P. Solomon, who has been the key working interface with the Center, offered to characterizes the squishable molecular layers. IBM has better facilities with which to observe and measure the mechanical motion in and therefore to confirm the electromechanical behavior of our squitches. The collaboration is in its very early stages at the time of this writing, but we have already sent dummy samples to IBM for them to assess the feasibility of testing at IBM.

2. International Partnerships:

   - International participation on the organizing committee for the 3rd Berkeley Symposium on Energy Efficient Electronic Systems included H. Riel, IBM-Zurich, Switzerland, and H. Ohno, Tohoku University, Japan. The symposium's program included 6 speakers (4 invited) from Europe and 2 from Japan (both invited).

- We have continued to leverage the relationships with the international contacts who participated in the organizing committee of the 2nd Berkeley Symposium on Energy Efficient Electronic Systems. Our interactions with A. Ionescu of École Polytechnique Fédérale de Lausanne (EPFL) over the last two years led to an agreement for an undergraduate research internship at EPFL. In summer 2013, **M. Monroe** *(Berkeley)*, a participant of the Center's ETERN program since the 2012 spring semester, spent eight weeks at EPFL doing research on nanoelectromechanical relays, mentored by EPFL staff, M. Fernandez-Bolanos Badía and A. Bazigos. Besides enabling an international experience, this internship was also a scientifically broadening experience for the undergraduate, who did three semesters of nanomagnetics research at the **J. Bokor** lab *(Berkeley)* before undertaking a research project in nanomechanics at EPFL. EPFL contributed two-thirds while the Center contributed one-third to the undergraduate's summer stipend. The ETERN student has since returned to the Bokor lab to continue research in nanomagnetics.
- As part of a research partnership with E. Y. Chang, National Chiao-Tung University (NCTU) in Taiwan on material growth and characterization that was first reported in the last annual report, **C. Hu** *(Berkeley)* has been hosting a NCTU graduate student at Berkeley. Plans are for the graduate student to be at Berkeley until April 2014. The visiting student is supported through the I-Rice program of Taiwan of which C. Hu is a collaborator.
- The **A. Javey** group *(Berkeley)* partnered with Y.-L. Chueh, currently at National Tsing Hua University in Taiwan and an alumnus of the Javey lab, on TEM characterization.

3. Other Research Partnerships: Section 6 under Centerwide Output gives a list of Center's Partners, many of whom are researchers who are contributing to the Center's research project.

   - Material growth for the Negative Capacitance project: R. Droopad, Texas Tech University
   - Fabrication of magnetic Schottky diodes on wide bandgap GaN substrates for the Ultrafast Magnetic Switching project: D. Jena, University of Notre Dame.
   - III-V epitaxial wafers for TFET projects: S. Krishna at University of New Mexico; and
   - Optical characterization of XOI structures: H. A. Bechtel and M. C. Martin at Lawrence Berkeley Laboratory.

4. Collaborations with Research Centers in the Energy Efficiency Domain: In establishing the organizing committee of the 3rd Berkeley Symposium on Energy Efficient Electronic Systems, **E. Yablonovitch** and **J. Bokor** invited the center directors of the Center for Low Energy Systems Technology (LEAST) that is funded by the Semiconductor Research Corporation (SRC) and the Defense Advanced Research Projects Agency (DARPA) and the Center for Energy-Smart Electronic Systems (E2S), a NSF I/UCRC. A. Seabaugh, of Notre Dame and Center Director of the LEAST Center, and B. Sanmakia of Binghamton, Center Director of E2S, were on the symposium's organizing committee.

5. Education and Diversity Partnerships: Partnerships have allowed the Center for E^{3}S to deliver education and outreach programs both at Berkeley, the lead institution, and at MIT, a member institution.

   - MIT: Since the Center's full-time Education and Outreach team is located at Berkeley, we have used partners to deliver and support the educational and outreach activities for the Center's MIT members. The Office of Engineering Outreach Programs (OEOP) and the MIT Summer Research Program (MSRP) have continued to be the Center's partners in delivering pre-college and undergraduate programs at MIT. These partnerships are effective due to regular coordination teleconferences between the partners and **S. Artis**, E^{3}S Education and Outreach Director. In Period 4, monthly teleconferences were held with **I. Porro** of OEOP, and quarterly teleconferences were held with **M. Orta** of MSRP. A highlight in Period 4 is a joint application and selection process for E^{3}S MSRP Summer Interns that E^{3}S and MSRP established. This resulted in three summer interns placed with E^{3}S faculty at MIT, the highest number since the inception of the Center.

- Berkeley: Being located on the Berkeley campus, the Center has partnered with other campus organizations, particularly other NSF-funded centers, in delivering REU programs. The leveraging of resources has helped the collaborating summer internship programs, including that of E^{3}S, to provide more substantive experiences and a large community for the participants.
  - E^{3}S REU Program for Juniors and Seniors: We have continued to partner with Center of Integrated Nanomechanical Systems (COINS) and Team for Research in Ubiquitous Secure Technology (TRUST) on the REU program for juniors and seniors. Joining the collaboration for the first time is the Berkeley REU program for the Center for Translational Applications of Nanoscale Multiferroic Systems (TANMS), a NSF ERC headquartered in UCLA. E^{3}S stepped in to be the delivery partner of the TANMS REU program at Berkeley, as several Berkeley faculty are in both centers. The partnerships among the centers have included joint recruitment, professional development seminars, lab tours, industry field trips and a GRE preparation course. A highlight of Period 4 is the Research Experience for Undergraduates Science Communication Workshop (REU SCW) that is designed to: encourage students to explore the broader context of their research; guide them in developing professional science communication skills; and enhance their confidence in pursuing careers in science and in speaking about science in a variety of settings. This workshop was jointly led by the E^{3}S and COINS Education Directors, **S. Artis** and M. Erol.
  - TTE REU Program for Community College Students: For the second summer, Synthetic Biology Engineering Research Center (SynBERC) joined E^{3}S, COINS and TRUST in hosting community college students for research. Under the leadership of **T.-J. King Liu** and **S. Artis**, the collaboration leverages the funding of a NSF REU Site award and E^{3}S funding as the education directors of each center jointly plan and oversee the TTE REU program. Another partner, the Transfer Alliance Project (TAP), a Berkeley campus entity, provided one-on-one personalized advising to the community college research interns that included design and monitoring of individual academic course plans and assistance with transfer applications, required personal essays, financial aid forms and scholarships applications. TAP and E^{3}S also co-hosted two information sessions, one in the Bay Area and one in the Southern California area, to recruit students for the TTE programs. The TTE REU program continued its partnership with UCLA's Center for Community College Partnerships (UCLA CCCP) and Mathematics, Engineering, and Science Achievement (MESA) to enhance our recruitment of students from California Community Colleges. CCCP and MESA sends out recruitment emails and flyers to their program participants, and this period **L. Marlor** participated in California MESA's Fall Student Leadership Conference as an invited speaker to present on transferring to a 4-year university and applying for summer research internships. The program also partnered with Berkeley's International Computer Science Institute (BFOIT) again to provide leadership and outreach opportunities to the TTE REU participants. The TTE summer interns organized a science and engineering panel for 25 middle- and high school-participants in BFOIT. The event started with an icebreaker where the high school and community college students each shared personal experiences about their family, goals, and interest in science and engineering. Then the community college students served as panelists, sharing their experience in science and engineering with the high school

students. In addition, **S. Artis** was invited to be a speaker for the institute. She presented a talk tilted, *Multiple Faces of an Engineer and Scientist.*

- New Partnerships: During Period 4, the Center continued to seek new partners based on the needs of our Education and Diversity programs. We established five new partnerships, three at Berkeley and two with active NSF-funded Science and Technology Centers (STC). At Berkeley, the Center partnered with Berkeley Engineering's Engineering Students Services (ESS), Berkeley Edge Conference, and the Transfer, Re-entry, and Student Parent Center (TRSP). The two new STC partners are Bio-Computational Evolution in Action Consortium (BEACON) and Center for Integrated Quantum Materials (CIQM).
  - Engineering Students Services (ESS): Berkeley Engineering's ESS provides student support services and programs for undergraduate engineering students at UC Berkeley. The Center partnered with ESS to provide student recruitment, retention, and advising support. For student recruitment, **T. Reardon**, ESS's Electrical Engineering and Computer Sciences (EECS) advisor and **L. Marlor** co-presented at three events: UC Berkeley's Community College Day, Alan Hancock College Community College Day, and Applying for Summer Internships at UC Berkeley (online webinar). For retention, ESS offers the Center's TTE alumni who are accepted into UC Berkeley as transfer students an opportunity to participate in the Transfer Pre-Engineering Program (T-PREP). T-PREP is a two-week transition program and a mentoring program during the academic year. For advising, the Center worked with three advisors from ESS, **T. Reardon, S. Mueller, and E. Foon**, to provide advising support to students in our REU programs. Students had access to advisors to learn about admission criteria for transferring to UC Berkeley and applying for graduate school.
  - Berkeley Edge Conference: The Berkeley Edge Conference is designed to encourage underrepresented minority students who are competitively eligible for our Ph.D. programs to plan to apply to UC Berkeley. Approximately thirty students are chosen from the applications submitted. In period 4, the Center partnered with the Berkeley Edge Conference to recruit underrepresented minority students for the Center. The Center hosted five students in the Berkeley Edge Conference, providing an overview of E^3S research and programs, a tour of the Center, and an intimate social gathering with current E^3S graduate students and staff so the prospective students can learn more about the student experience and ask questions about applying to UC Berkeley or life as a graduate student.
  - Transfer, Re-entry, and Student Parent Center (TRSP): The Center received a REU supplement to fund 2 veterans in the NSF-funded TTE REU Site. To provide recruitment, advising, and professional development for veterans students in the TTE REU program, the Center partnered with UC Berkeley's TRSP. E^3S and TSRP hosted information sessions and one-on-one advising for student veterans to learn about support and transition programs and financial aid available for veterans.
  - Bio-Computational Evolution in Action Consortium (BEACON): The Center partnered with BEACON to create a repository of REU applications. Applications that had a strong academic profile, but were ineligible for the E^3S REU because of major or discipline interest, were shared with BEACON and considered for the BEACON REU Program. This process was used to share BEACON applications as well. Together, the centers were able to place 4 students from the application repository. Because of the success of this process, E^3S introduced the STC REU Application Repository to active STCs at the STC Director's Meeting in August. This repository will be expanded to include all the STC hosting summer REU programs.

- Center for Integrated Quantum Materials (CIQM): The Center partnered with CIQM, a new STC, to host a REU Information Session at Howard University to recruit students for the E^3S REU. **S. Artis**' presentation included an introduction to STCs, overview of preparing for graduate school, and strategies for applying for summer REU programs.

2b. Outcomes and Impact

Outcomes and impact are included above in the description of the activities.

2c. Performance Against Metrics

Objective	Metrics	Targets	Results
Knowledge Transfer	Number of contacts with industry	Period 2: 18 Period 3: 36 Period 4: 36	Period 2: 66 Period 3: 20 Period 4: 42

2d. Partnerships Plans for Period 5

The Center will work to increase its technical engagement with industry members in Period 5. In particular, there are two opportunities at IBM: the characterization of the organic films for the Squitch project with IBM Watson Research Center through P. Solomon and the provision of III-V material on insulator for TFETs (Theme I, MIT) by L. Czornomaz of IBM Zurich Research Laboratory.

We are seeking international partners to host the Center's ETERNs for research. We will do so through the Center's alumni outside the U.S. As the Center accelerates its online education and outreach activities, partnering with experts in online teaching platforms and multimedia tools will help jump start the Center's efforts.

We will apply additional efforts to expand industry membership, particularly to include mid-size companies.

VI. DIVERSITY

1a. Goals and Objectives

The goal of the diversity programs of the Center for E^{3}S is to: increase the number of students from historically underrepresented groups in engineering who attend university and graduate programs in technical disciplines that will contribute to low energy electronics.

While the Center seeks to ensure that the composition of our participants reflects the diversity of the US, with a particular focus on underrepresented racial/ethnic backgrounds, women, and people with disabilities, there is increasing recognition that the more tangible nearer term goal is to attain a diversity profile that is better than a comparable benchmark. During the last reporting period, Period 3, we introduced the use of benchmark data as part of goal setting. This change has not detracted from the Center's critical focus to enhance the diversity of the Center's participants, especially given the Center's existing demographics.

To meet this diversity goal, the Center has an array of pipeline programs to promote interest, resilience, and excellence in STEM among students from underrepresented groups at different levels. Accordingly, many of the Center's educational programs also have a strong diversity focus. In particular, the pipeline programs for high school seniors and community college students are undertaken to cultivate a talent of students to enter the E^{3}S pipeline. The Center chose California community college students as a target population because California has the largest community college system in the US and it is the educational destination of choice for many ethnic minorities, women, and first generation college students in the state. While the Center included two California community colleges, Contra Costa College and LA Trade-Technical College as education partners at the inception of the Center, the Center-led Transfer-to-Excellence program has impacted student in 15 colleges since it was started in 2011.

Sustained Diversity Recruitment Initiatives: The Center has continued to focus on recruiting graduate and undergraduate students from underrepresented groups. Appendix I: Joint Recruitment Calendar and Appendix J: TTE REU Recruitment Calendar presents the recruitment activities in Fall 2013. New in Period 4 is an online dimension to recruitment efforts to broaden prospective students' access to the Center and enhance the number and quality of applicants applying to our programs.

Reorganization of Diversity Programs: The Center has continued to review the effectiveness of its diversity programs towards achieving our diversity vision and goals. Our direction is to: 1) enhance educational content in our diversity programs; 2) increase the number of students who are exposed to energy efficient electronics science; and 3) migrate from localized programs to programs with a national focus and the capacity to reach a large number of participants.

In Period 4, placing additional resources for a stronger emphasis on energy efficient electronics science, rather than a broad focus on electronics, has meant expanding and improving the Research Experiences for Undergraduates (REU) programs for juniors and seniors. The Transfer-to-Excellence REU program for community college students was expanded to include a one-week bootcamp to introduce the fundamentals of electronics and design of energy-efficient electronic devices. The Center enhanced the educational content of the MIT Online Science Technology Engineering Community (MOSTEC) by leveraging iLab, established over the past decade by E^{3}S faculty, **J. del Alamo** *(MIT)*, an online laboratory platform for which he received the 2012 IEEE Electron Devices Society Education Award. On behalf of the Center, the **J. del Alamo** laboratory developed a new laboratory experiment for energy flow, storage and dissipation in a digital inverter during switching for the use by ~100 high school participants of MOSTEC remotely (see Section III – Education).

At its inception, the Center adopted the strategy of partnering with pre-existing programs for high school students that have a diversity focus. The partners were MIT's Office of Engineering Outreach Programs (OEOP) and the Berkeley Nanosciences and Nanoengineering Institute (BNNI). Our role is to augment the activities of the partners with education components while leveraging the partners' experiences and resources for program delivery. Some partnership programs were impacted as the Center underwent program review based on the criteria articulated above and concluded that there is insufficient synergy to continue the partnership. At the end of Period 3, we phased out participation in the pre-college programs with a local focus (Summer High-School Apprenticeship Program (SHARP) at Berkeley and the Saturday Engineering Enrichment and Discovery (SEED) program at MIT). In summer 2013, the Center hosted its last and third cohort of students who took an electronics course as part of the MITES program, an electronics course that was developed in 2011, guided by E^{3}S faculty, **D. Antoniadis** *(MIT)*. In place of these programs, E^{3}S resources have been shifted to build education content for MOSTEC, an online community that was established in 2012 by MIT's OEOP with the Center for E^{3}S being a founding member. By Period 5, this two-year transition means the Center will no longer be partnering with pre-existing programs. Our role in an online community aligns with our education strategy of promoting broad learning of energy efficient electronics science via online venues.

The practice to assess effectiveness also impacted a program that the Center initiated and managed directly at Berkeley. The E^{3}S Hands On Practical Electronics Summer Research Workshop (E^{3}S HOPE SRW) was initiated in 2012 with the goal of preparing lower-division students (freshmen and sophomores) from underrepresented groups to be competitive for REU opportunities. In particular, the goal is for the participants to apply for the E^{3}S REU programs at the Center's member institutions. Unfortunately, our two year experience showed that neither the applicant pool nor the interest of the workshop alumnae in the Center's research has justified the workshop. Thus, the workshop hosted its last cohort at Berkeley in Summer 2013.

In Period 5, we plan to continue to cultivate a pipeline of students from underrepresented groups for graduate study in our field. However, we will shift our focus from preparing lower-division undergraduates to upper-division students (juniors and seniors). We plan to develop a summer school for upper-division undergraduates in energy efficient electronics science with formal classroom lectures taught by E^{3}S faculty. Lab experiences and seminars on planning for graduate school will also be included to expose the students to research and requirements for graduate study. We anticipate that the E^{3}S Summer School will help the Center attract a larger number of prospective graduate students from underrepresented groups who are interested in low-energy electronic devices. Additionally, this summer school will target students at institutions that may not offer, or have limited offerings in courses and research on energy efficient electronics science, to introduce them to our field.

1b. Performance Metrics

Below are the benchmarks and targets for the diversity performance indicators and metrics in the Center's current Strategic Plan.

Objective	Metrics	Frequency	Targets
Diversity	Number of women participating in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 30%
	Number of underrepresented minorities participating in the Center's research programs	Annually	Period 2: Baseline Period 3: 15% increase Period 4: 5% Period 5: 10%
	Number of diversity program participants from groups underrepresented in STEM	Annually	Period 3: Baseline Period 4: 80% Period 5: 80%

	Number of pre-college students who pursue a bachelor’s degree in science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 70% Period 5: 70%
	Number of community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor’s degree science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80%
	Number of undergraduates who pursue advanced degree in science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 30% Period 5: 35%

1c. Problems Encountered

This is the third year the Center has offered the Transfer-to-Excellence Cross-Enrollment program (TTE X-Enroll) for California community colleges in the Bay Area. The program enables community college students to take free credit-bearing science, math or engineering course at Berkeley. In Period 4, the third year of the program, we again, had only one participant. As a result of the low number of applicants and participants, **L. Marlor**, Education and Outreach Program Manager, conducted a needs analysis, and informal interviews with advisors and students. She met with community college advisors and students to learn more about students’ interest in taking courses at a 4-year institution. From these meetings, the Center learned that by expanding the opportunities to more than the summer, the number of community college students enrolling in classes at Berkeley may increase because they no longer have to choose between taking a course and working full-time.

As the Center has aspirations to include students with disabilities to participate in the Center’s programs, we have strived to design the Center’s website to be user-friendly for the visually impaired. In the last annual report, we shared that while a Berkeley group’s assessment gave high rating to the E^{3}S website in its friendliness towards the visually impaired visitors, the navigational design has to be improved. This responsibility falls on the Center’s part-time systems administrator, **M. Stewart**, and the Center’s Executive Director, **J. Yuen**, who is the webmistress. The demands on the time of both individuals have prevented any significant progress to resolve the gaps in the website’s navigation scheme.

2a. Development of US Human Resources

Since mid-2011, the Center’s programs and initiatives in education and diversity have been led and executed by **S. Artis**, E^{3}S Education and Outreach Director, complemented with logistics support from **J. Peng**, E^{3}S Administrative Manager, and the sharing of responsibilities on selected programs by **J. Yuen**, E^{3}S Executive Director. In order that **S. Artis** can put a greater emphasis on Education, particularly the development of educational content for online training, the Center hired a program manager to coordinate our diversity programs in Period 4. **L. Marlor**, E^{3}S Education and Outreach Program Manager, has a B.S. in Materials Science and Engineering from Rensselaer Polytechnic Institute, and is responsible for managing the education and outreach programs. Prior to joining the Center, she was attending graduate school at Purdue University and working for Purdue’s Graduate Mentoring Program, a program offered by the Women in Engineering Program.

Details of the Center’s efforts in diversity in Period 4 are given in this section. The details include:

- Program status (if it has not been reported previously in the Education section);
- The diversity profiles of all programs;

  - Outcomes of program alumni; and
  - The Center's recruiting efforts.

- *Pre-college Programs*

In Period 4, the Center continued to partner with MIT's Office of Engineering Outreach Programs (OEOP) on programs for high school seniors. These programs promote early interest in science and engineering careers to students from underrepresented groups, and the Center's role is to promote the increased awareness of electrical engineering and related technical fields as exciting and rewarding career paths. We do so by supporting the offering of electronics training in the MITES and MOSTEC programs. Previously in the Goals and Objectives section, we have shared the history of our involvement with OEOP and these remaining partnership programs that have continued to Period 4.

Activity Name	MIT Minority Introduction to Engineering and Science (MITES) - Electronics Elective
Led by	**S. Young** (MIT) and **S. Artis** (Berkeley)
Intended Audience	Rising 12th grade high school students
Approx Number of Attendees (if appl.)	Total: 12 Females: 5 (42%), URMs: 9 (75%)

MITES is a six-week residential summer program that offers rising high school seniors the opportunity to develop the skills critical for success in mathematics, science and engineering at top universities, and eventually in academia or in careers in the technical fields. Summer 2013 (Period 4) was the third time that an electronics course that was developed with energy efficiency content under the direction of an E^{3}S faculty, **D. Antoniadis** *(MIT)* in 2011, was offered. The Center supported the instructors for this course, **J. Steinmeyer**, a Ph.D. student in Electrical Engineering, and **N. Abebe**, an undergraduate student in electrical engineering *(both, MIT)*. The 2013 E^{3}S funding not only allowed the college-level course on digital and analog electronics to be taught through lectures and on-hands experimentation, but also enabled a change in pedagogy. Instead of starting with pure electronics (hardware) and then moving onto programming later in the course, the entire curriculum was revised to allow students to begin merging software and hardware from the very beginning.

This year, 12 of the 80 MITES students participated in the electronics elective. Of the 12 students, 42% were females and 75% were from underrepresented minority groups.

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**S. Young** (MIT) and **S. Artis** (Berkeley)
Intended Audience	Rising 12th grade high school students
Approx Number of Attendees (if appl.)	Total: 41 Females: 21 (51%), URMs: 37 (90%)

As a founding member of the MIT Online Science, Technology, and Engineering Community (MOSTEC), the role of the Center for E^{3}S is to provide electronics education resources. Now in its third year, the MOSTEC program continues to promote increasing the students' interest in various fields of engineering and science and to assist them with aspects of the college application process. MOSTEC students complete online coursework and projects in science, engineering, and technical writing. In July, MOSTEC students from all over the country come together for the MOSTEC Conference at MIT (Appendix K: MOSTEC 2013 Agenda), where the participants are exposed to MIT's faculty and staff who provide them with admissions and financial aid tips, lead electronics workshop, facilitate discussions about science and engineering research, and provide mentorship opportunities. After the conference, the students continue to learn more about science and engineering, interact with college faculty and staff, and receive online mentorship from undergraduates, graduate students, and industry professionals.

In Period 4, the Center supported 41 students who participated in the electronics workshop at the MOSTEC Conference. Of the students, 51% were females and 90% were from underrepresented racial groups. The electronics workshop was adapted from newly revised material for the MITES electronics course, leveraging the Center's efforts. In the fall, MOSTEC also featured **E. Fitzgerald,** E^{3}S faculty at *MIT***,** in a weekly webinar, where he shared his education background and career trajectory from high school to his current position as a professor at MIT. He also discussed how his research activities attack the current limitations of electronic materials, explaining the limitations created by imperfections in materials such as point, line, and planar defects.

- *Undergraduate Programs*

At the undergraduate level, the Center's programs target two different audiences - community college students and students at 4-year universities. The Center aims to provide a bridge experience for community college students to help promote their transfer to a 4-year baccalaureate institution. For undergraduates at 4-year institutions, research is used as an early engagement vehicle to attract the students to the Center's focus on low-energy electronic devices.

Community College Programs: The Transfer-to-Excellence (TTE) program, founded by the Center at its inception, consists of two components:

- A stipend paying residential summer research program (TTE REU) that brings community college students to Berkeley to undertake a research project hosted by a Berkeley faculty.
- A cross-enrollment program (TTE X-Enroll) enabling community college students to take a free credit-bearing science, math or engineering course at UC Berkeley. Participant support also includes a stipend for books and transportation, free tutoring, if necessary, and a book incentive upon completion of the course with a grade of B+ or better.

While at Berkeley, TTE participants have access to enrichment activities to build resilience in the pursuit of a STEM education and career. For the academic year following the completion of one component, each participant continues to receive advising and support in his/her efforts to transfer to a STEM baccalaureate program from Berkeley's Transfer Alliance Project (TAP) (Section V External Partnership for details on TAP).

Activity Name	Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU)
Led by	**S. Artis** (Berkeley) and **T.-J. King Liu** (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	Total: 7 Females: 2 (29%), URMs: 1 (14%)

During summer 2013 (Period 4), the Center at Berkeley hosted 7 of the 16 community college students in the TTE REU program (Appendix L: TTE Recruitment Flyer). These students completed nine weeks of research in the laboratories of E^{3}S faculty**, T.-J. King Liu, A. Javey, E. Yablonovitch, C. Chang-Hasnain,** and **J. Wu,** and E^{3}S Education Affiliates**, A. C. Arias** and **X. Zhang**. Education Affiliates are not part of the Center's research team, but their research disciplines are similar to those of the Center. **X. Zhang** joins the Center as an affiliate in Period 4.

In Period 4, the TTE REU experience starts with a one-week bootcamp on the fundamentals of electronics before embarking on independent research. Lectures and hands-on projects on circuit theory, network analysis, semiconductors and devices, and discrete and integrated circuits provided the students with baseline knowledge about energy efficient electronics science. During the 8 weeks of hands-on independent research, the TTE REU students also attend a variety of enrichment activities and participated in weekly one-on-one mentorship meetings with **S. Artis.** For details on enrichment activities, see Appendix M: TTE REU Calendar. TTE participants were trained on scientific ethics, technical presentations, and science communication, received individualized academic and transfer advising, and participated in group enrichment activities provided by TAP. At the end of the program, the students present their research at a poster session.

To date, all of the Center's TTE REU alumni (2011-2012 cohorts) who were eligible to apply for transfer admission to a 4-year institution are currently enrolled in a baccalaureate program. Seven students (2 females, 3 URMs) are pursuing B.S. degrees in STEM fields at UC Berkeley (5), UCLA (1), and UC San Diego (1). Among this group, five of these students transferred to a 4-year institution in Period 4 and two transferred in Period 3.

Activity Name	Transfer-to-Excellence Cross-Enrollment (TTE X-Enroll)
Led by	**S. Artis** (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	Total: 1 Female: 0, URM: 0

One student from Berkeley City College participated in TTE X-Enroll, successfully completing a 4-credit lower division electrical engineering course in summer 2013. The student also received individualized academic and transfer advising and had access to group enrichment activities from Berkeley's TAP, the Center's partner. As with all TTE students, TAP continues to provide transfer support as the X-Enroll student seeks to transfer to a 4-year institution.

In Periods 2 and 3 we had a total of two participants in the TTE X-Enroll program. Both participants are currently STEM undergraduates at UC Berkeley. In Period 4, one of these students transferred to a 4-year institution. The other transferred in Period 3.

- *Summer Research Programs for Undergrads from 4-Year Institutions:* The Center hosts a Summer REU program at Berkeley and MIT and a Summer Research Workshop at Berkeley. The primary goal is to attract undergraduate students, particularly those from groups underrepresented in science and engineering, to the Center's research in energy efficient electronics science and graduate study in science and engineering at the Center's member institutions.

Activity Name	E^{3}S Research Experiences for Undergraduates at Berkeley & MIT (E^{3}S REU)
Led by	**S. Artis** (Berkeley) and **E. Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx Number of Attendees (if appl.)	Total: 14 Female: 5 (36%), URMs: 5 (36%)

The Center's 9-week research program received over 200 applications (Appendix N: E^{3}S Recruitment Flyer). Eleven of these students were matched with Center faculty at Berkeley and three were matched with faculty at MIT. At Berkeley, they were hosted by E^{3}S faculty, **E. Alon, J. Bokor, A. Javey, T.-J. King Liu, S. Salahuddin, I. Siddiqi, M.C. Wu,** and **E. Yablonovitch**. At MIT, they were hosted by E^{3}S faculty, **E. Fitzgerald,** and **T. Swager**. In addition, the students attended weekly enrichment activities that included field trips and preparation for GRE. This summer, Lam Research, one of the Center's industrial partners, provided the students an overview of Lam research technology and a tour highlighting the development of semiconductors, including the processes and equipment used. Each student also received weekly one-on-one mentorship meetings with **S. Artis**, Education and Outreach Director. For calendar of events and activities, see Appendix O: E^{3}S REU Calendar.

At the end of the summer research program, the students completed a short research paper, a 15-minute research presentation, and a poster at the poster session that featured over 35 posters from several REU programs. **E. Yablonovitch**, the Center Director, as the professor of record for the E^{3}S REU independent study course, interviewed each student about his/her research project during the poster session.

Activity Name	E^{3}S Hands On Practical Electronics Summer Research Workshop (E^{3}S HOPE SRW)
Led by	**S. Artis** (Berkeley) and **J. Bokor** (Berkeley)
Intended Audience	1st and 2nd year undergraduate students
Approx Number of Attendees (if appl.)	Total: 10 Female: 4 (40%); URMs: 6 (60%)

The goal of the E^{3}S HOPE SRW is to prepare lower-division undergraduates, including community college students, for future research opportunities. The one-week residential program at Berkeley provides hands-on laboratory experience, exposes participants to the field of energy efficient electronics science, shares information on where and how undergraduates can secure summer research opportunities, and motivates students to set their academic goals to pursue graduate studies in science and engineering. In Period 4, one of the students from the Period 3 program returned to Berkeley as a participant in the 9-week E^{3}S REU program.

This summer (Period 4), we had 10 participants (40% females, 60% URMs) in the E^{3}S HOPE SRW. Led by instructor **A. Ragsdale**, a graduate student in EECS at Stanford, the four day workshop's curriculum included modules on electronic circuits, capacitors and signals, and semiconductors. The laboratory activities included design and trouble-shooting circuits with power amplifiers. The students also received an overview of microelectronics and the Center's research themes from **J. Bokor,** E^{3}S Deputy Center Director, and a tour of the Marvell Nanofabrication Laboratory, led by **W. Ko**, E^{3}S graduate student.

- *Recruitment and Public Outreach*

In addition to these diversity programs, Center members attend diversity conferences and give seminars to local pre-college, undergraduate and graduate audiences to share the exciting work the Center is doing and enlighten them about the opportunities that await them in the Center. Often, these seminars target underrepresented groups, including individuals from underrepresented racial/ethnic backgrounds, women, and students from low socioeconomic backgrounds.

This fall, E^{3}S collaborated with the Berkeley College of Engineering and the Team for Research in Ubiquitous Secure Technology (TRUST), another NSF-funded Science and Technology Center at Berkeley, to recruit for the Center's diversity programs for students at 4-year institutions. The sharing of responsibilities allowed 16 universities to be visited and 4 diversity conferences to be covered (Appendix I: Joint Recruitment Calendar). For the university visits, **S. Artis** conducted graduate preparation workshops and information sessions. These activities were typically one-hour presentations on the Center's research themes and diversity programs and on how to prepare for graduate school. At the diversity conferences, the Center sponsored a booth at the graduate fairs for prospective undergraduate and graduate students to meet Center members and to learn about the Center's research areas and opportunities for undergraduate and graduate students and postdocs.

S. Artis visited 12 universities: California State University, Long Beach; Howard University; Morgan State University; Norfolk State University; The Ohio State University; Purdue University; University of California, Los Angeles; University of California, San Diego; University of Maryland, College Park; University of Southern California; University of Texas at El Paso; and Virginia Tech. The Center also sponsored booths at four diversity and graduate fair conferences: National Society of Black Engineers (NSBE), Society for Advancement of Chicanos and Native Americans in Science (SACNAS), Society of Hispanic Professional Engineers (SHPE), and Society of Women Engineers (SWE) (Appendix Q: Summary of Diversity Enhancing Activities).

In Period 4, the Center increased its recruitment efforts for the Transfer-to-Excellence (TTE) programs targeting community college students (Appendix J: TTE Recruitment Calendar). **L. Marlor** was an invited speaker at the Mathematics, Engineering, Science Achievement (MESA) Student Leadership Conference. While there, she led an interactive workshop engaging students on topics related to strategies for being competitive applicants for transferring to a baccalaureate program in science and engineering. The Center also hosted information sessions about the TTE programs at 5 community colleges: Alameda College, Chabot College, LA Trade-Technical College, Reedley College, and Sacramento City College.

The Center has supported the diversity and recruitment initiatives of its lead institution, UC Berkeley. This has included the Berkeley Edge conference that brings prospective minority graduate students to visit Berkeley and the Bay Area. In support, **L. Marlor** organized an event where the prospective students, including an alumna of the Center's REU program, learned of the benefits of being an E^{3}S graduate student from an E^{3}S graduate student, **K. Li**. The Center also supported UC Berkeley's Electrical Engineering and Computer Sciences Department (EECS) Visit Day for admitted graduate students. This March, 30 admitted Berkeley students attended: 1) Open House for admitted students interested in physical electronics and E^{3}S research; and/or 2) Coffee Hour to learn about Women in Computer Science and Engineering (WICSE), Black Graduate Engineering and Science Students (BGESS), and Latino Association of Graduate Students in Engineering and Science (LAGSES). Center faculty, graduate students, and postdocs participated as poster presenters, speakers, or hosts, and in one-on-one meetings with the visiting students.

During Period 4, the Center added webinars as a way to recruit students for our programs (Appendix R: E^{3}S REU Webinar Flyer and Appendix S: TTE REU Webinar Flyer). The Center offered two webinar series, one for undergraduates at 4-year institutions and one for students at community colleges. Four webinars took place from November through January prior to the application deadlines. During these webinars **S. Artis, L. Marlor,** and T. Reardon *(UC Berkeley, College of Engineering)* provided students information on successful application tips, the importance of research for graduate school applications and transfer applications, and tips on how to get good letters of recommendation, and also allowed time for students to ask questions.

- *Other Outreach and Diversity Activities*

Social Media: The Center has begun to use social media as a tool to broaden access and participation. All undergraduate researchers are asked to post weekly on Facebook about E^{3}S related topics to make the site more dynamic. Since the Center started posting regularly on Facebook in May 2013, the Facebook page has received 109 likes. An average of 156 people has viewed each post made by the Center, with a range of 19-1246 views. The total number of views on all of the Center's posts is over 7,600. To increase visibility, we disseminated information about our education and diversity programs, including program dates, deadlines, tips for participating in the program, and posted science and career development articles.

The Center also organizes the alumnae of each diversity program into a Facebook group. Through the group, the students can communicate with each other during and after their participation in the E^3S program. The Center also uses the Facebook group to share information with past participants about other education and diversity program opportunities and undergraduate and graduate admissions.

Other Diversity Activities & Training: **S. Artis** served on the Women in Engineering Proactive Network (WEPAN) conference committee as chair of the 2013 Annual WEPAN Conference. She and **L. Marlor** also attended a number of diversity training sessions offered at UC Berkeley (Appendix Q). To ensure a supportive environment for all participants of the Center's program, the Center began to offer diversity training for mentors in the REU programs in Berkeley in Period 4.

2b. Impact on the Center's Diversity

In Period 4, the Center has committed significant resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. We believe this approach ensures that these programs will have access to competitive candidates and highly qualified participants, regardless of race, color or sexual orientation. As a result, we are beginning to see positive outcomes from these efforts. From Period 3 to Period 4, the Center has seen a 5% increase in the percentage of underrepresented minority students. This increase can be attributed largely to our proactive and assertive approach to engage UTEP faculty and students in our E^3S research programs. In Period 4, **D. Zubia** (UTEP) and his graduate student, **B. Aguirre,** conducted an 8-week summer research project in **C. Chang-Hasnain's** group at Berkeley. **D. Zubia** has also provided research projects and mentoring to two undergraduate students in the E^3S Internship Program (ETERN).

In Period 5, we expect to see a continued increase in the number of underrepresented students as a result of the Center's commitment to developing a pipeline of undergraduate students that have been exposed to energy efficient electronics science through research or lecture. For our undergraduate programs targeting community college students, we have seen a significant impact on diversity. All nine of the Center's alumni from the Transfer-to-Excellence (TTE) programs have transferred to a 4-year institution, where 77% (7) of these students are current undergraduate students at Berkeley. Among this group of students that are now pursing STEM degrees at Berkeley, 85% (6) of the students are either women (3) or from underrepresented minority groups (4). This pipeline of diverse students is now eligible and will be recruited to continue participation in other E^3S research programs. To sustain continued interest in the Center's research, these students will be recruited for these programs. For our upper-division undergraduate programs for juniors and seniors (E^3S REU), 47% (7) of our students have graduated with a Bachelor's degree. Five REU alumni are pursuing Ph.D. degrees in science and engineering, where four are currently Ph.D. students at UC Berkeley, including two that are part of the Center as graduate students. Although these students are not from underrepresented groups, this recruitment strategy shows promise for URMs and women that are in the E^3S pipeline who are applying to graduate programs at an E^3S-member institution this fall. In Period 4, approximately 56% (10) of our E^3S REU alumni will be applying to graduate school. This group is comprised of 6 women and 3 URMs. In Period 5, we expect to see a similar trend, where our former E^3S REU students enroll at an E^3S-member institution and join the Center.

As shown in this section of the report, the Center has continued to make diversity a high priority in Period 4. The Center leveraged existing partnerships with nationally recognized higher education programs and has formed new alliances, as described in External Partnerships, to collectively tackle the challenge of building a diverse pipeline of students who will eventually contribute to a diverse workforce.

2c. Performance Against Metrics

The following table displays metrics for Periods 2, 3, and 4, and future targets to measure diversity success.

Objective: Diversity

Metrics	Targets	Results		
		Period 2	Period 3	Period 4
Number of women participating in the Center's research programs	Period 3: 5% increase Period 4: 30% Period 5: 30%	13 (22%)	15 (25%)	13 (19%)
Number of underrepresented minorities participating in the Center's research programs	Period 3: 15% increase Period 4: 5% Period 5: 10%	2 (2%)	1 (2%)	5 (7%)
Number of diversity program participants from groups underrepresented in STEM	Period 3: Baseline Period 4: 80% Period 5: 80%	n/a	93 (82%)	Women: 37 (44%) URM: 58 (68%) Total: 73 (86%)
Number of pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline Period 4: 70% Period 5: 70%	20 (22%)	31 (68%)	98 (75%)
Number of community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Period 3: 5% Period 4: 80% Period 5: 80%	0 (0%)	3 (100%)	6 (100%)
Number of undergraduates who pursue advanced degree in science and engineering	Period 3: 5% Period 4: 30% Period 5: 35%	0 (0%)	0 (0%)	5 (38%)

2d. Plans in Period 5

In Period 5, the Center will continue to target recruitment efforts to attract a pool of diverse students to our programs and expand our public outreach activities across the E^{3}S institutions. E^{3}S will visit and inform minority serving institutions and colleges and universities that do not have research opportunities for undergraduate students of E^{3}S opportunities. The Center will also continue to offer information sessions, attend diversity conferences, and host webinar series.

New in Period 5 will be E^{3}S Outreach Kits to increase students' interest in science and engineering. The Center is planning to develop a suite of outreach activities that can be used across E^{3}S institutions to engage students from underrepresented groups in areas of energy efficient electronics science. Building upon Period 4’s outreach activity on graphene, the Center will create the E^{3}S Outreach Kit, which will come with training and resource materials and program supplies. These modules will be centered on the Center's research and can be adapted for students who do not have a science and engineering background. The kits will include three components: education, application, and evaluation. E^{3}S will also pilot the energy flow during switching module developed on the iLab laboratory platform with the MOSTEC class of 2014.

VII. MANAGEMENT

1a. Organizational Structure and Underlying Rationale

In Period 4, the Center is similarly organized as in previous reporting periods; Appendix **B** gives the current organizational chart. Explanation of the organizational structure and its underlying rationale can be found in past Annual Reports. Below we highlight changes in Period 4.

- Changes in Member Institutions: The Center's lead institution has continued to be University of California, Berkeley, home institution of the PI of the STC award, **E. Yablonovitch**. MIT, Stanford and Tuskegee continued to be the subaward institutions through Period 3.

  Towards the end of Period 3, the Center petitioned for NSF's permission to admit The University of Texas at El Paso (UTEP) as an additional subaward institution. The request resulted from a prolonged and systematic effort by the Center to broaden its relationship with minority serving institutions that was initiated in Period 2. In mid-2013, the Center completed the formal process of "admitting" UTEP, a process that included the receipt of the 2013 cooperative agreement with NSF that identifies UTEP as a subaward institution, the execution of a subaward contract, the inclusion of UTEP in the Center's joint intellectual property agreement, and a memorandum of collaboration executed between the Center and the research administration of UTEP. In May 2013, the Center formally welcomed **D. Zubia**, Associate Professor, Department of Electrical and Computer Engineering, UTEP, as one of its faculty. The integration of UTEP is discussed later in Section VII.2.

  Meanwhile, at the end of Period 3, Tuskegee submitted a letter of withdrawal to the Center. This was accepted by University of California, Berkeley upon receipt of permission from NSF. This acceptance led to final accounting of subaward expenses and the termination of Tuskegee's participation in the Center's joint intellectual agreement. The withdrawal of Tuskegee resulted in two faculty leaving the Center.

  In Period 5, the Center is expecting the addition of another new subaward institution, Florida International University (FIU). This is driven by the synergy of the research of a FIU faculty, S. Khizroev, with Theme IV; see Section II.*2cv* – Research Thrust in Period 5.

  The biosketches of new faculty are given in Appendix A.

- Leadership Team: The E^{3}S Executive Committee continues to provide leadership to the Center. Membership on this committee, which has not changed since the inception of the Center, has been discussed in previous annual reports and identified in the organization chart in Appendix B. The leadership is governed by a set of by-laws that were adopted in Period 2 and continues, as adopted, to be in effect; see Period 2 annual report for the by-laws. In Period 4, the committee's decision making was based on the full committee of 10 members. In Period 3, M.C. Wu was excused from his duties as an Executive Committee member as he was on academic leave. He has since returned to fully participate on the Executive Committee. Period 4 transactions of the E^{3}S Executive Committee are given below; see Management & Communications.

- Administrative and Programmatic Team: The Center has a team of full-time personnel who are responsible for the Center's operations and programmatic activities. This team, led by **J. Yuen**, Executive Director, has continued to include three additional full time positions and one part-time position. New in Period 4 is **L. Marlor**, who joined the Center as a full-time program manager, working with **S. Artis** on the Center's Education and Diversity programs. This addition filled all staff positions in the Center. The Center's administrative and programmatic team is located at Berkeley.

- Theme Leaders: Each of the Center's Research Theme is led by a Theme leader.
  - Theme I: **E. Yablonovitch**
  - Theme II: **T.-J. King Liu**

- Theme III: **M.C. Wu**
- Theme IV: **J. Bokor**

In Period 4, **E. Yablonovitch**, as the Center Director, has continued to work with Themes II and IV to guide the Theme's scientific direction and technical approaches. His work with the Theme Leaders have resulted in major changes in the technical approaches undertaken in Theme IV and to a lesser extent that of Theme II. Theme I of which Yablonovitch is also the Theme Leader is undergoing substantive changes in scientific directions as well.

- E^{3}S Faculty: The introduction to the Center's research (Section II.2a) provides an overview of the Center's faculty by Research Themes for Period 4 and the changes anticipated in the coming Period 5 is given in discussion on Research Thrusts in Period 5 (Section II.*2c*). Here, we are summarizing the aggregate changes in faculty participation by institution as the Center ends Period 4 and enters Period 5; for details on faculty changes, see Section II – Research.

	UC Berkeley	MIT	Stanford	Tuskegee	UTEP	FIU
Period 2	11	6	1	1		
Period 3	12	7	1	2		
Period 4	12	7	1		1	
Period 5	11	7	1		1	1

- Graduate Students and Postdoc Council: The Center's organizational structure provides for a Graduate Students and Postdoc Council (GSPC) with the goal of promoting community and leadership building among the students and postdocs; however, the format of a council has not been fully utilized by the Center's students and postdocs. Instead, students and postdocs activities are organized through ad hoc participation. Interests and concerns are typically communicated to the Center staff as they arise or when meeting with **E. Yablonovitch** at the end of each annual Graduate Students and Postdocs Retreat. Each year, as part of the annual Graduate Students and Postdocs Retreat, **S. Artis**, E^{3}S Education Director, has mentored the participants to reconsider the role of the GSPC.

  In Period 4, **B. Aguirre**, a graduate student at UTEP, and **F. Niroui**, a graduate student at MIT, led the meeting, where the students and postdocs discussed their involvement in the Center and future activities. They also discussed the role they wanted the GSPC to play in the future. The majority of the students and postdocs expressed interest in formalizing the GSPC and having a student retreat more than once per year. **E. Yablonovitch** then met with the attendees who provided an update on student and postdoc participation and discussed topics raised by the attendees. We expect the discussion on whether to formalize the GSPC to continue at the Graduate Students and Postdocs Winter Networking Meeting in January 2014.

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly	Yearly
Center Management	Centerwide Communications	Yearly	• 1 newsletter • Annual Retreat • Annual NSF

			Review • Updated website
	Number of disputes	Yearly	Period 2: Baseline Annual decrease
	Annual Surveys:	Yearly	3 or higher on Likert Scale
	• Students/Postdocs		
	• Co-PIs		
	• External Advisory Board		
	Authorship disputes	Yearly	Period 2: Baseline 20% decrease annually
	Plagiarism	Yearly	

1c. Performance Against Metrics

Objective	Metrics	Targets	Results		
			Period 2	Period 3	Period 4
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly	January 5, 2012	December 19, 2012	December 17, 2013
	Centerwide communications	1 newsletter Annual Retreat Annual NSF Review Updated Website	• None • August 29-30, 2011 • None • Continuously	• June 2012 • Aug 21-22, 2012 • Jan 9-10, 2013 • Continuously	• June 2013 • August 26-27, 2013 • January 9-10, 2014 • Continuously
	Number of disputes	• Period 2: Baseline • Annual decrease	0	0	0
	Annual Surveys:	3 or higher on Likert Scale			
	Students / Postdocs		Average: 3.9±0.2	Average: 4.0±0.3	Average: 4.2±0.2
	Co-PIs		No survey in Period 2	Leadership: 4.46 Collaboration: 3.25	Leadership: 4.7±0.5* Collaboration: not available
	External Advisory Board		Strategic Plan: 4.2 Center Status: 4.0	Strategic Plan: 4.1 Center Status: 4.0	Strategic Plan: 4.6 Center Status: 4.6
	Authorship disputes	• Period 2: Baseline • 20% decrease	0	0	0
	Plagiarism			Ethics Survey:	Ethics Survey:

		annually		4.39	n/a**

* new leadership questions ** no longer available due to changes in assessment method

The Center measures the effectiveness in its leaders primarily through two perception surveys of the faculty, postdocs and graduate students. Of key interest is the Center's leadership ability to instill what it espouses as values into the Center.

- Inclusiveness
- Teamwork
- Open and timely communications
- Agility
- Focus on Performance
- Ethical Conduct

Student and Postdoc Survey: Period 4 is the third year that the Center has surveyed its graduate students and postdocs. The Period 4 results are given in Appendix T, and for comparison purposes, data from prior surveys are also given.

Graduate students and postdocs were surveyed on the climate of the Center in terms of the first five stated values of the Leadership Team. Overall, survey results indicate that the students and postdocs agree (Likert score = 4.1±0.2) the Center is living up to its values given above. The Period 4 aggregate result is similar to results of the two previous reporting periods: Period 3 = 4.0±0.3; Period 2 = 3.9±0.2. The respondents' Period 4 view of the climate of the Center relative to each espoused value is as follows:

Inclusiveness	4.1
Teamwork	3.9
Open and timely communications	4.2
Agility	4.2
Focus on Performance	4.1

The Center's Strategic Plan measures whether the Center members are behaving ethically, in terms of plagiarism and sharing of credits when working together. Year after year, we have not received any direct complaints of plagiarism nor are there authorship disputes. Nevertheless, we took a proactive approach by including survey questions to understand the graduate students' and postdocs' view of the ethical climate of the Center. In Period 4, the section on ethics in the survey was modified to bring further clarity, especially to allow our external evaluator to follow up should the answers call for intervention. We conclude from the data in Part B of Appendix U that there are no unethical situations in the Center.

Co-PIs Perception of Center's Collaboration, Ethics, and Leadership Team: A Survey of E^{3}S faculty's perception was administered for the second time in Period 4. The first survey only addressed collaboration and ethical conduct and the Period 4 survey was expanded to include questions on the behavior of the Leadership Team. As mentioned in the next section, Problems Encountered, faculty participation in this period's survey was not sufficient to allow conclusions on collaboration. Only results on Ethics and perception of the Leadership Team are given in Appendix U**.**

The survey on the Leadership Team addresses the Leadership team's practice of the values promised in the Strategic Plan and the provision of technical leadership in relationship to the Center and each faculty respondent.

Promoting an inclusiveness environment	4.8
Promoting teamwork	4.7

Communicating in an open and timely manner	4.7
Making decision in the Center's interest	4.3
Recognizing a co-PI's performance	4.8
Promoting strong ethics	4.9
Providing technical leadership	4.9

The section on ethics in the Period 4 co-PIs survey was modified similarly as in the Graduate Students and Postdocs survey. We conclude from the data in Part C of Appendix U that there are no unethical situations in the Center.

1d. Problems Encountered

The faculty survey administered in Period 4 did not receive full faculty participation, which lessened the ability to draw conclusions on collaborations among the faculty and thus, there is no reporting of this metric for Period 4.

2. Management and Communications Systems

- Center Management

Integration of New Subaward Institution: During Period 4, the Center welcomed the addition of **D. Zubia** and students from The University of Texas at El Paso *(UTEP)* with the recognition that the emerging collaboration is challenging for both parties. The solution is to ramp up the new faculty's acquaintance with the Center's faculty and activities. This was accomplished through a two-month residence at Berkeley by **D. Zubia** and a UTEP graduate student during which they collaborated with **C. Chang-Hasnain** on the Selective Growth of InP Nanopillar. In addition, **T.-J. King Liu** and **E. Alon** each hosted a junior from UTEP in last summer's REU program. Besides research, the Center's new members from UTEP were integrated into the Center's life. **D. Zubia** was a facilitator at a Science Communication Workshop for the E^{3}S summer interns. They also participated in the E^{3}S Summer Journal Club. The visit also enabled opportunities to visit the labs of other E^{3}S faculty at Berkeley and discussions with **S. Artis**, E^{3}S Education and Outreach Director, who worked with **D. Zubia** to identify development opportunities that can be established at UTEP. The research collaboration on Selective Growth led to quantifiable results, and the **D. Zubia** and **C. Chang-Hasnain** labs are continuing their collaboration after the summer. **S. Artis** visited UTEP to further work with **D. Zubia** and other UTEP faculty on student development, including expanding the ETERN and REU programs of the Center to include UTEP faculty.

Executive Committee: The E^{3}S Executive Committee provides management oversight as well as planning and decisions for the Center. From the survey data, we learned that graduate students and postdocs of the Center agree that the Center's leadership has been effective and agile in decision making; with a Likert average rating of 4.2. They also agree that the Center's leadership has focused on performance; with a Likert rating of 4.1.

The committee's work has mainly been done through regular meetings, which are pre-announced with agendas. These processes were shared previously in the Period 2 annual report.

The following is a list of six Executive Committee meetings that were scheduled in Period 4. All meetings are held via teleconferencing.

Executive Committee – Period 4 Meetings	
Meeting Dates	**Agenda Topics**
Feb 19	*New*: Review of Site Visit Team Report; Change in Member Institutions: Withdrawal of Tuskegee & Admittance of UTEP; Debrief of the Visit by Zubia to Berkeley; 3rd Berkeley Symposium on Energy Efficient Electronic Systems
Apr 4	*New*: Period 4 Budget Review; Membership in the External Advisory Board: candidates as new chair and new members; *Carry Over*: Change in Member Institutions
June 3	*New*: Education and Diversity Board; Framework and Process to Engage the Center for the Renewal Proposal; Planning of 2013 Annual Retreat *Carry Over*: Berkeley Symposium on Energy Efficient Electronic Systems
August 28	*New*: Annual Meeting Debrief, Review of Industrial Research Board Input, Candidates for new members of the External Advisory Board *Carry Over*: Education and Diversity Board
October 8	New: Review of Proposals for Period 5 Funding
December 17	*New*: Review of Strategic Plans and Results, Review of External Advisory Board Input, Preparation for NSF Site Visit *Carry Over*: New and Revised Funding Proposals for Period 5

Outside the scheduled meetings, the Executive Committee considers matters of the Center in a timely manner via email exchanges. Key decisions are made via balloting per the rules defined in the by-laws. In Period 4, there was one email ballot.

Administrative and Programmatic Management: The effectiveness in the Center's operations rest on its administrative and programmatic staff who have been identified on the Organization Chart given in Appendix B. The team's activities are guided by an administrative calendar that is established after the annual Site Visit. Standing staff meetings of all full-time staff are used to coordinate and plan. These are held either monthly or biweekly, depending on the needs of the Center.

In Period 4, the Administrative and Programmatic team held its own day long retreat, which was instituted to allow a more systematic and longer range planning and to enhance a more processed approach to management of the Center's operations. Agenda for Staff Retreat is given in Appendix V. At the end of retreat, the staff met with **E. Yablonovitch**, Center Director, and **J. Bokor**, Deputy Center Director, and provided a readout of the staff's discussions and considerations. In particular, the staff discussed the Center's needs in preparing for the renewal proposal.

- Center Communications

The Center has used a variety of venues to maintain timely communication with its faculty, postdocs, students and staff. The effectiveness of the Center's communication was measured in Period 4 as part of the annual Students and Postdocs Survey. Figure 65 shows the effectiveness of different communications vehicles the Center has and is using to share information. This chart also gives a comparison with the respondents' perception in the previous period.

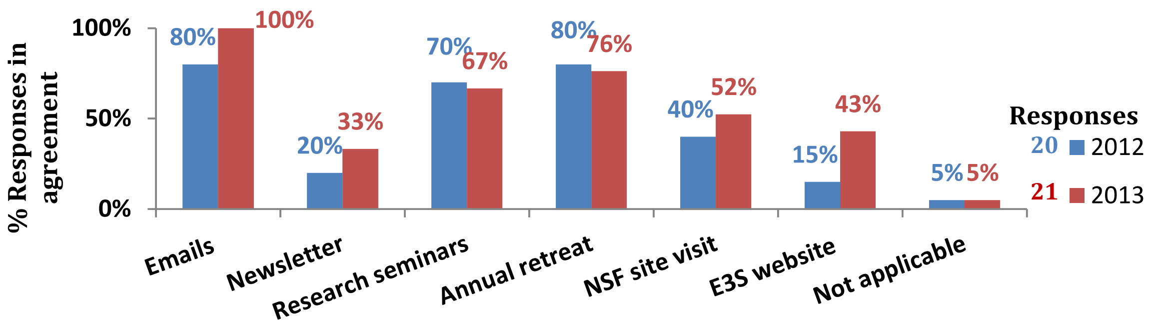


Figure 65: The Center communicates with the respondents effectively and in a timely manner using the following resources.

Information on the various venues is given below.

- *Center's Annual Retreat*: The 4th Annual Center-wide Retreat was held on August 27-28 at UC Berkeley with the theme of "Charting the Center's Future"; the agenda is given in Appendix W. While the theme was chosen to galvanize the members on the Center's funding renewal, the annual retreat also offered the opportunity for a review of the Center's current status and future directions.

  The two-day meeting was attended by the Center's faculty, postdocs, graduate students, staff, education and diversity partners, and industry members. The first day was devoted to research presentations and discussions, while the second day was devoted to Education and Diversity, including engaging our partners. Discussions of the competitive research landscape and an assessment of the Center's progress were topics on the second day.

  The meeting also offered the opportunity for the industry members who make up the Center's Industrial Research Board to provide input to the Center; see below - *Internal and External Advisory Bodies*. The Retreat included a recognition ceremony when the Center's faculty, postdocs, students and industry members were thanked for their support of the Center's programmatic activities.

- *Seminars and Journal Club*: The E^{3}S seminars and the Journal Club are both communication as well as education venues. As education vehicles, they have been discussed in Section III. Education. There were 11 seminars and 4 journal club meeting in Period 4.

- *Newsletter*: The newsletter was initiated in Period 3 and continued in Period 4 to give the Center members a cohesive mid-year view of the Center. The 2013 issue of the newsletter is given in Appendix X. While the Center's reception of the newsletter has improved, the survey indicated that there is significant room for improvement.

- *Website:* The E^{3}S website informs the Center members of events and news and provides access to slides used in past events. It is updated regularly. Additional efforts were applied to improve the website content in Period 4. The Students and Postdocs survey indicated that the improvements have been effective to some extent, but there is still significant room for improving the website for internal communications. The website's effectiveness is directly measured as part of Knowledge Transfer through traffic data. We conclude from the yearly traffic increase and the timing of the increases that the website is effective as an outreach tool, particularly for summer program recruitment.

3. *Internal and External Advisory Bodies*

The primary sources of advice and guidance for the Center for E^{3}S are two groups: the External Advisory Board and the Industrial Research Board. This section presents the Period 4 activities for each group.

- *External Advisory Board (EAB)*: In Period 4, the E^{3}S External Advisory Board continued to be governed by a charter that was adopted by the E^{3}S Executive Committee in 2011; see page 156 of the Period 2 Annual Report. In Period 4, the Advisory Board experienced the following changes:
  - Resignations: Nick Alexopoulos, Broadcom; Elizabeth Weitzman, formerly Semiconductor Research Corporation
  - New Appointments: Paolo Gargini, International Technology Roadmap for Semiconductors (ITRS); Elsa Garmire, Dartmouth College; Mark Pinto, Blue Danube Labs; Diane Rover, Iowa State U.
  - Retirement of Chair: John Heritage, UC Davis, completed a two year term, but is continuing as as a member on the External Advisory Board
  - Appointment of New Chair: Daniel Radack, Institute for Defense Analysis

The E^{3}S Executive Committee made special efforts to appointment new members with interests and experience to advise on education, particularly online education, and diversity. Table VII-1 provides the list of the current members and their interests.

Member	**Affiliation**	**Research**	**Education**	**Diversity**	**Knowledge Transfer**	**Center Management**
Samuel Bader	Argonne National Lab	x				x
John Chen	Nvidia	x	x		x	
Luigi Colombo	Texas Instruments	x			x	
Peter Delfyett	U. of Central Florida	x	x	x		x
Katherine Dunphy-Guzman	Sandia National Lab		x	x		
Paolo Gargini	International Technology Roadmap for Semiconductors (ITRS)	x			x	
Elsa Garmire	Dartmouth College	x	x	x		x
Jonathan Heritage	UC Davis	x	x			
Witek Maszara	Global Foundries	x			x	
Mark Pinto	Blue Danube Labs	x		x	x	
Daniel Radack	Institute for Defense Analysis (IDA)	x				x
Diane Rover	Iowa State U.		x	x		x

In compliance with the charter, the annual meeting of the EAB took place on October 30 at Berkeley, with D. Radack serving as the chairperson, beginning a two year term. Dr. Radack presented a summary of the outcome of the 2013 review and a full assessment report that is made up of two parts, a qualitative assessment and a quantitative assessment were available at the January 2014 NSF Site Visit. The Executive Committee is scheduled to review the written assessment at its meeting on February 2014. The assessments report has been shared with all funded faculty members in the Center and with the Vice Chancellor of Research of Berkeley and the Dean of Engineering of MIT. Berkeley and MIT serve as home for 90% of the E^{3}S faculty in Period 4.

- *Industrial Research Board (IRB)*: The Center for E^{3}S is fortunate to have received strong support from four leaders in the semiconductor industry even before its inception. The IRB monitors, advises, and participates in the Center's research, education, and knowledge transfer goals. In Period 4, we expanded the Industrial Research Board to reflect the addition of a new industry member; see Section V.1c. The Period 4 board's membership is as follows:

Name	**Affiliation**
David Hemker	Lam Research
Ghavam Shahidi	IBM
Stan Williams	Hewlett-Packard
Ellie Yieh	Applied Materials
Ian Young	Intel

At the Center's 2013 Annual Retreat in August, the Industrial Research Board met with the Center's Executive Committee. Representatives of all five member companies participated in the 2013 Industrial Research Board meeting:

  - David Hemker, Lam Research
  - Ian Young, Intel
  - Stan Williams, Hewlett-Packard
  - Paul Solomon, IBM
  - Adam Brand, Applied Materials

The industry representatives provided input on the technical presentations and shared how their companies are planning for the need of lower energy device technologies.

4. *Changes in the Strategic Plan*

No changes in Strategic Plan are planned at this time.

VIII. CENTERWIDE OUTPUT

1a. *Publications*

1ai. *Peer Reviewed (in chronological order)*

Journal Articles

1. F. Ren, K.W. Ng, K. Li, H. Sun, and Connie J. Chang-Hasnain, “High-quality InP nanoneedles grown on silicon,” *Applied Physics Letters,* vol 102, 012115 (2013).
2. J.-Y. Cheng, C. W. Yeung, and C. Hu, “Extraction of Front and Buried Oxide Interface Trap Densities in Fully Depleted Silicon-On-Insulator Metal-Oxide-Semiconductor Field-Effect Transistor,” *ECS Solid State Letters2.5* (2013): Q32-Q34.
3. D. Y. Qui, K. Ashraf, and S. Salahuddin, “Nature of Magnetic Domains in an Exchange Coupled BiFeO3/CoFe Heterostructure,” *Applied Physics Letters*, vol. 102, no. 11, pp. 112902(1)-112902(5), 2013.
4. E. M. Levenson-Falk, R. Vijay, N. Antler, and I. Siddiqi, “A Dispersive NanoSQUID Magnetometer for Ultra-Low Noise, High Bandwidth Flux Detection,” *Superconductor Science and Technology*, Vol 26, No. 5, 055015, 2013.
5. H. Fang, M. Tosun, G. Seol, T. C. Chang, K. Takei, J. Guo and A. Javey, “Degenerate n-Doping of Few-Layer Transition Metal Dichalcogendies by Potassium,” *Nano Letters*, 13, 1991-1995, 2013.
6. K. Takei, R. Kapadia, H. Fang, E. Plis, S. Krishna, and A. Javey, “High Quality Interfaces of InAs-on-Insulator Field-Effect Transistors with ZrO_2 Gate Dielectrics,” *Applied Physics Letters*, vol 102, 153513, 2013.
7. M. Trassin, J. D. Clarkson, S. R. Bowden, J. Liu, J. T. Heron, R. J. Paull, E. Arenholz, D. T. Pierce, and J. Unguris, “Interfacial Coupling in Multiferroic-Ferromagnet Heterostructures,” *Physical Review B*, vol. 87, no. 13, pp. 134426(1)-134426(6), 2013.
8. D. Lee, W.S. Lee, C. Chen, F. Fallah, J. Provine, S. Chong, J. Watkins, R. T. Howe, H.-S. P. Wong, S. Mitra, “Combinational Logic Implementation with Six-Terminal NEM Relays,” *IEEE IEEE Trans. Comput.-Aided Design Integr. Circuits Syst.*, vol. 32, issue 5, pp. 653 – 666, 2013.
9. H. Fang, H. A. Bechtel, E. Plis, M. C. Martin, S. Krishna, E. Yablonovitch, and A. Javey, “Quantum of Optical Absorption in Two-Dimensional Semiconductors,” *Proceedings of the National Academy of Sciences (PNAS)*, Vol. 110, No. 29, 11688-11691, May 2013.
10. N. Antler, E.M. Levenson-Falk, R. Naik, Y.-D. Sun, A. Narla, R. Vijay, I. Siddiqi, “In-Plane Magnetic Field Tolerance of a Dispersive Aluminum Nanobridge SQUID Magnetometer,” *Applied Physics Letters*, 102, 232602, 2013.
11. S. Chuang, R. Kapadia, H. Fang, T. C. Chang, W.-C. Yen, Y.-L. Chueh, A. Javey, "Near-ideal electrical properties of InAs/WSe2 van der Waals heterojunction diodes", *Applied Physics Letters*, 102, 242101, 2013 (cover article).
12. T. J. Seok, A. Jamshidi, M. Eggleston, and M. C. Wu, “Mass-producible and efficient optical antennas with CMOS-fabricated nanometer-scale gap,” *Optics Express*, Vol 21, Issue 14, pp. 16561-16569, July 2013.
13. Y. Zeng, C.-I. Kuo, R. Kapadia, C.-Y. Hsu, A. Javey, C. Hu, “2-D to 3-D tunneling in InAs/AlSb/GaSb quantum well heterojunctions”, *Journal of Applied Physics*, 114, 024502, 2013
14. R. Going, M.-K. Kim, and M. C. Wu, “Metal-optic cavity for a high efficiency sub-fF Germanium photodiode on a Silicon waveguide,” *Optics Express*, vol. 21, no. 19, pp. 22429–224420, Sep. 2013.
15. M.-K. Kim, Z. Li, K. Huang, K. Huang, R. Going, M. C. Wu, and H. Choo, “Engineering of Metal-Clad Optical Nanocavities to Optimize Coupling with Integrated Waveguides,” *Optics Express*, Vol 21, Issue 22, pp. 25796-25804, 2013.

16. D. Fu, J. Zhou, S. Tongay, K. Liu, W. Fan, T.-J. King Liu, and J. Wu, “Mechanically Modulated Tunneling Resistance in Monolayer MoS2,” *Appl. Phys. Lett.*, v 103, no. 4, pp. 183105(1)-183105(3), 2013.
17. K. W. Ng, T. Tran, W. S. Ko, R. Chen, F. Lu, C. Chang-Hasnain, “Single Crystalline InGaAs Nanopillar Grown on Polysilicon with Dimensions beyond Substrate Grain Size Limit," accepted by *Nano Lett.*, vol 13, pp 5931-5937, 2013.
18. D. Bhowmik, L. You, and S. Salahuddin, “Spin Hall effect clocking of nanomagnetic logic without a magnetic field,” *Nature Nanotechnology Letters*, doi:10.1038/nnano.2013.241, 2013.
19. T. Yu, J.T. Teherani, D.A. Antoniadis, and J.L. Hoyt, “$In_{0.53}Ga_{0.47}As/GaAs_{0.5}Sb_{0.5}$ Quantum-Well Tunnel-FETs With Tunable Backward Diode Characteristics,” *IEEE Electron Device Letters*, v 34, n 12, pp. 1503-1505, Dec. 2013.
20. K. Li, H. Sun, F. Ren, K. W. Ng, T.-T. D. Tran, R. Chen, and C. J. Chang-Hasnain, “Tailoring the Optical Characteristics of Microsized InP Nanoneedles Directly Grown on Silicon,” *Nano Lett.*, Publication Date (Web): December 3, 2013 (Letter), DOI: 10.1021/nl403712f.

In Press

21. J. Yaung, L. Hutin, J. Jeon and T.-J. K. Liu, “Adhesive force characterization for MEM logic relays with sub-micron contacting regions,” *IEEE/ASME Journal of Microelectromechanical Systems*, Vol. 22, 2013.
22. R. Going, J. Loo, T.-J. King Liu, and M. C. Wu, “Germanium Gate PhotoMOSFET Integrated to Silicon Photonics,” accepted for publication in *IEEE Journal of Selected Topics in Quantum Electronics*, 2013.

Under Review/Submitted

23. S. Agarwal and E. Yablonovitch., “Pronounced Effect of pn-Junction Dimensionality on Tunnel Switch Threshold Shape,” Under Review, *Proceedings of the National Academy of Sciences.*
24. S. Agarwal and E. Yablonovitch, “Fundamental Conductance ÷ Voltage Limit in Low Voltage Tunnel Switches,” Under Review, *IEEE Electron Device Letters.*
25. S. Agarwal and E. Yablonovitch, "Band-Edge Steepness Obtained from Esaki and Backward Diode Current-Voltage Characteristics," Under Review, *IEEE Transactions on Electron Devices.*
26. S. Agarwal, J. T. Teherani, J. L. Hoyt, D. A. Antoniadis, and E. Yablonovitch, "Optimized Design of the Electron Hole Bilayer Tunneling Field Effect Transistor," Under Review, *IEEE Transactions on Electron Devices.*
27. T. Yu, J. T. Teherani, D. A. Antoniadis and J. L. Hoyt, “Temperature Dependent Measurements and Analysis of $In_{0.53}Ga_{0.47}As/GaAs_{0.5}Sb_{0.5}$ Quantum-Well Tunneling Field-Effect Transistors (QWTFETs),” Under Review, *Applied Physics Letters*.
28. J. Lin, X. Zhao, D. A. Antoniadis, J. A. del Alamo, “A Novel Digital Etch Technique for Deeply Scaled III-V MOSFETs,” submitted to *IEEE Electron Device Letters*.
29. L. Hutin, W. Kwon, C. Qian, and T.-J. King Liu, “Electro-Mechanical Diode Cell Scaling for High-Density Non-Volatile Memory,” submitted to *IEEE Transactions on Electron Devices*.
30. J. Fujiki, N. Xu, L. Hutin, I.-R. Chen, C. Qian, and T.-J. King Liu, “Micro-Electro-Mechanical (MEM) Relay and Logic Circuit Design for Zero Crowbar Current,” submitted to *IEEE ASME Journal of MicroElectroMechanical Systems*.
31. J. Bokor, B. Lambson, D. Carlton, Z. Gu, and J. Hong, “Exploring the Thermodynamic Limits of Computation using Nanomagnetic Logic,” submitted to *Journal of Energy and Power Engineering*.
32. X. Zhao and J. del Alamo, “Nanometer-scale Vertical-Sidewall Reactive Ion Etching of InGaAs for 3-D III-V MOSFETs,” submitted to *IEEE Electron Device Letters.*

Conference Proceedings

1. H. Kam, Y. Chen and T.-J. K. Liu, "Reliable micro-electro-mechanical (MEM) switch design for ultra-low power logic," *IEEE International Reliability Physics Symposium*, Monterey, CA, USA, April 14-18, 2013.
2. C. W. Yeung, A. I. Khan, A. Sarker, S. Salahuddin, C. Hu , "Low power negative capacitance FETs for future quantum-well body technology", *International Symposium on VLSI Technology, Systems, and Applications (VLSI-TSA)*, Hsinchu, Taiwan, April, 2013.
3. S. Artis, C. Amelink, "Development of a Multidisciplinary Summer Research Program for Community College Students in Science and Engineering," *In Proceedings of the 2013 American Society for Engineering Education Annual Conference & Exposition*, Atlanta, GA, USA, June 2013.
4. I-R. Chen Y. P. Chen, L. Hutin, V. Pott, R. Nathanael and T.-J. King Liu, "Stable Ruthenium-contact relay technology for low-power logic," *17th International Conference on Solid-State Sensors, Actuators and Microsystems, Transducers 2013*, Barcelona, Spain, June 16-20, 2013.
5. J. A. del Alamo, D. Antoniadis, A. Guo, D.-H. Kim, T.-W. Kim, J. Lin, W. Lu, A. Vardi, and X. Zhao, "InGaAs MOSFETs for CMOS: recent advances in process technology," Invited Talk, *IEEE International Electron Devices Meeting (IEDM)*, Washington DC, USA, December 9-11, 2013.
6. J. Lin, X. Zhao, T. Yu, D. Antoniadis, and J. del Alamo, "A New Self-aligned Quantum-Well MOSFET Architecture Fabricated by a Scalable Tight Pitch Process," *IEEE International Electron Devices Meeting (IEDM)*, Washington DC, USA, December, 2013.
7. J. Teherani, W. Chern, D. Antoniadis, and J. Hoyt, "Simulation of Enhanced Hole Ballistic Velocity in Asymmetrically Strained Germanium Nanowire Trigate p-MOSFETs," *IEEE International Electron Devices Meeting (IEDM)*, Washington DC, USA, December, 2013.
8. X. Zhao, J. Lin, C. Heidelberger, E. A. Fitzgerald and J. A. del Alamo, "Vertical Nanowire InGaAs MOSFETs Fabricated by a Top-down Approach," *IEEE International Electron Devices Meeting (IEDM)*, Washington DC, USA, December 9-11, 2013.
9. A. Wang, W. Chang, A. Murarka, J. H. Lang, and V. Bulovic, "Transfer-Printed Composite Membranes for Electrically-Tunable Organic Optical Microcavities," *IEEE MEMS 2014 Conference*, San Francisco, CA, USA, January 26-30, 2014.
10. F. Niroui, P. Deotare, E. Sletten, A. Wang, E. Yablonovitch, T. M. Swager, J. H. Lang, and V. Bulovic, "Nanoelectromechanical Tunneling Switches Based on Self-Assembled Molecular Layers," *IEEE MEMS 2014 Conference*, San Francisco, CA, USA, January 26-30, 2014.

1aii. Books and Book Chapters (alphabetized by first author)

To Be Published

1. S. Agarwal and E. Yablonovitch, "Designing a Low Voltage, High Current Tunneling Transistor," in CMOS and Beyond: Logic Switches for Terascale Integrated Circuits, T.-J. K. Liu and K. Kuhn, Eds., Cambridge University Press.
2. T.-J. King Liu, "NEMS Switch Technology," to appear in Emerging Nanoelectronic Devices, An Chen, Jim Hutchby, Victor Zhirnov, and George Bourianoff, editors (John Wiley & Sons, Ltd), 2013

1aiii. *Other Non-Peer Reviewed Publications, Books and Book Chapters (alphabetized by first author)*

1. C. Amelink, and S. Artis, "Improving Community College Student Transfer Through a Multidisciplinary Summer Research Program," *Eastern Educational Research Association Conference*, Sarasota, FL, February 2013.
2. J. Bokor, B. Lambson, D. Calrton, Z. Gu, and J. Hong, "Exploring the thermodynamic limits of computation using nanomagnetic logic," Invited, NanoEnergy 2013, Perugia, Italy, July 10-13, 2013. Published in Nanoenergy Letters, vol. 6, pp. 23-24, 2013.
3. C. Hu, "A Bold New Era of Nano Materials and Devices", Keynote, *IEEE NMDC(Nano Materials and Devices Conference)*, Tainan, Taiwan, October 2013
4. H.-S. P. Wong, "Innovating Our Way Through the End of Moore's Law," invited keynote paper, IC China, Shanghai, China, November 12 – 14, 2013

1b. *Conference Presentations (in chronological order)*

Talks:

1. F. Niroui, A. Wang, E. Sletten, A. Murarka, M. D'Asaro, T. Swager, V. Bulovic, and J. H. Lang, "Tunneling nanoelectromechanical switches," *MTL Annual Research Conference*, Cambridge, MA, USA, January 29, 2013.
2. J. T. Teherani, "Tunneling Transistors for Low Power Electronics," *MTL Annual Research Conference (MARC)*, Cambridge, MA, USA, January 29, 2013. (Featured presenter, top submitted abstract).
3. X. Zhao, J. A. del Alamo, "Towards a Superlattice-Source Nanowire FET with Steep Subthreshold Characteristics," *MTL Annual Research Conference (MARC)*, Cambridge, MA, USA, January 29, 2013.
4. C. Hu, "The Changing IC Device Technology", *ISQED Symposium*, March 4-6, 2013.
5. N. Antler, E. Levenson-Falk, R. Naik, S. Hacohen-Gourgy, R. Vijay, I. Siddiqi, "In-Plane Magnetic Field Tolerance of a Nanobridge SQUID Magnetometer," *APS March Meeting 2013*, Baltimore, MD, USA, March 21, 2013.
6. H.-S. P. Wong, "Semiconductor Technologies for N+*m* Nodes, where $m \geq 4$," invited Distinguished Speaker, *IEEE Texas Workshop on Integrated System Exploration (TexasWISE)*, Winedale, TX, USA, March 8, 2013.
7. H. Fang, "High-performance Single Layered WSe2 FETs with Chemically Doped Contacts", San Francisco, CA, USA, *MRS*, April 4th, 2013.
8. H. Sun, T. Tran, F. Ren, K.W. Ng, E. Yablonovitch, C. J. Chang-Hasnain, "High bandgap lattice-mismatched InGaP micropillars grown on Silicon," *Materials Research Society Spring meeting 2013*, April 1-5, 2013, FF1.02.
9. T. Tran, H. Sun, F. Ren, K.W. Ng, K. Li, F. Lu, E. Yablonovitch, and C. J. Chang-Hasnain, "Contactless I-V Measurements on InP Micropillars with Fermi-level Splits > 0.9V under 1 Sun", *Materials Research Society Spring meeting 2013*, April 1-5, 2013, FF2.09.
10. M.-K. Kim, Z. Li, M. C. Wu, R. Going, and H. Choo, "Engineering Metallic Nanocavity Radiation for Efficient Uni-/Bi-directional Coupling into Integrated Waveguide," presented at the CLEO: QELS-Fundamental Science, San Jose, California, June 9-14, 2013, p. QW3N.2.
11. T. Tran, H. Sun, F. Ren, K. W. Ng, K. Li, F. Lu, E. Yablonovitch, and C. J. Chang-Hasnain, "High Brightness InP Micropillars Grown on Silicon with Fermi-level Splits Larger than 1 eV," *39th IEEE Photovoltaic Specialists Conference*, June 16-21, 2013.
12. I. Gaeta, L. Snow-Solum, S. Artis, and S. Hernandez, "Improving the Match Between Early College Students and Company Internships or Research Experiences for Undergraduates," *2013 Women in Engineering ProActive Network National Conference*, Atlanta, GA, USA, June 19-21, 2013.

13. R. M. Iutzi, M. T. Bulsara, E. A. Fitzgerald, “MOCVD Growth and Tunnelling Characteristics of InAs/GaSb- Based Heterostructures” *55th Electronic Materials Conference*, Notre Dame, IN, USA, June 26-28, 2013.
14. F. Niroui et al; “Electromechanical organic thin film transistor”; *LASERION*, Schloss Ringberg, Tegernsee, Germany, July 3-6, 2013.
15. H. Sun, F. Ren, T.-T. D. Tran, K. W. Ng, K. Li and C. J. Chang-Hasnain, “High Quality InGaP Micropillars Directly Grown on Silicon,” *IEEE summer topicals,* Waikoloa, HI, paper WA1.2, July 8-10, 2013.
16. M. Eggleston and M. C. Wu, “Efficient Coupling of Optical-Antenna Based nanoLED to a Photonic Waveguide,” *IEEE International Photonics Conference*, Bellevue, WA, USA, September 8-12, 2013. (First place winner of Best Student Paper).
17. R. Going, T.-J. King Liu, M. C. Wu, “Rapid Melt Grown Germanium Gate PhotoMOSFET on a Silicon Waveguide,” *IEEE International Photonics Conference*, Bellevue, WA, USA, September 8-12, 2013.
18. A. I. Khan, J. Ravichandran, C.W. Yeung, M. J. Lee, L. You, C. Hu, R. Ramesh and S. Salahuddin, “Thickness scaling of ferroelectric negative capacitance,” *TECHCON*, Austin, TX, USA, September 9-10, 2013.
19. S. Agarwal, E. Yablonovitch, "Why Tunneling FETs Don’t Work, and How to Fix It,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
20. M. Eggleston, K. Messer, S. Fortuna, E. Yablonovitch and M. C. Wu, “Waveguide-Integrated Optical Antenna nanoLEDs for On-Chip Communication,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
21. R. Going, J. Loo, T.-J. King Liu, M. C. Wu, “2.5 GB/s Germanium Gate PhotoMOSFET Integrated to Silicon Photonics,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
22. A. Javey, “Quantum Membranes: a new materials platform for future electronics,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
23. S. Lee, J. Cao, A. Tang, J. McVittie, H.-S. P. Wong, “NEM Relays Using 2-Dimensional Nanomaterials for Low Energy Contacts,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28 – 29, 2013.
24. J. T. Teherani, T. Yu, D. A. Antoniadis, and J. Hoyt, “Electrostatic Design of Vertical Tunneling Field-Effect Transistors,”, *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
25. C.W. Yeung, A. Khan, S. Salahuddin, and C. Hu, “Device Design Considerations for Ultra-Thin Body Non-Hysteretic Negative Capacitance FETs,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
26. K. Li, T. Tran, K. W. Ng, H. Sun, F. L. Lu, and C. J. Chang-Hasnain, “Single crystalline InP nanopillar grown on silicon with very low surface recombination velocity,” *55th Electronic Materials Conference (EMC2013)*, paper Z9, December 3, 2013.

<u>Posters</u>:

1. F. Niroui, A. Wang, E. Sletten, A. Murarka, M. D'Asaro, T. Swager, V. Bulovic, and J.H. Lang, “Electromechanical modulation of electrical conduction through organic thin films,” *MRS*, San Francisco, CA, USA, April 2013.
2. J. T. Teherani, T. Yu, D. A. Antoniadis, and J. L. Hoyt, “Tunneling Transistors for Low Power Electronics,” *MTL Annual Research Conference (MARC)*, Cambridge, MA, USA, 2013.
3. Y. P. Chen, E. S. Park, I-R. Chen, L. Hutin, V. Subramanian and T.-J. King Liu, “Micro-relay reliability improvement by inkjet-printed microshell encapsulation,” *17th International*

Conference on Solid-State Sensors, Actuators and Microsystems, Transducers 2013, Barcelona, Spain, June 16-20, 2013.

4. S. Agarwal, J.T. Teherani, J. L. Hoyt, and D. A. Antoniadis and E. Yablonovitch, “Optimization of the Electron Hole Bilayer Tunneling Field Effect Transistor,” *71st Device Research Conference*, Notre Dame, IN, June 23-26, 2013.
5. J. Hong, B. Lambson, M. Nowakowski, and J. Bokor, “Experimental Investigation of Landauer Erasure of Nanomagnetic Logic Bits,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
6. J. Clarkson, R. Paull, C. Nelson, X. Marti, S. Salahuddin, and R. Ramesh, “Electrical Control of Epitaxial FeRh Phase Transition,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
7. L. Hutin, W. Kwon, T.-J. King Liu, “Non-volatile Electro-Mechanical Memory (NEMory) Cell Scaling for Energy-efficient and High-density Cross-point Arrays,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
8. R. Iutzi and E. Fitzgerald, “Effect of Materials Properties on Interband Tunnelling in MOCVD-Grown InAs/GaSbbased Diodes,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
9. W.S. Ko, R. Chen, K. W. Ng, D. Parekh, F. Lu, T.-T. D. Tran, K. Li, and C. Chang-Hasnain, “Nanophotonic Link Using Nanopillar LED and Detector Grown on Silicon,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
10. K. Messer, M. Eggleston, S. Fortuna, M. Wu, and E. Yablonovitch, “Optical Antenna for Large Spontaneous Emission Rate Enhancement of an InP Emitter,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.
11. S. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch, and M. Wu, “Electrically Injected High Speed NanoLed Utilizing Optical Antenna Enhanced Light Emission,” *3rd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, USA, October 28-29, 2013.

1c. Other Dissemination Activities (in chronological order)

1. E. Yablonovitch, "Powering Down High-Tech Energy," *Hewlett Chair Celebration*, University of California, Berkeley, CA, USA, Nov. 3, 2012
2. E. Yablonovitch, "Searching for the Milli-Volt Switch," University of Texas at El Paso, Texas, USA, Dec. 12, 2012.
3. Zhao, J. A. del Alamo, “Towards a Superlattice-Source Nanowire FET with Steep Subthreshold Characteristics,” presented at *Microsystems Annual Research Conference*, a student conference of Microsystems Technology Laboratories, Cambridge, MA, USA, January 2013.
4. E. Yablonovitch, "Case Histories for the Introduction of New Technology Through Entrepreneurship," *National Research Council, Xerox PARC Research Center meeting on Trends in the Innovation EcoSystem*, Feb. 26, 2013.
5. E. Yablonovitch, "Introduction to the E3S Center," Intel, Portland, OR, USA, April 10, 2013.
6. Hu, "Microchips--Heart of Electronics", *Seminar at Cal Day to prospective students and parents*, University of California, Berkeley, USA, April 20, 2013
7. Hu, "Microchips-- Can They Continue To Do More For and With Less?", *California Commonwealth Forum*, April 24, 2013
8. Yablonovitch, "Energy Efficient Electronics; Searching for the MilliVolt Switch," *Scott Lecture* at University of Cambridge, United Kingdom, May 15, 2013.
9. Yablonovitch, "What New Device Will Replace the Transistor?", *NanoElectronics & NanoPhotonics Workshop*, Hong Kong University of Science and Technology, Hong Kong, May 27, 2013.

10. J. A. del Alamo, “Progress at MIT on III-V nFETs and pFETs”, Taiwan Semiconductor Manufacturing Corporation, Hsinchu, Taiwan, June, 2013.
11. T.-J. King Liu, “New Logic Switches for Energy-Efficient Computation Energy-Efficient Computing,” presented at the *CEA-LETI 15th Annual Review*, Grenoble, France, June 26, 2013.
12. T.-J. King Liu, “Moore’s Law – What’s Next?”, *Semiconductor Equipment and Materials International (SEMI) Silicon Manufacturers’ Group General Meeting,* San Francisco, CA, USA, July 11, 2013.
13. Yablonovitch, "Forthcoming Breakthroughs in Electronic Devices," *Royal Society New Fellows Seminar*, London, United Kingdom, July 11, 2013.
14. E. Yablonovitch, "Searching for the Milli-Volt Switch,” *Radcliffe Institute Next Transistor Workshop,* Cambridge MA, USA, Sept. 12, 2013.
15. T.-J. King Liu, “Moore’s Law – What’s Next?”, *Department colloquium*, Materials Science and Engineering Department, University of California, Berkeley, USA, September 19, 2013.
16. E. Yablonovitch, "The Energy Efficient Internet; Searching for the milli-Volt Switch," *Plenary Lecture, European Conference on Optical Communication*, London, UK, Sept. 23, 2013.
17. T.-J. King Liu, “Beyond Moore’s Law – Challenges and Opportunities,” *Berkeley Nanotechnology Club*, University of California, Berkeley, USA, October 25, 2013.
18. E. Yablonovitch, "From Science to Startup: Introduction of New Technology Through Entrepreneurship," *ETH Alumni Meeting*, San Francisco, CA, USA, Nov. 1, 2013.
19. H.-S. P Wong, “Innovating Our Way Through the Long Tail of Moore’s Law,” *Samsung Future Technology Forum*, November 5, 2013.
20. E. Yablonovitch, "The NSF Center for Energy Efficient Electronics Science: A Resource for Industry," *NRI monthly TPG Meeting Teleseminar*, Nov. 6, 2013.
21. H.-S. P Wong, “Innovating Our Way Through the Long Tail of Moore’s Law,” *invited plenary talk, IBM Semiconductor Technology Symposium*, Yorktown Heights, New York, December 5, 2013.

2. *Awards & Honors*

Recipient	Reason for Award	Award Name	Sponsor	Date	Award Type
Jesus del Alamo	“For pioneering contributions to the development of online laboratories for microelectronics education on a worldwide scale”	EDS Education Award	IEEE – Electron Devices Society	December 10, 2012	Education
Vladimir Bulovic	Leadership in energy and nanotechnology	Fariborz Maseeh Professorship in Emerging Technology	MIT EECS Department	January, 2013	Scientific
Vladimir Bulovic	Contribution to innovation of practical applied nanotechnologies	Xerox Distinguished Lecturer	Xerox Corp	June, 2013	Scientific
Vladimir Bulovic	Innovative work of “the greatest likely long-term	Finalist, Fellow of the World Technology	World Technology Network	November, 2013	Scientific

	significance" in Materials research	Network			
Connie Chang-Hasnain	World-renowned researcher of Chinese descent working in fields of electronics and information technology	Outstanding Research Award	Pan Wen Yuan Foundation	June 2, 2013	Scientific
Michael Eggleston	Invention of arch dipole antenna-enhanced nanoLED	James H. Eaton Memorial Scholarship	International Engineering Consortium through EECS Dept	May 3, 2013	Fellowship
Michael Eggleston	Best Paper	IPC 2013 First Place Best Student Paper	IEEE Photonics Society	September 9, 2013	Scientific
Chenming Hu	BSIM model	Phil Kaufman Award	EDA Consortium (EDAC) & IEEE Council of EDA (CEDA)	June 2, 2013	Scientific
Rehan Kapadia	Outstanding research	2013 David J. Sakrison Memorial Prize	UC Berkeley EECS Department	May 3, 2013	Scientific
Yue Lu	Demonstrating keen sense of creativity and inventiveness	James H. Eaton Memorial Scholarship	UC Berkeley EECS Department	May 3, 2013	Fellowship
Timothy Swager	Invention of Chemical Sensors	Creative Invention	American Cancer Society	April, 2013	Scientific
Chun Wing Yeung, Asif I Khan, Asis Sarker, Sayeef Salahuddin, Chenming Hu	Best Paper	Best Student Paper Award	VLSI-TSA Symposium	May 3, 2013	Scientific
Eli Yablonovitch	For broad contributions to optics and electronics; for introducing the idea that strained semiconductor laser could have superior	Foreign Member of the Royal Society of London	The Royal Society (UK National Academy of Science)	May 3, 2013	Scientific

	performance due to reduced valence band (hole) effective mass; and for introducing the photonic bandgap concept				
Tao Yu	Academic	Rolf Locher Graduate Fellowship	MIT EECS	October, 2013	Fellowship

3. Graduates

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Ayana Andalcio	B.S. EE, *Rice University*	May, 2013	4	Epic Systems
Steven Drapcho	B.S. Chemistry, *Pennsylvania State University*	May, 2013	4	Physics Graduate Program at Berkeley
Daniel Drew	B.S. MSE, *Virginia Tech*	May, 2013	4	Electrical Engineering Graduate Program at Berkeley
Duanni Huang	B.S. EE, *MIT*	May, 2013	4	Chemistry Graduate Program at University of California, San Diego
Yuniu (Peter) Huang	B.S., MSE, *UC Berkeley*	May, 2013	4 (2 in community college, 2 at Berkeley)	R&D Engineer, Marvell Nanofabrication Lab, UC Berkeley
Stephen Meckler	B.S. Physics, *MIT*	May, 2013	4	Electrical Engineering Graduate Program at Berkeley
Peida Zhao	B.S. MSE, *University of California, San Diego*	May, 2013	4	Electrical Engineering Graduate Program at Berkeley

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree*	Placement
Khalid Ashraf	Ph.D., *Berkeley*	December, 2013	4.5	Postdoc at UC Berkeley in K. Keutzer group (Computer Science)
Xiangyu (Helen) Chen	Ph.D., *Stanford*	December, 2012	5	McKinsey Consulting
Roger Chen	Ph.D., *Berkeley*	May, 2013	N/A	N/A
Kartik	Ph.D., *Berkeley*	December, 2013	5	IMI Inc.

Ganapathi				
John Heron	Ph.D., *Berkeley*	February, 2013	4.5	Postdoc at Cornell (groups of Darrell Schlom & Dan Ralph)
Rehan Kapadia	Ph.D., *Berkeley*	May, 2013	5	Postdoc in Javey Lab through May 2014; Assistant Professor, Department of Electrical Engineering, USC, beginning July 2014
Nikhil Kumar	Ph.D., *Berkeley*	December, 2012	5.5	Skorpios Technologies, Inc.
Brian Lambson	Ph.D., *Berkeley*	May, 2013	5	iRunway, Santa Clara, CA
Farnaz Niroui	S.M., *MIT*	June, 2013	2	MIT EECS PhD program in the same group
Tae Joon Seok	Ph.D., *Berkeley*	December, 2012	5	Postdoc at UC Berkeley in same group
Mun E (Mandy) Woo	S.M., *MIT*	June, 2013	2	Product Development Associate, NutraClick
Stephen Wu	Ph.D., *Berkeley*	January, 2013	5.5	Postdoc at Argonne National Lab

Postdocs

Name	Departure Date	Placement (where did they go?)
Guneeta Bhalla	December, 2012	N/A
Louis Hutin	December, 2013	Device Engineer for Ultra-Low-Power Electronics, CEA-Leti, France
Daesung Lee	February, 2013	InvenSense, San Jose, CA
Fan (Stephon) Ren	June, 2013	N/A
Andrew Schmidt	August, 2012	IBM
Kuniharu Takei	March, 2013	Assistant Professor, Dept of Physics and Electronics, Osaka Prefecture University (Japan)
Morgan Trassin	February, 2013	Research Staff, ETH, Zurich
Rajamani Vijayaraghavan	November, 2012	Assistant Professor, Tata Institute of Fundamental Research, Mumbai, India
Christoph Weis	September, 2013	N/A
Youngki Yoon	April, 2013	Assistant Professor, University of Waterloo

4a. General Outputs of Knowledge Transfer Activities

Patent Name	**Inventors/ Authors**	**Number**	**Application Date**	**Receipt Date (leave empty if pending)**
Piezoelectric Voltage Transformer for Low Voltage Transistors	Sapan Agarwal	61/913894	12/9/2013 (provisional patent)	

Licenses: none to report

Startup companies: none to report

4b. Other Outputs of Knowledge Transfer Activities

None to report

5a. Participants

In the current reporting period, the Center has 121 participants.

	Summer	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	10	1	0	12	23

	Funded by E^3S			**Other Funding Source Total**	**Total Participants**
Category	50% or more	less than 50%	**Total**		
Postdocs	8	0	8	9	17
Grad Students	13	12	25	22	47
Undergrads	0	27	27	0	27
TOTAL	**21**	**39**	**60**	**31**	**91**

Category		**Institutional Affiliation**		**Department**		**Gender**		**Disability Status**		**Ethnicity**		**Race**		**Citizenship**	
23	Faculty	12	Berkeley	18	E.E.	20	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	18	US Citizens
		7	MIT	2	Mats Sci	3	F	0	Visual Impairment	18	Not Hispanic or Latino	8	Asian	3	Permanent Resident
		1	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	4	Decline to State	0	Black or African American	0	Other non-US Citizen
		1	UTEP	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	CCC					17	None			12	White	2	Not Available
		1	Other					4	Decline to State			3	Decline to State		
								2	Not Available			0	Not Available		
17	Postdocs	12	Berkeley	13	E.E.	13	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	5	US Citizens
		3	MIT	1	Mats Sci	4	F	0	Visual Impairment	17	Not Hispanic or Latino	11	Asian	1	Permanent Resident
		2	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	11	Other non-US Citizen
		0	UTEP	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								15	None			6	White	0	Not Available
								2	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
47	Graduate Students	32	Berkeley	33	E.E.	40	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	25	US Citizens
		12	MIT	8	Mats Sci	7	F	0	Visual Impairment	44	Not Hispanic or Latino	24	Asian	0	Permanent Resident
		1	Stanford	3	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	0	Black or African American	21	Other non-US Citizen
		2	UTEP	1	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	1	Decline to State
				2	Chemistry			46	None			20	White	0	Not Available
								1	Decline to State			3	Decline to State		
								0	Not Available			0	Not Available		
27	Undergraduate Students	4	Berkeley	9	E.E.	19	M	0	Hearing Impairment	6	Hispanic	0	American Indian or Alaskan Native	23	US Citizens
		2	MIT	3	Mats Sci	8	F	0	Visual Impairment	20	Not Hispanic or Latino	11	Asian	4	Permanent Resident
		0	Stanford	5	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	1	Black or African American	0	Other non-US Citizen
		2	UTEP	2	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	3	Chemistry			26	None			11	White	0	Not Available
		0	CCC	5	Other			1	Decline to State			2	Decline to State		
		19	Other					0	Not Available			2	Not Available		
7	Staff	5	Berkeley	0	E.E.	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	6	US Citizens
		2	MIT	0	Mats Sci	6	F	0	Visual Impairment	5	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	2	Black or African American	0	Other non-US Citizen
		0	UTEP	6	E3S			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
				2	Other			4	None			2	White	1	Not Available
								1	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
121	**TOTAL PARTICIPANTS**														

5b. *Affiliates*

Category		**Institutional Affiliation**		**Department**		**Gender**		**Disability Status**		**Ethnicity**		**Race**		**Citizenship**	
5	Faculty	3	Berkeley	2	E.E.	3	M	0	Hearing Impairment	2	Hispanic or Lantino	0	American Indian or Alaskan Native	3	US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	2	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	2	Chemistry			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC	1	ME			3	None			1	White	2	Not Available
		1	CCC	0	Other			0	Decline to State			1	Decline to State		
		0	Other					2	Not Available			1	Not Available		
1	Research Scientists & Visiting Faculty	0	Berkeley	0	E.E.	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	1	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	Other					0	None			1	White	0	Not Available
								1	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
7	Postdocs	7	Berkeley	4	E.E.	7	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	5	Not Hispanic or Latino	3	Asian	2	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Chemistry			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	4	Decline to State
				1	ME			6	None			2	White	1	Not Available
				2	Other			0	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
15	Graduate Students	12	Berkeley	13	E.E.	14	M		Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	7	US Citizens
		1	MIT	0	Mats Sci	1	F	1	Visual Impairment	11	Not Hispanic or Latino	7	Asian	0	Permanent Resident
		1	Stanford	1	Physics				Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	4	Other non-US Citizen
		1	UTEP	0	Chemistry				Other	4	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
				1	ME			10	None			2	White	4	Not Available
				0	Other				Decline to State			1	Decline to State		
								4	Not Available			4	Not Available		
18	Undergraduate Students	3	Berkeley	10	E.E.	11	M	0	Hearing Impairment	5	Hispanic	0	American Indian or Alaskan Native	16	US Citizens
		1	MIT	3	Mats Sci	7	F	0	Visual Impairment	12	Not Hispanic or Latino	5	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	4	Black or African American	1	Other non-US Citizen
		2	UTEP	2	Chemistry			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	1	ME			17	None			6	White	1	Not Available
		0	CCC	2	Other			0	Decline to State			1	Decline to State		
		12	Other					1	Not Available			2	Not Available		

Category		**Institutional Affiliation**		**Department**		**Gender**		**Disability Status**		**Ethnicity**		**Race**		**Citizenship**	
53	Pre-College Students	0	Berkeley	0	E.E.	27	M	0	Hearing Impairment	46	URM			0	US Citizens
		0	MIT	0	Mats Sci	26	F	0	Visual Impairment	7	Non-URM			0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment					0	Other non-US Citizen
		0	UTEP	0	Other			0	Other					0	Decline to State
		0	LATTC	53	N/A			0	None					53	Not Available
		0	CCC					0	Decline to State						
		53	Other					53	Not Available						
12	Staff	7	Berkeley	1	E3S	4	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	11	US Citizens
		4	MIT	4	OEOP	8	F	0	Visual Impairment	9	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	6	TAP			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					9	None			5	White	1	Not Available
								2	Decline to State			1	Decline to State		
								1	Not Available			1	Not Available		
111	**TOTAL AFFILIATES**														

6. *Center Partners*

	Organization Name	**Organization Type**	**Address**	**Contact Name**	**Type of Partner**	**160 hours or more?**
1.	Intel	Company	Hillsboro, OR	Ian Young	Research, Knowledge Transfer	N
2.	Lam Research	Company	Fremont, CA	David Hemker	Research, Knowledge Transfer	N
3.	IBM	Company	Yorktown Heights, NY	Ghavam Shahidi	Research, Knowledge Transfer	N
4.	Hewlett-Packard	Company	Palo Alto, CA	Stan Williams	Research, Knowledge Transfer	N
5.	Applied Materials	Company	Santa Clara, CA	Ellie Yieh	Research, Knowledge Transfer	N
6.	National Chiao-Tung University	University	Taiwan	Edward Y. Chang	Research,	N
7.	Intel Corporation	Company	Santa Clara, CA	Hai-Feng Liu and Botros Youssry	Research	N
8.	Bell Labs, Alcatel Lucent	Company	Holmdel, NJ	Liming Zhang	Research	N
9.	National Tsing Hua University	University	Taiwan	Yu-Lun Chueh	Research	N

10.	Texas Tech University	University	San Marcos, TX	Ravi Droopad	Research	N
11.	University of Notre Dame	University	Notre Dame, IN	Debdeep Jena	Research	N
12.	University of New Mexico	University	Albuquerque, NM	Sanjay Krishna	Research	N
13.	Lawrence Berkeley National Laboratory	National Laboratory	Berkeley, CA	Hans A. Bechtel and Michael C. Martin	Research	N
14.	École Polytechnique Fédérale de Lausanne (EPFL)	University	Lausanne, Switzerland	Adrian Ionescu	Education	N
15.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Keith Schoon	Education & Diversity	N
16.	UCLA Center for Community College Partnerships	University	Los Angeles	Alfred Herrera	Education & Diversity	N
17.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Shawna Young	Education & Diversity	N
18.	MIT Office of the Dean for Graduate Education	University	Cambridge, MA	Monica Orta	Education & Diversity	N
19.	Center of Integrated Nanomechanical Systems	University	Berkeley, CA	Meltem Erol	Education & Diversity	N
20.	Berkeley Foundations for Opportunities in Information Technology	University	Berkeley, CA	Orpheus Crutchfield	Education & Diversity	N
21.	Synthetic Biology Engineering Research Center	University	Berkeley, CA	Kate Spohr	Education & Diversity	N
22.	The Team for Research in Ubiquitous Secure Technology	University	Berkeley, CA	Aimee Tabor	Education & Diversity	N
23.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon	Education & Diversity	N
24.	Bio-Computational Evolution in Action Consortium	University	East Lansing, MI	Judy Brown Clark	Education & Diversity	N

25.	Mathematics Engineering Science Achievement	University	Oakland, CA	Mae Cendana Torlakson	Education & Diversity	N
26.	Center for Integrated Quantum Materials	University	Washington D.C.	Tina L. Brower-Thomas	Education & Diversity	N
27.	Berkeley Edge Conference	University	Berkeley, CA	Ira Young	Education & Diversity	N
28.	Re-entry Student and Veteran Services	University	Berkeley, CA	Ron Williams	Education & Diversity	N
29.	Special Programs and Veterans Affairs, Office of the Registrar	University	Berkeley, CA	Michael Cooper	Education & Diversity	N
30.	Outside Agency Program Manager & Veterans Benefits Liaison, UC Berkeley Financial Aid & Scholarships Office	University	Berkeley, CA	Sara Lopez	Education & Diversity	N

7. Summary Table for internal NSF reporting purposes

1	the number of participating institutions (all academic institutions that participate in activities at the Center)	5
2	the number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center)	30
3	the total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC)	$542,990
4	the number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF) .	121

8. Media Publicity of Center

None.

IX. INDIRECT/OTHER IMPACTS

The Center's international activities included:

- M. Monroe, an ETERN participant, spent 8 weeks at École Polytechnique Fédérale de Lausanne (EPFL) doing research in the A. Ionescu lab.
- C. Hu has continued the collaboration with E. Y. Chang, National Chiao-Tung University in Taiwan, on material growth and characterization.
- A. Javey partnered with Y.-L. Chueh, National Tsing Hua University in Taiwan, on TEM characterization.
- E. Yablonovitch was elected as a Foreign Member of the Royal Society of London by the Royal Society (UK National Academy of Science) and presented a talk at the New Fellows Seminar in London in July 2013.
- The Center's research was presented at seven conferences outside the US, 2 in Spain, 1 in Italy, 1 in Germany, 2 in Taiwan and 1 in China.
- E. Yablonovitch gave talks on the Center's research at 2 institutions in UK and Hong Kong, and T.-J. King Liu gave a talk at CEA-LETI in France. J. del Alamo gave a talk on III-V nFETs and pFETS in Taiwan.
- The 3rd Berkeley Symposium on Energy Efficient Electronic Systems included 12 international attendees - 4 from Europe, 2 from Latin/South America, 2 from the Middle East, and 4from Asia.

The Center's research will likely have impact beyond the goals of the Center.

- The research of D. Antoniadis and J.L. Hoyt to gain an improved understanding of band-to-band tunneling currents in strained-Si/strained-Ge for tunnel FETs is directly applicable to parasitic gate-induced drain leakage (GIDL) current in modern MOSFETs.
- The nanowire fabrication processes developed in the laboratory of J. del Alamo are useful in other devices such as III-V MOSFETs.
- The molecular doping studies to achieve Ohmic contacts for chalcogenides of A. Javey addresses a common problem to electrically contact extremely thin-body semiconductors, especially where the Bohr radii are large. Similar surface charge transfer doping or other doping mechanism can be developed for III-V materials to eliminate the contact resistance.
- The squitch research of V. Bulovic, J. Lang and T. Swager is currently focused on achieving a very low energy digital switch, but we believe that the squitch will have significant practical application beyond that of a digital switch. In between the two digital input-output regimes is a high-gain regime that can support amplification. Essentially, one can view the research as developing an analog valve that is optimized for a digital application. However, there are many applications for low-power temperature-insensitive analog electronics which exhibit high gain and a low noise floor. The squitch can be competitive in those applications.

Additional other impacts include:

- An undergraduate physics major has been a workstudy office assistant of the Center in this current reporting period. Her work in support of the Center's undergraduate programs has provided information and encouragement to her as she aspires to pursue graduate studies. She was a REU intern at University of California, San Diego in summer 2013 and is now in the process of applying to graduate programs in physics.

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XI. APPENDICES

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