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Center for Energy Efficient Electronics Science

Final

Second Annual Report

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Berkeley University of California
Massachusetts Institute of Technology
Stanford University
Tuskegee University
Contra Costa College
Los Angeles Trade-Tech

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I. GENERAL INFORMATION

1a. Center Information

Date submitted	December 5, 2011
Reporting period	March 1, 2011 – February 29, 2012
Name of the Center	Center for Energy Efficient Electronics Science (E^3S)
Name of the Center Director	Eli Yablonovitch
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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
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Role of Institution at Center	MIT is a lead research, education, and outreach partner.

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Role of Institution at Center	Stanford is a lead research, education, and outreach partner.

Institution Name	Tuskegee University Shaik Jeelani
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Role of Institution at Center	Tuskegee is a research, education, and outreach partner to encourage greater minority participation in engineering.

Institution Name	Contra Costa College Seti Sidharta
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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
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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. Two were added to the Center during Period 2 and a third will be added in Period 3.

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
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2. *Context Statement*

INTRODUCTION

Information processing equipment, including all computers, consumer electronics, telephony, office equipment, network equipment, data centers and servers, and supercomputers, consume significant amount of electricity, growing with time, both on an absolute basis as well as a fraction of the total. 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) technology.

Energy efficiency, and power consumption in circuits and devices, is emerging as one of 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 in the design of integrated circuits (ICs) 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 on heat extraction.

The confluence of these trends is of critical importance. The rapid growth in the demand for information processing within the economy is placing 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 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 ~1Volt, much in excess of what is 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 10^6 times greater than need be.

There are many elements that enter into the energy requirements of an information processing system. The Center for E^3S 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 on the energy consumption required to process information [1]. This goal represents a reduction from current energy levels, per operation, by 6 orders of magnitude.

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^3S 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 and initial approach in the Center for E^3S 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.

This partnership of UC Berkeley, MIT, Stanford University and Tuskegee University has a research program that is comprised of four Themes:

I. Nanoelectronics with a focus on solid state millivolt switching

II. Nanomechanics with a focus on low voltage operation and reliability

III. Nanophotonics focused on few-photon communication

IV. Nanomagnetics that has the potential of approaching the theoretical limit.

These technologies are critical elements of future ultra-low energy information processing solutions. Nanotechnology offers the potential for continuing the exponential growth in capabilities beyond the energy-imposed scaling limits of current CMOS technology, by laying the foundation for radically new approaches requires research among the basic disciplines (physics, nanomaterials, nanodevices) in a coordinated matrix fashion. Themes I, II and IV each pursue a different approach to switching. Theme III addresses optical communication for both intra-chip internal communication in processors, and chip-to-chip communication. Over-arching these four themes is the Systems Integration research targeted to provide detailed specifications for the new devices from a systems perspective. These will enable future ultra-low energy information systems to be built and integrated using elements of each of these approaches.

The Center's focus on achieving energy efficient devices with ultra- low operating voltage is novel. The focus on understanding how to achieve devices at or close to the fundamental limits is far ahead of industry. Moreover, a team of multi-disciplinary and multi-institutional researchers having joined forces to accelerate new fundamental science that can lead to a radically lower power successor to conventional technology is new.

Tunneling FETs, a key approach under the Nanoelectronics Theme, have been in research for many years, but the results have been disappointing, with simulation predicting phenomenal results and experiment faring far worse. A large record of device results came from a keen focus on technology development and device optimization. Moreover, the concept of the TFET itself is still in flux, with various mechanisms proposed. The lack of a sound scientific foundation has impeded achieving promising results. The Center is the first concerted effort to elucidate the physics of energy bandgap sharpness both theoretically and experimentally. In the Nanomechanics Theme, the Center focuses efforts on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of transistors. Prior research on micro/nano-electro-mechanical (M/NEM) switches were focused on achieving functional devices with good yield and reliability (to enable integrated circuit demonstrations), and on theoretical studies of their scaling behavior. Towards building a scientific foundation, the goal of the Nanomagnetics Theme is to evaluate the fundamental limits of energy dissipation in magnetic logic devices and also to explore a spin-based interconnect scheme for magnetic logic. This focus differentiates from other large research on magnetic logic, like in DARPA's Nonvolatile Logic (NVL) program and the program supported by the Nanoelectronics Research Initiative (NRI). The former is very focused on building a complete prototype full-adder circuit deliverable, while the latter is focus on benchmarking magnetic switching speed relative to other technologies.

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), as the Center strives to deliver on its education and outreach mission 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; 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 Center's education and diversity programs are targeted at graduate students and postdocs, as well as undergraduates, community college and high school seniors. The programs for the pre-graduate school populations have a strong emphasis on participation by underrepresented groups. The Center develops and manages most of its undergraduate programs, including programs for community college students. However, it leverages established high school programs at its partner research institutions to add value. The Center considers its Transfer-to-Excellence program to enable higher transfer rate of community college students to STEM baccalaureate programs a key focus of its diversity efforts. Part of the Center's vision is that students trained in new science and technology of energy efficient electronics will eventually be a new and diverse generation of scientists, engineers, and technicians who will apply their knowledge to the benefit of society.

Thus, knowledge transfer is another important part of the Center's mission. The Center's goals are to establish industry/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 was started with full support from four leading companies of the semiconductor industry. Representatives of these companies serve on an Industrial Research Board where the foremost role is to provide input and make certain that the Center's research directions will be practical, and lead to real successes. Through these and other companies of the semiconductor industry, the Center's research successes will eventually be transferred into low power consumption applications.

The Center, which is led by E. Yablonovitch of UC Berkeley, Center Director and Principal Investigator of the NSF Award, was started in October 2010 and its Kickoff Meeting took place in November 2010. This Period 2 Annual Report reflects the state of the Center after approximately 12 months of full operations.

SUMMARY OF THE STATE OF THE CENTER

At the highest level, the status of the Center can be viewed through the metrics that were defined in the Center's Strategic Plan. Leadership and ethical conduct shape the Center's environment, while Research, Education, Knowledge Transfer and Diversity are elements in the Center's mission. The Center does not have a metric solely for partnerships, but its partnership metric is part of Knowledge Transfer. While the Center's Strategic Plan remains substantively unchanged, additional metrics have been added in this Period to enable more appropriate tracking of outcomes. An asterisk denotes a new metric.

Objective	Metric	Targets	Period 2 Results
Leadership	Annual Surveys:	3 or higher on Likert Scale	
	• Perception Survey – Students /Postdocs		Average: 3.89
	• Perception Survey - Co-PI's		*In progress*
	• External Advisory Board Survey		Strategic Plan = 4.18 Center Status = 4.01
Ethical Conduct	Authorship disputes	Period 2: Baseline	*Part of co-PI survey*
	Plagiarism		*Part of co-PI survey*
	Integrity of laboratory notebooks		*Process being planned*
Research	Multi-PI projects	Period 2: 30%	44%
	Multi-Institutional projects	Period 2: 10%	4%
	Multi-Institutional themes*		50%

	Unplanned research projects	To begin in Period 3	3
	Publications with authors from multiple institutions	To begin in Period 3	n/a in Period 2
Education	Number of Center graduates who have completed E^3S training	Period 2: Baseline	Those trained in Period 1 have not graduated.
	Number of publications with students and postdoc authors who have published previously in other themes	To begin in Period 3	n/a in Period 2
	Number of students and postdocs participating in education programs	Period 2: 5%	52%
	Number of students and postdocs participating in leadership roles in the Center*	Period 2: Baseline	11%
	Number of events leading to external articles on the Center	Period 2: Baseline	1
Knowledge Transfer	Website hits & unique visitors	Period 2: Baseline	Hits: 11,354 Unique Visitors: 6,123
	Number of contacts with industry	Period 2: 18	66
	Presentation by industry	Yearly: 2	4
	Center publications	Per Year: 18	28
	External citations of publications	To begin in Period 3	15
	Patent disclosures	Period 3: 3 Period 5: 8	1
	Students hired into relevant industries	Period 5: 50% Period 10: 50%	1 postdoc
	Technology development attributable to Center's research	Period 10: 1	n/a in Period 2
Diversity	Number of underrepresented minorities participating in the Center's research and programs	Period 2: Baseline	2%
	Number of women participating in the Center's research and programs*	Period 2: Baseline	22%
	Number of students from underrepresented groups applying	Period 2: Baseline	5 Applied, 2 Accepted

	to and accepted by E^3S programs*		
	Number of E^3S participants involved in diversity-enhancing activities*	Period 2: Baseline	7
	Number of transfer students who have made contact with the Center who apply to and are accepted by 4-year colleges	Period 2: Baseline	3 Applied, Accepted TBD in Period 3

Research:

Center's Faculty: The start of the Center brought together 19 faculty researchers at four partnering institutions. These researchers bring expertise in electrical engineering, physics and materials science. They are:

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

During Period 2, the Center added a faculty researcher, Junqiao Wu of UC Berkeley, with six months of seed funding. Kaylan Das of Tuskegee is joining the Center to accelerate Tuskegee's research effort. Plans are to add Timothy Swager of MIT in Period 3 who will provide expertise in surface chemical functionalization.

Center Synergy: The Center's four research Themes and the System Integration effort are made up of multiple projects to address different aspects and utilize different approaches that will help the Center make progress toward its goals. The faculty researchers are taking advantage of the collaborative environment offered by the Center. The following summary of the status of the research program will show that some projects are collaborative efforts among faculty researchers. Moreover, three out of the four Themes have regular Theme meetings that include the faculty and their graduate student and postdoc researchers. These Theme meetings have been used to share project status, receive input and provide input among the project teams, and coordinate and brainstorm within a Theme. The schedules for these Theme meetings have ranged from biweekly to once every two months. In addition, the matter of Integrative Research has been on the agenda of the Center's Executive Committee and the 2011 Annual Retreat dedicated time for a panel to openly explore ways to enhancing integration across the Center. An informal survey of its faculty was undertaken to determine the value of being associated with the Center. Most responses expressed appreciation that the Center provides the ability to collaborate with others who have different expertise and disciplinary perspectives. Faculty researchers in one Theme acknowledged that the input received during Theme meetings has accelerated the projects. To date, three unplanned projects have been initiated, two of which are clear outcomes of team science in action at the Center. These two projects are: "Layered Chalcogenides for Monolayer Semiconductors", a Theme I project; and "Nanomechanical Relays with Magnetoelectric Switching Elements", a collaborative project between Themes II and IV.

Goals and Objectives: The Center's faculty researchers and their groups are working together to achieve the Center's research goals. At a high level, the new switch is targeted to have the following specifications:

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

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.

For Nanomagnetics, the Center's most futuristic Theme, the goal is to achieve a device that will operate as close as possible to the fundamental limit of energy dissipation of kTln2 that Landauer has predicted theoretically [1].

While these high level goals and objectives serve as a technical vision, the Center also is continuing to define more detailed technical requirements 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.

Research in Period 2: Research projects in the Center have been making progress. Also, noteworthy are the following projects: (i) One project in Theme I has been discontinued; (ii) One project in Theme II has changed direction; (iii) One project was added in Theme III to leverage research in an on-going Theme III project; (iv) A collaborative project is been initiated between Theme IV and II based on a research outcome of Theme IV, and (iv) A seed project was funded during this Period.

- *System Integration Research*: Detailed specification of the research goals of the Center is itself an ongoing research effort. **E. Alon** of *UC Berkeley* is working with the four Themes to elucidate circuit- and system-level requirements for new switching device technologies, to guide the science and technology research needed to realize the devices themselves. In Period 2, there are three emphases:

  i. Development of an analytical framework that quantifies the I_{on}/I_{off} and the variability requirements of new switching devices for digital logic applications;
  ii. Collection of models and/or predictive data for the alternative switches in order to numerically assess their potential benefits; and
  iii. Study of optimized low-energy communication links based on nanophotonic devices.

  Results to date include the following conclusions:

  - On/Off current ratio required: 10^6:1;
  - Current Density or Conductance Density (for miniaturization): 1 milli-mho/μm; i.e. a 1μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in milli-mho/μm conductance to reflect the Center's target is at operating voltage that is significantly less than the 1 volt that is typically assumed in the traditional unit of milli-Amps/μm.)
  - A steep switch needs threshold precision level that is proportional to the steepness of its threshold slope. If this constraint is not met, then for the same variability as a CMOS

transistor, the steep device could actually have worse effective I_{on}/I_{off} . It is therefore important to consider and quantify device variability mechanisms in advance.

- Optimization of a photonic link must take into account two key tradeoffs: (a) number of photons versus receiver sensitivity; and (b) amortizing the overhead of the transmitter over the bandwidth of the receiver.
- If a steep switching device has lower unity current-gain frequency (f_T) but better steepness than CMOS transistors, it will only provide energy-efficiency benefits over a certain range of link bandwidths.

- *Theme I - Nanoelectronics*: The Theme I team, led by **E. Yablonovitch,** comprises researchers from *UC Berkeley*, *MIT* and *Tuskegee*. The team's strategy on TFETs has two elements:

  i. A "Density of States" switching mechanism, as it has the potential to achieve simultaneously the three technical requirements for electronic switching that are given above; an objective that has been elusive despite many years of TFET research.

  ii. Type III band alignment, as in the lattice-matched p-GaSb/n-InAs heterostructure system, to allow a very thin tunnel barrier for good on-state current at milli-Volt gate voltages [2].

In Period 2, research is in progress to establish the scientific understanding of the sharpness of the density of states of the band edges through <u>Simulation and Experimental Verification</u> via device design, fabrication and characterization. In parallel, to address the unavoidable requirement of some form of quantum confinement, a parallel focus of Theme 1 is <u>Novel Device Structures and Materials</u>, where the research effort is also to understand fundamental device physics led by device fabrication and materials research. Identification of additional materials system Type III band alignment is part of the Theme I research program. Studies of layered Chalcogenides have been initiated at UC Berkeley (**E. Yablonovitch** and **A. Javey**) and assisted by **V. Rangari** at Tuskegee. The Center's need for InAs/GaSb epitaxial materials is temporary addressed through external partnership, while **E. Fitzgerald** is establishing a MOCVD capability at MIT to grow epitaxy materials for researchers at MIT and UC Berkeley.

Research in TFETs in Period 2 has led to the following results.

- **E. Yablonovitch**'s group studied analytically the effect of dimensionality of p-n junctions on turn-on characteristics and conductance. The most interesting case for TFETs is the 2d:2d case where conservation of energy and momentum during the tunneling process results in a much sharper turn-on somewhat close to a step function. Serendipitously, strong confinement can compensate for a weak tunneling probability. Efforts to experimentally verify this simulated conclusion in a 2-terminal InAs/GaSb diode are in progress.
- **D. Antoniadis** and **J. Hoyt**'s laboratories have been pursuing the measurement of bandedge sharpness. The approach is to establish a TFET simulation environment using a combination of commercially available device design programs and specialized atomistic codes for full band quantum transport, including phonon scattering to provide both rigorous physics and efficient device design. Initial efforts were applied to strained silicon/strained germanium Type II heterostructures. For the first time, measurement of the effective bandgap, a critical parameter for tunneling, at the strained Si/strained Ge Type II heterointerface has been effected. A value that is approximately 100 meV smaller than theoretically expected was extracted. The successful demonstration of the device design and simulation methodology in Type II hetero-interfaces is laying the foundation for studies tunneling in direct bandgap III-V heterostructures. By the end of Reporting Period 2, results from the first lot of InAs/GaSb vertical tunnel diodes are expected.

- **S. Salahuddin** is leading a research effort to establish a rigorous quantum simulation platform that accounts for non-equilibrium statistical mechanics properly to result in a capability that will realistically predict and guide device design optimizations. Technical achievements to date from this effort include the first simulation that accounts for electrons and phonons within the Non Equilibrium Quantum Transport regime for devices over 300 nm in length, demonstrating: (i) a smooth transition from ballistic to diffusive regime as the channel length is increased; and (ii) the prediction for a Non-Equilibrium Source Field Effect Transistor (NESFET) in an InAs-InGaAs heterostructure that shows potential improved behavior compared to a standard p-i-n type tunnel transistor design. Efforts to build simulation capabilities for 3D geometry are continuing, as the simulation software is being extended to achieve a 3D Poisson solution self-consistently.
- **A. Javey**'s group has been developing a novel epitaxial platform that centers on the ability to fabricate devices from ultra-thin compound semiconductor membranes placed on arbitrary substrates, enabling precise tuning of the electronic and optical properties of devices through materials engineering and quantum confinement. In Period 2, a first generation III-V tunnel transistor fabricated from this platform that has been dubbed XOI. Utilizing ultrathin InAs XOI, an InAs homojunction TFET on Si is demonstrated [3]. The device exhibited an ON current density of ~0.5 µA/µm at $V_{DS}=V_{GS}=1V$. The SS at $V_{DS}=0.1$ V was ~190 mV/dec. The SS at $V_{DS}=0.1$ V was ~190 mV/dec. In this device architecture, the ON current was dominated by vertical band-to-band tunneling and is thereby less sensitive to the junction abruptness. As importantly, the XOI platform has been used to study the physics InAs membranes. Achievements to date include: (i) The drastic effects of quantum confinement on the quantum resistance of the InAs has been explored, leading to the development of new device physics models for ultrathin III-V layers. (ii) Absorption study of ultrathin InAs membranes was performed and quantum confinement has been observed as steps in absorbance, and for the first time, the quantum unit of absorbance was observed for the first time in 2d semiconductors; (iii) High g_m and I_{ON} were achieved in III-V (InAs and InAsSb) nFETs on Si. Specifically, InAs XOI nFETs exhibiting g_m of 2.3 mS/µm at VDS=0.5 V, a body thickness of ~13 nm and channel length of ~ 200 nm were fabricated and demonstrated; and (iv) High hole mobility III-V (InGaSb) pFETs on Si were achieved. The InGaSb XOI pFETs display a peak effective mobility of ~820 cm2/Vs, ON/OFF current ratio of 10^3-10^4 with a respectable subthreshold swing of ~146 mV/decade. The device fabrication efforts of Javey's group have been integrated with the research efforts of **C. Hu**.

Theme I's research program also include non-TFET research. In this Period, one noteworthy effort is the use of negative capacitance to achieve steeper threshold slope. This project, led by **S. Salahuddin**, is studying the detailed energy landscape of ferroelectric insulators which can provide "transformer" action as gate insulators boosting the voltage seen by a transistor channel. While negative capacitance is the only concept available that does not require that the transport physics in a MOSFET be changed, it can also be complementary to tunneling action and if successful, two effects will multiply, significantly increasing device performance. The emphases in Period 2 are materials optimization and definition of process flow for device fabrication, the latter effort being a collaborative effort with **C. Hu**.

A Theme I project in the group of **J. del Alamo** attempted to use of Impact Ionization in Narrow Bandgap Materials to achieve steeper sub-threshold slope. It was discontinued after a conclusion was made that impact ionization simply requires too much voltage relative to the goals that are targeted by the Center.

- *Theme II - Nanomechanics*: Mechanical switches have zero off-state leakage and abrupt on/off switching behavior, which allows for aggressive supply voltage (V_{DD}) scaling for ultra-low active energy consumption (<1 aJ/bit). Theme II, led by **T.J. King Liu,** is the first and only major project to focus efforts on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of transistors. The Theme II research team is investigating new materials as well as device and circuit designs for voltage reduction, device scaling, and reliability improvement. The first major milestone for this research will be the demonstration of mechanical switches operating with voltage swings below 100 mV. A longer-term goal is to demonstrate switches operating with voltage swings below 10 mV.

The following four projects are being undertaken by Center researchers at *UC Berkeley*, *Stanford* and *MIT*. The first two projects are progressing in the direction planned at the beginning of the Period 2, but the third project has changed direction based on the findings in this Period. The fourth project was recently added as a consequence of research progress made under Theme IV, to mitigate against the risk of scaled mechanical switch failure due to surface adhesion forces.

- Technologies for Nanoscale and milliVolt Relays: The goal of this project, undertaken by the group of **T.J. King Liu,** is to ascertain whether there are any fundamental limits for scaling down the operating voltage of an electro-mechanical relay. The research in Period 2 builds on a theoretical study of relay scaling for ultra-low-voltage operation that was initiated in Period 1, indicating that thin (sub-100 nm thick) structural beams are required for ultra-low-voltage relay operation. The most significant practical challenge experienced in the experimental studies of Period 2 on such structural beams is strain gradient that can undesirably either increased operating voltage or device failure. The group is investigating approaches for achieving low strain gradient including a multi-layered deposition process that was suggested by other faculty researchers during the course of regular Theme-II teleconference meetings. By the end of Period 2, it is expected that the scaling of surface adhesion force with contact dimple area, for contact dimple sizes down to below 100nm will have been verified experimentally.
- Low-Energy-Consumption NEM relays with Carbon as a Structural and Interfacial Material: The goal of this project, undertaken by the group of **H.-S. P. Wong** is to lower the operating voltage of six-terminal electro-mechanical switching devices employing double-sided actuation of a movable beam, by utilizing mechanical energy stored in the beam during an initialization operation to reduce the electrical energy needed for switching. In addition, studies on the use of a thin interfacial layer of carbon nanotubes (CNTs), graphene, or SiC are also being conducted to address the issue of stiction. Theoretical analyses made in Period 2 indicated that (i) Sub-$10k_BT$ switching energy, 300 milliVolt switching voltage, and 1ns switching delay can be achieved using a cantilever beam that has beam thickness and actuation gap thickness below 10 nm, and whose surface is coated with a material that has a low Hamaker constant; and (ii) Virtually zero voltage swing and hence virtually zero switching energy is required to switch between two states – subject to noise margin requirements – so that milli-volt switching should be attainable. With the completion of process development, fabrication of three-terminal graphene-beam switches with sub-10 nm actuation gap thickness is in progress. The performance of a NEM relay is highly sensitive to dimensional variations. Characterization of the impact of such variations and development of approaches to control variability will be initiated in this Period.
- Nanomechanical Switch Based on Electrically Actuated Tunneling Gaps: The groups of **V. Bulovic** and **J. Lang** are jointly developing micro/nano-electro-mechanical (MEMS/NEMS) switches that conduct through charge tunneling across gaps with compressible insulators as a means to reduce or even eliminate contact sticking and wear. The initial switch design employs a plurality of tunneling gaps within a nanocomposite material comprised of a polymer doped with conducting nanoparticles that upon mechanical compression, or being squeezed, by the switching behavior will be effected. During Period 2, the first fully functional device in a near-

mm-scale, exhibiting four orders of magnitude of conduction modulation was demonstrated. A scaling study showed that if this design can be scaled down to have horizontal and vertical dimensions on the order of 100 nm, and if the nanocomposite material has a mechanical modulus of 1 MPa, then it can achieve the switch performance specifications targeted by the Center. Stenciled patterning at a much smaller scale is difficult. To address this challenge, a metal-film transfer printing technique has been developed [4]. Work is underway to demonstrate a large-scale single-gap switch with with compressible insulators that operates at very low voltage.

- Nanomechanical Relays with Magnetoelectric Switching Elements: A cross-Theme project between these Theme IV faculty researchers and the Theme II team leaders, **J. Bokor** and **T.J. King** has been initiated based on a Theme IV research outcome. The Electric Field Control of Nanomagnets project identified that heterostructures of ferromagnetic in contact with $BiFeO_3$can be integrated into a functional device architecture where the multiferroic and its magnetoelectric switching can concur, leading to the concept of magnetic-switched nanomechanical devices.

- *Theme III - Nanophotonics*: Toward the goal of atto-Joule communication, Theme III researchers at *UC Berkeley*, led by **M.C. Wu** have been undertaking research in optical nano-devices, using the following approaches:
  - Miniaturization of the laser cavity reduces the power consumed by laser bias, as laser bias, which is proportional to laser volume, can waste > 10 fJ/bit.
  - A revolutionary concept, called Spontaneous Hyper Emission (SHE), involves attaching an optical antenna to a semiconductor light emitter at the nanoscale to speed up the spontaneous emission to the point that it is faster than stimulated emission. Theoretically, the speed of SHE can be in excess of 100 GHz or even approaching THz when the emitter size is in the nanoscale ($< 0.01\ (\lambda_0/2n)^3$), as speed is inversely proportional to the square of the antenna gap spacing.
    - Reduction of capacitance to an ultra-low level in nanoscale photodetectors. For optical receivers, the key is to break the energy-sensitivity trade-off; i.e. achieve sensitive receivers (fewer photons/bit) at low overall energy consumption (10 aJ/bit). If the capacitance is small enough, the optical pulse produces a signal voltage larger than kT/q=26meV, and then pre-amps can be quite efficient; $Q/C > kT/q$, where Q is the photo-charge. To achieve a capacitance of 10aF, the linear dimension of the photodetector is on the order of 100nm, much smaller than the optical diffraction limit or the absorption length. Two ways of reducing capacitance are utilized in the Theme III receiver projects: (i) Optical antennas are attached to the photodetectors to achieve high quantum efficiency, while preserving the small capacitance; and (ii) Integrating the photodetector directly with a transistor, forming a photo-transistor, can eliminate the parasitic capacitance in the interconnect wire between the photodetector and the amplifying transistor contributes to the load capacitance.

  In Period 2, the Theme III research projects have focused on the following:

  - Nano-laser: The research efforts in Nano-laser in the laboratory of **M.C. Wu** is building on the successful demonstrations of nanopatch semiconductor lasers [5] [6] and one-dimensional plasmonic crystal lasers [7] that were reported in the Period 1 report. Both lasers were optically pumped at 77K. The nanopatch laser is the smallest semiconductor laser (physical size normalized to its wavelength) in the infrared. Efforts are underway to engineering the cavity to achieve electrical injection and room temperature operation while preserving their sub-wavelength-scale dimensions by incorporating metallo-dielectrics and metal-insulator-metal cavities into the nanopatch laser designs.

- SHE Nano LED: This collaborative project between **M.C. Wu** and **E. Yablonovitch** of *UC Berkeley* has the goal to create a nanoLEDS with modulation bandwidths exceeding tens of gigahertz at room temperature. During Period 2, the fabrication process to make SHE nanoLEDs with a dimension of 20nm has been established. Significant enhancement of emission with polarization parallel to the antenna has been observed experimentally.
- High Sensitivity III-V Photodetector on CMOS: The laboratory of **C. Chang-Hasnain** has been developing a new growth technique to monolithically integrate III-V semiconductor onto silicon at CMOS compatible temperature. Such integration is intended to achieve ultra-capacitance by eliminating the interconnecting wire between the III-V and silicon devices. Previously, a low power, highly efficient GaAs nanoneedle avalanche photodetector on silicon substrate with external QE > 11,000% at -5 V bias has been demonstrated. However, the detector design made contacts to several nanoneedles at the same time, leading to higher dark current and capacitance. Significant efforts were applied in Period 2 to address this shortcoming, including the use of metal contacts that are fabricated on individual nanopillar devices by electron beam lithography. All other device processing steps involved only conventional microfabrication techniques, demonstrating how nanopillars can easily leverage existing fabrication technology. Textbook IV curves were achieved by nanopillar diodes with low turn-on voltages of ~1 V. Under reverse bias, the dark current is only ~0.3 nA at -3 V, a respectable value for a GaAs-based diode.
- Optical Antenna-Coupled Nanophotodetector: This project was added during Period 2 by **M.C. Wu** to leverage the antenna enhancement research that is being pursued for the SHE NanoLED. While there have already been several attempts to utilize optical antennas for enhancing the efficiency of normal incidence nano-photodiodes, the reported efficiency has been below 0.1% in all reported cases [8] [9] [10]. The first goal of this Theme III project is to answer is whether the quantum efficiency of such antennas is intrinsically low due to metal loss. Coupled mode theory, recently used for examining antenna enhanced Raman spectroscopy, was used to design a nanophotodiode with very high efficiency. The design study showed two important factors to achieve high efficiency nanophotodetectors: (i) Q_{abs} and Q_{rad} should be matched to achieve maximum power transfer; (ii) $Q_{semi} << Q_{metal}$ to minimize optical loss in metals. A design, the nanopatch antenna with nearly completely matched Q_{rad} and Q_{abs}, and a better field confinement in the Ge region showed better efficiency with gold, 45%. Device fabrication has begun with the goal of achieving a working prototype by the end of Period 2. Nonetheless, the major expected problem is expected to mode matching between the antenna which generally has a dipole pattern, and the laser input which is far from such a pattern.

- *Theme IV – Nanomagnetics:* Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that can approach the Landauer limit [1], or perhaps even surpass it via reversible logic [11]. Theme IV research, led by **J. Bokor** is directed towards understanding switching dynamics, communications with spin logic, novel spin materials, and basic spin logic physics. There are four projects, three of which are collaborative efforts between and among the four faculty researchers at *UC Berkeley* working in Theme IV.
  - Electric Field Control of Nanomagnets: The goal of this project that is co-led by **R. Ramesh** and **S. Salahuddin**, in collaboration with **J. Bokor**, is ultimately to control ferromagnetism by using electric fields only. Prior research [22] has shown the possibility to alter the direction of a ferromagnet magnetization in contact with the multiferroic material $BiFeO_3$ when a voltage is applied across $BiFeO_3$. The focus of Period 2 is on the synthesis of the thin films and the reduction of the voltage applied to the heterostructure. In this Period, full magnetization reversal induced solely by an electric field at room temperature has been demonstrated; i.e. the first room temperature device that is capable of writing and rewriting the state of magnetization

with the application of only an electric field and reading the state with a simple electron transport measurement has been achieved. This heretofore unreported method of magnetization reversal is a critical advancement to the field of spintronics by providing a unique pathway to writing a magnetic state without the need for an energetically costly magnetic field or large current density. Furthermore, this investigation reveals that the heterostructures of these materials can be integrated into a functional device architecture where the multiferroic and its magnetoelectric switching can be studied in detail.

- Spin Diffusion for Spin Logic: The goal of this project that is led by **S. Salahuddin**, in collaboration with **I. Siddiqi** and **J. Bokor**, all of *UC Berkeley*, is to study and understand spin diffusion as a possible means of communication for spin based logic. This possible scheme for low energy communication between two spin-based logic blocks, if successful, will be the first demonstration of energy efficiency by mitigating the impedance mismatch between logic devices and the communication link. The focus of Period 2 is to optimize the growth and characterize the magnetic multilayers that eventually can be used to inject spins into metallic channels. The fabricated structures with non-local diffusion of spins can be probed and controlled. Progress in this Period includes the design of a process flow and subsequent fabrication of non-local spin diffusion structures with 100 nm x 100 nm magnets and sub-100 nm spacing between neighboring magnets. In the remaining months of this Period, current-voltage measurements will be made.

- Time Resolved Coherent Spin Detection using Magnetometry: Measurements of their relaxation times and studies on NV centers in diamond to understand coherence properties as a function of spin density is an objective of this project that is led by **I. Siddiqi**, in collaboration with **S. Salahuddin** and **J. Bokor**. Another activity planned for Period 3 is the investigation of the dynamics associated with the switching of nanomagnets either through multiferroic coupling, or the passage of a spin-diffusion current (as pursued in the first two projects described above). The goal of this work is to determine the minimum energy needed to flip a nanomagnet and studies of the magnetization dynamics will reveal the specifics of how angular momentum is transferred in these structures. To enable the execution of these plans, the group of **I. Siddiqi** developed a dispersive nanoSQUID magnetometer with 25 $nF_0/Hz^{1/2}$ flux sensitivity, which translates into a record spin sensitivity of 0.3 $m_B/ Hz^{1/2}$ for nanomagnets placed at a distance of 100 nm. Coupling between bulk samples of diamond NV centers and niobium resonators have successfully been observed, and have extracted a spin linewidth of ~ 6 MHz for samples with varying NV density has been extracted. The measurements suggest that the spin linewidth is *not* limited by dipolar relaxation and *thus maybe improved by adjusting the implant parameters.*

- Experimental Verification of the Landauer Energy Limit: The goal for this project that is led by **J. Bokor** is to experimentally verify that a minimum of exactly kTln2 of energy is dissipated in erasure of a single nanomagnetic bit (Landauer's limit) [1]. Bennett has shown [11] that energy dissipation even below Landauer's limit, in principle, is possible for logic systems, in which no information is erased or destroyed, and thus, the logic systems are thermodynamically reversible. Both theoretical predictions are as yet to be verified experimentally. The study of the dynamics of energy dissipation in single-domain nanomagnets will lay a foundation for further development of logic devices that can be built in this technology. Nanomagnetic logic circuits consist of interconnected majority logic gates (MLGs), which compute the majority vote of three input nanomagnets and write the result to an output nanomagnet. The Landau-Lifschitz-Gilbert equation was used to numerically calculate the hysteresis loops. By calculating the relevant hysteresis loops associated with MLG operation, dissipationless operation is possible when the output is reset before the inputs was shown to be possible, although Landauer efficiency is not achieved when the inputs are reset before the output.

- *Seed Project Added in Period 2:* In the second half of this Period, the Center funded a seed project to enable **J. Wu** to extend the research on metal-insulator transition (MIT) in the correlated oxide VO_2 with a focus of finding applicability in the Center's Themes, probably Themes I and II.

Education and Diversity

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

- To train in the graduate programs of the Center's participating institutions, a new generation of Ph.D. and M.S.-level scientists and engineers who, on completion of undergraduate and graduate programs at Center universities, will
  - be facile with 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 train an engaged, skilled and diverse technical workforce by cultivating a pipeline of students from secondary school to college.
- To develop methods to retain these individuals within the E^3S research areas.

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. Accordingly, many of the Center's educational programs are also the Center's diversity programs.

The goals of the diversity programs of the Center for E^3S are to:

- increase the number of students from historically underrepresented groups in engineering who attends university and graduate programs in electrical engineering; and
- develop methods to retain these individuals within the E^3S research areas.

In its effort to develop a new generation of Ph.D. and M.S.-level scientists and engineers, the Center offers ongoing training on energy efficient electronics topics and professional development opportunities for its graduate students and postdocs; these efforts are described in the Education section of this Annual Report. Because of a strong emphasis in recruiting female and students from under-represented groups, the programs to cultivate a pipeline of students from secondary school to college are presented in the Diversity section of this Annual Report.

Training on energy efficient electronics topics is embedded in many Center activities held in Period 2.

- Annual Retreat included research presentations, an panel discussion exploring integrating research activities, and a poster session with 18 posters;
- Research Seminars series and Journal Club held a total of 17 sessions in 2011;
- Theme meetings are held regularly at a frequency ranging from biweekly to once every two months;
- Centerwide Graduate Student and Postdoc Retreat and the Spring Research Meeting between UC Berkeley and Stanford allowed the participants learned from each other.
- 2^{nd} Berkeley Symposium on Energy Efficient Electronics Systems featured 17 external speakers from around the US, Europe and Japan, complementing five Center faculty who made presentations on the Center's research.
- Center sponsored 2 talks by speakers from industry and 2 talks from other academic institutions.

Other training included:

- Ethics training that was conducted as part of the Graduate Student and Postdoc Retreat;
- A panel with two IEEE technical editors (**J. del Alamo** and **E. Alon**) who presented their perspectives as editors on "How to Published Successfully";
- Project management and mentor training for mentors in summer research programs for undergraduates and high school students; and
- "Technology Commercialization" in form of an online course, being developed by **E Fitzgerald**, a Center faculty at MIT, for offer to all members of the Center before the end of Period 2.

Leadership opportunities included:

- Organizing the Research Seminar series, the Journal Club and activities of the Graduate Student and Postdoc Council;
- Serving as coordinators of Theme Meetings; and
- Mentoring undergraduate and high school students doing research at the Center.

Three postdocs had the special experience on the selection committee for applicants to undergraduate summer research program.

To cultivate a pipeline of students at the undergraduate, the Center has established three programs.

- ETERN supports undergrad students at the member institutions to do research through the year with the Center's faculty. One MIT undergraduate has joined the laboratory of Antoniadis.
- E^3S REU program at UC Berkeley had 5 rising juniors and seniors, including 1 black female student. The students participated 8 weeks of research, each hosted by an E^3S faculty (**J. Bokor**, **T.J. King Liu**, **R. Ramesh**, **S. Salahuddin**, **M.C. Wu**) and mentored by a graduate student. In addition, the students participated in enrichment activities, including ethics training and a leadership day where the undergraduates served as mentors at a community college outreach event.
- Transfer-to-Excellence (TTE) program consists of two elements: a REU program and a cross-enrollment program. TTE is intended to inspire California community college students to ultimately transfer and complete their Bachelor's degree in science and engineering. The community college student population is the targeted phase of the pipeline for the Center, as it is a pool with many students from under-represented minority groups, student who are first generation to attend college, and students from low income families.

  In Summer 2011, the Center hosted 2 REU students (a white male and an Asian female), one from each of its two community college partners, Contra Costa College and LA Trade-Technical College. They did research hosted by two Education Affiliates of the Center (J. Wu and A.C. Arias) and mentored by their graduate students. The Center is 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. The TTE REU program ran concurrently with the REU program for juniors and seniors. The Center hosted one cross-enrollment student from Chabot College, another Bay Area community college.

  A critical element in the TTE program design is the provision of year-long support for its participants. The Center partnered with the UC Berkeley Transfer Alliance Project (TAP) to deliver academic and transfer advising to the three community college students, while they are at UC Berkeley during the summer. Upon completion of the summer programs, the three students have continued to receive transfer advising and support during following academic year. The Center has arranged for TAP to support the two Bay Area students, while the LA Trade-Tech student is being advised by the UCLA CCCP's Scholars Program. This Fall, all three students are applying to science and engineering baccalaureate programs; one of the three students has been accepted by UC Davis.

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

- UC Berkeley's Summer High-School Apprenticeship Program (SHARP);
- MIT's Saturday Engineering Enrichment and Discovery Academy (SEED);
- 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, where the goals of these programs are to: 1) increase the awareness of engineering and other technical fields as an exciting and rewarding career path to a diverse population, and 2) increase the diversity of students who apply to, enroll, and graduate from undergraduate programs in engineering and applied science. In particular, 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 generation of scientists, engineers, and technicians that will reflect the diversity of the US society.

The E^3S impact on SHARP in Period 2 included funding of 6 students, successfully completed the research program in an E^3S faculty member's research group (**C. Chang-Hasnain**, **R. Ramesh**, **S. Salahuddin** and **E. Yablonovitch**), and mentor training by **S. Artis**, the Center's Education and Outreach Director.

The E^3S impact on the three MIT programs includes funding to establish energy efficient topics in the electronics course, funding to enable the courses to be offered, and involvement of the E^3S faculty (**D. Antoniadis** and **V. Bulovic**) and students of the Center at MIT.

Recruitment for the Center's diversity programs was initiated this Fall. **S. Artis** attended 5 diversity and graduate fair conferences and conducted graduate preparation workshops and information sessions at 10 universities. She also conducted a workshop on college success in engineering, covering topics such as time management, study skills, test-taking skills, and career planning to undergraduate students in UC Berkeley's Pre-Engineering Program (PREP). One outreach event to publicize the TTE program to California community college students took place in Summer 2011, to be followed by four additional events (two in Los Angeles and two in the Bay Area) that are planned for December and January.

Knowledge Transfer

Knowledge transfer goals of the Center for E^3S are to establish industry/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. Cross-fertilization would go in both directions. Knowledge transfer is envisioned to be through the following channels:

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

Being a new Center, the initial emphasis in Knowledge Transfer is to establish the recognition of the Center among the industrial, research and educational stakeholders in the electronics field. This recognition starts with dissemination of information on the Center's activities and receiving input from others outside the Center who are engaged or are interested in synergistic activities. The first venue is the Center's website, www.e3s-center.org, where the traffic of new visitors was 6,123 for the first 10 months in Period 2. The Center's Industrial Research Board with representatives from four leading companies in the semiconductor industry is an important element in the Center's two way knowledge transfer approach.

Moreover, the Center and/or its members held, sponsored or participated in the following events:

- 2nd Berkeley Symposium on Energy Efficient Electronics Systems, a symposium organized by the Center with 5 speakers from the Center, 17 external speakers, and ~130 attendees from the US, Europe and Japan;
- E^3S Annual Meeting attended by 6 representatives of industrial partners;
- Meeting with Delegation of Deans from Taiwan, attended by representatives of 12 Taiwan universities;
- Two seminars by the Center's industry partners; one as part of a departmental seminar series and another as part of the Center research seminar series; and
- Two seminars by academics on synergistic research topics.

Knowledge transfer to a broader audience can occur through press coverage. There were three internet articles providing information on the 2nd Berkeley Symposium on Energy Efficient Electronic Systems.

By the end of Period 2, training in the process of Technology Commercialization for the Center's members, faculty, students and postdocs is expected be available via an online course that is currently in development by **E. Fitzgerald**; previously discussed in the summary section on Education and Diversity.

External Partnerships

A strategy of partnerships is one of the underpinnings of the Center. Even before its inception, industry partnerships were formed, and now they form the cornerstone in the execution of the E3S' two-way knowledge transfer strategy. The Center has also established agreements to collaborate on research with groups around the world. The education and diversity plans in the proposal also calls for leveraging established programs to impact targeted student populations. In its first full year of operation, the key goal for the Center was to execute its partnership strategy, so that it could deliver the programs and activities in its plans. In Period 2, the Center's key partnership activities are as follows:

- Industrial Partnerships: Foremost in the Center's knowledge transfer goals is, as noted above, to use these industrial partnerships to make certain that the Center's academic technical directions will be practical, and lead to real successes. The next level is commitment of parallel research, and then, the eventual assignment of staff from the corporate partner companies to be resident at the Center.

  - Research partnership was secured in Period 2: Nanophotodetectors research collaboration between Hai-Feng Liu, Intel Research Labs and M.C. Wu, Theme III Leader
  - Advisory relationships have continued: Industry Research Board with representatives of Hewlett Packard, IBM, Intel, Lam

  In addition, the 2nd Berkeley Symposium on Energy Efficient Electronics Systems also served as a venue for relationship building with the corporate partners.

  - Lam Research was a co-sponsor and sent two attendees to the event.
  - IBM was a co-sponsor and three employees attended, including two speakers.

- George Thompson of Intel was on the Organizing Committee, and 3 employees attended. .

- Other Research Partnerships
  - New partnerships with research groups have been established to address the Center's needs for simulation tools and epitaxial materials in Theme I: Purdue University, Army Research Lab, U of New Mexico, and Technical University of Munich
  - Other research partnerships are in discussion to provide assistance to Theme I and Theme IV projects: Texas Tech University and UC Santa Barbara
  - F. Giustino, Oxford University, an international research partner, gave a seminar on his research inn Band-Edge Theory
  - 2nd Berkeley Symposium on Energy Efficient Electronics Systems, organized by the Center, had participation from Switzerland and Japan on the Organizing Committee as well as 2 speakers from Europe and 3 speakers from Japan.
- Education and Diversity Partnerships:
  - MIT's Office of Engineering Outreach Programs (OEOP) and the MIT Summer Research Program (MSRP) are the Center's partners in delivering pre-college and undergraduate programs at MIT.
  - UC Berkeley:
    - Berkeley Nanoscience and Nanoengineering Institute (BNNI), the host organization of the SHARP program, a pre-college program that the Center is leveraging to impact high school students in the Bay Area
    - Center of Integrated Nanomechanical Systems (COINS): The Education Director of this NSF-funded NSEC, M. Erol, was instrumental in helping the Center start during the startup phase of the Center's REU program.
    - Transfer Alliance Project (TAP) provides academic and transfer advising to the community college participants of the Center's Transfer-to-Excellence (TTE) program.
  - UCLA: Center for Community College Partnerships (CCCP)'s Scholars Program is providing transfer advising support to 1 TTE student who is based in Los Angeles.

Center Management

At the core of Center's management philosophy is the establishment of a culture in the Center that transcends physical and institutional boundaries. The Center's leadership team is dedicated to inspiring and leading the Center for E^3S based on the following values:

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

The Center's leadership is the Executive Committee that has the responsibility to enable the Center's culture. In Period 2, the Executive Committee established a governance structure that includes a set of by-laws, scheduled meetings with agendas and meeting minutes, code of conduct and annual proposal process.

The Center's communication has been facilitated by the following:

- The Center's website with public pages and an intranet for collaboration

- Centerwide Annual Retreat where the 2011 meeting theme was "Building an Integrated and Collaborative Center"
- Graduate Students and Postdocs Retreat
- Regular Research Seminars and Journal Club meetings
- Regular Theme Meetings

Annual feedback and input to the Executive Committee are in two forms: an annual survey of students and postdocs, completed in August 2011, and the data shared at the Annual Retreat; and an annual survey of the faculty researchers that is in progress, to be completed by the end of December.

The Center has two advisory bodies.

- External Advisory Board: Six of its seven members convened for the 1st annual meeting in November 2011 and subsequently provided a written evaluation of the Center
- Industry Research Board: Representatives of all four companies (Hewlett Packard, IBM, Intel and Lam Research) attended the Annual Retreat. The representatives of three companies held a meeting with the Executive Committee and provided verbal feedback and advice. The fourth company's representative sent written feedback.

Center Output

Publications		
	Peer Reviewed Publications	19
	Accepted/Submitted for Publication	5
	Non-Peer Reviewed (Invited) Publications	4
Conference Presentations		22
Other Dissemination Activities – Invited Talks		20
Awards and Honors		20
Ph.D. and M.S. Graduates		3
Postdoc Alumnus		1
Patents Disclosures		1

PLANS FOR PERIOD 3

The Center for E^3S will mainly continue in the research and programmatic directions that were initiated at its inception.

The number of Research faculty in Period 3 will increase to 23, an increase of 3 as compared to the start of the Center. The Research portfolio will continue to have the four Themes and the System Integration efforts.

- The System Integration research's principal goal 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. In Period 3, the collaborative efforts will mainly be focused on Themes I, II and III.

- In Theme I, the scientific elucidation of energy level sharpness, seen in transport, will continue to be a very fundamental project goal of this Theme. In Period 3, the Theme I research team at UC Berkeley and MIT are on track to answer the question: how sharp can an energy level, or a band-edge, be at room temperature for Type III InAs/GaSb devices, as accurate measurements of band edge sharpness in electronic transport in will be undertaken. The XOI platform is expected to expand to Type III layered chalcogenides as a novel channel material for future TFET devices, as the fundamental materials properties as well as the properties of resulting devices of these novel material systems are studied, and the method to transfer these materials is developed. Another key goal in Period 3 is that a MOCVD growth capability that will produce GaSb/InAs heterostructures be established to supply epitaxial materials for use by a number of Theme I co-PI's in the Center. Period 3 will have two projects that are not based on Density of States TFET's. A new project based on new concept for steep-slope nanowire FETs with a superlattice source (SLS) to create a miniband structure will be initiated, while the research on a negative capacitance FET will continue.
- The research goals for Theme II will continue to be voltage and size reduction, and reliability improvement, for nanomechanical switches. The projects at UC Berkeley and Stanford will be a continuation of those that were in progress in Period 2. At MIT, additional effort will be applied toward the development of single tunneling gap technology with the addition of a new faculty from the Chemistry Department, **T. Swager,** whose expertise is in surface chemical functionalization. The gap size will be actuated electromechanically and stood off with a mechanical spring formed by attaching sparsely spaced insulating organic molecules between the two surfaces in the form of a self-assembled monolayer (SAM). The project to investigate magnetoelectrically actuated mechanical switches will be a close collaboration between Theme II and Theme IV researchers during Period 3. Close collaborations with System Integration team to identify and explore compelling applications for zero-leakage switch technology with device performance and endurance requirements projected to be attainable with nanomechanical switches will ensure that these projects are relevant to future energy efficient electronic systems.
- Towards the ultimate goal of atta-joule communication, Theme III will continue to pursue the two projects on sources (nanolaser and nanoLED) and two projects on receivers. The underlying research efforts include the development of processes for nanofabrication and metrology techniques for characterizing nano-devices. The goal of the nanolaser project will continue to be electrical pumping and room temperature operation, while the challenge in the nanoLED project will be integrating nanoscale semiconductors with optical antennas while preserving the high optoelectronic quality of the semiconductors. For photodectectors, one primary focus is the understanding of the tradeoff in lowering the capacitance and having high sensitivity. Research in collaboration with the System Integration team will investigate from the receiver circuit level the energy consumption as a factor of these two variables to find an optimization point. Research on direct integration of photodetectors on silicon will continue to be an emphasis.
- All four Theme IV projects and the newly initiated collaborative project with Theme II will continue in Period 3. A key goal in Period 3 for the Electric Field Control of Nanomagnets project will be the development of theoretical simulations to validate and optimize a device structure, and the design of test structures to validate the fundamental principle of the device. To investigate spin diffusion for spin logic, the Period 3 focus is to optimize and fabricate working non-local device structures. For the Time Resolved Coherent Spin Detection using Magnetometry project, the team will undertake two basic experiments: (i) observation of spin dynamics in metallic spin diffusion magnetic switches; and (ii) the development of semiconductor spin ensemble memories/logic. The fundamental goal is to reduce the ensemble spin linewidth below 1 MHz so that a long-lived memory can be realized. Experimental verification of the Landauer Energy Limit will continue by measuring hysteresis loops when the magnetic fields are applied in a specific sequence.

Experimental studies that test the results of our simulations will use a magneto-optic Kerr effect (MOKE) apparatus with a quadrupole electromagnet to apply a DC magnetic field in the plane of the surface of a sample with arbitrary angular orientation of the field within the plane. The MOKE apparatus will also be used in the newly initiated collaborative project with Theme II.

- The seed project based on Metal-Insulator Transition in VO_2 is expected to develop new collaborations amongst researchers of the Center's Themes and become an integral member of the applicable Themes. Collaborations with the negative capacitance project in Theme I and with nanomechanics in Theme II will be explored.

In Period 3, the Center will continue to refine and formalize the processes and implementation of existing internal education programs. The Center is considering creating a formal agreement for all graduate students and postdocs funded by the Center. This agreement would require Center members to commit a small number of hours to educational and diversity programs. The Center would like to offer additional professional development opportunities in Period 3. Another area of focus for the Center will be to enhance the partnership with Tuskegee University and other Minority Serving Institutions (MSIs). E^3S will introduce the E^3S Rotation Program to provide the current graduate student at Tuskegee the opportunity to come to UC Berkeley to conduct research and collaborate with Center members. In Period 3, the Center will put additional efforts to develop external education activities for the general public. The Center plans to design a hands-on demonstration that can engage and educate the general public about the importance of designing energy efficient electronics devices and need for more scientists and engineers to pursue career opportunities this field.

The Center has made substantial progress in establishing and executing its plans that hopefully, in time, will enable broader participation in the Center. In Period 3, the Center's main focus will be to sustain and optimize these programs as they go into their second year. In addition, the Center will selectively add new programs and/or expand the capacity of established programs. The REU program for juniors and seniors will be expanded to a nine-week program, an increase of one week, in response to feedback from both the students and the mentors. To enable the pipeline of REU students for future years to include a large percentage of students from underrepresented groups, we will introduce the E^3S Research Workshop for freshmen and sophomores pursuing a Bachelor's degree in science and engineering with a focus on students at MSIs in Period 3. The Center will establish a Research Experience for Teachers (RET) program for four community college teachers to participate in a 6- to 8-week RET.

In Period 3, the Center's emphasis on knowledge transfer to industry will continue. Partnerships with industry will continue to be the key strategy. For the existing industry partners, a key focus in Period 3 is that the Theme III team will sustain and enhance the new parallel research engagement that has been achieved with Intel Research Labs. Additional research collaboration will be sought with the existing corporate partners. We will also begin to engage these corporate partners to offer internship positions and mentoring for the students in the Center and students from our community college partners. Another emphasis will be to expand the Center's industry partnership to include additional companies.

Another area of emphasis in knowledge transfer is disseminating research results to the general public. As previously mentioned under external education, in Period 3, the Center will focus on increasing public awareness of the Center's research through hands-on demonstrations and online multimedia communications.

CONCLUSION

The Context Statement section serves as an Executive Summary of this report. Details of the Center and its various research projects and programmatic efforts can be found in the following sections of this report.

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, even 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, which would allow switches with a swing of only few milli-volts.
- On/Off current ratio: 10^6:1;
- Current Density or Conductance Density (for miniaturization): 1 milli-mho/μm; i.e. a 1μm device should conduct at ~1 kΩ in the on-state. This requirement is often given as milli-Amps/μm, but that pre-judges an operating Voltage of 1Volt. Since voltage and current scale together according the impedance of the chip interconnects, it makes more sense to speak of milli-mho/μm conductance, at lower voltages.

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 (~10 aJ/bit), when including the receiver system.

For Nanomagnetics, the Center's most futuristic Theme, the goal is to achieve device that will operate as close as possible to the fundamental limit of energy dissipation of kTln2 that Landauer has predicted theoretically [1].

While these high level goals and objectives serve as a technical vision, the Center also is continuing to define more detailed technical requirements 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. Thus, more information of the Center's technical goals and objectives can be found in the description of the System Integration research; see Section *II.2ai*.

1b. *Performance Metrics*

Objective	Metrics	Frequency
Integrative Research	Multi-PI Projects	Yearly
	Multi-Institutional Projects	Yearly
	Unplanned research projects	Yearly after Period 2
	Publications with authors from multiple institutions	Yearly beginning in Period 2

In Period 2, a new indicator was added to assess multi-institutional collaboration in the Center's research themes.

Objective	Metrics	Frequency
Integrative Research	Multi-Institutional Themes	Yearly

1c. Problems Encountered

While the section reports on the problems being encountered by the researchers of the Center during Period 2, it must be recognized that the situations identified below mainly fall into the following categories: i) unplanned problems associated with being a new Center; ii) known gaps in capabilities and planned efforts to address the gaps are in progress; iii) projects that have major changed in direction due to the findings in Period 2; and iv) challenges with unanticipated level of difficulty encountered in research projects that will require additional time to resolve.

Center: The Period 1 report indicated delays in start of the Center across all subaward institutions. These delays were resolved before the end of Period 1. Since the end of January, all cooperative agreements have been in place to enable the research teams in the subaward institutions to start and make progress on their research.

Tuskegee: The research program at Tuskegee has made relatively less progress. Efforts to define a research project that would utilize the materials science skills of the Tuskegee team were not completed until the early months of Period 2. To help broaden his skills, the Center provided funding to the Tuskegee Material Science graduate student researcher to attend a weeklong summer course in Electronic Devices and Materials at Purdue University; see Section *III.2b*. The Center also worked with Tuskegee's Vice President, Research and Sponsored Programs and Director, Center for advanced Materials, S. Jeelani to expand the Tuskegee team to add K. Das, Associate Professor of Electrical Engineering to the Tuskegee research team. To enable a team with a critical mass, the Center doubled the budget for research at Tuskegee during Period 2.

UC Berkeley: The relocation of process equipment to a new cleanroom research facility (Marvell Nanofabrication Laboratory, Nanolab) resulted in delays in device fabrication that impact Themes I and III researchers. Setbacks have included equipment down time and large process variation. In particular, the equipment/process issues resulted in Si/Ge TFET device yield having been relatively low (<50%) and large variation (>100%) from device to device has been observed, impeding the ability to draw any definitive conclusions from the experimental results; see project at the end of Section *II.2aii*. Low yield and difficulties in reproducibility have also been encountered in the fabrication of optical devices; see projects in Section *II.2aiv*. While in time the operations in the relatively new Nanolab will improve, the Berkeley researchers also recognized that a general-use University cleanroom will never be as tightly controlled as a large scale semiconductor fabrication facility. This leaves an additional challenge for researchers who are working on precision structures to include the process flow simplification and streamlining as part of their research endeavors. Fast prototyping to quickly learn and address unique fabrication challenges is important. Incorporation of self-alignment fabrication methodologies will also enable a more resilient fabrication flow.

Theme I:

- One differentiation of this Theme is the emphasis of Type III bandgap devices. To date, the only known Type III example is the p-GaSb/n-InAs heterostructure system. One difficulty is that there are few sources of high-quality InAs/GaSb epitaxial material. In the near-term, Theme I researchers are collaborating with two groups in the growth of the epilayers that are needed for device fabrication. The MIT Theme I researchers have established a relationship with B. Bennett at the Army Research Laboratory for materials growth, and they will work to maintain this collaborative effort for materials growth. At UC Berkeley, the Theme I researchers have developed a relationship with S. Krishna of the Center for High Technology Materials of the University of New Mexico and the group of M.-C. Amann of the Technical University of Munich. In the longer term, the Center is establishing an internal epitaxial deposition capability using MOCVD in the group of E. Fitzgerald at MIT, a deposition method for GaSb/InAs epilayers that is an alternative to the MBE method used by both external collaborators. In Period 2, the Fitzgerald group constructed a unique MOCVD system capable of depositing III-V's, IV's and some oxides and nitrides, thus creating a unique capability for forming traditional systems of interest, experimenting with alternative growth conditions to study material properties, as well as for exploring novel heterovalent interfaces; see details Section *II.2aii*. The ramp of the internal epitaxial growth capability is continuing, as the graduate student researcher, now in his second year, is gaining expertise in material growth.

- Project at the end of Section *II.2aii:* Even though the key focus is TFET's with Type III bandgap alignment, the Theme I research portfolio also includes research in alternative device structure and materials composition. One such research project investigates the feasibility of Super-Steep Sub-Threshold Devices Based on Impact Ionization in Narrow Bandgap Material, led by J. del Alamo of MIT. During Period 2, In spite of the observation of impact ionization in the devices that were studied, the subthreshold characteristics of these devices did not show any sign of enhanced steepness at any temperature or any V_{DS}. Upon analysis, it was recognized that the observation is related to the fundamental properties of narrow bandgap materials, and thus, this project was terminated by del Alamo in the middle of Period 2.

Theme II:

- 1st project in Section *II.2aiii:* Scaling is one key approach to reducing operating voltage in solid state relays. While simulation studies shows that miniaturization of the actuation gap to nanometer width will allow reduction of the operating voltage to less than 10mV, the Theme II researchers under T.J. King Liu at UC Berkeley learned that the significant technical challenge to achieve experimental realization of nanometer sized gaps. The strain gradient in structural thin films has proven to be a major challenge for controlling the size of the actuation gap of electrostatic relays. Various approaches (including multi-layered deposition processes, amorphous structural materials) are being pursued to solve this key issue for realizing mV relay operation
- 2nd project in Section *II.2aiii*: Another Theme II research focus addresses the reliability of solid state relays. The approach, being pursued in the group of H.-S. P. Wong of Stanford, is the use of carbon and SiC contacting interfacial layers. The deposition capability of these materials continues to be lacking in the Center in Period 2. Construction of a graphene CVD deposition tool that began in Period 1is expected to be fully operational until the end of end 2011. In addition, we are ramping up activities on the use of carbon nanotube as the contacting interfacial material. This will involve the development of suitable carbon nanotube synthesis and transfer methods that are compatible with NEM relay fabrication. Plans are being developed and preliminary discussions have been initiated to explore collaboration with a university partner on the use of SiC as the interfacial materials.
- 3rd Project in Section *II.2aiii:* Exploring alternative actuation schemes is part of Theme II's research portfolio. The Center's proposal to NSF included the concept of the "squitch" that would use a squeezable nanocomposite material in the actuation gap. Research results from the groups of Vladimir Bulovic and Jeffrey Lang of MIT indicated that the scheme, as originally designed must be fabricated on a vertical and horizontal size scale of 100 nm to 1 μm in order to meet the low-loss and low-actuation-voltage switching metrics targeted by the Center. While the MIT groups devised a fabrication plan for devices on that size scale, there were several elements in that plan, upon careful analysis, will be extremely challenging to achieve on size

scales below one hundred microns. In summary, while the “squitch” behaves as expected and desired at larger size scales, its fabrication at the small size scales required to meet the metrics of the Center appears problematic. In response, we made a major change in the approach to making a new MEMS/NEMS switch design that is planar, and has a single tunneling gap between two metal surfaces.

Theme III:

- 2nd project in Section *II.2aiv*: The ability to characterize the performance of nano-scaled optical devices is a fundamental capability the Center must have to make rapid progress in Theme III. Availability of ultra-sensitive detectors has also restricted the ability to obtain time-resolved measurements. Although indirect measurements are capable of determining rate enhancement from nanoLEDs, these measurements are relative measurements and incapable of giving the absolute value of modulation rates possible. Through collaborations and new equipment we hope to solve this problem in the near future.
- 3rd project in Section *II.2aiv*: Electrical isolation of the p-i-n junction of a photodetector from the Si substrate is a continuing challenge. Without proper isolation, leakage current was high, resulting in poor diode ideality and high dark current. After employing the proper etching techniques to break off leakage paths, this difficulty was overcome and nearly ideal (n=2) diodes have been fabricated with extremely low dark current (0.3 nA at -3 V bias). The major remaining challenge will be to demonstrate low capacitance and thus low power operation of the nanopillar photodetectors. Addressing this challenge will involve developing expertise for proper characterization, electrical design and optimization, and fabrication process development. We believe we have the proper equipment for characterizing low capacitance, so this is not expected to be a bottleneck. Electrical design of our detectors is being refined using commercial software packages to simulate the electrical performance of our devices. Regarding fabrication, we intend to fabricate top contacts for both p- and n-contacts in order to lower capacitance and demonstrate high speed operation.

Theme IV: 2nd Project in Section *II.2av*: There were many challenges in the diamond metrology system, where we had to develop a new cryogenic microwave setup that would operate between 2-4 GHz. This is not traditionally the frequency range where most of qubit measurements are made and we had to order new circulators and other passive components as well as redesign our cryopackage. We also had to develop a colder cryostat capable of reaching 10mK to ensure that the ground state of diamond was exclusively populated. Nevertheless, we still experienced a reduction in Q value when the diamond sample was placed on the superconducting resonator. In the future, we will perform lithography directly on a doped diamond substrate. With the Bi work, we attempted several times to observe an avoided crossing but were unable to. We are not sure if the activation fraction of the Bi implants is high enough to allow strong collective coupling. We are working with our collaborators to combine bulk ESR measurements and potentially even pulsed ESR measurements to confirm that the spins are active and then measure them in our setup. This work involves tuning the implantation and annealing recipes. We anticipated that obtaining diamond samples would be an issue. We have discussed collaboration with D. Awschalom at UC Santa Barbara, who can grow thin diamond films to mitigate this problem.

2a. *Research Thrusts in Period 2*

The work of the Center for E^3S is initially organized into four distinct themes:

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

The most challenging aspect of electronic energy efficiency is internal communication in processors. Indeed the main function of the electronic switch is to drive signal currents and voltages along the internal wire interconnects. Themes I, II and IV each pursue 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 systems integration research, whose 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.

Period 2 started with 19 faculty researchers at four institutions. They are:

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

Together, they bring electrical engineering, material science and physics expertise to the Center.

During Period 2, the Center provided six months of seed funding to UC Berkeley faculty researcher, J. Wu, whose biographical information is given in **Appendix A**. Different Themes in the Center potentially benefit from the outcome of this seed project. The discussion of this seed project is reported in its only subsection for Periods 2 and 3. However, as collaborations with other Center faculty develop in Period 3, it is expected that J. Wu will be integrated into one or more Themes. K. Das of Tuskegee was added in Fall 2011 to accelerate Tuskegee's Theme I effort; see biographical information in **Appendix A**. During Period 3, T. Swager will join the MIT project in Theme II to provide expertise in surface chemical functionalization; see biographical information in **Appendix A**.

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	Systems Integration	Theme I	Theme II	Theme III	Theme IV
UC Berkeley	Alon	*x*	*x*	*x*	*x*	
	Bokor			*x*		*x*
	Chang-Hasnain				*x*	
	Hu		*x*			
	Javey		*x*			
	King Liu	*x*	*x*	*x*		
	Ramesh					*x*
	Salahuddin	*x*	*x*			*x*
	Siddiqi					*x*
	M.C. Wu	*x*			*x*	
	Yablonovitch		*x*		*x*	
MIT	Antoniadis		*x*			
	Bulovic			*x*		
	Del Alamo		*x*			
	Fitzgerald		*x*			
	Hoyt		*x*			

	Lang		*x*
Stanford	Wong		*x*
Tuskegee	Rangari	*x*	

Additions – Period 2			
UC Berkeley	J. Wu		*Seed Funding*
Tuskegee	Das	*x*	

Addition – Period 3			
MIT	Swager		*x*

The Center's four research Themes and the System Integration effort are made up of multiple projects to address different aspects and utilize different approaches that will help the Center make progress toward its goals. The faculty researchers are taking advantage of the collaborative environment offered by the Center. The following discussions of the Center's research program in Period 2 (Section *2a*) will show that some projects are collaborative efforts among faculty researchers. Moreover, three out of the four Themes have regular Theme meetings that include the faculty and their graduate student and postdoc researchers. These meetings have been used to share project status, receive input and provide input among the project teams, and coordinate and brainstorm within a Theme. The schedules for these Theme meetings have ranged from biweekly to once every two months. A clear example of team science in action at the Center is the brainstorming at a Theme I meeting led to an unplanned project in Layered Chalcogenides for Monolayer Semiconductors; see Section *II.2aii*. In additional, the matter of Integrative Research has been on the agenda of the Center's Executive Committee and the 2011 Annual Retreat, with a theme of "Building an Integrated and Collaborative Center", dedicated time for a panel to openly explore ways extract more value from the Center through integrative research; see Section *VII.2*. In Period 2, the on-going discussions among the Theme Leaders in search of synergies have resulted in a timely realization of an unplanned cross-Theme project, between Themes II and IV, based on a research outcome of a Theme IV project; see Section *II.2aiii*.

An informal survey of its faculty was undertaken to determine the value of being associated with the Center. Most responses expressed appreciation of the ability to collaborate with others who have different expertise and disciplinary perspectives. The Theme II faculty researchers from electrical engineering and material science disciplines have expressed that sharing of ideas with multidisciplinary perspectives have directly accelerated the progress of their projects. Theme III researchers, all electrical engineers, particularly appreciate the multidisciplinary collaboration among system/circuit, scientific foundation, materials and device design. Similarly, in Theme IV, the Center enabled complimentary skills of lithography, materials and ultra-sensitive metrology, and device and simulation expertise to work together. Even within Theme I where the groups are mainly electrical engineers with a history of TFET research, the faculty members have shared that E. Yablonovitch has driven the appreciation some of the important scientific questions associated with TFETs. This has enabled a collaborative focus towards TFET structures with Density of States switching mechanism and a direct bandgap InAs/GaSb material system. Though variations in device design exist among the groups, timely sharing of information about processing procedures, material choices, and design ideas among the groups working in Theme I, and early critical input that identified weaknesses and concerns are viewed positively.

2ai. System Integration Research

Detailed specification of the research goals of the Center is itself an ongoing research effort. **E. Alon** of *UC Berkeley* is working with the four Themes to elucidate circuit- and system-level requirements for new switching device technologies, to guide the science and technology research needed to realize the devices themselves. This circuit/system-level design specification effort will initially focus on the devices from Themes I, II, and III because they are currently more mature or well-understood as compared with the devices from Theme IV. Furthermore, the tolerable levels of device performance variability (and insight into how this variability affects energy efficiency) will be derived based on the characteristics of circuits implemented using the devices being explored in Themes I and II.

In Period 2, these high-level goals were pursed through the following specific activities:

- Development of an analytical framework that not only quantifies the I_{on}/I_{off} requirements of new switching devices for digital logic applications, but that can be extended to quantify the variability requirements as well.
- Collection of models and/or predictive data for the alternative switches in order to numerically assess their potential benefits. This data will be utilized to construct energy-performance curves for each of the new devices, and will be continuously updated as the understanding (and hence accuracy) of the device models improves. Furthermore, we will carry out an exploration of circuit topologies optimized for the specific device characteristics in order to ensure that each device is utilized (and hence evaluated) in the most optimal manner. Specifically, significant work in this context on circuits for relay-based digital logic has already been carried out in collaboration with **T.J. King Liu** of *UC Berkeley,* leader of Theme II, beginning in Period 1. Collaboration with **S. Salahuddin** of *UC Berkeley* to explore the circuit and energy-performance implications of the polarization-switching delay in Ferroelectric FETs was initiated during Period 2 (see Section *II.2aii* for information about Ferroelectric FETs).
- Study of optimized low-energy communication links based on nanophotonic devices, in collaboration with **M.C. Wu** of *UC Berkeley,* leader of Theme III. This objective, which was added in the middle of Period 2, will be used to ascertain the impact of nanophotonic device characteristics on the overall energy and performance of the optical interconnect. Furthermore, this study provides an opportunity to explore non-digital logic applications of the devices from Themes I and II. Specifically, although initial devices with low I_{on}/I_{off} may not be immediately applicable to digital logic, they may still offer advantages over CMOS as analog pre-amplifiers within a photonic link due to the local steepness of their I-V curves.

Accomplishments to date in Period 2 are:

- An analytical approach for establishing the I_{on}/I_{off} requirements for any new switching device was completed. This works extends upon previous results by utilizing a fully analytical and general framework (rather than approximate approaches based on specific CMOS device characteristics) that enables conclusions to be drawn for non-CMOS switches with arbitrary control voltage versus output current characteristics. The study concluded that:
  - On/Off current ratio required: 10^6:1;
  - Current Density or Conductance Density (for miniaturization): 1 milli-mho/μm; i.e. a 1μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in milli-mho/μm conductance to reflect the Center's target is at operating voltage that is significantly less than the 1 volt that is typically assumed in the traditional unit of milli-Amps/μm.)
  - In order to optimize the energy-delay tradeoff, the I_{on}/I_{off} requirements of a generic switching

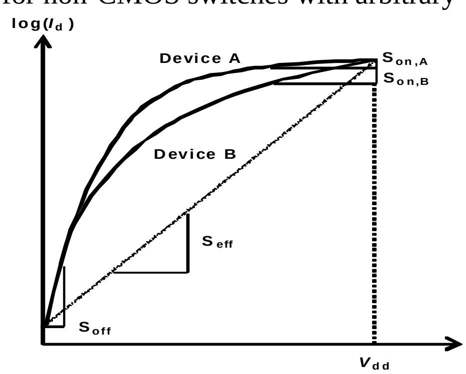


Figure 1: Comparison of two devices and definition of various subthreshold slopes (S_{on}, S_{of}f, and S_{eff})

device are set only by circuit-level parameters (logic depth, activity factor, and fanout) and three subthreshold slopes: S_{on} (the local slope in the on state), S_{off} (the local slope in the off state), and S_{eff} (the overall effective slope for a given supply voltage). See **Figure 1.**

- The entire optimal energy versus delay tradeoff curves for digital logic based on a generic new switching device can be predicted very well by utilizing the local subthreshold slopes at a single given design point. See **Figure 2**.

These results have been accepted for publication in the IEEE Transactions on Electron Devices. See Section *VIII.1ai*.

- A preliminary analysis of the impact of device variability on the energy versus performance tradeoffs of steep devices has been completed. In particular, the analysis showed that:
  - A steep switch needs threshold variability level that is proportional to the steepness of its threshold slope. If this constraint is not met, then for the same variability as a CMOS transistor, the steep device could actually have worse effective I_{on}/I_{off} (i.e., S_{eff}) due to the sharp increase in average leakage from the devices with (randomly) lower threshold. It is therefore important to consider and quantify device variability mechanisms in advance. See **Figure 3**.

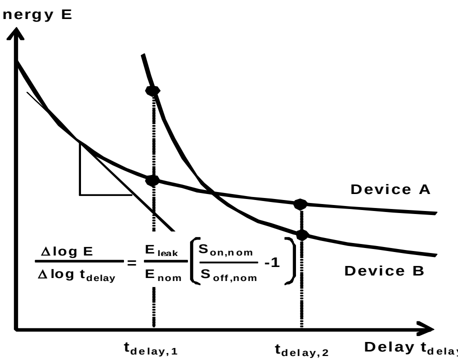


Figure 2: Device energy-delay curve prediction based upon local subthreshold slopes

- Building on an initial analysis of M.C. Wu, a preliminary analysis and design optimization of low-energy photonic links has been completed, enabling predictions of optimal energy per bit and throughput given device characteristics such as a photodetector capacitance. The analysis framework also enables preliminary quantification of the benefits provided by utilizing steep switching devices within the receiver amplification circuitry. The preliminary findings are:
  - Optimization of a photonic link must take into account two key tradeoffs: (i) number of photons versus receiver sensitivity; and (ii) amortizing the overhead of the transmitter over the bandwidth of the receiver. See **Figure 4**.
  - If a steep switching device has lower unity current-gain frequency (f_T) but better steepness than CMOS transistors, it will only provide energy-efficiency benefits over a certain range of link bandwidths. See **Figure 5**.

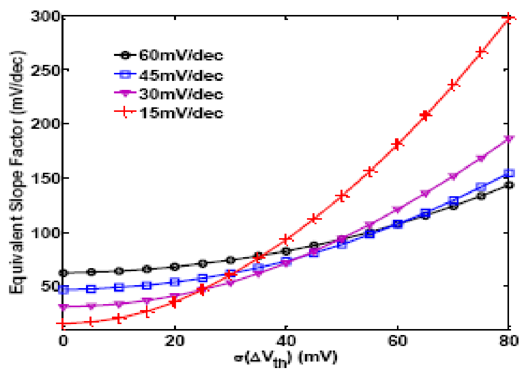


Figure 3: Effective subthreshold slope (S_{eff}) including the effective of threshold variability for various nominal sub-threshold slopes

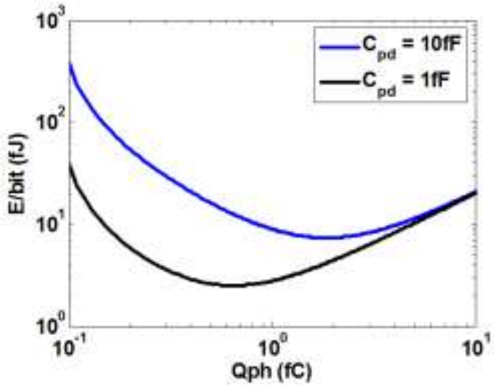


Figure 4: Photonic link optimal energy/bit as a function of photodetector parasitic capacitance

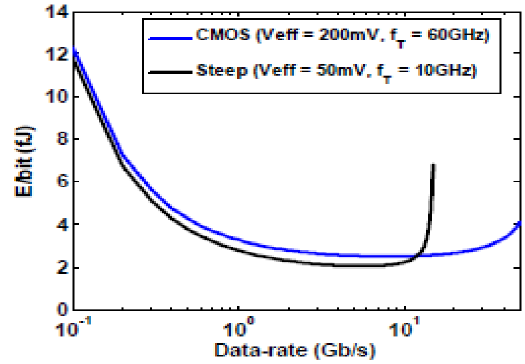


Figure 5: Photonic link optimal energy/bit as a function of data-rate for a CMOS pre-amplifier vs. a hypothetical steep switching device.

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

In Theme I, the approach is to continue to use a solid-state switch, but to alter the switching principle, so that it can operate at a drastically lower voltage than 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. Tunneling Field Effect Transistors (TFET's) have the potential to be a more sensitive switch, responding more steeply than kT/q, or 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 and experiment faring far worse [12]. While there have been reports of steeper subthreshold current versus voltage slope, or reports of good On/Off current ratio, or good tunnel conductance, the goal of achieving all three simultaneously, as spelled out in Research Goals and Objectives (Section *II*), has been especially 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 Theme I Research team believes that a different mechanism, "Density of States" switching has the potential to achieve all three requirements simultaneously. But that would require a scientific understanding of the sharpness of the density of states of the band edges. It is believed that the band-edge fuzziness arises from phonon lattice distortions operating through deformation potentials. Until now most simulations assume infinitely sharp bands and consequently over-estimate the performance.

This mechanism has existed since the days of "Backward Diodes" [13], but has been little studied. Type III band alignment, as in the lattice-matched p-GaSb/n-InAs heterostructure system allows a very thin tunnel barrier for good on-state current at milli-Volt threshold voltages [14]. The n-InAs layer can be quantum well thin, allowing good gate modulation efficiency in the 2d electron gas. Indeed the n-type layer is likely to be so thin that lattice mismatch would be acceptable, permitting a much wider choice of material combinations.

InAs/GaSb has attributes that make it ideal for research and for determining fundamental principles. Many scientific problems can be investigated in this system, including the issues of: i) quantum level repulsion; ii) contact broadening; iii) Coulomb Blockade energy shifts/broadening, and iv) phonon assisted broadening and inelastic scattering.

While the InAs/GaSb Type III band alignment system is a fortuitous gift of Nature, it may not be able to take us all the way to a fully manufacturable technology. It appears that TFETs will unavoidably require some form of quantum confinement. In that case, the exact position of the bandedge will be very sensitive to quantum well thickness. This is a long-standing problem that leads, for example, to inhomogeneous broadening. While this would not necessarily prevent us from learning the science on individual research devices, it would lead to unacceptable threshold variation in a system.

One way to overcome the problem of quantum well thickness variation is to make the quantum well out of a monolayer semiconductor. Graphene is famously a monolayer semi-metal. Research has just begun on monolayer semiconductors drawn from the chalcogenide class of materials. Many chalcogenides are layered compounds, and there are very many such layered materials, of which *n*-MoS_2 is a famous example. There are other chalcogenides that tend to be p-type, and there might be combinations that form pn junctions with Type III band alignment.

Prior to the insertion of a new device technology into the high pressure world of integrated circuits,there need to be some intermediate commercialization goals, These intermediate goals would validate the physics of the new tunneling devices, and demonstrate their manufacturability, and their ability to satisfy a commercial need. While many claims have been made, even a single successful example of commercialization would help focus our attention on the real problems that need to be solved.

A device that can satisfy a small market need, yet test out many of our concepts, is the "Backward Diode". The relevant market is highly nonlinear radio mixers, that are already making advantageous use of the old-fashioned Ge-homojunction Backward Diodes. The Type III Backward Diodes have not yet made their presence felt, nor have we fully defined the metric for how they would provide improved performance. It appears that threshold steepness of the nonlinear characteristic would be one of the important specifications.

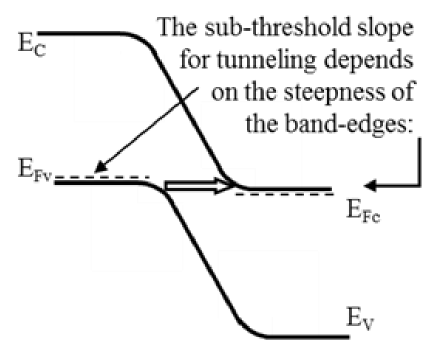


Figure 6: Schematic of bandgap overlap enabling the current to flow

Therefore one of the intermediate goals of Theme 1 will the development of a commercializable 2-terminal Backward Diode technology. If the new technology fails to penetrate such a small market for high performance nonlinear mixers, it would indicate that much work still needs to be done, before addressing the much more challenging TFET market.

Guided by the above roadmap, in Period 2, the key element in the Theme I Research program is the *Study of Band Edge Shape* through Simulation and Experimental Verification via Device Design, Fabrication and Characterization, comprising the following three major research components:

- **Effect of pn-Junction Dimensionality on Tunnel Switch Turn-on Shape**: There are two ways of achieving a sensitive switch; i.e. achieving turn-on steepness. The gate or drain voltage can be used to modulate the tunneling barrier thickness and thus the tunneling probability. We prefer to use the band overlap or density of states threshold function. In a density of states switch, if the conduction and valence band do not overlap, no current can flow. Once they do overlap, as illustrated in **Figure 6**, there is a path for current to flow.

The density of states switch is similar to the "Backward Diode" concept, which is similar to the Esaki diode concept, but at lighter doping where the overlap region manifests itself slightly at reverse bias. At small amounts of reverse voltage in a p-n junction, the valence band density of states just begins to overlap the conduction band density of states. This band overlap turn-on has the potential for a very sharp On/Off transition that is more complete than that which can be achieved by modulating the tunneling barrier height or thickness [15]. If the band edges are ideal, one might expect an infinitely sharp turn on when the band edges overlap. In our analytical approach, we took into account the effect of the dimensionality on the density of states on either side of the p-n junction. **E. Yablonovitch** and his UC Berkeley group studied nine different possible p-n junction dimensional combinations, as shown in **Figure 7**. The key question of this effort is to ascertain which dimensional forms of p-n junctions are promising for adaptation into a TFET switch, or for a new generation [2] [14] [16] of Backward Diodes. It was found that in a typical 3d-3d bulk pn junction, as has been studied since p-n junctions began, the nature of the turn-on is only quadratic in the control voltage. A sharper density-of-states imposed turn-on shape occurs at reduced dimensionality. Since the nature of the turn on is directly linked to the density of states, the dimensionality on either side of the tunneling junction will directly impact the shape of the turn on. The most interesting case for TFETs is the 2d:2d case where conservation of energy and momentum during the tunneling process results in a much sharper turn-on somewhat close to a step function. Serendipitously, strong confinement can compensate for a weak tunneling probability. **Figure 8 a** and **b** show the results for junctions with different dimensionality and in particular, **Figure 8b** shows that a 2d-2d junction has sharper turn-on and larger turn-on current at low voltages.

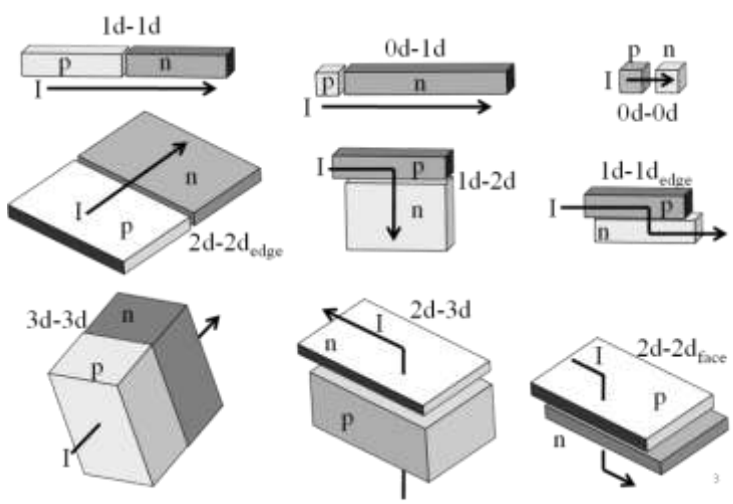
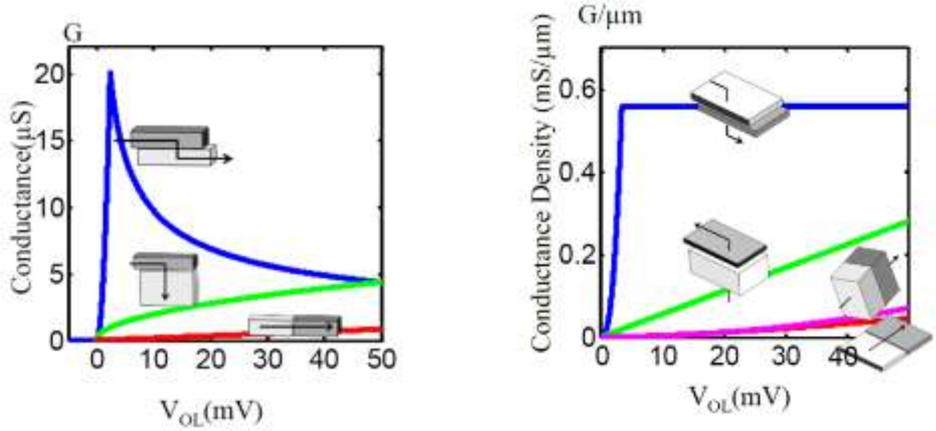


Figure 7: We have identified nine distinct dimensionality possibilities that we believe can exist in p-n junctions. Each of the different tunneling p-n junction dimensionalities shown have different turn on characteristics.



(a) (b)

Figure 8: The conductance curves for junctions of various dimensionalities are plotted in (a) and (b). (b) 2d-2d junction is shown to have sharper turn-on and larger turn-on current at low voltages.

In addition, the research analyzed the impact of factors that would smear out the transition as the two quantum levels are being aligned. Level broadening, which will broaden the sub-threshold slope of TFETs, can arise from: i) quantum level repulsion; ii) contact broadening; iii) Coulomb Blockade energy shifts/broadening, and iv) phonon assisted broadening and inelastic scattering. The analytical studies showed that quantum confinement leads to substantially increased current, owing to increased "attempt rate" in a quantum confined geometry. Counter-intuitively, we found that too high a tunneling transmission probability, above a few percent, causes quantum level repulsion which would prevent sharp switching action.

After analytically deriving the turn on characteristics of these junctions, we proceeded to numerical simulation of the new device properties through an atomistic non-equilibrum Green's function code. We are also experimentally demonstrating the new device physics in an InAs /GaSb based heterostructure tunnel diode which has a favorable type III band alignment. As stated in the previous section, it will take some time for the Center to develop our own growth capabilities. For experimental verification, we developed or in the process of developing research relationships with other Universities and Institutes that are already growing InAs/GaSb heterostructures. In particular, for the team at UC Berkeley, we are working with the University of New Mexico and the Technical University of Munich, who have provided, or are planning to provide hetero-structures for the Center's projects.

The question arises whether it is more desirable to make 3-terminal gate controlled transistors, or whether it would be necessary to first demonstrate the sharp response in a 2-terminal device such as the "backward diode". We believe that there is much scientific information to be gained by using 2-terminal devices to obtain spectroscopic information about the shape of the band-edges, as a pre-requisite before making 3-terminal gate controlled devices. This priority makes our approach different from some of the other work that is being conducted in TFETs. Nonetheless our experimental efforts include both 3-terminal TFETs, as well as 2-terminal backward diodes.

The results from the analytical studies on the impact of dimensionality have been submitted for publication to IEEE Proceedings. See Section *VIII.1ai*.

- **Tunneling in Gated 2D-to-2D Electron Gas Systems**: The project of at the laboratory of **D. Antoniadis** and **J. Hoyt** at *MIT* builds on the previous findings regarding the impact of dimensionality by exploring tunneling in gated 2D-to-2D electron gas systems. The first goal was to establish a TFET simulation environment using a combination of commercially available programs (Sentaurus Device), and specialized atomistic codes for full band quantum transport, including phonon scattering (the OMEN code from the NSF-supported NCN at Purdue). The benefits of using these programs together, to provide both rigorous physics and efficient device design, were first demonstrated on strained silicon/strained germanium Type II heterostructures, where the band alignments at the hetero-interfaces are poorly known. The band alignments at the heterointerface for various levels of strain were extracted by fitting experimentally measured capacitance-voltage curves to simulation results. Thus, for the first time, measurement of the effective bandgap, a critical parameter for tunneling, at the strained Si/strained Ge Type II heterointerface has been effected. A value of 190 meV was extracted, which is approximately 100 meV smaller than theoretically expected. Although we do not plan to further pursue Si/Ge for TFETs, this work highlights the importance of experimentally quantifying band alignments, which are uncertain even in materials systems that are supposedly well understood. We have explained that this discrepancy based on updated values for linear deformation potential theory in Si and Ge materials by proposing new deformation potentials for Si and Ge that are consistent with published literature. The theoretical and experimentally extracted valence band offsets at the strained-Si/strained-Ge heterointerface are much larger than previous theoretical values, which could affect group IV heterostructure devices.

The successful demonstration of the device design and simulation methodology in Type II hetero-interfaces is laying the foundation for studies tunneling in direct bandgap III-V heterostructures. Similarly, full-band quantum transport simulations, using Purdue's OMEN simulator, are being used to guide experiments and for understanding tunneling transport in InAs-GaSb TFET device structures. As in the research discussed in the prior section, the initial experimental work focuses on heterojunction diode fabrication and analysis. By the end of Reporting Period 2, we expect initial experimental results from the first lot of InAs/GaSb vertical tunnel diodes. This will be a training lot with tunnel diodes and a large array of test structures to measure material properties, such as sheet resistance, specific contact resistance, dielectric quality, etc. We plan to use this lot to improve fabrication procedures and to optimize material and structure properties such as choice of metals and QW layer thicknesses.

The simulation work was performed in collaboration with M. Luisier of the Birck Nanotechnology Center and the Network for Computational Nanotechnology (NCN) at Purdue, while the Si/Ge bandgap calculations was done in partnership with J. Menendez and C. Poweleit of Arizona State University.

The results on Type II heterointerfaces have been submitted for publication to Physical Review B. See Section *VIII.1ai*.

- **Enhanced Atomistic Simulator for TFET Structures:** Like the OMEN code of Purdue, **S. Salahuddin** research group at UC Berkeley has developed a model based on a bottom-up approach that takes into phonon scattering in the Non Equilibrium Quantum Transport regime. The goal of the Berkeley Quantum Transport Simulator (BQTS) is to establish a rigorous quantum simulation platform that can account for non-equilibrium statistical mechanics properly, resulting in a simulation tool that can effectively predict and guide design optimization. Most commercially available software are based upon drift-diffusion type of transport models where tunneling is only brought in phenomenologically. The simulation work is leveraged with other funding sources. With the Center's funding, efforts are directed at developing numerical capability to be able to simulate realistic size devices while some other aspects of the simulation software, like transport formalism development, rigorous modeling of electron-phonon coupling are funded from other sources. However, all these aspects are critical for a successful simulation platform that is intended to be a tool available for the Center's researchers. Technical achievements to date from this effort include the first simulation that accounts for electrons and phonons within the Non Equilibrium Quantum Transport regime for devices over 300 nm in length, demonstrating a smooth transition from ballistic to diffusive regime as the channel length is increased; and the prediction for a Non-Equilibrium Source Field Effect Transistor (NESFET) in an InAs-InGaAs heterostructure that shows much improved behavior compared to a standard p-i-n type tunnel transistor design.

In the remaining time of this Period, efforts to build enhanced simulation software for obtaining 3D Poisson solution self-consistently will continue. This will enable researchers to look at nanowire TFETs, vertical TFETs and other 3D geometry. We will also use this simulation platform to study the experimental data on tunnel diodes fabricated as part of the Center's research at A. Javey's group at UC Berkeley (see below for the research by A. Javey's group). We are also looking at new tunnel FET structures in terms of optimization of device design and performance.

Three technical papers have resulted from this research; see Section *VIII.1ai*.

To address the unavoidably requirement of some form of quantum confinement, a parallel focus of Theme 1 is *Novel Device Structures and Materials*, where the research effort is also to understand fundamental device physics led by device fabrication and materials research. The focus is Type III band alignment, as in the lattice-matched p-GaSb/n-InAs heterostructure system, permits a very thin tunnel barrier that will enable good on-state current at milli-Volt threshold voltages. The n-InAs layer can be a quantum well, with small enough quantum capacitance to allow good gate modulation efficiency in the 2d electron gas. Indeed the n-type layer is likely to be so thin that lattice mismatch would be acceptable, permitting a much wider choice of material combinations.

- **Compound Semiconductor on Insulator (XOI):** The group of **A. Javey** at *UC Berkeley* is exploring both novel device architectures and novel materials. This platform centers on the ability to fabricate devices from ultra-thin compound semiconductor membranes placed on arbitrary substrates, which enable precise tuning of the electronic and optical properties of devices through (i) materials engineering and (ii) quantum confinement. It is an epitaxial transfer technique enabling precise dimensional control of arbitrary semiconductors transferred to substrates. These semiconductors are freestanding membranes that are typically heavily quantum confined, leading us to term these materials quantum membranes (QM). The two material system classes being explored with the XOI platform are (i) high mobility III-V compound semiconductors and (ii) layered metal sulfides (MS) and metal oxides (MO) that are similar to graphene, but have appreciable bandgaps, enabling fabrication of low power devices.

  Additionally, the two architectures studied are metal-oxide-semiconductor field effect transistors (MOSFET) and tunnel field effect transistors (TFET). Here, MOSFETs are initially studied to enable rapid characterization and optimization of materials transfer techniques and processing techniques as well as developing a 0.5 V switch, which is an important milestone on the road to a millivolt switch. The results for these devices are summarized below. Building on the lessons learned from MOSFET development, we will fabricate TFETs from III-V heterojunctions as well as metal sulfide/metal oxide heterojunctions. While III-V TFETs have been widely explored in the past, we believe the level of control afforded by the XOI platform enables optimization of electronic properties to a degree previously unavailable, thus opening up novel device architectures for exploration. The devices explored will be type-III (broken gap) heterojunctions, which are optimal for tunneling devices. Furthermore, the use of metal sulfide or metal oxide heterojunctions for device applications is almost entirely unexplored and present significant opportunity for novel devices, especially type-III heterojunctions.

  The fundamental physics learned of InAs membranes via the XOI platform are as follows [3] [17].

- Quantum Resistance and Mobility: We have explored the drastic effects of quantum confinement on the quantum resistance of the InAs. The work has led to the development of new device physics models for ultrathin III-V layers.
- Fundamental Absorption for a 2d Sub-Band: Absorption study of ultrathin InAs membranes was performed and quantum confinement is observed as steps in absorbance. These steps match closely with the calculated transition energies, thereby enabling the direct measurement of the band gap and band structure of XOI films. Critically, the quantum unit of absorbance was observed for the first time in 2d semiconductors.
- n-Type XOI FETs: High gm and I_{ON} were achieved in III-V (InAs and InAsSb) nFETs on Si. Specifically, InAs XOI nFETs exhibiting gm of 2.3 mS/µm at V_{DS}=0.5 V, a body thickness of ~13 nm and channel length of ~ 200 nm were fabricated and demonstrated. Additionally, the design trade-offs between InAs thickness and device performance were studied.
- p-FETs: High hole mobility III-V (InGaSb) pFETs on Si were achieved. The InGaSb XOI pFETs display a peak effective mobility of ~820 cm^2/Vs, ON/OFF current ratio of 10^3-10^4 with a respectable subthreshold swing of ~146 mV/decade.
- InAs XOI TFET: Utilizing ultrathin InAs XOI, an InAs homojunction TFET on Si is demonstrated. The junction was formed via a post-growth zinc surface doping method to form a p+ source contact. This method was chosen to minimize lattice damage to the ultrathin body InAs, which causes ion implantation to be unsuitable for doping. The transistor exhibited gated negative differential resistance behavior under forward bias, confirming the tunneling operation of the device. The device exhibited an ON current density of ~0.5 µA/µm at V_{DS}=V_{GS}=1V. The SS at V_{DS}=0.1 V was ~190 mV/dec. The SS at V_{DS}=0.1 V was ~190 mV/dec. In this device architecture, the ON current was dominated by vertical band-to-band tunneling and is thereby less sensitive to the junction abruptness. The work illustrates a first generation III-V tunnel transistor fabricated from the XOI platform. In the future, the device performance can be improved by moving to a heterojunction TFET.

In the remaining months of Period 2, we will continue to perform studies of the fundamental properties of the resulting membranes. Furthermore, we will continue to develop the techniques necessary for fabrication of heterojunction TFETs based on the XOI platform. Specifically, heterojunctions with InAs/GaSb are being pursued for future TFET devices.

These research efforts have partners who are internal and external of the Center. The focus of C. Hu of *UC Berkeley* to optimize the InAs/GaAlSb/GaSb transistor fabrication process is an integral part of A. Javey's effort. C. Hu's efforts are reported later in the Theme 1 Research section. As previously reported, S. Salahuddin's simulation research is also being applied to analyze the devices from A. Javey's laboratory. The III-V materials used in these reported efforts were provided by University of New Mexico.

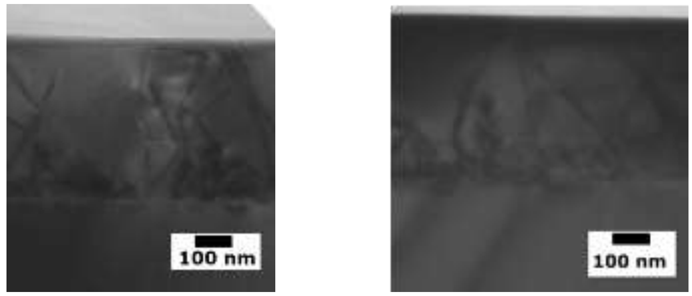
- **Layered Chalcogenides for Monolayer Semiconductors:** The Center's focus on monolayer semiconductors drawn from the chalcogenide class of materials was the result of a Theme 1 brainstorming session that involved **E. Yablonovitch**, **A. Javey**, and **S. Salahuddin**, all of *UC Berkeley*. Many chalcogenides are layered compounds, and there are very many such layered materials, of which *n*-MoS_2 is a famous example. There are other chalcogenides that tend to be p-type, and there might be combinations that form pn junctions with Type III band alignment. **E. Yablonovitch** together with **A. Javey** and assisted by **V. Rangari** of *Tuskegee* have begun to explore these many compounds to find examples where p-n junctions can be formed, perhaps eventually leading to TFETs with sharp reproducible threshold voltage. Owing to thickness fluctuations, we cannot rely upon quantum well thickness uniformity to provide reproducible device thresholds. The solution is to employ monolayer quantum well materials, like graphene, but with a bandgap like MoS_2. This interest also addresses the need to search for additional

Type III bandgap materials. The Javey group has begun exploring these novel material systems in order to study the fundamental materials properties as well as the properties of resulting devices. The method to transfer these materials is being developed and the resulting films will be characterized optically and electrically. The main characterization will be through photoluminescence (PL) measurement, Raman scattering and carrier transport measurements. Complementing these efforts, **V. Rangari** is focusing on the synthesis and characterization of layered metal sulfide nanoparticles. The layered chalcogenides such as MoS_2, WS_2, TiS, TiS_2 ZnS_2, TaS_2, PtS_2 SnS_2 and NiS etc, will be synthesized using microwave or sonochemical synthesis technique. The as-prepared layered structured materials will be tested for their Current and Voltage (IV) characteristics. These nanomaterials will be further characterized for their band-gap and other optical properties. The structure and morphology also will be characterized by using X-ray diffraction, and high-resolution transmission electron microscopy. Finally selected layered chalcogenides will be tested for their electrical switching applications. In this direction we are synthesizing FeS, CdS and ZnS nanoparticles. These systems we have chosen to cover wide range of conduction and valence bands. CdS and ZnS are in the category of low conduction and high valence bands, whereas FeS is in the category of close conduction and valence band. Nanoparticles such as CdS and CuS nanoparticles were synthesized and characterized for their size and shape. The morphological and structural characterization of ZnS nanoparticles are under progress.

As the research efforts to understand device and materials physics of TFETs continues, Theme I researchers are, in parallel, establishing internal capabilities and know-how for *Epitaxial Materials and Device Fabrication.*

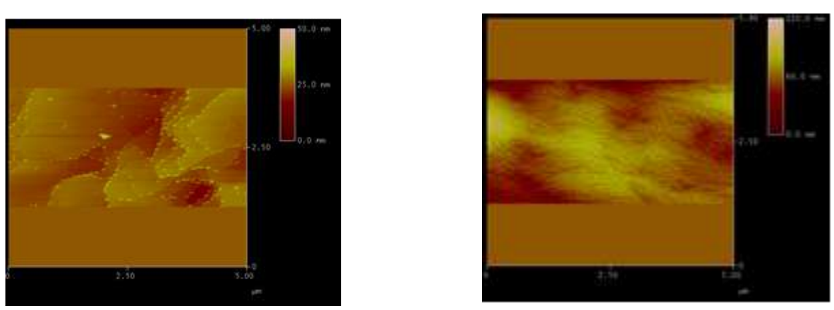
- **MOCVD for III-V's, IV's, Oxides and Nitrides:** The objective of the laboratory of **E. Fitzgerald** at *MIT* to both ramp materials growth capability for the Center's heterostructure fabrication, as well as address fundamental issues regarding fabrication and electrical properties of heterovalent interfaces. The Fitzgerald group constructed a unique MOCVD system capable of depositing III-V's, IV's and some oxides and nitrides, thus creating a unique capability for forming traditional systems of interest as well as exploring novel heterovalent interfaces. The AlInGaAsSb system has lattice-matched Type III heterojunction capability, and therefore has been used as the starting standard materials system for testing fundamental problems in tunnel switches. In this first aspect of this project, our goal is to ramp calibration and growth conditions for creating InAs/GaSb tunnel junctions. The material growth capability is an avenue for the Center to have excellent flexibility in heterostructure design as well as a way to add insight into controlling process variables. When established, this growth capability will feed into collaborations with the Hoyt, Antoniadis, Yablonovitch, Javey and Hu groups. The unique capability of the MOCVD system also means that we can explore fundamental issues surrounding band alignments and heterostructures within the context of searching for new electronic switches. We are inserting Ge as a replacement for GaSb. This first step will allow us to explore the effect of heterovalency at the Ge/InAs interface in the electrical behavior of the tunnel diode. These investigations will lead us to understanding III-V/IV heterovalent interfaces and determine if such interfaces can play a beneficial role in new electronic switch development.

  For the novel heterostructures, the first step has been focused on creating a process for relaxed InAs on GaAs. We have measured the surface roughness of 450 nm thick InAs film over a 5 μm x 5μm area to be 2.5 nm when grown on (100) substrates, and 15.0 nm when grown on off-cut substrates with a 6° off-cut towards the [011] direction, concluding that the roughness of these surfaces is low enough to form diode structures and study tunneling across the InAs-Ge interface. Transmission Electron Microscopy (TEM) images of these films can be seen below, for both on-axis substrates (left) and off-cut substrates (right).



We have also learned that the direct growth of thin InAs layers on GaAs, as possible candidates for forming InAs quantum wells, forms quantum dot structures on the GaAs surface, due to the large lattice mismatch, that leads to too high of a compressive strain in the InAs. We have also found, from the deformation potentials of InAs, that a compressive strain would be detrimental to the performance of a tunnel device, as such strain causes the conduction band energy to increase by about 60 meV/% strain, which decreases the band overlap and results in a much higher required turn-on voltage for devices. Ge layers can then be grown with tensile strain, and the deformation potentials of Ge indicate that any tensile strain in the Ge film that is not relaxed by dislocation formation will lead to a 0.57eV/% strain increase in the light-hole conduction band, increasing the overlap, and increasing the chances of obtaining type-III alignment. Despite the thickness of these InAs films (as shown above), we expect to be able to still obtain quantum confined InAs layers by simply utilizing a high-band-gap spacer material, such as AlSb, above the relaxed InAs layer, and then growing a much thinner, quantum-confined InAs layer above. This is illustrated below (note a barrier may not necessarily be included).

Additionally, we have found that Ge forms quantum dots that nucleate from step-bunches on the InAs surface. Hence, Ge particles nucleate with a much greater density on InAs films grown on off-cut substrates, given the high density of steps which run along the [0 -1 1] direction. This can be seen from the atomic force microscope (AFM) images below, in which nucleation can be seen for InAs films on on-axis substrates (left) and off-cut substrates (right).



Given the higher density of Ge particles on InAs surfaces grown from off-cut substrates, the growth time can likely be increased so to allow the particles to grow larger and coalesce into a solid film. Hence, a 3D-3D tunnel diode consisting of an InAs layer and a Ge layer can theoretically be grown. We intend to grow such a diode and test the I-V characteristics in the near future. We are also interested in studying tunneling between the Ge quantum dots and either a thick or thin InAs film, in order to obtain the first experimental results on 1D-2D and 1D-3D tunneling.

In the remainder of period 2, we intend to grow planar Ge films to obtain a 3D-3D diode structure. We also intend to complete a study on the surface-roughness of InAs films grown on off-cut GaAs substrates, in hopes of obtaining surfaces that are similar to those grown on on-axis substrates.

- **Device Fabrication Optimization:** As the Center is focusing on InAs/GaAlSb/GaSb for Type III bandgap alignment devices, one objective in Period 2 is to establish an optimized fabrication sequence for cleaning, lithography, etching, contact and metal formation. While these steps are easily available for silicon devices, they require special equipment and procedures for InAs and GaSb systems. **C. Hu** and **A. Javey** of *UC Berkeley* have successfully set up the necessary equipment and optimized time, temperature, gas pressure, etc. for each of the steps. We have successfully fabricated InAs/GaAlSb/GaSb tunnel diode. The forward bias IV showed clear negative differential conductance indicative of a tunneling junction with good material quality. This diode experiment identified several flaws in the device fabrication process flow. As a result, we have also redesigned the tunnel transistor fabrication process flow.

While the primary focus is TFET's with Type III Bandgap alignment, the Theme I research team recognized the need to support alternative approaches in the search for a solid state millivolt switch. These approaches not only can be viewed as risk management alternatives, but more importantly, the lessons learned through these efforts may also have applicability in the team's primary path, TFETs.

- **Use of Negative Capacitance for a Steeper Sub-Threshold Sloop:** The project is studying the detailed energy landscape of ferroelectric insulators which can provide "transformer" action as gate insulators boosting the voltage seen by a transistor channel. These ferroelectric gate architectures, as a framework, can provide new opportunities for reducing the subthreshold slope. While negative capacitance is the only concept available that does not require that the transport physics in a MOSFET be changed, it can also be complementary to tunneling action and if successful, two effects will multiply significantly increasing the device performance. In Period 2, **S. Salahuddin** of *UC Berkeley* is continuing to work on materials optimization. We have made several runs of growing $BaTiO_3$ on single crystalline STO substrate and on Pt coated Si. Extensive efforts have been applied to characterize these films by atomic force microscopy, piezo force microscopy, x-ray diffraction and capacitance-voltage measurements. In collaboration with **C. Hu** of *UC Berkeley*, the process flow design and initial fabrication of structures for negative capacitance FET has been defined. This process will include the source and drain to be defined with implantation. Then STO will be formed on Si in partnership with R. Droopad at Texas Tech University. Next, the ferroelectric thin films will be deposited at Berkeley. Finally, contacts will be made after ion milling. Device fabrication has been initiated and will continue for the remaining of Period 2.

- **Use of Impact Ionization in Narrow Bandgap Material for Super-Steep Sub-Threshold Devices:** This project builds on the previous findings of **J. del Alamo** of *MIT*, whose group previously has demonstrated a subthreshold swing of less than 60 mV/decade in partially depleted silicon-on-insulator (PDSOI) MOSFETs [17]. It arises from the interaction of impact ionization and the floating body of the transistor. Holes generated at the drain side accumulate in the body under the gate, resulting in an increase in the body potential. This, in turn, leads to more drain current and a greater generation of holes. The strong positive feedback loop results

Center for Energy Efficient Electronics Science in a large increase in the drain current in the subthreshold regime. The goal of this project in Period 2 targets the demonstration of steep subthreshold characteristics in transistors based on narrow bandgap materials such as InGaAs and InAs. We have experimentally studied impact ionization in InAs HEMTs fabricated in our laboratory. Due to the very short gate length of these devices (L_g=30 nm) and the high current that they sustain, we expected a strong signature of impact ionization. Instead, we found that these devices displayed little impact ionization. In fact, the subthreshold characteristics were dominated by short-channel effects up to the highest voltages that they could sustain. Based on this and other studies, we concluded that impact ionization in transistors with highly-quantized channels (as needed in a future nanometer-scale technology) is unlikely to be present to the degree that it could steepen in a significant way the subthreshold characteristics at the reduced voltages that are targeted by the Center. In consequence, this project has been discontinued.

- **Enhancing ON/OFF Current in Type II TFET:** As stated in the introduction of this Theme 1 research section, improvements in on/off current ratio (Ion/Ioff) are critically needed in TFETs to be a compelling alternative to the conventional MOSFET transistor for low-voltage electronics. This project in the group of **T.J. King Liu** of *UC Berkeley* builds on previous Type II TFET research of prior research programs. First, this project is investigating the effect of trap states on the performance of TFETs, by selectively introducing defects via ion implantation of erbium (Er) into the tunneling region (source junction) of p-n junctions and TFETs. Second, this project is investigating the effect of back-gate biasing on thin-body TFET Ion/Ioff via two-dimensional device simulations. Two-terminal (diode) and three-terminal (FET) devices have been successfully fabricated and electrical characterization has commenced. From two-dimensional device simulations, reverse back biasing of a planar thin-body germanium FET is found to provide for dramatic (>30x) enhancement in I_{on}/I_{off}. This is because the application of a reverse back bias causes tunneling to increase in a more vertical direction, so that the tunneling area increases. Also, reverse back biasing mitigates short channel effects and improves the output resistance for enhanced transistor intrinsic gain. The performance boosting benefit of reverse back biasing is expected extend to TFETs implemented in other semiconductor material systems, which are being investigated under the Center. By the end of this Reporting Period, analysis of the measured characteristics of two-terminal (diode) and three-terminal (FET) devices against theory and/or simulations is expected to be completed, and any interesting or anomalous would be explained. We expect that this work will conclude with a manuscript on the effect of thin-body TFET back-biasing for journal publication.

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

Mechanical switches have zero off-state leakage and abrupt on/off switching behavior, which allows for aggressive supply voltage (V_{DD}) scaling for ultra-low active energy consumption (<1 aJ/bit). Prior research on micro/nano-electro-mechanical (M/NEM) switches conducted by the Theme-II co-PIs and other research groups around the world were focused on achieving functional devices with good yield and reliability (to enable integrated circuit demonstrations), and on theoretical studies of their scaling behavior. The E^3S Center is the first and only major project to focus efforts on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of transistors. To be a viable alternative to transistors, a mechanical switch must operate at reasonable speed and have dimensions in the nanoscale regime. Issues such as surface adhesion and wear must be addressed in order to realize relay-based integrated circuits (ICs) that operate not only with good energy efficiency but also with good reliability ($>10^{12}$ on/off cycles). Thus, the Theme II research team is investigating new materials as well as device and circuit designs for voltage reduction, device scaling, and reliability improvement. The first major milestone for this research will be the demonstration of mechanical switches operating with voltage swings below 100 mV. A longer-term goal is to demonstrate switches operating with voltage swings below 10 mV.

The following four projects are being undertaken by Center researchers at *UC Berkeley, Stanford and MIT.* The first two projects are progressing in the direction planned at the beginning of the Period 2, but the third project has changed direction based on the learnings in this Period. The fourth project was recently added as a consequence of research progress made under Theme IV, to mitigate against the risk of scaled mechanical switch failure due to surface adhesion forces.

- **Technologies for Nanoscale and milli-Volt Relays**: The goal of this project undertaken by the group of **T.J. King Liu** at *UC Berkeley* is to ascertain whether there are any fundamental limits for scaling down the operating voltage of an electro-mechanical relay. Also, key challenges (and their solutions) for achieving milliVolt relay operation are to be identified. Finally, improvements in electrostatic design and innovations in materials and fabrication processes are being explored to achieve milliVolt operation and to improve reliability, in collaboration with other co-PIs under this Theme. The research in Period 2 builds on a theoretical study of relay scaling for ultra-low-voltage operation that was initiated in Period 1. It was found that, if surface adhesion force continues to scale down with the area of the contact dimple regions, then sub-10 milliVolt operation should be feasible with 3.5um-long × 83nm-wide × 40nm-thick flexures **(Figure 9).** The focus of the work in Period 2 is an experimental study of thin (sub-100 nm thick) structural beams, which are required for ultra-low-voltage relay operation. Strain gradient has been identified to be the most significant practical challenge. (Strain gradient causes out-of-plane deflection, which undesirably alters the actuation and contact gaps and thereby results either in increased operating voltage or device failure.) Investigation of various approaches to reducing the strain gradient in thin structural films has commenced, to enable milli-Volt relays to be fabricated. Approaches for achieving low strain gradient include a multi-layered deposition process, which was suggested by other co-PIs during the course of regular Theme-II teleconference meetings. By the end of Period 2, it is expected that the scaling of surface adhesion force with contact dimple area, for contact dimple sizes down to below 100nm will have been verified experimentally using an atomic-force-microscopy (AFM) based technique described by Lee *et al* [18].

PARAMETER	VALUE
Actuation Area	1.08 µm²
Actuation Gap	4.3 nm
Dimple Area	16 nm x 16 nm
Dimple Gap	3 nm
Effective Spring Constant*	0.036 N/m
Effective Mass	0.52 fg
Mechanical Delay^	25 ns
Electrical Delay	1.2-1.7 ps
Pull in Voltage	9.44 mV
Release Voltage	6 mV

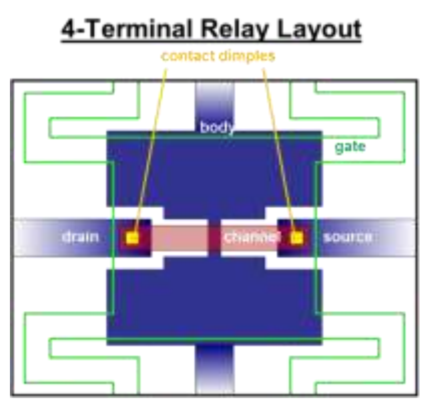


Figure 9: Scaled Relay Design and Performance Parameters show promise for milli-volt switching.

- **Low-Energy-Consumption NEM relays with Carbon as a Structural and Interfacial Material:** The goal of this project, undertaken by the group of **H.-S.P. Wong** at *Stanford University*, is to lower the operating voltage of six-terminal electro-mechanical switching devices employing double-sided actuation of a movable beam, by utilizing mechanical energy stored in the beam during an initialization operation to reduce the electrical energy needed for switching. Steady-state and dynamic analyses are being pursued to delineate design considerations. In addition, studies on the use of a thin interfacial layer of carbon nanotubes (CNTs), graphene, or SiC are also being conducted to address the issue of stiction. Fundamental understanding of contact physics is critical to achieving reliable mechanical switches. A predictive model of contact behavior (resistance and endurance) will be developed. The objective of this work is to build a science and technology knowledge base to enable reliable, low-voltage nano-electro-mechanical (NEM) relays.

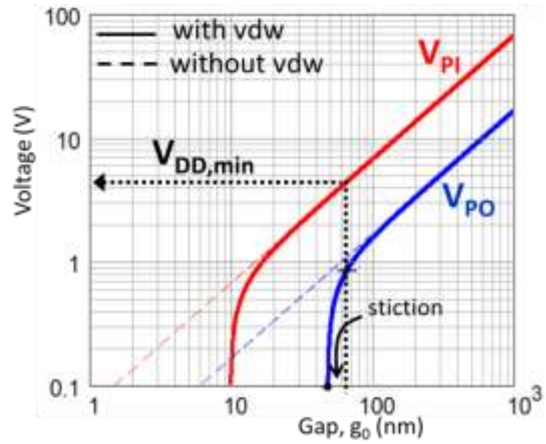


Figure 10: Impact of van der Waals force on the switching voltages (pull-in voltage V_{PI} and pull-out voltage V_{PO}) of an electrostatically actuated cantilever beam, as a function of the actuation gap thickness g_0. The beam thickness is assumed to be equal to g_0 and the beam length is assumed to be $30g_0$. The sensitivity S is defined as the change in (log V_{PO}) with a change in (log g_0). The minimum value of g_0 corresponding to the maximum acceptable value of S (indicated by '+') establishes the minimum operating voltage $V_{DD,min}$.

Progress made in Period 2 is summarized as follows:

- Theoretical performance limits for NEM relays due to van der Waals force were investigated, by applying a constant-sensitivity scaling strategy to minimize the switching energy (**Figure 10**). Sub-10k_BT switching energy, 300 milli-Volt switching voltage, and 1ns switching delay can be achieved using a cantilever beam that has beam thickness and actuation gap thickness below 10 nm, and whose surface is coated with a material that has a low Hamaker constant (*e.g.* Teflon).
- Theoretical analysis of the energy-reversible operation scheme using a one-dimensional parallel-plate model with two fixed actuation plates was performed. For the optimum design, it was found that virtually zero voltage swing and hence virtually zero switching energy is required to switch between two states – subject to noise margin requirements – so that milli-volt switching should be attainable.
- A process was developed for fabricating scaled laterally actuated NEM relays with sub-lithographic features using a four-mask multi-spacer process. Also, a process was successfully developed to fabricate a wafer with embedded gate and drain electrodes to which a graphene layer can be easily transferred without stiction issues. Three-terminal graphene-beam switches with sub-10 nm actuation gap thickness are being fabricated using this process. A tool for chemical vapor deposition of graphene is being constructed to expedite graphene switch fabrication.

The performance of a NEM relay is highly sensitive to dimensional variations. For the remainder of Period 2, the impact of such variations will be characterized and approaches to control variability will be developed – which is critical for large-scale integrated circuit design and implementation. A methodology will be established to quantify the critical dimension (g_{c0}) at which a relay should be scaled down according to Constant Sensitivity Scaling (CSS) rather than traditional Constant Field Scaling (CFS) for better variation tolerance. Since stiction is the most significant reason for device failure, the critical gap dimension ($g_{stiction}$) at which NEM relay stiction appears also will be quantified.

- **Nanomechanical Switch Based on Electrically Actuated Tunneling Gaps**: The focus of this project undertaken jointly by the groups of **V. Bulovic** and **J. Lang** of *MIT* is the development of micro/nano-electro-mechanical (MEMS/NEMS) switches that conduct through charge tunneling across gaps, as a means to reduce or even eliminate contact sticking and wear. Modulation of tunneling conduction requires only small changes in gap thickness, so that a large on/off conductance ratio can be achieved with a small change in voltage. Theoretical analyses indicate that such a MEMS/NEMS switch can achieve the performance metrics listed earlier in this section. The initial switch design employs a plurality of tunneling gaps within a nanocomposite material comprised of a polymer doped with conducting nanoparticles. The nanocomposite is mechanically compressed, or squeezed, by the MEMS/NEMS structure to increase conduction and effect switching behavior. Thus, this device is referred to as the "squitch".

  During Period 2, the first fully functional squitch was demonstrated [19]. This mm-scale device (illustrated in **Figure 11a**) employs a mechanically soft nickel-polydimethysiloxane (PDMS) nanocomposite material (**Figure 11b**) that exhibits five orders of magnitude change in conductance with 20% strain (**Figure 11c**). Measured current-vs.-voltage (*I-V*) characteristics of the first squitch are shown in **Figure 11d**. The mechanical properties of the nanocomposite can be optimized by applying different amounts of the curing agent to the PDMS, making it possible to engineer a nanocomposite with a reduced mechanical modulus so as to reduce the switching voltage and energy. The first squitch was fabricated with a 10% curing agent.

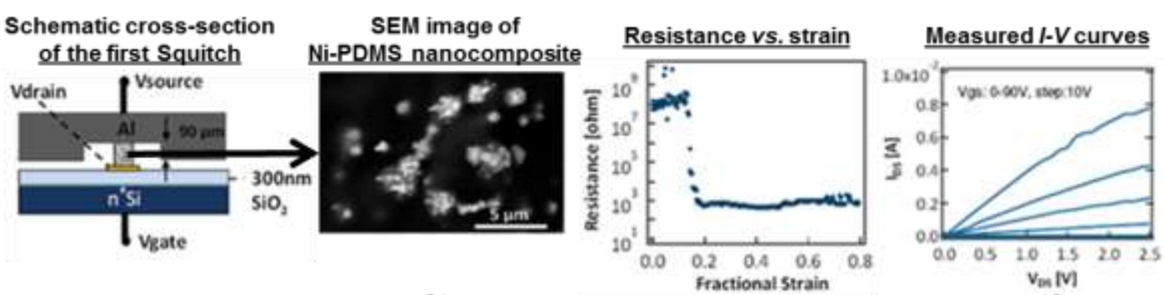


Figure 11: Electro-mechanical switch design in which a nanocomposite material is mechanically compressed to increase tunneling conduction and effect switching behavior.

A scaling study showed that if the squitch can be scaled down to have horizontal and vertical dimensions on the order of 100 nm, and if the nanocomposite material has a mechanical modulus of 1 MPa, then it can achieve the switch performance specifications targeted by the Center. Thus, a study of nanocomposite materials with reduced mechanical modulus and an increased range of conductivity with strain was initiated. The materials considered include PDMS doped with either metal nanoparticles, carbon black, or carbon nanotube fragments. In one experiment with carbon-black-doped PDMS, more than seven orders of magnitude change in conductance was observed with 30% strain. Furthermore, the mechanical modulus has been reduced to 1 MPa by reducing the amount of curing agent to 2%.

The first squitch was fabricated using stenciling to form the movable aluminum (Al) electrode at the 10-100 μm scale. (Conventional sputter deposition and reactive-ion etching to pattern the metal is not possible due to the polymeric character of the underlying nanocomposite.) Stenciled patterning at a much smaller scale is difficult. To address this challenge, a metal-film transfer printing technique has been developed [4]. Work is underway to demonstrate a large-scale single-gap switch that operates at very low voltage.

- **Nanomechanical Relays with Magnetoelectric Switching Elements**: Research within Theme IV has convincingly demonstrated full 180° switching of nanomagnets using electric fields (see Section *II.2av*). A scaling study indicates that the switching energy required can be reduced down to the aJ regime. By incorporating a nanomagnet into an anchored movable structure, and by embedding a switchable magnet on the substrate underneath, it should be possible to actuate a nanomechanical switch with magnetic force rather than electrostatic force. A potential advantage of this new approach is that magnetic force can be repulsive, counteracting stiction which can cause device failure.

  The goal of this new collaborative project between **T.J. King Liu** and **J. Bokor** of *UC Berkeley*, initiated in Fall 2011, is to explore the feasibility of this approach. Rough estimates of the magnitude of magnetic force that can be achieved compare favorably with that of the electrostatic force in a conventional NEMS relay. In the remaining months of Period 2, a study of various magnetoelectrically actuated mechanical switch designs will be conducted.

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

State of the art optical communication in long haul transmission has a sensitivity of $\sim 10^4$ photons/bit and consumes energy of ~10 pJ/bit. Today's optical communication is still far less competitive in energy consumption compared to electrical interconnects for chip scale applications. The Theme III research team is taking advantage of what Nanophotonics can offer for novel optical emitters and receivers to achieve the goal of atto-Joule communication. In Theme III that is led by **M.C. Wu** of *UC Berkeley*, we are pursuing nanolasers and nano-LEDs (light-emitting diodes) for energy efficient emitters. Miniaturization of the laser cavity reduces the power consumed by laser bias, as laser bias, which is proportional to laser volume, can waste > 10 fJ/bit. A revolutionary concept being pursued in Theme III is Spontaneous Hyper Emission (SHE). By attaching an optical antenna to a semiconductor light emitter at nanoscale, the spontaneous emission can be made stronger and faster than stimulated emission. Theoretically, the speed of SHE can be in excess of 100 GHz or even approaching THz when the emitter size is in the nanoscale ($< 0.01\ (\lambda_0/2n)^3$), as bandwidth is inversely proportional to the square of the antenna gap spacing. For optical receivers, the key is to break the energy-sensitivity trade-off; i.e. achieve sensitive receivers (fewer photons/bit) at low overall energy consumption (10 aJ/bit). Nanoscale photodetectors with ultrasmall capacitance, C ~ aF, will enable this goal. If the capacitance is small enough, the optical pulse produces a signal voltage larger than kT/q=26meV, and then pre-amps can be quite efficient, Q/C > kT/q, where Q is the photo-charge. The minimum energy consumed by the photoreceiver (including photodetector and pre-amp) is proportional to the capacitor, or more precisely, the geometric mean of the photodetector capacitance and the load capacitance. To achieve a capacitance of 10aF, the linear dimension of the photodetector is on the order of 100nm, much smaller than the optical diffraction limit or the absorption length. By attaching optical antennas to the photodetectors, high quantum efficiency can be achieved while preserving the small capacitance. In addition to the photodetector, the interconnect wire between the photodetector and the amplifying transistor contributes to the load capacitance. Integrating the photodetector directly with a transistor, forming a phototransistor, can eliminate the parasitic capacitance.

Period 2 started with two emitter projects and one photodetector project. One new receiver project was initiated during this Period, as a consequence of the collaboration with System Integration Research under **Alon** (see Section *II.2ai*).

- **Nano-Laser:** This project, led by **M.C. Wu**, explores new approaches to create energy-efficient coherent light sources for short-distance communications. Since dielectric (semiconductor) cavity cannot be scaled below wavelength scale, we proposed to use metal optical cavity to further reduce the physical size as well as the mode volume of the laser. During the first Period, we have successfully demonstrated nanopatch semiconductor lasers [5] [6] and one-dimensional plasmonic crystal lasers [7]. Both lasers were optically pumped at 77K. The nanopatch laser is the smallest semiconductor laser (physical size normalized to its wavelength) in the infrared (see **Figure 12**). In Period 2, we have been investigating various properties of the metallo-dielectric nanopatch lasers (**Figure 13a**). Specifically, we are interested in engineering the cavity to achieve electrical injection and room temperature operation while preserving their sub-wavelength-scale dimensions.

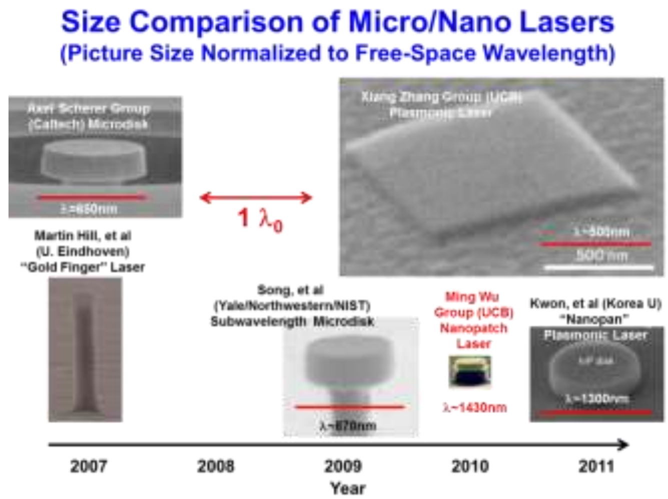


Figure 12: Comparison of the physical sizes (normalized to wavelength) of various semiconductor nanolasers. The nanopatch laser developed by the M.C.Wu group (2010) is 5x smaller than other reported nanolasers.

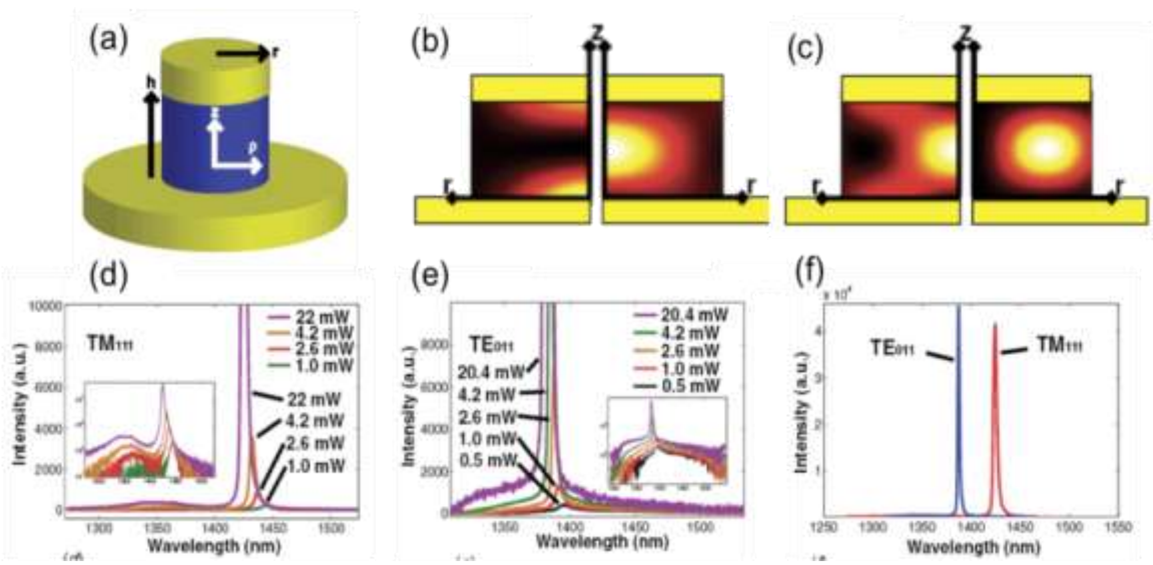


Figure 13: A schematic of a nanopatch laser with circular cross-section can be seen in (a), where the yellow represents gold and the blue represents InGaAsP semiconductor. The electric (magnetic) energy densities can be seen in the right (left) color plots of (b) and (c) for the TM_{111} and TE_{011} modes, respectively. Power dependent linear spectra for the TM_{111} and TE_{011} modes are seen in (d) and (e), respectively (the inset provides the same data in log scale). Finally, fully lasing spectra of the TM_{111} and TE_{011} modes can be seen in (f).

For the remaining months of this Period, we will focus on designing robust metal-insulator-metal cavities that will be doped to support electrical injection of carriers. Although lasing was achieved in the two most fundamental modes of the nanopatch geometry, creating an electrically injected device may prove to initially be easier if a larger nanopatch structure is used. A larger structure will use a higher order eigenmode of the nanopatch geometry (TM_{112}), and the quality factor of the nanopatch structure will be much improved. Using a thicker height for the semiconductor pillar, electrical injection of carriers may become feasible, since technology that allows ultra-shallow p-/n-junctions is not mature in III-V direct bandgap semiconductors. In **Figure 14** is a schematic of a simple electrical injection scheme is shown for a nanopatch semiconductor laser. The epilayer structure consists simply of a double heterostructure with ~250 nm of InGaAs bulk gain material sandwiched between InAlAs barrier layers and highly p- and n-doped InGaAs small bandgap layers that will form ohmic contacts to Ti/Au metallization (400 nm total epilayer thickness). Thus, we will focus on designing a cavity with a metal air bridge for electrical contacts. We will also do optical simulation, process development, measurement setup, and experimental characterization.

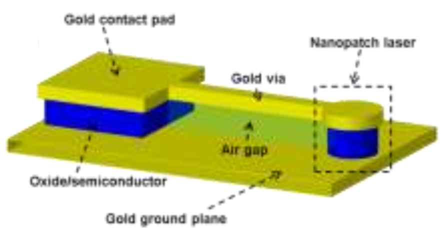


Figure 14: A schematic of a nanopatch laser with accessible n- and p- electrodes

We expect that by the end of Period 2, we will have finished design of optical cavity with the metal air bridge and be near completion of process development and fabrication of new devices, including development of new etching techniques to reduce surface states on nano-scale devices.

- **Spontaneous Hyper Emission (SHE) Nano LED:** This collaborative project between **M.C. Wu** and **E. Yablonovitch** involves the design and fabrication of a nanoscale LED coupled to an optical antenna designed for high modulation bandwidths. The goal of this project is to create a nanoLEDS with modulation bandwidths exceeding tens of gigahertz at room temperature. Ultimately, such nanoLEDs should be integrated with silicon transistor. During this Period, our primary goal has been to measure spontaneous emission enhancement by the optical antenna. We have developed the fabrication process to make SHE nanoLEDs with a dimension of 20nm. Enhancement of emission with polarization parallel to the antenna has been observed experimentally. In the coming months we will continue to perfect the nanofabrication process and also begin to perform dynamic measurements of the fabricated devices.

  Building on previous research that is focused on modifying device structure and improving fabrication methods to increase the modulation speeds of the device, a novel optical antenna-based nanoLED with 1500nm wavelength has been fabricated. The nanoLED, with epitaxial layers grown by MOCVD, consists of a 35nm-thick InGaAsP active layer on a ~350nm InP spacer layer above a metal reflector plane (**Figure 15**). Devices were fabricated using e-beam lithography and wet chemical etching to define an array of semiconductor ridges followed by e-beam patterning and metal lift-off to define the metal antennas. Devices with ridges as narrow as 24nm were fabricated. The ridges are 35nm high and the optical antennas are 350nm long, 50nm wide, and 40nm thick (**Figure 15**). The effective optical mode volume is as small as

0.015 $(\lambda_0/2n)^3$, and the optical Q is ~7. An enhancement of photoluminescence of >10x has been observed [20]. The nanoLED is also physically small (50nm x 40nm x 350nm, or $3x10^{-4}$ λ_0^3), making them attractive for on-chip optical interconnect applications.

(a) (b) (c)

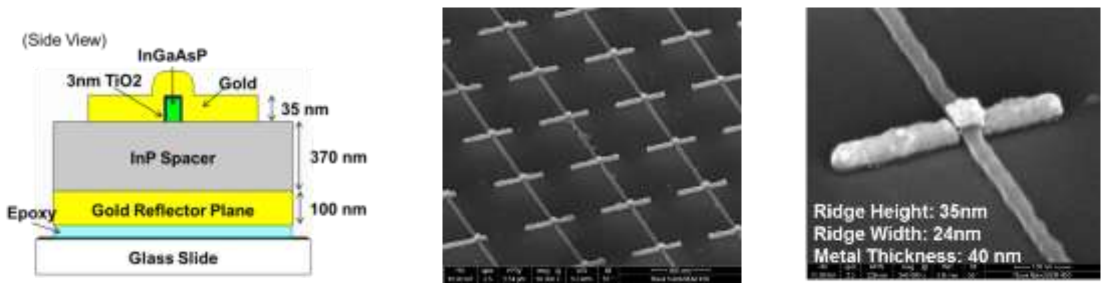


Figure 15: (a) Schematic, (b) SEM, and (c) close-up SEM of the SHE nanoLED

These structures show much greater photoluminescence compared to previous results due to recent changes in the etch process. By switching to a wet etching chemistry, ridges were created with significantly less damage compared to results obtained using dry etching (RIE). This has allowed for faster and more accurate measurements which have enabled in-depth studies of the polarization dependence of the devices. Photoluminescence parallel to the antenna show large enhancements (>50x) compared to ridges without an antenna; while emission perpendicular to the antenna is suppressed, however the total photoluminescence is greater (>10x) than without an antenna. These results show that the radiation patterns can be effectively engineered using an antenna which will be necessary for use in optical interconnects.

Due to the small power output of the nanoLEDs, ultra-sensitive equipment is required to directly obtain time-resolved information. By using a streak camera, we can excite the bulk LED material optically and then measure how fast the carriers in the semiconductor recombine. By the end of Period 2, we expect to have measured radiative and non-radiative recombination rates and applied this information to estimate rate enhancement of nanoLED devices before direct measurements can be performed.

- **High Sensitivity III-V Photodetector on CMOS:** The capacitance of a photodetector can be drastically reduced by making a nano-sized detector. To further reduce the need for amplifying a weak signal, nanoscale III-V material with high optical absorption should be used to create highly sensitive, nano-sized photodetector. The biggest challenge in realizing such a detector lies in integrating high quality III-V material onto silicon with CMOS compatible processes. To overcome such a challenge, the group of **C. Chang-Hasnain** of *UC Berkeley* has developed a novel catalyst-free growth of single-crystalline GaAs nanoneedles on silicon at CMOS compatible growth temperature. These GaAs nanoneedles have excellent optical and crystal quality, making them the ideal material to be made into a highly-sensitive photodetector. Also, due of the enhanced electric field of a cylindrical geometry, these nanoneedle photodetectors exhibit strong avalanche gain even at low bias voltage of less than 5V [21]. Demonstrating such low power, highly sensitive photodetector will be a big stepping stone in reaching Theme III's goal of building energy efficient optical interconnects.

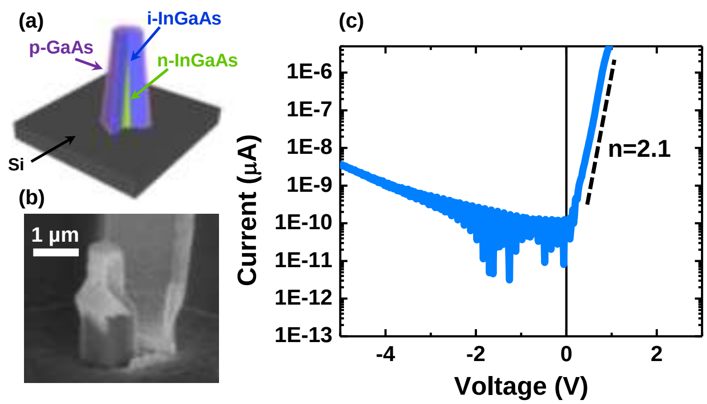


Figure 16: Single nanopillar devices. (a) A schematic elucidates the core-shell nature of nanopillars and the radial p-i-n junctions as well as heterostructures that they can form. (b) An SEM image of a single nanopillar device. Electron beam lithography was used to isolate single nanopillars for electrical contacts in order to study the physics of a single nanopillar junction. All other fabrication processes used only standard microfabrication techniques. (c) A dark current-voltage (IV) trace of a single nanopillar diode. Nanopillar diodes exhibit ideality factors approaching n=2, which is among the lowest reported for nanowire-type diodes. Under -3 V reverse bias, a single nanopillar has a dark current of only 0.3 nA, which is quite low given that the material system is GaAs-based. Note that the current near zero bias is limited by the noise floor of our experimental setup.

With the new growth technique of monolithically integrating III-V semiconductor onto silicon at CMOS compatible temperature, we recently demonstrated a low power, highly efficient GaAs nanoneedle avalanche photodetector on silicon substrate with external QE > 11,000% at -5 V bias. However, the former detector design made contacts to several nanoneedles at the same time, leading to higher dark current and capacitance. To address this shortcoming, metal contacts have been fabricated on individual nanopillar devices by electron beam lithography as shown in **Figure 16**. All other device processing steps involved only conventional microfabrication techniques, demonstrating how nanopillars can easily leverage existing fabrication technology. As shown in **Figure 16**, textbook IV curves are achieved by nanopillar diodes with low turn-on voltages of ~1 V. Under reverse bias, the dark current is only ~0.3 nA at -3 V, which is quite respectable for a GaAs-based diode. The dark current at 0 V is presently limited by the noise floor of our instruments and is expected to be on the order of a pA or less. Such low level of dark current demonstrates that our devices are capable of low noise operation, reducing the need of energy consuming amplification to boost the signal-to-noise ratio. Typical nanopillar diodes exhibit ideality factors as low as n~2, which is comparable to ideality factors for planar devices, further testifying to the quality of our radial p-n junctions. It should be noted that for these experiments, as-grown nanopillars on silicon were processed without mechanically removing them from their original silicon substrates.

Preliminary photodetector experiments were carried out by focusing a 633 nm continuous wave (CW) laser beam onto a single nanopillar device using a 100x 0.7 NA objective as depicted in **Figure 17**. Based on solid angle considerations and objective lens insertion loss, we estimate that ~11% of incident illumination couples into the nanopillar since it is mostly clad with reflecting metal. **Figure 17**, I-V curves under different levels of illumination, reveals promising photocurrent generation in our nanopillars. The fill factor (FF) remains fairly constant at 61% under various powers, which compares well to the highest reported value of 65% for nanowire systems [22]. These preliminary results correspond to a respectable external quantum efficiency of 90% at 0 V bias. We believe that the quantum efficiency can be further improved by increasing the device bias voltage and further device optimization.

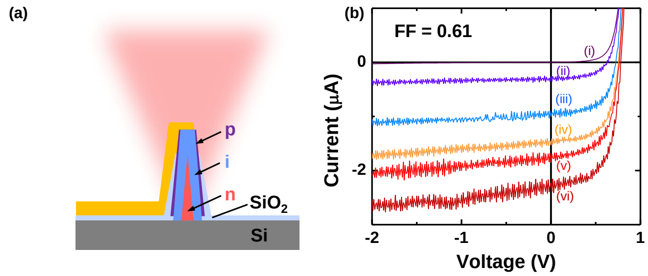


Figure 17: Promising photodetection capability observed in nanopillars on silicon. (a) Preliminary experiments consisted of using an objective to focus 633 nm CW laser light onto a single nanopillar device. (b) Photocurrent generation can be clearly seen from IV curves under illumination at (i) 0 µW, (ii) 10 µW, (iii) 20 µW, (iv) 30 µW, (v) 40 µW, and (vi) 50 µW. The fill factor remains fairly constant at 61% all illumination intensities.

We are continuing to improve our current design of the single nanopillar photodetector to achieve low capacitance and high speed operation. By the end of Period 2, we expect that measurements will be have been made to assess gain in the device when it operates at the avalanche photodetection regime. S-parameter measurement to characterize the capacitance and bandwidth of the single nanopillar photodetector will also be near completion.

- **Optical Antenna-Coupled Nanophotodetector:** This project was initiated in Period 2 by **M.C. Wu** of *UC Berkeley* to leverage the antenna enhancement research that is being pursued for NanoLED. Traditional photodiode designs are limited to micrometer-dimensions due to both the diffraction limit for focusing light and the absorption length of the semiconductor material. In recent years nanostructured metal has been used to greatly enhance optical intensity orders of magnitude larger than that of the incident light. While there have already been several attempts to utilize optical antennas for enhancing the efficiency of normal incidence nano-photodiodes, the reported efficiency has been below 0.1% in all reported cases [8] [9] [10]. The first goal is to answer is whether the quantum efficiency of such antennas is intrinsically low due to metal loss, given that all experimental demonstrations reported to date have recorded efficiency below 0.01%. This was pursued using coupled mode theory, recently used for examining antenna enhanced Raman spectroscopy, which would allow for an extremely intuitive picture of efficiency [24]. Using this theory our goal was to design a nanophotodiode with very high efficiency. After deciding on a design through simulations, we have begun fabrication with the goal of achieving a working prototype by the end of Period 2.

  A systematic approach to optimize optical antenna design and achieve high efficiency nanophotodetectors was undertaken. Using coupled mode theory (CMT) for antennae, the maximum absorption efficiency as high as 72% can be achieved in a germanium absorber embedded in a nanopatch antenna. Antenna geometries were simulated using both gold and silver Drude models and germanium as the absorbing material for the photodiode. Both structures were made to be resonant at 1.5µm wavelength. The Q values for radiation and absorption were calculated by fitting the ringdown curve of the cavity, and by successively adding material loss into the system.   The design study showed two important factors to achieve high efficiency nanophotodetectors: (1) Q_{abs} and Q_{rad} should be matched to achieve maximum power transfer; (2) $Q_{semi} << Q_{metal}$ to minimize optical loss in metals. Two optical antenna structures were studied in detail. One with mismatched dipole structure and a significantly lower Q_{metal} versus showed Q_{semi} was calculated to have 5% efficiency. The second design, the nanopatch antenna with closer, but not completely matched Q_{rad} and Q_{abs}, and a better field confinement in the Ge region showed better efficiency with gold, 45%. The absorbing efficiency can be further increased to 75% by replacing Au with lower loss Ag.

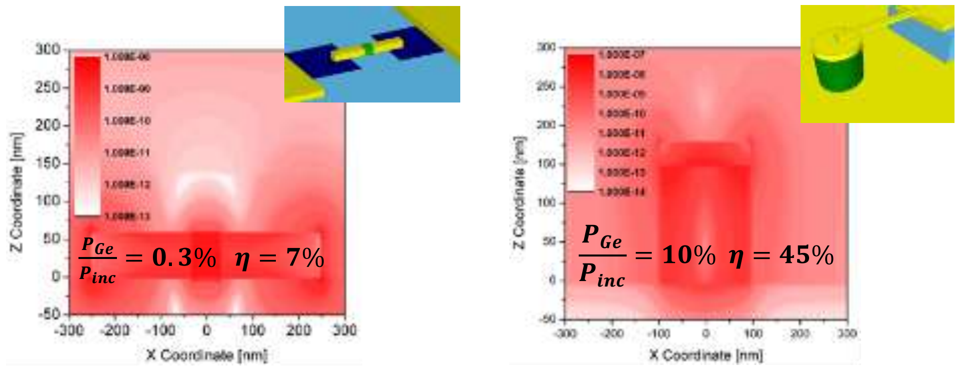


Figure 18: Energy density plots from electromagnetic simulation of (Left) dipole antenna photodiode, and (Right) patch antenna photodiode. Insets show cartoon schematics of the simulated devices.

Figure 18 shows the dipole antenna, which was commonly reported in the literature and used as our baseline for comparison. The internal efficiency, η, in the dipole is 7%, however due to its poor Q matching, and directivity, when illuminated with a 2µm beam, the efficiency is simulated to be 0.3%, similar to reported values. The nanopatch design, which was chosen due to the characteristic perceived to be beneficial from the CMT treatment, shows a 45% internal efficiency with germanium and gold, and when illuminated with the same size beam an overall efficiency of 10%, a nearly 100 fold improvement over the dipole design. Using silver and InGaAs, the nanopatch design shows an internal efficiency as high as 84%.

Recently we have begun fabricating the nanopatch using a design for electrical injection originally envisioned for the nanopatch laser project. With the only difference between the two structures being the cylindrical dimensions, we are able to use the same masks and fabrication procedure for each, and produce both devices in one fabrication run. By the end of the Period, we expect to complete fabrication of an electrically contacted nanopatch PIN photodiode with InGaAs semiconductor and gold nanopatch antenna. Once made, we will measure the spectral response and rough responsivity of the device to compare its efficiency with the simulations.

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

Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that can approach the Landauer limit [1], or perhaps even surpass it via reversible logic [11]. The goal of Theme IV to first evaluate the fundamental limits of energy dissipation in magnetic logic devices and then, build devices that operate as close as possible to the fundamental limits of energy dissipation. This is to be differentiated with other research programs in magnetic logic where the focus is prototype building or trying to understand the device speeds. This Theme is the most futuristic and forward looking of the Center's initial themes.

Theme IV research is directed towards understanding switching dynamics, communications with spin logic, novel spin materials, and basic spin logic physics. There are four projects, three of which are collaborative efforts between and among the four faculty researchers working in Theme

IV. These four projects have progressed in the directions defined at the beginning of Period 2, but the progress in magnetoelectrics in the first half of this Period spawned a collaborative research project between this Theme and Theme II for nanomagnetic switching of nanomechanical devices. The new project, details of which have been presented in the Theme II research section, is an example that while this Theme is the most futuristic, the research can produce results that have nearer term applications.

- **Electric Field Control of Nanomagnets**: The focus of this project that is co-led by **R. Ramesh** and **S. Salahuddin**, in collaboration with **J. Bokor**, all of *UC Berkeley*, is to explore the science of ferromagnet-multiferroic interfaces to enable electric field control of spin transport. More specifically, the goal is ultimately to control ferromagnetism by using electric fields only. Prior research [24] has shown the possibility to alter the direction of a ferromagnet magnetization in contact with the multiferroic material $BiFeO_3$ when a voltage is applied across $BiFeO_3$. The focus of Period 2 is on the synthesis of the thin films and the reduction of the voltage applied to the heterostructure.

  In this Period, we demonstrated full magnetization reversal induced solely by an electric field at room temperature, and elucidated the details of the mechanism. Specifically, two magnetization configurations, anti-parallel and parallel, in a giant magnetoresistance GMR device architecture can now be achieved. The first room temperature device that is capable of writing and rewriting the state of magnetization with the application of only an electric field and reading the state with a simple electron transport measurement has thus been demonstrated.

  The reversal of the magnetization of the ferromagnetic in contact with $BiFeO_3$ is mediated by a strong interfacial coupling. The electric field direction was engineered to result in a 180° rotation of the magnetoelectric domains. This heretofore unreported method of magnetization reversal is a critical advancement to the field of spintronics by providing a unique pathway to writing a magnetic state without the need for an energetically costly magnetic field or large current density. Furthermore, this investigation reveals that the heterostructures of these materials can be integrated into a functional device architecture where the multiferroic and its magnetoelectric switching can be studied in detail. It provides a pathway for further optimization of the device (reduction of physical dimensions and applied voltages across the films thickness). Besides being applicable to logic and memory devices, this finding led to the concept of magnetic switched nanomechanical devices. During this Period, a new collaboration between these Theme IV faculty researchers and the Theme II team leader has been initiated; see Section *II.2aiii*.

  By the end of Period 2, we expect to reduce, by an order of magnitude, the voltage required to reverse the magnetization of the coupled ferromagnet layer. The insertion and the optimization of spin valve devices on top of epitaxial multiferroic $BiFeO_3$ thin films will also be processed.

- **Spin Diffusion for Spin Logic**: The project that is led by **S. Salahuddin**, in collaboration with **I. Siddiqi** and **J. Bokor**, all of *UC Berkeley*, provides a possible scheme for low energy communication between two spin-based logic blocks. This communication scheme, if successful, will be the first demonstration of energy efficiency by mitigating the impedance mismatch between logic devices and the communication link. The goal is to study and understand spin diffusion as a possible means of communication for spin based logic. Magnetic multilayers that can be used to inject spins into metallic channels will be fabricated and structures with non-local diffusion of spins can be probed and controlled. The immediate focus of Period 2 is to optimize the growth and characterize the magnetic multilayers.

  Progress in this Period includes the design of a process flow and subsequent fabrication of non-local spin diffusion structures with 100 nm x 100 nm magnets and <100 nm spacing between neighboring magnets. Sub-100 nm spacing between adjoining magnets sitting on a Cu channel has been realized. Process optimization is continuing. In the remaining months of this Period, we will perform current-voltage measurements.

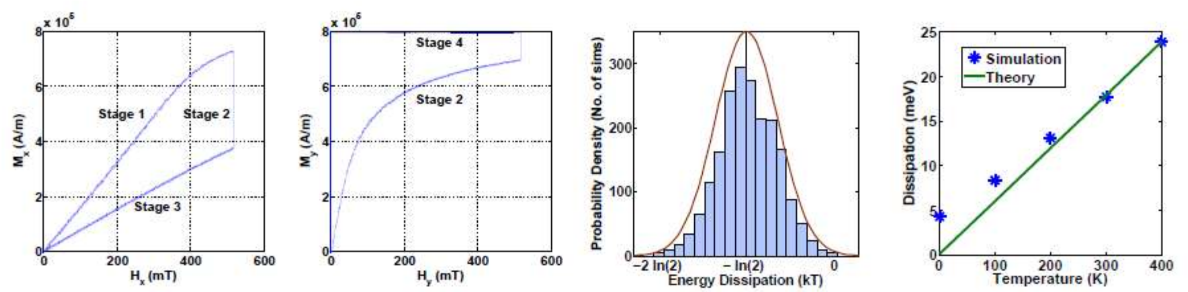
- **Time Resolved Coherent Spin Detection using Magnetometry:** All electrical readout and control of spin systems with superconducting circuitry is an attractive route for studying spin dynamics and relaxation times. This is an ideal setup for performing NMR or ESR studies on doped semiconductors and magnetic nanoparticles, and studying interactions between spins and their substrates. Species with a zero-field splitting (ZFS), such as bismuth doped silicon or NV centers in diamond, are particularly attractive as the absence of a strong magnetic bias field facilitates compatibility with low loss superconducting circuitry. Interactions between a tunable superconducting resonator and an ensemble of spins in a bulk doped diamond NV crystal have been observed, including an avoided crossing indicative of collective strong coupling, as the resonator tunes through the ZFS. Measurements of their relaxation times, and studies on NV centers in diamond using a dispersive nanoSQUID magnetometer and collective coupling to high Q resonators to understand coherence properties as a function of spin density is an objective of this project that is led by **I. Siddiqi**, in collaboration with **S. Salahuddin** and **J. Bokor**. Utilizing species with a zero-field splitting (ZFS), experiments will be designed to explore the link between the classical Landauer limit and the unitarity present in coherent quantum interactions. Another activity planned for Period 2 is the investigation of the dynamics associated with the switching of nanomagnets either through multiferroic coupling, or the passage of a spin-diffusion current (as pursued in the first two projects described above). The goal of this work is to determine the minimum energy needed to flip a nanomagnet and studies of the magnetization dynamics will reveal the specifics of how angular momentum is transferred in these structures.

  To date in Period 2, we have developed a magnetometer with 25 $nF_0/Hz^{1/2}$ flux sensitivity, which translates into a record spin sensitivity of 0.3 $m_B/\ Hz^{1/2}$ for nanomagnets placed at a distance of 100 nm. Our novel design does not employ conventional tunnel junctions and is based on 25 nm wide weak-link junctions incorporated into a 4-8 GHz microwave tank circuit—simultaneously allowing efficient flux coupling and high measurement bandwidth. We have also developed a custom 3-axis vector magnet to manipulate nanoscale spins coupled to the sensor. In addition, we have simulated and measured different lumped and distributed element microwave resonators to coherently couple to a spin ensemble in a semiconductor matrix. The electromagnetic field distribution has been adjusted in different devices to coupling to either bulk doped samples or shallow surface defects. We have successfully observed coupling between bulk samples of diamond NV centers and niobium resonators, and have extracted a spin linewidth of ~ 6 MHz for samples with varying NV density. Our measurements suggest that the spin linewidth is *not* limited by dipolar relaxation and *thus maybe improved by adjusting the implant parameters.*

  In the remaining months in this Period, besides pursuing additional NV loss measurements using 2.8 GHz cavities, the project will also integrate the detectors with nanomagnets produced as part of the other projects in this Theme.

- **Experimental Verification of the Landauer Energy Limit:** The goal for this project is to experimentally verify the fundamental limits of nanomagnetic logic energy dissipation. The direction of this research, led by **J. Bokor**, has largely remained as envisioned at the start of the Center in the Fall 2010. Our interest is Landauer's famous theoretical result that predicts a minimum of exactly kTln2 of energy being dissipated in erasure of a single nanomagnetic bit (Landauer's limit) [1]. This limit has yet to be experimentally verified in the context of a memory bit, and it is our goal to perform such an experiment. To our knowledge, no such experiments have been attempted or reported. We are also interested in the prospects for reversible logic. Bennett has shown [11] that energy dissipation even below Landauer's limit, in principle, is possible for logic systems, in which no information is erased or destroyed, and thus, the logic systems are thermodynamically reversible. However, this possibility has also not been experimentally demonstrated and remains controversial. This project provides the fundamental basis that underlies the overall Theme IV goals. Through the study of the dynamics of energy dissipation in single-domain nanomagnets, we will be laying a foundation for further development of logic devices that can be built in this technology. Landauer erasure, sometimes called the 'restore to one' operation, involves driving a bit that is initially in either its 'zero' or 'one' state with equal probability to the 'one' state with unity probability. To execute Landauer erasure in a nanomagnet with uniaxial shape anisotropy, two magnetic fields are required, one along the magnetic hard axis to lower the energy barrier between the two states and the other along the easy axis to drive the nanomagnet into the 'one' state. This means the total energy dissipation in the nanomagnet is equivalent to the sum of the area of two hysteresis loops, one along each in-plane axis.

We have numerically solved the Landau-Lifschitz-Gilbert equation to calculate the hysteresis loops. The outputs of the simulation were the vectors M(t) and H(t). The hysteresis loops, averaged over the 2000 simulations, are plotted in **Figure 19a a**nd **b**, and a histogram of the energy dissipation, calculated from the area of the hysteresis loops from each simulation, is plotted in **Figure 19c**. The mean energy dissipation was found to be 0.6842kT, which corresponds to a 95% confidence interval of 0.6740kT to 0.6943kT . These values are in very close agreement with the Landauer limit, kT ln(2) = 0.6932kT . Similar simulations were carried out for a range of temperatures from 0K to 400K to verify the linear dependence of energy dissipation on temperature, plotted in **Figure 19d**.



(a)X-axis hysteresis loop (b)Y-axis hysteresis loop (c)Probability density function (d)Energy dissipation vs. temperature

Figure 19: (a) X-axis and (b) Y-axis hysteresis loops of a nanomagnet during the 'restore to one' operation at 300K, obtained by solving the stochastic LLG equation. Each point on the curve is the average of 2000 simulations. The total area of the loops is very close to kT ln(2). Stage numbers correspond to the raising and lowering of external applied fields as described in here. (c) Histogram of the energy dissipated at 300K. The envelope curve was obtained using the Boltzmann thermal distribution calculation described in the supplementary material. (d) Energy dissipation versus temperature. The green line is the Landauer limit, kTln(2), and the blue points are the average dissipation over 2000 simulations carried out at each temperature. The simulations deviate from theory at low temperatures because the nanomagnets take longer to reach thermal equilibrium, weakening the quasi-static approximation.

Nanomagnetic logic circuits consist of interconnected majority logic gates (MLGs), which compute the majority vote of three input nanomagnets and write the result to an output nanomagnet. By calculating the relevant hysteresis loops associated with MLG operation, we showed that although Landauer efficiency is not achieved when the inputs are reset before the output, dissipationless operation is possible when the output is reset before the inputs. Note that while the analysis is for a single MLG, the approach can be scaled to a nanomagnetic logic circuit of arbitrary complexity.

The significance of this simulation work is that it lays the groundwork for an effort aimed at making experimental tests of Landauer's limit and reversible computing. Hysteresis loops as simulated here can be measured if magnetization of nanoscale magnets can be measured accurately while the magnetic fields are applied following the prescription used in the simulations. These ultimate limiting cases of energy efficiency in information processing have never been experimentally tested. Testing these limits will begin by performing initial tests of methods for making well-calibrated measurements of magnetization of nanomagnets. We are planning on using a magneto-optic Kerr effect (MOKE) magnetometer. During the remaining months of Period 2, we will make progress towards developing this magnetometer and calibrating it against vibrating sample magnetometry (VSM) of magnetic thin-film samples.

2avi. Seed Project in Period 2

Metal-Insulator Transition in VO_2. The research of **J. Wu** of *UC Berkeley* included a wide range of discoveries on the metal-insulator transition (MIT) in the correlated oxide VO_2. Phase transition materials are of interest to the Center, as the project can enable new types of energy efficient devices. For example, if successful, new types of transistors can be envisioned: i) a field-effect Mott transistor that could offer extremely steep sub-threshold swing and aggressive size scaling, because the mechanism is based on a sharp, first-order phase transition rather than free charge dynamics; and ii) an electromechanical switch without moving parts, which can reduce or eliminate material fatigue and hysteresis issues in ordinary nanomechanical relays, thus potentially achieving high energy efficiency. These examples mean that Theme I and Theme II both can potentially benefit from this materials research.

Preliminary data have shown that using ionic liquids as the gating medium, a surface metal-insulator transition can be triggered in single-crystal VO_2 nanowires, which stabilizes a ultra-thin (~1nm), ultra-dense (~ $10^{15}cm^{-2}$) electron system on the surface of the nanowires, resulting in reduction of the overall channel resistance by two orders of magnitude (see **Figure 20**).

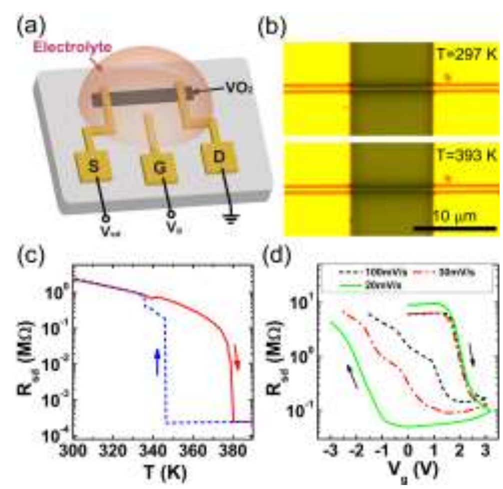


Figure 20: (a) Schematic of device configuration for liquid gating. (b) VO_2 nanobeam below (upper) and above (lower) the MIT temperature. (c) Temperature-dependent source-drain resistance showing the MIT. (d) Source-drain resistance as a function of gate voltage at different sweeping rates.

In Fall 2011, the Center decided to provide seed funding to test the possibility of driving the metal-insulator transition through electrostatic gating. These investigations are focused with the goal of finding applications within the Center. By the end of Period 2, the research plan calls for (i) initial experimental demonstration of electrolyte gated surface metal-insulator phase transition in VO_2; and (ii) the development of an analytical and numerical model of the VO_2 Mott transistor.

2b. *Performance Against Metrics*

Objective	Metrics	Targets	Period 2
Integrative Research	Multi-PI Projects	Period 2: 30% Period 5: 30%	44% (11)
	Multi-Institutional Projects	Period 2: 10% Period 5: 30%	4% (1)
	Multi-Institutional Themes	Period 5: 100%	50% (2)
	Unplanned research projects	Period 3: 1 Period 4: 3	3
	Publications with authors from multiple institutions	Period 3: 12	n/a

2c. *Research in Period 3*

2ci. *System Integration Research*

Continuing in the direction of Period 2, the principal goal of this research area under **E. Alon** of *UC Berkeley* 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. In collaboration with the Themes, we further aim to not only develop circuit techniques that utilize the characteristics of these emerging devices, but to eventually carry out experimental demonstrations of the proposed circuits and perhaps even systems constructed out of the proposed devices. During Period 3, we plan to continue our activities in four key directions:

- Expand our initial analysis on the impacts of device variability to utilize our newly developed generalized framework. This will enable us to provide general predictions of required variability levels for any CMOS-like device. (Themes I and II)
- Complete a comprehensive framework for the design of low-energy photonic links including noise constraints as well as energy/bit versus throughput tradeoffs. We aim to make the framework as general as possible by abstracting the device-level details into a small set of critical parameters - e.g., photo-detector capacitance and responsivity, transmitter efficiency and bias power, switching device transconductance efficiency, etc. (Theme III)
- Continue investigating the ultimate limits of relay-based integrated circuit performance, area, and energy. Device/circuit co-design for 1GHz operation of complete systems such as microprocessors will be explored. (Theme II)
- Collect information, in collaboration with any of the other interested researchers from the center, on a broader variety of the alternative switching devices (e.g., TFETs, FeFETs, etc.) being explored in the center and evaluate their tradeoffs with respect to CMOS technologies. We will develop device-specific circuit design techniques that optimally exploit the device characteristics, and will further provide feedback to the device designers as to the highest impact axes for improvement. (All Themes, but focusing on Themes I and II).

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

The scientific elucidation of energy level sharpness, seen in transport, will continue to be a very fundamental project goal of this Theme. In Period 3, the Theme I research team will continue to answer the question: how sharp can an energy level, or a band-edge, be at room temperature? This is on track to be discovered by several co-PI's in the Center, as the Type III InAs/GaSb devices that we have been making will allow accurate measurement of band edge sharpness in electronic transport for the first time.

- At UC Berkeley, the **E. Yablonovitch** group will be determining the bandedge sharpness arising from the overlap of valence and conduction bands in a nano-device, or alternately spectroscopically of the sharpness of individual pairs of levels between quantum dots. Anticipated problems include the possibly that spatial inhomogeneity of the larger size test devices may prevent the problem to be elucidated. The conduction step in the forward direction is actually the Esaki diode negative resistance region. We also have anticipated a problem with the specific devices that were designed in the group may have numerous parasitic effects that prevent the observation of a very sharp step in the reverse direction, and thus, the true limiting bandedge sharpness. During Period 3, we anticipate that additional series of growth runs will likely be required to achieve the goal of scientific elucidation of energy level sharpness. The design of structures for additional growth runs will be assisted by the Berkeley Quantum Transport Simulator (BQTS) that will continue to be enhanced in Period 3, under the direction of **S. Salahuddin**, in its capability for real time particularly for tunneling transistors.
- At MIT, the groups of **D. Antoniadis** and **J. Hoyt** will focus on fabrication and analysis of a second lot of InAs/GaSb diodes and MOS capacitors to assess maximum tunneling current, study 2D to 2D tunneling, and characterize the gate dielectric/semiconductor interface. This will be followed by fabrication and analysis of InAs/GaSb vertical QW TFETs, optimized from experimental diode and MOS capacitor results. In addition, "calibration" of a fast semi-empirical device simulator to advanced physics-based simulator (Sentaurus Device to OMEN). The simulators will be used in tandem to analyze results from fabricated diodes and capacitors, and to model TFETs. The goal for the end of the Reporting Period is to design InAs/GaSb three-terminal TFET structures via modeling and simulation that can reveal the physics and are practical to fabricate.

The experimental study of device physics using the XOI materials platform will continue under the direction of **A. Javey.** We will continue to use this approach for fabrication of III-V TFETs, specifically InAs/GaSb, from the XOI platform. We will expand the set of materials that can be transferred using the XOI platform; however, each material system requires a different set of etch chemistries and transfer conditions. This issue will be addressed by taking advantage of the significant volume of research on III-V etch chemistries as the starting point for transfer of each material, to be followed by optimization of the etch chemistries.

The screening for Type III layered chalcogenides such as MoS_2, WS2, TiS, TiS_2 ZnS_2, TaS_2, PtS_2 SnS_2 and NiS etc, will continue by **V. Rangari** and **K. Das** at *Tuskegee*, involving material synthesis using microwave or sonochemical synthesis technique, and characterization for morphology, their bandgap and other optical and electrical properties. The screening effort will complement the effort of **A. Javey** to expand the XOI platform to include layered semiconductors as a novel channel material for future TFET devices. The fundamental materials properties as well as the properties of resulting devices of these novel material systems will be studied. The method to transfer these materials is being developed and the resulting films will be characterized optically and electrically. The main characterization will be through photoluminescence (PL) measurement, Raman scattering and carrier transport measurements.

Another key goal in Period 3 is that **E. Fitzgerald** to have established a MOCVD growth capability that will produce GaSb/InAs heterostructures for use by a number of co-PI's in the Center, in particular for **D.Antoniadis, J. Hoyt**, and **E.Yablonovitch**. Establishing an internal capability of producing heterostructures in this system will also allow the Center's co-PI's to observe the influence of growth parameters on device characteristics, which will also help determine the influence of interface abruptness etc. on device performance. Investigations of a derivative of the

GaSb/InAs system in which the GaSb hole-gas layer is replaced with Ge will continue to be pursued. We are interested in the effect of the heterovalent Ge/III-V interface on tunnel characteristics. In addition, this type of heterostructure could evolve into a tunnel system in which all layers are comprised of column IV elements except for the InAs electron gas layer.

For device approaches, alternative to TFETs, Salahuddin, in collaboration with Hu, will continue to work on design and fabrication of negative capacitance FET. Growth of $BaTiO_3$ on single crystalline BTO substrates and on Pt coated Si under optimized growth conditions are key milestones in Period 3.

In Period 3, another approach, alternative to the density of states TFETs, will be initiated by **J. del Alamo,** who will investigate a new concept for steep-slope nanowire FETs with a superlattice source (SLS) in which a miniband structure has been created. This concept has been proposed by Gnani et al. [26] [27], and verified through simulations. Achieving a steep-subthreshold swing (S) in an FET requires suppressing the subthreshold regime. This, in essence, is the injection of relatively high-energy source electrons above the energy barrier with the channel. A way to accomplish this suppression is to create a mini-band in the source with a mini-gap above where no states are allowed [26] [27]. If appropriately designed, no current is possible until the top of the source miniband lines up with the conduction band edge in the channel. The transition between the ON state and the OFF state can be quite sharp and the attainable ON current can reach a value comparable to that of a regular FET. In theoretical calculations performed by Gnani et al., they have concluded that a variety of SL's can accomplish these goals: AlGaAs/GaAs, InAlAs/InGaAs, and AlGaN/GaN, among others. These are short period SL's with barriers and wells in the 1-2 nm regime. 7 periods appears to be enough to accomplish the filtering action of the SL. They have shown that values of S in the 10-20 mV/dec are possible (at 300K). The Center's goal is to demonstrate a prototype SLS NW-FET in the InAlAs/InGaAs system and to study its suitability for steep-subthreshold and ultra-low voltage operation.

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

The research goals for Theme II will continue to be voltage and size reduction, and reliability improvement, for nanomechanical switches. The projects at UC Berkeley and Stanford University will be a continuation of those that were in progress in Period 2. At MIT, additional effort will be applied toward the development of single tunneling gap technology with the addition of a new co-PI. The project to investigate magnetoelectrically actuated mechanical switches will be a close collaboration between Theme II and Theme IV researchers during Period 3. Close collaborations with the group of **E. Alon** to identify and explore compelling applications for zero-leakage switch technology with device performance and endurance requirements projected to be attainable with nanomechanical switches will ensure that these projects are relevant to future energy efficient electronic systems.

- The key goal in Period 3 for the group of **T.J**. **King Liu** will be the demonstration of electrostatic relays operating with voltage swings below 100 mV. Approaches for achieving thin and electrically conductive structural beams with very low strain gradient will continue. Examples of such approaches include ion implantation to fine-tune the strain gradient, and the use of an amorphous metallic structural material. Scaling of surface adhesion force with contact dimple area reduction will be verified for deep-sub-micrometer (<50 nm) contact dimple areas. The impact of contact area scaling on relay on-state resistance also will be assessed. Monolayer coatings to mitigate surface adhesion forces and improve relay reliability will be explored in collaboration with other faculty researchers at UC-Berkeley and MIT.
- The continuing research efforts in of the group of **H.-S. P.Wong** have four goals in Period 3:

- Demonstrate 3-terminal graphene-beam switches with sub-10 nm actuation gap whose dimensions are within the range for achieving sub-10k_BT switching energy without stiction and stress-related issues. CNTs will be investigated as an alternative structural material.
- Establish fabrication processes for NEM relays that incorporate a graphene or CNT interfacial layer at the contact. This is expected to provide for improved reliability due to the wear-resistant and low-stiction features of carbon, which will be investigated in detail and compared against other materials (*e.g.* self-assembled monolayers, TiO_2, Al_2O_3). Two types of devices will be used for this study: one is a laterally actuated switch whose sidewall is coated with thin SiC or metal catalysts and then is annealed for direct synthesis of a graphene interfacial layer on the beam; another is a vertically actuated switch for which transferred graphene or CNT is used as interfacial layer; this process can easily accommodate fabrication of 4-terminal relays as well as 3-terminal switches. The SiC films will be deposited in the Marvell Nanofabrication Laboratory at UC-Berkeley.
- Experimentally demonstrate the proposed optimum energy-reversible operation. Also, experimentally demonstrating the dynamic characteristics of a 3-terminal switch with an integrated feedback resistor. Analyses have shown that these two designs are beneficial for reducing the impact velocity at the contact, which should enhance the switch reliability.
- Complete an assessment of the feasibility of contact-less relays that use a deformable dielectric tunneling layer. Dielectric materials that are sub-10nm thick and are highly compressible are the key to the success of these devices, driving new collaboration with a chemist or material scientist to explore this option.

• A nanomechanical relay that switches via tunneling through a single gap in the form of a nanocomposite material is the goal of **V. Bulovic** and **J. Lang** in Period 3. The new switch design is planar, and has a single tunneling gap between two parallel metal surfaces. The gap size will be actuated electromechanically, and stood off with a mechanical spring formed by attaching sparsely spaced insulating organic molecules between the two surfaces in the form of a self-assembled monolayer (SAM). The molecules will be bent and compressed as the gap closes. Alkyl-thiols, for example, might serve as an elastic insulating layer between electrodes. Given that the SAM will be sparse, conventional metalization through sputtering or e-beam deposition is not appropriate. Thus, metalization through metal-film transfer printing, as described above, will be a critically important fabrication process step. There are two significant fabrication-related challenges for the new switch design. First is the assembly of the sparse insulating monolayer on the surface of the bottom electrode; **T. Swager**, John D. MacArthur Professor of Chemistry at *MIT*, will be added to the Center to aid in selecting the proper monolayer material; see Swager's biosketch in **Appendix A**. Second is the creation of the second electrode; a modification of the newly developed metal-film transfer printing process, to reduce the stress required to transfer the metal film (to adhere to the SAM) will be made to meet this challenge.

• The newest Theme II project to investigate magnetoelectrically actuated mechanical switching will be pursued as a collaboration between **T.J. King Liu** and **J. Bokor** and other Theme IV researchers. This project will tightly integrate Themes II and IV. The first phase of this project will involve making calculations of the force between opposing nanomagnets as a function of the magnet dimensions, geometry, magnetization direction, and other parameters. These calculations will allow for an evaluation of the potential of this new switch concept. Based on these results, a process flow for fabricating test structures to experimentally validate the concept will be designed, and initial fabrication efforts will be commenced. The design of the switch and its fabrication process will involve close collaboration between Theme II researchers with great experience in NEM devices and Theme IV researchers with experience in nanomagnetic materials.

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

All four Theme III projects will continue in Period 3.

- **Nano-Laser:** This project under **M.C. Wu** will continue to focus on achieving electrical pumping. Upon completion of device fabrication, the measurement equipment will be setup to test the devices. This will be followed by full optical characterization of the electrically pumped lasers. Assessment will be made on the optimization that will be pursued. Activities to increase of operation of the laser will be initiated in the later part Period 3.

- **Spontaneous Hyper Emission (SHE) Nano LED:** The fundamental challenge for creating nanophotonic devices is the nanofabrication process for integrating nanoscale semiconductors with optical antennas while preserving the high optoelectronic quality of the semiconductors. Another challenge is to control the surface states of the semiconductor as the surface-to-volume ratio for these nanoscale photonic devices is extremely high. Although low-damage etching has been developed, passivation of surface states remains a challenge that must resolved to obtain a high-efficiency device. This project will develop surface passivation techniques to solve this problem. Solving this problem will also make detection much easier since a high-efficiency device will be capable of higher power output.

  For the next Period, guided by **M.C. Wu** and **E. Yablonovitch**, the primary goals include: (1) Explore the experimental setup for measuring the radiative lifetime in nanoLED. (2) Quantify the enhancement factor of spontaneous emission in nanoLED.

  Even with more efficiency devices, more sensitive equipment will be needed to accurately measure the nanoLEDs. Different measurement setups will be explored and possible device changes will be assessed. To obtain sensitive enough equipment the wavelength of operation may be changed to the visible wavelength range where more sensitive equipment is available. Collaborators will also be sought out that have the ability and background in measuring low-power long-wavelength devices.

- **High Sensitivity III-V Photodetector on CMOS:** For the next research period, the group of **C. Chang-Hasnain** will continue to develop highly sensitive, low power nanopillar photodetector for energy efficient optical interconnects. We plan to further develop our processes to realize avalanche gain at <5V reverse bias in single nanopillar photodetector. We will also improve sensitivity and electrical characteristics to demonstrate > 10 GHz operation with low energy consumption. Device characteristics, such as carrier transport, capacitance and optical absorption, will be further refined with electrical and optical simulation to optimize the detector design. Process optimization, such as finding better capping material and better process control, will be done to reduce device capacitance and leakage current.

  In addition to demonstrating low power, highly sensitive single nanopillar photodetector, we propose to develop site-controlled growth of nanopillar with > 50% yield so that a photodetector array can be made. Our preliminary experimental results show that the growth location of the nanopillar can be controlled by a patterned SiO_2 mask. We will develop a detailed experimental study and theoretical modeling to study the nucleation mechanism of nanopillar to get to site-controlled growth. Site-controlled growth of nanopillar photodetector will move the project closer to Theme III's goal of fully integrated, energy efficient optical interconnects.

- **Optical Antenna-Coupled Nanophotodetector:** One of the primary considerations is the tradeoff in lowering the capacitance and having high sensitivity. To address that we need to investigate from the receiver circuit level our energy consumption as a factor of these two variables to find an optimization point. We will work with **E. Alon** in designing and analyzing a receiver circuit for this. Additionally we need to fabricate and characterize an optimized nanophotodiode, in order to verify the simulation results obtained in Period 2. This will give us confidence in our theory and simulations, and demonstrate a working high efficiency nanophotodiode. Finally since many other photonics components are integrated directly onto silicon waveguides [25], it is very interesting to investigate how to create an efficient nanophotodiode integrated onto such a waveguide. We can use our existing theory to guide our design and simulation of such a device.

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

All four Theme IV projects and the newly initiated collaborative project with Theme II will continue in Period 3. All projects involving Theme IV are collaborative research efforts.

- **Electric Field Control of Nanomagnets:** A key goal in Period 3 for this project that will be led by **R. Ramesh**, in collaboration with **S. Salahuddin** and **J. Bokor**, is the development of theoretical simulations to validate and optimize a device structure. Test structures will be designed to validate the fundamental principle of the device. Furthermore, we will continue to investigate the possibility of electric field induced magnetization control using multiferroic materials with different orientations and domain configuration.

  Characterization of the magnetic state of the top ferromagnetic layer using magnetic force microscopy (MFM) and photoemission electron spectroscopy will be performed towards an initial readout of the device. Ultimately the readout will be based on transport using incorporated magnetic tunnel junction (MTJ) devices.

- **Spin Diffusion for Spin Logic:** The focus to optimize and fabricate working non-local device structures will continue, led by **S. Salahuddin**. These devices will be fully characterized in the R-H-V phase space at room temperature, in collaboration with **I. Siddiqi** and **Bokor**. Low temperature measurements will be initiated during the latter part of Period 3.

- **Time Resolved Coherent Spin Detection using Magnetometry:** In the coming year, the team that is led by **I. Siddiqi**, will undertake two basic experiments: (i) observation of spin dynamics in metallic spin diffusion magnetic switches and (ii) the development of semiconductor spin ensemble memories/logic.

  The experiments to observe spin dynamics will be undertaken in collaboration with **S. Salahuddin** and who is developing the spin transport structures. The devices envisaged at present consist of two separate ferromagnetic dots coupled via a high diffusivity copper conductor. A spin current injected via one magnet will induce state inversion in the other, which maybe be biased into a region of metastability via an external magnetic field. The key scientific goal of this experiment is to determine the energy required to initiate switching by directly measuring either the rf transient voltage or magnetic flux during switching with the sensors described above. During the coming year, we will (i) modify our sensors to operate with lower flux sensitivity but higher bandwidth to sense the transient fields of a switching nanomaget, (ii) integrate our sensors with devices produced by **S. Salahuddin** and **J. Bokor**, and (iii) characterize the operation of the spin diffusion switch at various temperatures.

  For the experiments on semiconductor spin ensembles, we will characterize the spin linewidth of different diamond NV samples prepared with varying implant energies/recipes and densities.

We will also characterize Bi impurities in isotopically purified ^{28}Si. Both of these samples are being prepared by Dr. Thomas Schenkel at LBNL. The fundamental goal is to reduce the ensemble spin linewidth below 1 MHz so that a long-lived memory can be realized. We will (i) indentify the dominant relaxation mechanism and (ii) quantify the role of surface defects, (iii) bulk defects, and (iv) dipolar relaxation.

- **Experimental Verification of the Landauer Energy Limit:** The experimental effort to confirm the theoretical demonstration that nanomagnet erasure can reach Landauer's limit of energy dissipation will continued to be led by **J. Bokor**. Our approach shows a clear path for how to do this by measuring hysteresis loops when the magnetic fields are applied in a specific sequence. Experimental studies that test the results of our simulations involve the use of a magneto-optic Kerr effect (MOKE) apparatus with a quadrupole electromagnet to apply a DC magnetic field in the plane of the surface of a sample with arbitrary angular orientation of the field within the plane. The MOKE apparatus will be used to carefully measure hysteresis loops for nanomagnets and extract energy dissipation from this data. The sensitivity of this system is not sufficient to measure the magnetization of a single nanomagnet, but we can fabricate an array of identical nanomagnets and overlap a large number of them with the laser spot in the MOKE system. In this way we can get a sufficiently large signal.
- N**anomechanical Relays with Magnetoelectric Switching Elements**: The Period 3 direction of the relatively new collaborative project between Theme II and Theme IV has been described in Section *II.2ciii*. Here we note that the MOKE apparatus developed to support the fourth Theme IV project will also be used for this nanomechanical relay project.

2cvi. Seed Project in Period 3:

Metal-Insulator Transition in VO_2: The group under **J. Wu** will continue to study the properties of the ultra-thin, ultra-dense surface electron system in VO2 and develop theoretically understanding of the gate-controlled surface metal-insulator transition using the numerical and analytical model that will be completed by the end of Period 2.

Planned Period 3 milestones include: i) growth of high-quality VO_2 thin films using pulsed laser deposition, comparing effects of ionic liquid and solid HfO2 gating, and performing Hall effect and magneto-transport measurements on the gated VO_2 surface; ii) optimized the materials and structures to reduce the hysteresis and enhance the ON/OFF ratio for operation as a Mott transistor; and 3) completion of finite-element modeling of the electrostatics and electrodynamics of the system to understand the physics and energetics of the surface metal-insulator transition.

It is part of the responsibility of **J. Wu** to develop new collaborations with researchers of the Center's Themes and become an integral member of the applicable Themes. Collaborations with **S. Salahuddin** on the negative capacitance project in Theme I, and **T.J. King Liu** on nanomechanics in Theme II will be explored.

III. EDUCATION

1a. *Goals and Objectives*

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

- To train in the graduate programs of the Center's participating institutions, a new generation of Ph.D. and M.S.-level scientists and engineers who, on completion of undergraduate and graduate programs at Center universities, will
  - be facile with 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 train an engaged, skilled and diverse technical workforce by cultivating a pipeline of students from secondary school to college.
- To develop methods to retain these individuals within the E^3S research areas.

The focal point of the Center is research. Therefore, the Center's leadership is making a concerted effort to develop education programs that integrate research and education. In its effort to develop a new generation of Ph.D. and M.S.-level scientists and engineers, the Center offers ongoing training on energy efficient electronics topics and professional development opportunities for its graduate students and postdocs; these efforts are described in this Section III. Because of a strong emphasis in including female and students from under-represented groups, the efforts to cultivate a pipeline of students from secondary school to college will be presented in Section *VI* – Diversity.

1b. *Performance Metrics*

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

Objective	Metrics	Frequency
Education	E^3S Training	Yearly
	Students and postdocs participating in leadership programs	Yearly beginning in Year 2
	Increase transfer rate to 4 year college among those students who have made contact with Center	Yearly beginning in Year 2
	Number of events leading to external articles on Center	Yearly beginning in Year 2

In Period 2, we recognized the need for more accurate and measureable goals for Education. Thus, the Education performance indicators have been revised in the Center's Strategic Plan as follows:

Objective	Metrics	Frequency	Targets
Education	Number of Center graduates who have completed E^3S training	Yearly beginning in Period *2*	Period 2: Baseline Period 3: 50% Period 5: 100%

	Number of publications with student and postdoc authors who have published previously in other research themes	Every 2 years beginning in Period 3	Period 3: 9 Period 5: 12
	Number of students and postdocs participating in education programs	Yearly beginning in Period 2	Period 2: 5% Period 3: 60% Period 5: 75%
	Number of students and postdocs serving in leadership roles in the Center	Yearly beginning in Period 2	Period 2: Baseline Period 3: 15% Period 5: 20%
	Number of events leading to external articles on the Center	Yearly beginning in Period 2	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase

1c. Problems Encountered

Two primary problems were encountered during this reporting period: 1) difficulty in building a Center community at all partner locations, and 2) difficulty in widespread participation of students in activities. While a natural sense of community has been developed at UC Berkeley, the lead institution where the majority of the Center's faculty, graduate students, postdocs, and staff are located, it has been difficult for the Center to build a sense of community at the partner locations. The student and postdoc community at the partner institutions (MIT - 12, Stanford, - 3, and Tuskegee - 3) is much smaller, making it more difficult to replicate this sense of community cultivated at UC Berkeley (57). The Student and Postdoc Retreat was intended to help overcome this challenge by bringing students and postdocs together annually to share research experiences, participate in ethics and professional development training, and thereby, foster a sense of community across the Center. However, in August, inclement weather prevented participation of most of MIT's graduate students and postdocs at the Center's Annual Retreat and the Annual Student and Postdoc Retreat. This resulted in a missed opportunity to build a sense of community across the institutions and less individuals completing the Center's ethics training.

In this reporting period, the Center has had difficulty in widespread participation of students in activities. Approximately 42 students from the Center participate in the majority of the Center's activities. We have found that the same students volunteer for the Center's research and educational activities. The Center's leadership is concerned that this level of involvement from a small number of students and postdocs will result in burnout and frustration. Therefore, the Center plans to develop a process to engage a larger number of graduate students and postdocs in Center activities. The Center plans to explore the concept of a formal agreement requiring all students and postdocs funded by the Center to commit a small number of participation hours to educational and diversity programs.

2a. Internal Educational Activities

Activity Name	Annual Retreat
Led by	**E. Yablonovitch** (Berkeley)
Intended Audience	Faculty, Staff, Students, Postdocs, and Partners
Approx Number of Attendees (if appl.)	Total – 29 Graduate Students: 20 Berkeley, 3 MIT, 0 Stanford, 1 Tuskegee Postdocs: 4 Berkeley, 0 MIT, 1 Stanford

The 2nd Annual Retreat was also an education event for the graduate students and postdocs (see **Appendix K: 2011 Annual Retreat Agenda**). E. Yablonovitch, Center Director, communicated the

Center's values, while J. Yuen, Executive Director, presented a summary of the Center's Management. The audience learned about the Center's research, through technical talks led by Center Theme Leaders (E. Yablonovitch, T.J. King Liu, M.C. Wu, and J. Bokor) and Systems Integration lead, E. Alon, and the Center's Education and Outreach mission and programs presented by S. Artis, Education and Outreach Director, and S. Sidharta, Faculty at Contra Costa College, an Education Partner. The students and

Activity Name	Annual Student and Postdoc Retreat
Led by	**S. Artis** (Berkeley), Graduate Student and Postdoc Council (GSPC)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 14 Graduate Students: 9 Berkeley, 3 MIT, 0 Stanford, 1 Tuskegee Postdocs: 1 Berkeley, 0 MIT, 0 Stanford

In August, the Center hosted an Annual Student and Postdoc Retreat for graduate students and postdocs (see **Appendix L**). Graduate students and postdocs spent a half-day in breakout sessions by research theme as well as a group session discussing their research projects and opportunities to collaborate. The other half of the day was focused on ethics training. This portion of the meeting was organized as part of the Center's objective to ensure all members are informed of responsible conduct of scientific research. Students and postdocs participated in ethics training conducted by S. Artis, Education and Outreach Director. The Student and Postdoc Retreat also consisted of a professional development workshop on publishing, but the event was postponed to a later date due to inclement weather, which prevented the speakers from attending the retreat (see description in Section *III.2b*, Professional Development Activities). This retreat also included an evening activity where the participants continued to informally discuss and share research results.

Activity Name	Graduate Student and Postdoc Council (GSPC)
Led by	**R. Going** (Berkeley) and **J. Teherani** (MIT)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 14 Graduate Students: 9 Berkeley, 3 MIT, 0 Stanford, 1 Tuskegee Postdocs: 1 Berkeley, 0 MIT, 0 Stanford

The goal of the Graduate Student and Postdoc Council (GSPC) is to build a community of leadership and peer relationships among a diverse group of students and postdocs. At the beginning of this reporting period, the GSPC met regularly to organize centerwide events for graduate students and postdocs. These events include the spring research meeting between UC Berkeley and Stanford, the Journal Club, and the Annual Student and Postdoc Retreat. Even though these centerwide activities were implemented, regular GSPC organizing meetings have been poorly attended, so participation in the GSPC meetings are now called as needed. At August's GSPC meeting, students and postdocs discussed their involvement in the Center and future council programs and activities and participated in an evaluation of the Center's Leadership (see **Appendix M: Student and Postdoc Evaluation of Center's Leadership Team**). In this Period, the GSPC meeting was led by 2 graduate students (1 Berkeley and 1 MIT) and was mentored by S. Artis, Education and Outreach Director. The majority of the students and postdocs expressed interest in more networking and professional development opportunities. The GSPC also expressed concerns about a small number of students and postdocs being involved in education and diversity programs and being more engaged in the Center's management. They also discussed resolutions to their concerns. It was suggested that the Center incorporate more professional development during the Annual Student and Postdoc Retreat, require all students and postdocs funded by E^3S to commit to a small number of education and outreach hours per year, and to have graduate student and postdoc representation on the Center's Executive Committee.

Activity Name	Research Seminars
Led by	**S. Agrawal** (Berkeley) and **A. Khan** (Berkeley)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	**Appendix B: Research Seminars**

Research Seminars was the first regularly scheduled centerwide activity, having been initiated within weeks of the start of the Center. It is a vehicle to share research being undertaken at the Center across research themes and member institutions, as well as an educational forum. To date in Period 2, eight Research Seminars were conducted via WebEx to enable participation by all Center institutions. See **Appendix B: Research Seminars and Journal Clubs**.

Activity Name	Journal Club
Led by	**A. Khan** (Berkeley)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	**Appendix B: Research Seminars**

A Journal Club was initiated by the GSPC as a vehicle to learn about relevant research undertaken outside the Center in Summer 2011. A. Khan, a graduate student at UC Berkeley, has been coordinating this activity. Presenters share a series of published papers prior to the meeting. During the meeting, the presenters review the research of the selected papers and share the findings that they consider to be significant and interesting and relevant to the Center's goals. Starting this past summer, the Journal Club held seven meetings. There was faculty participation at all Journal Club meetings. See **Appendix B: Research Seminars and Journal Clubs**.

Activity Name	Spring Research Meeting
Led by	Graduate Student and Postdoc Council (GSPC)
Intended Audience	Students and Postdocs at UC Berkeley and Stanford
Approx Number of Attendees (if appl.)	Total – 10 Graduate Students: 7 Berkeley, 1 Stanford Postdocs: 0 Berkeley; 2 Stanford

The GSPC organized the Spring Research Meeting to build relationships between the students and postdocs of UC Berkeley and Stanford. The weekend event, which took place at Stanford, included research presentations in the afternoon and an evening informal networking activity.

Activity Name	E^3S Symposium – 2nd Berkeley Symposium on Energy Efficient Electronics Systems
Led by	**E. Yablonovitch** (Berkeley)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 44 Graduate Students: 35 Berkeley, 3 Stanford Postdocs: 5 Berkeley; 1 Stanford

While one purpose of the 2nd Berkeley Symposium on Energy Efficient Electronic Systems is to promote international collaboration in the growing research field of energy efficiency in devices and circuits, it also served as an educational forum for the students and postdocs of the Center to learn about research outside the Center, as there were 16 presentations on research and perspectives from outside the Center. This symposium helped graduate students and postdocs see the Center's work in the context of others in the field. For details, see Section *IV.2a*

Activity Name	E^3S Course on Commercialization and Innovation
Led by	**E. Fitzgerald** (MIT)
Intended Audience	All Center Members
Approx Number of Attendees (if appl.)	Will vary by course offering

By the end of Period 2, in the spring semester/winter quarter, E. Fitzgerald will teach an online course. The course, entitled "Commercialization and Innovation", will be offered to all Center members, including the Center's faculty. The goal of the course is to educate Center members on how to translate innovation into products in a changing marketplace. Furthermore, this course will serve as an education course for the graduate student and postdocs as well as fulfill the goal of two-way knowledge, information, and technology exchange in the Center's Strategic Plan.

Activity Name	E^3S Internship (ETERN)
Led by	**S. Artis** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx Number of Attendees (if appl.)	Not available at this time.

The primary goal of E^3S Internship (ETERN) program is to provide research experiences to lower-level undergraduate student to attract students to research opportunities in energy efficient electronics science and the pursuit of graduate study in science and engineering. The ETERN program is an academic program for undergraduates at all of the Center's institutions. This first cohort of ETERN scholars will begin their research in E^3S faculty groups in January 2012. One student at MIT has already been assigned to work with D. Antoniadis. These students will be supervised by E^3S faculty and mentored by E^3S graduate students and may participate in any Center-wide activities for students and postdocs.

2b. *Professional Development Activities*

- Activities Open to the Entire Center

Activity Name	Poster Session at Annual Retreat
Led by	**S. Artis** (Berkeley)
Intended Audience	All Attendees of Annual Meeting
Approx Number of Attendees (if appl.)	Total – 28 Graduate Students: 20 Berkeley, 3 MIT, 0 Stanford, 1 Tuskegee Postdocs: 4 Berkeley, 0 MIT, 1 Stanford

The Poster Session at the Center's Annual Retreat was an opportunity for the graduate student and postdoc attendees to present their E^3S related research. Public technical presentation and dialog contributes to the building of communication and leadership skills. This event gives graduate students and postdocs presentation experience and an opportunity to network with industry partners. This portion of the meeting was organized as part of the Center's objective to provide leadership experiences to the Center's graduate student and postdocs. There were 18 posters at the 2011 Annual Retreat; see **Appendix K**.

Activity Name	Ethics Training
Led by	S. Artis (Berkeley)
Intended Audience	All Attendees of Annual Meeting
Approx Number of Attendees (if appl.)	Total – 14 Graduate Students: 9 Berkeley, 3 MIT, 0 Stanford, 1 Tuskegee Postdocs: 1 Berkeley, 0 MIT, 0 Stanford

At the Annual Student and Postdoc Retreat, S. Artis, trained the students and postdocs on scientific ethic. The hour-long ethics training covered the following topics: scientific standards, history of scientific ethic codes, types of research misconduct. In addition, the students examined and presented solutions to engineer case studies on ethical misconducts. 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	Project Management and Mentor Training
Led by	**J. Yuen** (Berkeley); **S. Artis** (Berkeley)
Intended Audience	Graduate Student and Postdoc mentors
Approx Number of Attendees (if appl.)	Total – 12 Graduate Students: 9 Berkeley; Postdocs: 3 Berkeley

As part of the Center's objective to provide leadership experiences to the Center's graduate student and postdocs, graduate students and postdocs who served as mentors in the Center's summer undergraduate and precollege programs participated in a project management and mentor training. The project management training provided an overview of project management, including the following topics: important of project management, project management defined, steps in project management. Whereas, the mentor training provided an overview of how to be a mentor, including the following topics: what is/is not mentoring, impact of effective mentorship, and mentoring in action.

Activity Name	Graduate Student and Postdoc Council (GSPC) Event Coordinator
Led by	**R. Going** (Berkeley)
Intended Audience	All Students and Postdocs of the Center
Approx Number of Attendees (if appl.)	Total – 9 Graduate Students: 6 Berkeley, 1 MIT, 1 Stanford Postdocs: 0 Berkeley; 0 MIT, 1 Stanford

Throughout the reporting period, the GSPC organized several center-wide events that allow graduate students and postdocs to further develop their leadership, organization, and planning skills. These events include the spring research meeting between UC Berkeley and Stanford, the summer journal club, and Annual Student and Postdoc Retreat. As event organizers of these events, graduate students and postdocs are the primary points of contact for successfully implementing these different events.

Activity Name	Theme Meeting Coordinator
Led by	Theme Leaders (Berkeley)
Intended Audience	All Attendees of Theme Meetings
Approx Number of Attendees (if appl.)	Total – 2 Graduate Students: 2 Berkeley

Three of the four themes host bi-weekly theme meetings for the faculty, graduate students, and postdocs in their theme. This is an opportunity for theme members across different research groups, research projects, and institutions to come together to share research updates and foster collaborations. The theme meeting coordinator is typically responsible for the logistics of scheduling and setting up a virtual meeting across institutions. In some instances, the theme meeting coordinator also participates in agenda setting.

Activity Name	Professional Development Seminar: *How to Publish Successfully – Two Editors' Perspectives*.
Led by	**J. Yuen** (Berkeley)
Intended Audience	All Graduate Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 18 Graduate Students: 10 Berkeley, 3 MIT, 0 Stanford, 0 Tuskegee Postdocs: 5 Berkeley; 0 MIT, 0 Stanford

In September, the Center hosted a seminar titled, *How to Publish Successfully – Two Editors Perspective*. Two E^3S faculty, **E. Alon** (UC Berkeley) and **J. del Alamo** (MIT), and current technical journal editors of IEEE Transactions on VLSI Systems and IEEE Electronic Device Letters, respectively, provided their perspectives on what they believe are successful strategies for academic publication, providing real examples of what works and what does no work. After each professor provided a 15-20 min talk of his perspective specific to the journal with which he is working. The session concluded with time for questions and answers.

- Activities for Postdocs Only

Activity Name	REU Selection Committee
Led by	**J. Yuen** (Berkeley)
Intended Audience	All Postdocs at Berkeley
Approx Number of Attendees (if appl.)	Total – 3 Postdocs (Berkeley)

Postdocs were invited to serve on the selection committee for the E^3S Research Experience for Undergraduates. As a member of the selection committee, each postdoc reviewed the application, personal statement, transcript, and letters of recommendations of ~6 applicants. Based on the review, the postdoc provide a list of applicants that should be considered for placement in a summer research project.

Activity Name	Organizers and Presenters at REU Visit to Stanford
Led by	**S. Artis** (Berkeley); **D. Lee** (Stanford)
Intended Audience	All Postdocs at Stanford
Approx Number of Attendees (if appl.)	Total – 3 Postdocs (Stanford)

During this past summer, three postdocs at Stanford University hosted a visitation day for summer research students from the Center's Research Experiences for Undergraduates program. The postdocs were in charge of planning the visit, which included three presentations from Center members about their energy efficient electronics science research, a tour of the Stanford Nanofabrication Center to observe and learn about the fabrication of semiconductors, a tour of Stanford University, and an overview of the graduate admissions process.

- Individual Activities

  Students and Postdocs

  - Summer Course at Purdue University: **T. Johonson**, a Ph.D. student at Tuskegee University, attended the NSF-funded Network for Computational Nanotechnology's weeklong summer course titled, *Electronics from the Bottom Up: A New Approach to Nanoelectronic Devices and Materials*, at Purdue University. The summer course featured a set of ten lectures on the topic "Near-Equilibrium Transport: Fundamentals and Applications" and a set of five lectures on "Solar Cell Fundamentals." Five tutorials on selected topics in nanoscience and nanotechnology were also presented. T. Johnson was able to get cross training in a new topic area, quantum physics of nanoelectronics.
  - Student Representative at Science and Technology Center (STC) Director's Meeting: **R. Going**, a Ph.D. student at UC Berkeley, served as the student representative at the STC Director's Meeting. R. Going participated in the student breakout sessions and participated in the poster session. This was a great opportunity for R. Going to network with students from other STCs and to further cultivate his leadership skills as Chair of the Graduate Student and Postdoc Council.
  - Group Coordinator: In the absence of R. Ramesh, **M. Trassin**, a postdoc funded by the Center, played a leadership role coordinating the research activities of Ramesh's group. He also served as the liaison between the group and the Center, fulfilling requests that the Center sent to funded faculty.
  - 2011 Ana G. Méndez University System Research Symposium: The abstract of **A Andalcio**, one of the Center's summer REU student, was selected for the 2011 Ana G. Méndez University System Research Symposium in San Juan, Puerto Rico. She presented a poster presentation titled, *Scheme for Observing Magnetization Dynamics of Nanomagnets with On-Chip Clocking*. This was research completed in J. Bokor's research group. This conference targets students from underrepresented ethnic groups with an interest in pursuing a graduate degree in science and engineering.

  Staff

  - NSF Review Panel: **S. Artis** served as a reviewer on NSF panels for the Research Initiation Grants in Engineering Education (RIGEE) and Transforming Undergraduate Education in Science, Technology, Engineering and Mathematics (TUES) programs.
  - UC Berkeley's Office of Undergraduate Admissions Fall 2011 Professional Development Training: **S. Artis** attended a week-long training about UC Berkeley's undergradaute admissions and collaborative efforts. The training covered the following topics: student affairs, college and school updates, student services, and fall outreach plans.

2c. External Educational Activities

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.)	~45

Each year, UC Berkeley invites the high school seniors, who have received admission offers, to spend a day on campus with their families. The visit is to showcase the campus and the opportunities the university has to offer. J. Yuen gave a talk about the need for the Center for E^3S and its research, and shared the availability of the ETERN program to support undergraduate research at the Center.

Activity Name	Bay Area Science Festival
Led by	**S. Artis** (Berkeley)
Intended Audience	General Public
Approx Number of Attendees (if appl.)	50

The Center partnered with Science@Cal to participate in the 2011 Bay Area Science Festival. The festival, a Bay Area celebration of science, had over 70,000 people participating in over 100+ events. As a participant, the Center provide support staff at the "Explore What You Eat: Hands-On Science at Local Farmers' Markets" event. This was Science@Cal's first year participating in this event so this was an exploratory opportunity for the Center to learn what type of demonstrations and exhibits the Center can plan to implement in future.

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. 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^3S Undergradaute Research Programs	• Research on energy efficient electronics science topics	• Graduate student as mentors: Education to enhance mentoring and project management skills of graduate students

SHARP	• Research on energy efficient electronics science topics	• Graduate student as mentors: Education to enhance mentoring and project management skills of graduate students
SEED and MITES	• Application of energy efficient electronics science topics	• Graduate student as instructors: Education to enhance curriculum development and teaching skills of graduate students

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

2e. *Performance Against Metrics*

All of the Center's education programs are still in its infancy stage, so it premature to report on the effectiveness of these programs. During this reporting period, the Center established a baseline for the education metrics. The table below displays baseline data and future metrics to measure education success.

Objective	Metrics	Targets	Period 2 Results
Education	Number of Center graduates who have completed E^3S training	Period 2: Baseline Period 3: 50% Period 5: 100%	0
	Number of publications with student and postdoc authors who have published previously in other themes	Period 3: 9 Period 5: 12	n/a
	Number of students and postdocs participating in education programs	Period 2: 5% Period 3: 60% Period 5: 75%	52% (42)
	Number of students and postdocs serving in leadership roles in the Center	Period 2: Baseline Period 3: 15% Period 5: 20%	11% (9)
	Number of events leading to external articles on Center	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase	1

During Period 2, the Center recognized the need to identify the methodology for assessing program effectiveness earlier in the life of the programs to ensure that the data needed for assessment will be collected in a timely and appropriate manner. Thus, in this reporting period, S. Artis, Education and Outreach Director, developed a comprehensive evaluation plan concerted on the Center's performance indicators and metrics identified in the Strategic Plan. Given that, S. Artis, is also the program director for many of the Center's education and diversity programs, she hired an external expert evaluator to independently assess programs she manages. As external evaluator, C. Amelink, will help the Center maintain the integrity of the Center's internal evaluation process. She will assist S. Artis by: 1) reviewing the evaluation process, including the assessment tools and methods; 2) analyzing the data and writing up the results and evaluation report; and 3) providing recommendations to improve the evaluation process.

2f. Education Activities in Period 3

- Internal Education Activities

  In Period 3, the Center will continue to refine and formalize the processes and implementation of existing internal education programs. The Center would like to streamline professional development opportunities and offer them at the Annual Student and Postdoc Retreat and consider partnering with organizations at the Center institutions that offer professional development training for graduate students and postdocs. Additionally, the Center will consider creating a formal agreement for all graduate students and postdocs funded by the Center. This agreement would require Center members to commit a small number of hours to educational and diversity programs.

  Another area of focus for the Center will be to enhance the partnership with Tuskegee University and other Minority Serving Institutions (MSIs). E^3S will introduce the E^3S Rotation Program to provide the current graduate student at Tuskegee the opportunity to come to UC Berkeley to conduct research, and collaborate with Center members. The goal of this program is to broaden the resources for the graduate student as well as build a stronger sense of engagement and community. This program will allow Tuskegee students to come to UC Berkeley for 8 to 10 weeks during a summer term. During the student's tenure at UC Berkeley, s/he will be fully immerged into the research environment, including theme meetings, faculty group meeting, summer journal clubs, and other education activities offered during the student's visit.

- External Education Activities

  In Period 3, the Center will further develop external education activities for the general public. The Center will use this year's involvement in Cal Day and the Bay Area Science Festival as a springboard for a larger role in the 2012 Cal Day and Bay Area Science Festival. The Center plans to design a hands-on demonstration that can engage and educate the general public about the importance of designing energy efficient electronics devices and need for more scientists and engineers to pursue career opportunities this field.

IV. KNOWLEDGE TRANSFER

1a. *Goals and Objectives*

Knowledge transfer is the conveying of the research results of the Center's faculty and students to society. Knowledge transfer goals of the Center for E^3S are to establish industry/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. Cross-fertilization would go in both directions, up and down the food chain, for device researchers at the leading electronics companies, circuit designers, CAD software writers, all the way to manufacturing workers in the semiconductor equipment industry. 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 directions will be practical, and lead to real success;
- Advice to policy makers at all levels of government on the implications for various device systems;
- Demonstration projects that test the devices and materials resulting from the Center's research projects;
- Meetings, summits, and workshops where results and knowledge gained through Center research activities are shared; and
- Knowledgeable students who have been trained through research internships and entrepreneurial clubs.

1b. *Performance Metrics*

Objective	Metrics	Frequency
Knowledge Transfer	Website hits & unique visitors	Yearly
	Number of contacts with industry	Yearly
	Presentations by industry	Yearly
	Center publications	Yearly
	External citations of publications	Yearly
	Patent disclosures	Yearly
	Students hired into relevant industries	Yearly
	Technology development attributable to Center's research	Yearly beginning in Period 10

1c. *Problems Encountered*

None to report.

2a. *Knowledge Transfer Activities*

Being a new Center, the initial emphasis in Knowledge Transfer is to establish the recognition of the Center among the industrial, research and educational stakeholders in the electronics field. This recognition starts with dissemination of information on the Center's activities and receiving input from others outside the Center who are engaged or are interested in synergistic activities.

- **Activity Enabling Two-Way Transfer of Knowledge**:

Energy Efficient Devices and Circuits		
Led by	**E. Yablonovitch** and **J. Bokor**, UC Berkeley	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Palo Alto, CA

In 2009, prior to the inception of the Center, the Center's PI and co-PI, Yablonovitch and Bokor (UC Berkeley) organized the 1st Berkeley Symposium on Energy Efficient Electronic Systems to promote collaborations among researchers working on increasing energy efficiency for information processing systems. In 2011, the Center "adopted" the responsibility for the forum and organized the 2nd Berkeley Symposium on Energy Efficient Electronic Systems with the goal of promoting international collaboration in the growing research field of energy efficiency in Devices and Circuits. This 2-day symposium was co-sponsored by IBM and Lam Research, two companies that are on the Center's Industry Research Board. In addition, the Center reached out to individuals from the US and outside the US to participate in the organizing committee that was co-chaired by Yablonovitch and Bokor. Joining them and other Center faculty, D. Antoniadis (MIT) and H.-S. P. Wong (Stanford), on the organizing committee were the following individuals:

- Adrian Ionescu, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
- Jan Rabaey, UC Berkeley
- Dan Radack, Institute of Defense Analyses
- George Thompson, Intel
- Naoki Yokoyama, National Institute of Advanced Industrial Science and Technology (AIST), Japan

The symposium's program, which reflected the Center's interest for two-way knowledge transfer, included five talks on the Center's five areas of research and 18 external talks; the agenda is presented in **Appendix F**. More information on the symposium can be found on http://www.e3s-center.org/events/11/sym2011-home.htm. Approximately130 people attended the two-day symposium.

Press coverage at the event ensured that the knowledge transfer can reach a broader audience. There were three internet articles providing information about the symposium:

- http://mandetech.com/2011/11/24/low-power-electronics-ucb-e3s-by-kip-brown/
- http://mandetech.com/2011/11/24/energy-efficient-electronics-ucb-e3s-day-2/
- http://www.edn.com/article/520180-Driving_toward_millivolt_electronics.php

- **Activities to Transfer Knowledge from the Center:**

Online Access to the Center: Research, Education Programs and Events		
Led by	**J. Yuen** (Berkeley)	
Organizations Involved		
	Name	*Address*
	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 to the general public. Information on the site's traffic can be found in **Appendix Q**.

Center's Research and Education Programs		
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.	Tuskegee University	Tuskegee, AL
5	Contra Costa College	San Pablo, CA
6.	LA Trade-Technical College	Los Angeles, CA

The Center also used its Annual Retreat to share the Center's direction and progress in research and education with its partners. The attendees from industry were:

- Hewlett Packard: Stan Williams
- IBM: Paul Solomon
- Intel: George Thompson, William Wang, Prashant Majhi
- Lam Research: David Hemker

For the first time, the Center's community college partners sent two teachers. S. Sidharta from CCC and M. Diaz from LATTC had the opportunity to learn about the Center's research. Other Education partners who also attended were S. Young and L. Fouche from MIT's Office of Engineering Outreach Programs and P. Riofski from the Berkeley Nanosciences & Nanoengineering Institute.

Overview of the Center		
Led by	**T.J. King Liu** and **M.C. Wu**, UC Berkeley	
Organizations Involved		
	Name	*Address*
	U of California, Berkeley	Berkeley, CA

The Center participated in a "Confidential Briefing" for the Taiwan Delegation of University Deans of R&D who visited the College of Engineering of UC Berkeley on June 26, 2011. M.C. Wu provided a brief overview of the Center during his introduction of centers at UC Berkeley. This visit, which was organized by Taiwan Economic and Cultural Office in San Francisco, included the head of Taiwan's National Science Council, Dr. Willis Lin, and Deans or their representatives from 12 Taiwanese universities. This visit led to an inquiry by Dr. Edward Y. Chang, Dean of Research and Development of National Chiao Tung University, Hsinchu, Taiwan, who expressed interest in collaborating with the Center under the Dragon Gate program of the National Science Council of Taiwan. Collaboration will depend on the outcome of Dr. Chang's proposal for funding from the Dragon Gate program.

Energy Efficient Electronics and the Center		
Led by	**E. Yablonovitch**, UC Berkeley	
Organizations Involved		
	Name	*Address*
	U of California, Berkeley	Berkeley, CA

During the Berkeley Symposium on Energy Efficient Electronic Systems in November 2011, an attendee from Applied Materials expressed interest to learn more about the Center. This interaction is resulting in a visit scheduled in January 19, 2012 where Yablonovitch will be a speaker at Applied Materials' ET Speaker Series. A meeting to discuss the Center with Klaus Schuegraf, Vice President and CTO, Silicon Systems Group at Applied Materials, has also been scheduled.

- **Activities to Transfer Knowledge to the Center**:

Energy Efficiency as an Innovation Driver: A Systems Perspective		
Led by	**E.Yablonovitch**	
Organizations Involved		
	Name	*Address*
	Intel	Santa Clara, CA

This is one of two seminars that the Center sponsored as part of the Solid State Seminar of the EECS department at UC Berkeley. The speaker was George Thompson of Intel who made his presentation in March 2011. This seminar, attended by ~50 people at Berkeley, was also broadcast via videoconference to 5 people at MIT.

Graphene-Based Tunnel-Transistors for Low-Power Computation: Surprises in Symmetry		
Led by	**T.J. King Liu** (Berkeley)	
Organizations Involved		
	Name	*Address*
	U of Notre Dame	South Bend, IN

The Center sponsored a second Solid State Seminar of the EECS department at UC Berkeley this Fall. The speaker was Debdeep Jena, Associate Professor of Electrical Engineering at U of Notre Dame.

Energy Bandgap Simulation		
Led by	**E. Yablonovitch** (Berkeley)	
Organizations Involved		
	Name	*Address*
	Oxford University	Oxford, UK

The speaker, Felicano Guistino, a theorist from Oxford, provided an update on his simulation on bandgaps during a visit to UC Berkeley in March 2011. This talk built upon the research he presented when he was invited to the Center's Kickoff Meeting in November 2010.

The Tunnel FET and Low Voltage Devices		
Led by	**D. Antoniadis** and **J. Hoyt** (MIT)	
Organizations Involved – IBM		
	Name	*Address*
	IBM	Yorktown Heights, NY

Paul Solomon of IBM, who has been collaborating with the Center's research faculty at MIT, was an invited speaker at the Center's Research Seminar series. The seminar was attended by 7 faculty, 8 postdocs, and 26 graduate students from MIT, UC Berkeley and Stanford. The speaker shared many new devices concepts that solicited a dialog during the seminar.

2b. Outcomes

The outcomes of the Center's knowledge transfer activities have been discussed in the previous section, as part of the description of an activity. In addition, the Center's research has been disseminated through publications and conferences; see Sections *VIII.1a* and *VIII.1b*. The table in the next section also provides information on the number of citations of the Center's publications.

2c. Performance Against Metrics

Objective	Metrics	Targets	Period 2 Results
Knowledge Transfer	Website hits & unique visitors	Period 2: Baseline Period 3: 20% increase	Website Hits: 11,354 Unique Visitors: 6,123 (see **Appendix Q**)
	Number of contacts with industry	Period 2: 18 Period 3: 36	66
	Presentations by industry	Yearly: 2	4
	Center publications	Yearly: 18	28
	External citations of publications	Period 3: 10 Period 5: 100	15
	Patent Disclosures	Period 3: 3 Period 5: 8	1
	Students hired into relevant industries	Period 5: 50% Period 10: 100%	3
	Technology development attributable to Center's research	Period 10: 1	n/a

2d. Transfer Activities in Period 3

In Period 3, the Center's emphasis on knowledge transfer to industry will continue. Greater efforts will be applied to develop effective mechanisms for disseminating research results to the general public. The Center will focus on increasing public awareness of the Center's research through hands-on demonstrations and online multimedia communications. We plan to explore the design of demonstration projects that test the devices and materials resulting from the Center's research projects. It is our goal to create a demonstration for each theme, which becomes a suite of demonstrations that can serve as a traveling exhibit for the Center to showcase our research to the general public. For online multimedia communications, the Center will consider live webinars, blogs, or YouTube videos created by faculty, postdocs, and students. These different multimedia tools will allow the Center to widely disperse research to a virtual audience, inclusive of the general public.

V. EXTERNAL PARTNERSHIPS

1a. *Goals and Objectives*

A strategy of partnerships is one of the underpinnings of the Center's proposal to NSF. Even before its inception, industry partnerships were formed, and now they form the cornerstone in the execution of the E3S' two-way knowledge transfer strategy. The Center has also established agreements to collaborate on research with groups around the world. The education and diversity plans in the proposal also calls for leveraging established programs to add value. In its first full year of operation, the key goal for the Center was to execute its partnership strategy to deliver the programs and activities in its plans.

1b. *Performance Metrics*

Objective	Metrics	Frequency
Knowledge Transfer	Number of Contacts with Industry	Yearly

1c. *Problems Encountered*

While the early interactions with F. Giustino of Oxford University, U.K. on Band-Edge Theory have been encouraging, activities with international academic partners have been slow in gaining traction. Thus, the Center utilized the 2nd Berkeley Symposium on Energy Efficient Electronics Systems as a forum to expand international partnerships.

2a. *Activities in Period* 2

In Period 2, the Center has been engaged in four different categories of partnership activities:

- **Industrial Partnerships**: Foremost in the Center's knowledge transfer goals is, as noted above, to use these industrial partnerships to make certain that the Center's research directions will be practical, and lead to real successes. Four leaders in the electronics industry supported the proposal to NSF to fund the Center for E^{3}S. In Period 2, the interactions with representatives of these four companies, IBM, Intel, Lam Research and HP, have continued and increased. These four corporate partners are working with the Center through an Industry Research Board; see Section *VII.3* – Center Management.

  In addition, the 2nd Berkeley Symposium on Energy Efficient Electronics Systems also served as a venue for additional interactions with the corporate partners.

  - Lam Research was a co-sponsor and sent two attendees to the event.
  - IBM was a co-sponsor and three employees attended, including two speakers.
  - George Thompson of Intel was on the Organizing Committee. There were 3 attendees from Intel, including Paolo Gargini, who is on the Industry Research Board.

  The next level is the commitment of parallel research, and then the eventual assignment of staff from the corporate partner companies to be resident at the Center. In Period 2, the Center successfully secured an agreement of parallel research with Intel. M.C. Wu, Theme III Leader, secured an agreement with Hai-Feng Liu of Intel Research Labs to collaborate on Nanophotodetectors.

- **Other Research Partnerships**: New research partnerships were developed in Period 2 to address the Center's needs for epitaxial materials. Theme 1 researchers are collaborating with B. Bennett at the Army Research Laboratory, S. Krishna at University of New Mexico, M.-C. Amann at Technical University of Munich, R. Droopad at Texas Tech University, and M. Luisier at Purdue University. Theme IV researchers are initiating collaborations with D. Awschalom at UC Santa Barbara.

In Period 1, we reported that we have collaboration agreements with four academic research groups and one research institute outside the US. As mentioned in the previous section, progress with most of these groups has been slow, even though the interactions with F. Giustino of Oxford University have been encouraging. Thus, the Center sponsored the 2nd Berkeley Symposium on Energy Efficient Electronics Systems to be a forum to promote "international collaboration in the growing research field of energy efficiency in Devices and Circuits"; a stated goal on the Symposium's website (http://www.e3s-center.org/events/11/sym2011-home.htm). This goal was enabled by international participation in the Organizing Committee. On the committee were: (i) A. Ionescu of École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, who is the lead coordinator of the STEEPER, the European Union program on energy efficient electronics; and (ii) N. Yokoyama of the National Institute of Advanced Industrial Science and Technology (AIST), one of the largest public research institute in Japan, where there are programs in green electronics and energy efficient electronics.

The Symposium's program included 2 speakers from Europe and 3 speakers from Japan. At the Symposium, the Center had discussions of future joint activities which will be reported later as activities in Period 3.

- **Education and Diversity Partnerships**: The Center's partners in this category, while external to the Center, but internal to Center's member institutions, run existing programs that we have leveraged in Period 2.
  - MIT: The Office of Engineering Outreach Programs (OEOP) and the MIT Summer Research Program (MSRP) are the Center's partners in delivering pre-college and undergraduate programs at MIT. The partnership with OEOP was initiated with Antoniadis and Bulovic being involved in SEED and MITES, as will be described in Section *VI.2a*- Diversity. This partnership was reinforced with a visit by S. Artis, who participated in some MITES activities and through subsequent frequent follow-ups with S. Young, the Director of OEOP. Alignment of goals and objectives between the Center and OEOP was furthered by Young's participation at the Center's Annual Retreat; see Section *VII.2* – Center Management.
  - UC Berkeley: The Center started Period 2 with two partners at Berkeley (first two given below) and added a third UC Berkeley program to help in program delivery. While the following paragraphs provide information on the activities with the partners, it must also be recognized that as a new Center, headquartered in UC Berkeley, the Center staff has received invaluable advice, help and information from individuals in the partner organizations that have accelerated the ramp up of the Center's Education and Diversity efforts.
    - i. Berkeley Nanoscience and Nanoengineering Institute (BNNI): BNNI is the host organization of the SHARP program, a pre-college program that the Center is leveraging to target high school students. Section *VI.2a* – Diversity provides details.
    - ii. Center of Integrated Nanomechanical Systems (COINS): The Education Director of this NSF-funded NSEC, M. Erol, has been most instrumental in helping the Center start its first REU program. The Period 1 report of our Center included a letter from M. Erol offering support. Indeed, she delivered more than she promised. She disseminated recruitment information about the E^3S REU program through her network, guided and supported the Center through the application, selection and "registration" phases, including being the "face" to the applicants, and included E^3S programmatic needs in the logistics plan of the COINS REU program. She essentially played the role of the Center's Education Director for the REU program before S. Artis, the Center's Education and Outreach Director, could join. In Summer 2011, the E^3S REU program ran in conjunction with the COINS REU

program, sharing the same activities outside research and with both programs jointly hosting project presentations and a final poster session. The data collection for this first year of the E^3S REU program was made possible through the data collection process of the COINS REU program.

iii. Transfer Alliance Project (TAP): TAP became a partner of the Center when E^3S rolled out the Transfer-to-Excellence (TTE) program for community college students. During this time, the Center became aware of TAP's pipeline of community college students. TAP is a highly successful program as evident by TAP being one of 16 recipients of the 2011 Examples of Excelencia awards from the federal government for being one of the top programs in America that increases degree completion among Latinos. Since its founding in 1999, more than 85% of TAP participants who applied to UC Berkeley have been admitted. In 2010, nearly 300 TAP students were admitted to UC Berkeley. The vast majority enrolled. This past summer, the Center partnered with TAP on the Center's TTE program to leverage TAP's expertise in advising community college students. TAP provided one-to-one personalized advising to the Center's TTE participants, including design and monitoring of individual academic course plans and assistance with transfer applications, required personal essays, financial aid forms and scholarships applications.

- UCLA: The Center's TTE program provides one additional year of transfer advising support after a TTE participant leaves the program. Through the introduction by Los Angeles Trade-Technical College, the Center for Community College Partnerships (CCCP) at UCLA is delivering that the transfer advising help to one TTE-REU student who lives in Los Angeles. CCCP's nine-month long Scholars Program provides Saturday academies to help community college students navigate through the transfer process and eight 30-minutes sessions with peer mentors. We are also working with CCCP on recruitment of students for the TTE-REU program of 2012. We are hosting an information session at the office of CCCP to attract students from Los Angeles based community colleges.

- **Center Management Partnership:** The Center for E^3S is fortunate enough to be located on the same campus as TRUST, a STC of the Class of 2005; a situation unique to UC Berkeley. As the Center for E^3S ramps up its capabilities and implement processes, we have benefited from the informal partnership with TRUST's Executive Director, L. Rohrbough, who has guided us with examples of his center's capabilities and practices. One substantial help has been the ability to quickly build the E^3S website on a platform that is commonly shared with TRUST and another UC Berkeley center.

2b. *Outcomes and Impact*

Reported above in the description of the activities.

2c. *Performance Against Metrics*

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

* The count is based on the number of individuals with corporate affiliation and the number of times the Center has contact with each of them through the Center's activities.

2d. *Partnerships Plans for Period 3*

For the existing industry partners, a key focus in Period 3 is that the Theme III team will sustain and enhance the new parallel research engagement that has been achieved with Intel Research Labs. Additional research collaboration will be sought with the existing corporate partners. We will also begin to engage these corporate partners to offer internship positions and mentoring for the students in the Center and students from our community college partners. Another emphasis will be to expand the Center's industry partnership to include additional companies.

We will build on the newly developed relationship with two international research groups. E. Yablonovitch has been invited to speak at a conference in Japan that is organized by N. Yokoyama. He will use this opportunity to interact with the researchers at AIST who are working on TFET's as the Center is doing in Theme I. The Center has been invited to support a workshop that EPFL is organizing in San Francisco in March 2012. While the workshop is not directly related to the core mission of the Center, there are aspects of the workshop that involves low energy consumption electronic devices.

The use of external partnerships to deliver on Diversity focused programs will continue in Period 3. Relationships with MIT's OEOP, Berkeley's BNNI and COINS will be sustained. The Center will continue fostering the relationships with transfer advising partners, UC Berkeley Transfer Alliance Project (TAP) and UCLA's Center for Community College Partnerships (CCCP). The Center will also leverage UC Berkeley College of Engineering's existing relationship with the statewide community college office of California Mathematics, Engineering, Science Achievement (MESA) to build a new partnership with MESA, a nationally recognized academic development program that engages thousands of educationally disadvantaged students to help them excel in math and science and graduate with math-based degrees.

VI. DIVERSITY

1a. *Goals and Objectives*

The goals of the diversity programs of the Center for E^3S are to:

- increase the number of students from historically underrepresented groups in engineering who attends university and graduate programs in electrical engineering; and
- develop methods to retain these individuals within the E^3S research areas.

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. Accordingly, many of the Center's educational programs are also the Center's diversity programs. It should be noted that the Center's Diversity goals and objectives are not standalone; they are integrated with Education and Research.

With this overlap, it should be noted that the Center's diversity goals and objectives are not standalone; they are integrated with education and research. The Center's diversity programs are education programs that will grow the pipeline of these aforementioned underrepresented groups. The Center has collaborated with existing diversity programs and similar initiatives to integrate education components into ongoing activities, thus augmenting and enhancing effective programs already in place and leveraging resources. In Period 2, efforts to impact all levels of diversity have begun. The diversity activities being pursued have or will involve and/or impact postdocs, graduate students, undergraduate students, and high school students. The Center has used this Reporting Period to establish a baseline of the composition of its participants and affiliates after 12 months of operations.

Given the Center's existing demographics, the Center recognizes that enhancing the diversity of its participants must be a critical focus. To achieve this objective, the Center is engaging in activities and has designed programs that utilize the following strategy: to increase diversity among the Center's personnel (students, postdocs, faculty, advisory board members, and staff). The Center has committed resources for the recruitment of graduate and undergraduate students from underrepresented groups into Center activities. These students must be nurtured in a supportive environment that recognizes and enhances individual professional aspirations. In this Period, we have designed and implemented gateway experiences as a means of growing the pipeline of students, and in Period 3, the Center will continue to focus on enhancing the diversity of the Center and begin creating mechanisms to retain these individuals within the E^3S research areas.

1b. *Performance Metrics*

In the current strategic plan, the following performance indicator is used to measure the Center's diversity performance:

Objective	Metrics	Frequency
Diversity	Increase in the number of Underrepresented Minorities associated with the Center	Period 2: Baseline Every 2 years thereafter

In Period 2, we recognized the need for a more detailed set of performance indicators to help track the progress of the Center's diversity programs. Thus, the Diversity performance indicators are revised in the Center's Strategic Plan as follows:

Objective	Metrics	Frequency	Targets
Diversity	Number of underrepresented minorities participating in the Center's research and programs	Annually	Period 2: Baseline Period 3: 15% increase Period 4: 10% increase Period 5: 5% increase
	Number of women participating in the Center's research and programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 5% increase Period 5: 5% increase
	Number of students from underrepresented groups applying to and accepted by E^3S programs	Annually	Period 2:Baseline Period 3: 75% increase Period 4: 50% increase Period 5: 25% increase
	Number of E^3S participants involved in diversity-enhancing activities	Annually	Period 2: Baseline Period 3: 75% increase Period 4: 50% increase Period 5: 25% increase
	Number of transfer students who have made contact with the Center who apply to and are accepted by 4-year colleges	Annually	Period 2: Baseline Period 3: 75% increase Period 4: 60% increase Period 5: 50% increase

1c. Problems Encountered

As reported in the first annual report, the Center's Diversity team included Tanjula Farlough, then the Director of Education and Outreach at Tuskegee University. In Spring 2011, the Center was informed that T. Farlough had resigned from the university. The Center had planned that its recruitment would leverage the outreach programs that T. Farlough had previously established at Tuskegee. She was to help the Center in her outreach to URM students at Tuskegee, Cornell, U of Wisconsin - Madison, Alabama State and Auburn. Because the Tuskegee position vacated by Ms. Farlough's resignation has yet to be filled, the Center has not been able to take advantage of Tuskegee University's access to underrepresented student populations. S. Jeelani of Tuskegee recently communicated that Tuskegee is in the midst of interviewing for a replacement. He has provided a letter indicating that Tuskegee will continue to be an education and outreach partner, even though he indicated that the University does not require any of the E^3S funding for its support; see **Appendix C**.

The Center's REU program, which was designed to leverage the well-established MSRP of MIT, had difficulty attracting students. Last fall, with the Center's operations in its infancy and the delay of subawards to the partner institutions, the MSRP program did not include the Center as part of its recruitment efforts. Thus, we were unsuccessful in having a cohort of REU students at MIT in Summer 2011. We do not expect this difficulty to persist to 2012, as S. Artis, E^3S Education and Outreach Director, has met with MSRP and is in contact with M. Orta, the head of the MSRP program.

The Center recognizes the difficulty it is facing when recruiting postdocs and new faculty from underrepresented groups. A significant factor in this challenge is the very small pool of applicants from which the Center can draw. This fall, the Center has implemented plans to expand this base by tapping into larger organizations that support doctoral students. These plans include attending conferences and meetings sponsored by minority science and engineering societies (such as the Compact for Faculty Diversity Institute on Teaching and Mentoring, the National Society of Black

Engineers, and the National Society of Hispanic Professional Engineers); strengthening relationships with NSF-sponsored diversity programs at Center institutions (UC Berkeley's Berkeley Edge); and exploring partnership with additional predominantly minority-serving institutions.

2a. *Development of US Human Resources*

In Period 2, with S. Artis joining the Center to provide leadership (see Section *VII.1a* on S. Artis' background), the Center is designing and implementing a more complete and ambitious institutional plan for diversity enhancement. The Center plans to maximize its education and research programs by including a strong current diversity focus. The Center has identified nationally recognized pre-college and higher education programs and has formed alliances to collectively tackle the challenge of building a diverse pipeline of students who will eventually contribute to a diverse workforce. The Center is also seeking to further develop a clearer understanding of what is really working in high schools, community colleges, 4-year institutions, and graduate schools to develop — and draw upon — the talent of underrepresented groups. In order to do this the Center has initiated several on-going strategy meetings with representatives from diversity programs at UC Berkeley, MIT, Contra Costa College, and Los Angeles Trade-Technical College to discuss partnership opportunities amongst all programs.

- **Pre-college Programs**

  At the pre-college level (grades 9-12), the Center has leveraged the existing partnership and infrastructure established by UC Berkeley's Summer High-School Apprenticeship Program (SHARP) and MIT's Saturday Engineering Enrichment and Discovery Academy (SEED) and Minority Introduction to Engineering and Science (MITES) program. All of these pre-college programs promote student's early interest in science and engineering careers, where the goals of these programs are to: 1) increase the awareness of engineering and other technical fields as an exciting and rewarding career path to a diverse population, and 2) increase the diversity of students who apply to, enroll, and graduate from undergraduate programs in engineering and applied science. In particular, emphasis is placed on introducing electronics courses and research experiences in science and engineering to high school students from underrepresented groups in science and engineering. As a result, the Center envisions pre-college participants as individuals who will enhance the pipeline for a future generation of scientists, engineers, and technicians that will reflect the diversity of the US society.

Activity Name	Summer High School Research Program (SHARP)
Led by	**C. Chang-Hasnain** (Berkeley) & **A. Rosenzweig** (Berkeley Nanosciences & Nanoengineering Institute - BNNI), **S. Artis** (Berkeley)
Intended Audience	Rising 11^{th} and 12^{th} grade high school students
Approx Number of Attendees (if appl.)	5

SHARP: The Summer High-School Apprenticeship Research Program (SHARP) was launched in 2007 at UC Berkeley by C. Chang-Hasnain who is currently the Associate Director of Education of the Center for E^3S. In this program, a high school student spends four weeks conducting hands-on scientific investigations at UC Berkeley under the mentorship of a graduate student on a one-to-one basis. This program impacts high school students with early first-hand exposure to state-of-the-art scientific research, as well as provides opportunities for graduate students to lead, guide, mentor, and design of short research projects that can make progress in a relatively short period of time. Since the inception of SHARP, approximately 70 SHARP participants (SHARPies) have completed the program and all have enrolled in 4-year universities. About 80 graduate students from 20+ laboratories and 10 departments at UC Berkeley have participated as mentors. SHARP participants have included 45% female and 15% underrepresented minorities. In 2011, SHARP admitted a group of 14 rising seniors selected from an applicant pool of about 140 from sixty-five high schools, with the cohort representing 14 schools in the Bay Area.

E^3S' Impact on SHARP: Five of the 18 SHARP participants were designated as E^3S SHARP interns. Each SHARPie successfully completed the research program in an E^3S faculty member's research group (C. Chang-Hasnain, R. Ramesh, S. Salahuddin and E. Yablonovitch) and presented an oral research progress report with an accompanying PowerPoint presentation. The E^3S SHARPies class was composed of 5 males interested in science and engineering majors (i.e., physics, material science engineering, mechanical engineering, electrical engineering). It should be noted that this class was selected prior to the arrival of the Center's Education and Outreach Director, and in the next reporting period, the Center focus will be to enhance the applicant pool with more women and high school students from underrepresented minority groups. A significant innovation to this year's SHARP program was a new workshop conducted by S. Artis on mentoring and project management skills for the participating graduate student mentors, who also received the benefit of an extended review of their research project descriptions. The Center's staff also provided support to the processing of applications to supplement the efforts of BNNI, and C. Chang-Hasnain and E. Yablonovitch, E^3S faculty, led the participant selection process.

Activity Name	MIT Saturday Engineering Enrichment and Discovery (SEED) Academy - Electronics Course
Led by	**J. Green** (MIT)
Intended Audience	12^{th} grade high school students
Approx Number of Attendees (if appl.)	20

SEED: The Saturday Engineering Enrichment and Discovery (SEED) Academy, an established program of MIT's Office of Engineering Outreach Programs (OEOP), is a seven-semester academic enrichment and technical career exploration program that has been preparing high school student participants for college. The focus is to strengthen their fundamental math, science, and communication skills through hands-on engineering activities. The students are recruited from traditionally underserved, public high schools from Boston, Cambridge, and Lawrence, Massachusetts.

E^3S' Impact on SEED: Beginning in 2006, SEED has offered a course in Electrical Engineering as an elective to high school seniors. With the Center adopting the sponsorship of the course, SEED revised the curriculum to incorporate concepts related to energy efficiency in electronics. The goal of this expansion is to garner the interest of college-bound seniors and perpetuate study in this emerging field of electrical engineering. The revision of the curriculum, completed in summer 2011, was undertaken by the Fall 2010 Electronics Co-Instructors, Joy Johnson, Ph.D. student in Electrical Engineering, and Rhonda Jordan, Ph.D. student in Engineering Systems Division, with E^3S faculty, Antoniadis, serving as the faculty advisor.

The SEED Academy Class of 2010 consisted of 21 students. This electronics class was composed of 48% (10) males and 52% (11) females. Among this class, 48% (10) of the students were from underrepresented minority groups. At the end of the program, participants completed a survey to evaluate the effectiveness of the program. The following results were concluded:

- 66.7% of the students felt that their experience in SEED Academy was very productive.

- 10.6% of the students felt that the electronics course was their best semester yet/far exceeded their expectations.
- 100% of the students agreed or strongly agreed that they felt valued and supported by the staff and other students in SEED Academy.
- 62.5% of the students strongly agreed that in the electronics course, they learned about technical fields that they would not be exposed to outside of SEED Academy.
- 53.1% of the students strongly agreed that they are interested in pursuing a related field in college or career of the course they took this fall.
- 93% of the students said that they enjoyed the instruction in their engineering course.

In addition, 100% of this class is currently enrolled in college as freshmen. Thirty-three percent (7) of these students are majoring in science, 14% (3) in engineering, 19% (4) in non-STEM majors, and 33% (7) of the students are undecided about their majors.

Activity Name	MIT Minority Introduction to Engineering and Science (MITES) - Electronics Elective
Led by	**S. Young** (MIT), **S. Artis** (Berkeley),
Intended Audience	Rising 12^{th} grade high school students
Approx Number of Attendees (if appl.)	12

MITES: As a six-week residential summer program of MIT's OEOP, the MITES Program 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. Since 1975, MITES has introduced more than 1,900 students to the rigors of an MIT educational experience; of these students, 35 percent have matriculated at MIT and 80 percent have gone on to top universities to major in technical fields. More recently, 49 of the 80 students (72%) in the MITES 2010 class were accepted to MIT and 32 of the 49 (65%) of those students are currently freshmen at MIT.

<u>E^3S' Impact on MITES</u>: Summer 2011 was the fourth time that the electronics course was offered in MITES. The course has typically covered college-level digital and analog electronics through hands-on labs and lectures. This year, 12 of the 80 students participated in the electronics elective that has been revised to incorporate concepts related to energy efficiency. The electronics elective was composed of 58% (7) males and 42% (5) females. Among this class, 83% (10) of the students were from underrepresented minority groups. In addition, 100% of the students were interested in science and engineering majors (i.e., physics, biomedical engineering, electrical engineering, computer science, and molecular biology).

For this revised electronics course, approximately one third of the electronics labs were modified in summer 2011 to investigate concepts especially related to energy efficiency in electronics. The concepts included: power, conservation of energy, and energy efficiency in general. The instructors for this course were Joe Steinmeyer, a Ph.D. student in Electrical Engineering, and Brian Wu, an undergraduate student in electrical engineering. The Center has provided the opportunity for MITES to introduce concepts related to energy efficient electronics science. The changes in course curriculum were: (i) the concept of power and subsequently energy efficiency, which in that past few years have taken a back seat to other concepts, was investigated in more detail in both homework and lectures. Conservation of energy, energy efficiency, and other related concepts were all covered. (ii) ~ 1/3 of the labs were modified in summer 2011 to investigate concepts of power and energy efficiency in electronics. With the newly integrated energy efficient electronics science theme, high school students are able to connect electronics concepts to everyday application such as energy efficient devices, making the idea of electronics easier to grasp, easier relate to, and easier to investigate. (iii) the MITES course gave students the opportunity to interact with researchers and faculty affiliated with E^3S topics, adding an invaluable new level to both the electronics course in general and to the discussion about energy efficiency in particular. A concrete example is provided by the lasting impact of the presentation by E^3S faculty, V. Bulovic. The students immediately showed a level of interest and excitement rarely seen before at lectures by leading researchers from the field of electronics.

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**S. Young** (MIT), S. Artis (Berkeley),
Intended Audience	70
Approx Number of Attendees (if appl.)	5

This new program was added during Period 2. MIT's OEOP is piloting MIT Online Science, Technology, and Engineering Community (MOSTEC), an online community that provides high school seniors an enriching online experience during the fall and spring of their senior year. The goal of this program is to increase the students' interest in various fields of engineering and science and to assist them with aspects of the college application process. To learn more about the fields of engineering and science, MOSTEC students have access to several educational components: weekly webinars, professor profiles, online journal club, discussions forum, student bloggers, and research share. In addition, in November 2011, MOSTEC students from all over the country came together for the MOSTEC Conference at MIT. Throughout this program, participants are exposed to MIT's faculty and staff who provide them with admissions and financial aid tips, facilitate discussions about science and engineering research, allow them to share their own research, and provide mentorship opportunities.

With respect to the Center's participation in MOSTEC, 32 students participated in the electronics workshop at the MOSTEC Conference. This workshop was adapted from newly created material for the SEED Academy and MITES electronics course. In the spring, MOSTEC will feature E^3S Center faculty in the professor profiles and a weekly webinar, an E^3S Center graduate student will lead an online journal club session, and the Center will contribute to the discussion forum. Through the Center's involvement in MOSTEC, students are being exposed to a sub-field of electronics and career paths for scientists and engineers interested in energy efficient electronic devices.

- **Undergraduate Programs**

The Center also seeks to impact diversity in science and engineering at the undergraduate level. As a whole, the undergraduate programs promote student's early interest in science and engineering research, where the goals of these programs are to: 1) increase the awareness of research in science and engineering as an exciting and rewarding career path to a diverse population, and 2) increase the diversity of students who apply to, enroll, and graduate from graduate programs in engineering and applied science. In particular, emphasis is placed on providing in-depth research experiences in science and engineering to undergraduate students of diverse backgrounds. As a result, the Center envisions undergraduate participants as individuals who will enhance the pipeline for a future generation of M.S. and Ph.D. scientists and engineers that will reflect the diversity of the US society.

At the undergraduate level, the Center's programs target two different audiences - community college students and students at 4-year universities. For community college students, one goal of the Center's diversity efforts is to bridge the transition from community college to 4-year institution where students will earn a Bachelor's degree in science and engineering. The goal for current undergraduates at 4-year institutions is to earn Bachelor's degree in science and engineering and to pursue a graduate degree in science and engineering.

Community College Programs: During Period 2, the Center initiated the Transfer-to-Excellence (TTE) program for community college students. This signature program involves the Center's community college education partners, Contra Costa College and Los Angeles Trade-Technical College. TTE is intended to inspire California community college students to ultimately transfer and complete their Bachelor's degree in science and engineering. The program consists of two components:

- A residential summer research program (TTE REU) brings community college students to UC Berkeley to undertake a science or engineering research project hosted by a UC Berkeley faculty. The student is provided a stipend, housing, and meals.
- A cross-enrollment program (TTE X-Enroll) enables community college students to take a science, math or engineering course at UC Berkeley. Tuition is free for the student, who also receives a stipend for books and transportation at the start of the course, and an incentive stipend upon completion of the course with a grade of B+ or better.

While at UC Berkeley, TTE participants have access to academic, professional, and personal development seminars to enhance the overall preparation and confidence to pursue studies in science and engineering and, eventually, a career that applies the STEM education. 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 science and engineering baccalaureate program from the UC Berkeley Transfer Alliance Project (TAP) and UCLA's Center for Community College Partnerships (CCCP). Both are highly successful academic advising and enrichment programs that prepare low-income, first generation college students, and otherwise educationally disadvantaged community college students throughout California, to be competitive transfer applicants to 4-year colleges (see Section *V.2a* for details on TAP and CCCP).

Activity Name	Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU)
Led by	**S. Artis** (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	2

TTE REU: In its first full year, the Center has focused the development of the TTE REU program as a vehicle to engage its education partner institutions, Contra Costa College and Los Angeles Trade-Technical College and to provide community college students early exposure to research to increase their interest and confidence in science and engineering. In summer 2011, the Center at UC Berkeley hosted 2 community college students, one from each partner institution for eight weeks of research in the labs of the Center's Education Affiliates. Education Affiliates are not part of the Center's research faculty, but their research disciplines mirror the disciplines of the Center research faculty. We have opted to develop a network of Education Affiliates for the TTE program, in part, because we want to have the flexibility to offer a wider range of STEM experiences to community college students, who are still in an exploratory stage in their interest in STEM. Moreover, with the large number of summer education and diversity programs hosted by the Center and the small number of Center faculty at UC Berkeley, it is difficult to provide one-on-one faculty supervision to all student participants. Education Affiliates and their graduate students and postdocs serve in the same role as Center faculty, graduate students, and postdocs for the Center's education and diversity programs. In addition, the Center provides a continuing impact to Education Affiliates beyond their involvement in education and diversity programs. All of the Center's education activities are extended to graduate students and postdocs of Education Affiliates beyond the hosting period. The first two Education Affiliates were **A.C. Arias,** an Associate Professor of Electrical Engineering and **J. Wu,** an Assistant Professor of Materials Science, both of UC Berkeley, hosted the Center's first two TTE REU students.

During the TTE REU, summer researchers participated in independent hands-on research projects, attended weekly seminars on research report writing, oral presentation skills, graduate school preparation, and career pathways in science and engineering, went on lab tours and field trips, and participated in weekly one-on-one mentorship meetings with S. Artis, Education and Outreach Director. The students also joined the REU students who are juniors and seniors on a visit to Stanford University (see details in the next section on Summer Research Programs for Undergrads from 4-Year Institutions). In addition to research, TTE participants were trained on scientific ethics, received individualized academic and transfer advising, and participated in group enrichment activities provided by TAP; these activities were designed to prepare the TTE participants to be competitive applicants to 4-year colleges. After completion of the summer program, TTE continues to provide students with transfer-advising support. The Bay Area student receives support from a TAP counselor, while the LA-based student receives support from CCCP. This fall, the two TTE REU students are applying for transfer admission to the following schools: UC Berkeley, UC Davis, and UCLA.

The TTE REU students had the same end-of-program requirement as their counterparts in the REU program for juniors and seniors (see below). One requirement is the presentation at the poster session held on the last day of the program. The Center's education partner, CCC, sent four science faculty members and four students to support the poster session.

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.)	1

TTE X-Enroll: This program at UC Berkeley is initially targeted at community colleges in the Bay Area. In the first year, we utilized the partnership with UC Berkeley TAP, recruiting from the community students that TAP has been mentoring. This summer, one student from Chabot College participated in TTE X-Enroll, successfully completing a 4-credit lower division math course with a grade significantly high enough to earn him the incentive stipend at the end of course. While on campus, the student was part of the cohort that includes TTE REU students who received individualized academic and transfer advising and group enrichment activities from UC Berkeley TAP. Like other TTE students, the X-Enroll student continues to receive TTE support for transfer to a B.S./B.Eng program delivered through the Center's partner, TAP. This fall, he is applying for transfer admission to the following schools: UC Berkeley, UC Davis, UCLA, UC San Diego, and UC Santa Barbara. He has already been admitted to UC Davis and plans to major in chemical engineering.

Activity Name	Transfer-to-Excellence Outreach Event
Led by	**S. Artis** (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	18

To publicize the Transfer-to-Excellence program, the Center sponsored a hiking event. This event also served as a day of leadership for the juniors and seniors from two NSF-funded REU programs, E^{3}S and COINS. Each community college student was paired with either a junior or a senior, who was asked to share their experience and insights as science and engineering majors and future career aspirations. About 1/3 of the community college students came from Contra Costa College, the Center's education partner, with the remaining from community colleges supported by UC Berkeley TAP. S. Sidharta, the Center's contact at CCC, and L. Seblega, a TAP counselor, participated in the event.

Activity Name	Other Transfer-to-Excellence Outreach Events
Led by	S. Artis (Berkeley) and J. Yuen (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	TBD

Outreach events to publicize the TTE program have been planned for December and January. In December, we will visit Contra Costa College and LA Trade-Technical College, the Center's education partners. In additional, an outreach event is also scheduled to take place in the office of UCLA's CCCP office so that we can attract the community college student population in Southern California. In January, we are planning an event for the Bay Area community college student population in conjunction with UC Berkeley TAP.

Summer Research Programs for Undergrads from 4-Year Institutions: The Center is establishing Summer REU programs at UC Berkeley and MIT. The primary goal is to provide gateway experiences for undergraduate students that will attract students to research opportunities in energy efficient electronics science and pursue graduate study in science and engineering. In addition, the Center places emphasis on attracting undergraduate students from underrepresented groups in science and engineering to enhance the pipeline of future diverse M.S. and Ph.D. students.

Activity Name	E^{3}S Research Experiences for Undergraduates at Berkeley (E^{3}S REU)
Led by	S. Artis (Berkeley),
Intended Audience	3rd and 4th year undergraduate students
Approx Number of Attendees (if appl.)	5

In its inaugural year, the Center's summer research program received 41 applications. Five of these students were matched with Center faculty at UC Berkeley. One participant was an African-American female electrical engineering student. Successful completion of the 8-weeks, hands-on research on an E^{3}S project at the laboratory of an E^{3}S faculty (J. Bokor, T.J. King Liu, R. Ramesh, S. Salahuddin, M.C. Wu) enabled the students to earn one UC Berkeley academic credit. In addition, the students also attended weekly seminars on research report writing, oral presentation skills, graduate school preparation, and career pathways in science and engineering, and went on lab tours and field trips. Each student also received weekly one-on-one mentorship meetings with S. Artis, Education and Outreach Director.

The activities outside research that were provided to the students were: (i) completed a one-hour ethics training on being a responsible scientist and engineer; (ii) visited Stanford University to learn about energy efficient electronics science research being conducted by Center faculty, postdocs, and graduate students, tour the Stanford Nanofabrication Center to learn about the fabrication of semiconductors, and meet graduate admission advisors and learn about Stanford's admission process; and (iii) participated in a Saturday event designated Leadership Day, where students served as mentors and were paired with a community college student in the TTE outreach activity mentioned earlier in the Community College Programs section. The juniors and seniors were provided with questions to initiate a conversation on their insights on science and engineering majors and future career aspirations.

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 nearly 30 posters from several REU programs. E/ Yablonovitch, the Center Director, as the professor of record for the E^3S REU independent study course, interviewed each student about his/her research project during the poster session. Other E^3S faculty who reviewed the posters included C. Chang-Hasnain and J. Bokor, in their roles as the Associate Directors of Education and Diversity, respectively.

New for this program and other summer research programs on campus, the Center introduced project management training for graduate student mentors. This training was open to the Center's summer research program partner, Center of Integrated Nanomechanical Systems (COINS). The Center and COINS also partnered on ethics training, professional development, and social activities throughout the summer research program. This partnership allowed COINS and E^3S to improve its program model and provided cost-savings on joint activities.

At the end of the program, participants completed a survey to evaluate the effectiveness of the program. The following results were concluded:

- 100% of the students agreed or strongly agreed that the summer undergraduate research program improved their knowledge of nanotechnology.
- 100% of the students agreed or strongly agreed that the summer undergraduate research program increased their interest in pursuing a graduate degree.
- 86% of the students agreed or strongly agreed that the summer undergraduate research program improved their leadership skills.
- 100% of the students agreed or strongly agreed that the summer undergraduate research program improved their research, technical, and communication skills.

In addition, the one senior in the 2011 REU class has applied to graduate school at UC Berkeley to study chemistry.

- **Recruitment and Public Outreach**

In addition to these diversity programs, Center members attend diversity conferences, 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, S. Artis collaborated with another NSF-funded Center, COINS, and UC Berkeley's College of Engineering to recruit for the Center's diversity programs. Among the three organizations, 21 universities were visited and 8 diversity conferences were covered (See **Appendix D: UC Berkeley Joint Recruitment Schedule**). S. Artis attended 5 diversity and graduate fair conferences (Society of Women Engineers (SWE) National Conference, American Indian Science and Engineering Society (AISES), Hispanic Engineer National Achievement Awards Corporation Conference (HENAAC), Compact for Faculty Diversity Institute on Teaching and Mentoring, Cornell University Graduate Fair) and conducted graduate preparation workshops and information sessions at 10 universities (Cornell University, University of California, Los Angeles, University of Central Florida, University of Michigan, University of Southern California, Georgia Tech, Notre Dame, The Ohio State University, Tuskegee University, and Virginia Tech). At the diversity and graduate fair conferences, the Center hosted a booth for 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. At the information sessions, S. Artis provides a one-hour presentation on the Center's research themes and diversity programs and on how to prepare for graduate school. For a complete list of these recruitment and public outreach events, see **Appendix E: Summary of Diversity-Enhancing Activities**.

S. Artis was also invited to speak to undergraduate students in UC Berkeley's Pre-Engineering Program (PREP) and Berkeley Edge Program. PREP is an intensive eleven-day, residential academic session held annually in August by the College of Engineering. The purpose of PREP is to provide incoming students with insight into the rigors of the first-semester engineering curriculum at UC Berkeley. S. Artis presented a workshop on college success in engineering, covering topics such as time management, study skills, test-taking skills, and career planning. As a result of her involvement, the UC Berkeley's College of Engineering has extended an invitation to the Center to provide a similar workshop for incoming freshmen in next year's program (September 2012).

The Berkeley Edge conference provided an opportunity to increase the number of master's and doctoral degrees granted to minorities at UC Berkeley. Berkeley Edge is designed to give prospective minority graduate students, and other students who find the program beneficial, an opportunity to visit UC Berkeley and the Bay Area and receive an overview of the graduate degree programs. In November 2011, as a guest speaker, S. Artis shared with students the benefits of a graduate degree. As a result of her involvement, the Electrical Engineering and Computer Sciences department at UC Berkeley has extended an invitation to the Center to provide an information session on opportunities in the Center for incoming students at next year's conference (November 2012).

Other Diversity Activities

To enhance diversity, the Center is exploring research collaborations with additional Minority Serving Institutions (MSIs). In November, Sakhrat Khizroev, Associate Professor at the Nanofabrication Facility at Florida International University, a Hispanic-Serving Institution, visited the Center to learn more about E^3S research and education programs.

The Center disseminates information about all its education and diversity programs on its website (discussed in Section *VII.2*). With respect to diversity, it is important for the Center to lead by example. As we have future aspirations to target students with disabilities to participate in the Center's programs, we are in the process of implementing the Center's website to be compliant with the Americans with Disabilities Act. As an example, images are accompanied by alt text with lengthier descriptions for visitors who rely on a sight reader.

2b. Impact on the Center's Diversity

All of the Center's diversity programs are still in its infancy stage, so the Center can only report immediate impact on the Center's diversity. To measure the impact of the Center's diversity programs, the Center will examine its diversity performance and management indicators. To track these demographics, the Center has created a Center-wide demographic database that will be updated annually to report diversity success.

For the TTE program, the Center's signature diversity program, the first class of TTE participants have all applied for transfer admission as a science or engineering major to the following schools: UC Berkeley, UC Davis, UCLA, UC San Diego, and UC Santa Barbara. One student has already been admitted to UC Davis.

This year, S. Artis participated in 13 recruitment events at: Society of Women Engineers (SWE) National Conference, American Indian Science and Engineering Society (AISES), Hispanic Engineer National Achievement Awards Corporation Conference (HENAAC), Compact for Faculty Diversity Institute on Teaching and Mentoring, Cornell University, University of California, Los Angeles, University of Central Florida, University of Michigan, University of Southern California, Georgia Tech, Notre Dame, The Ohio State University, Tuskegee University, and Virginia Tech (See **Appendix E: Summary of Diversity-Enhancing Activities**.) As a result of the Center's recruitment effort, E^3S has been able to actively solicit applications that will result in a larger number of students from underrepresented groups to Center programs in Period 3.

2c. Performance Against Metrics

In Period 2, the Center established a baseline of the composition of its participants and affiliates after 12 months of operations and set objectives to increase underrepresented minority participation in subsequent years. The following table displays baseline data and future metrics to measure diversity success.

Objective	Metrics	Targets	Period 2 Results
Diversity	Number of underrepresented minorities participating in the Center's research and programs	Period 2: Baseline Period 3: 15% increase Period 4: 10% increase Period 5: 5% increase	2% (2)
	Number of women participating in the Center's research and programs	Period 2: Baseline Period 3: 5% increase Period 4: 5% increase Period 5: 5% increase	22% (20)
	Number of students from underrepresented groups applying to and accepted by E^3S programs	Period 2:Baseline Period 3: 75% increase Period 4: 50% increase Period 5: 25% increase	5 Applied, 2 Accepted
	Number of E^3S participants involved in diversity-enhancing activities	Period 2: Baseline Period 3: 75% increase Period 4: 50% increase Period 5: 25% increase	7
	Number of transfer students who have made contact with the Center who apply to and are accepted by 4-year colleges	Period 2: Baseline Period 3: 75% increase Period 4: 60% increase Period 5: 50% increase	3 Applied, Accepted TBD in Period 3

2d. Plans in Period 3

The Center has made substantial progress in establishing and executing its plans that hopefully, in time, will enable broader participation in the Center. In Period 3, the Center's main focus will be to sustain and optimize these programs as they go into their second year. In addition, the Center will selectively add new programs and/or expand the capacity of established programs. We will continue to work with our partners and if necessary grow new partnerships to execute our plans. While S. Artis, Education and Outreach Director, has both the skills and experience to lead the Center's

Education and Diversity programs, we recognize that we have to grow her team for the Center to be successful. We expect to grow the team to include a Program Coordinator and a Diversity Manager; see Section *VII.1a* – Center Management.

The Center will continue to support the pre-college programs, SEED and MITES at MIT and SHARP at UC Berkeley. However, we will attempt to build connections between MIT's Office of Engineering Outreach Programs (OEOP) and SHARP to leverage the existing talent pool that OEOP has in the Bay Area, as a way to enhance the diversity of the SHARP program. Additionally, the Center will provide guidance to SHARP on how to increase their level of effort to recruit more students from underrepresented minority groups.

The REU program for juniors and seniors will be expanded to a nine-week program, an increase of one week, in response to feedback from both the students and the mentors. To enable the pipeline of REU students for future years to include a large percentage of students from underrepresented groups, we will introduce the E^3S Research Workshop for freshmen and sophomores pursuing a Bachelor's degree in science and engineering with a focus on students at MSIs in Period 3. The E^3S Research Workshop will be designed to serve as an early engagement research program exposing undergraduates to research opportunities early in their tenure as an engineering student. The purpose of the program is to: 1) expose students to the field of and careers associated with energy efficient electronics science; 2) provide participants an overview of research opportunities and guidance for securing undergraduate research experiences; and 3) motivate students to pursue Ph.D.s in science and engineering. In addition, this program will serve as an early recruitment effort for the E^3S REU Program.

During Period 3, the Center plans to have a cohort of three summer research students participating in the MIT Summer Research Program (MSRP). We expect to leverage the well-established MSRP to attract underrepresented science and engineering students to conduct research with E^3S faculty at MIT. S. Artis, E^3S Education and Outreach Director, and M. Orta, MSRP Director, have developed an additional strategy to assist with placement in the Center. In addition to MSRP's traditional recruitment efforts, S. Artis will be able to help MSRP place students from the REU application pool at UC Berkeley who meet the selection criteria for MSRP

A recommendation was made at the Center's External Advisory Board meeting to consider the impact of a more focused effort on a single stage pipeline. As a result, the Center will explore more focused efforts on community college students. In Period 3, we will expand the size of the cohort of the TTE REU program and open the program to students from more community colleges. The third level of expansion may happen in Period 3 as well, if a NSF REU Site proposal is awarded. The Center submitted a proposal to NSF for expanding the current TTE REU program into a REU Site. The proposal, led by Center faculty, **T. J. King Liu**, and E^3S Education and Outreach Director, **S. Artis**, was a collaborative effort with two other NSF-funded centers at UC Berkeley, the Center of Integrated Nanomechanical Systems (COINS) and the Synthetic Biology Engineering Research Center (SynBERC), and UC Berkeley's Transfer Alliance Project (TAP). In Period 3, if awarded the REU Site, the Center will expand the existing TTE REU cohort to 15 students who will be hosted by one of the three partnering centers. While we plan to place some of the TTE REU students in the research labs of the Center's faculty, we will also attract UC Berkeley faculty who are in the College of Engineering, Chemistry and Physics to become Education Affiliates of the Center to host some of the community college students.

Period 3 will see a new program targeted at community colleges. The Center will establish a Research Experience for Teachers (RET) program for four community college teachers to participate in a 6- to 8-week RET. Funding to support this program will come from the Center's existing education budget of two RET participants per year. Since the Center did not support any RET participants in Period 2, funding from this period will be carried over to Period 3 to allow two additional participants. Under the supervision and mentorship of E^{3}S faculty members, these instructors will conduct a research project and develop a course module that can be integrated into their current course at their respective community college.

We will continue to strengthen partnerships with minority serving institutions. First and foremost, we will put additional effort on the education and outreach partnership with Tuskegee. Second, we will continue to explore adding other MSI's as partners; see the end of Section *VI.2a*. Third, in our recruitment, we will begin to reach out to rural and tribal colleges, including community technical colleges, as well as offices that support people with disabilities, focusing on centers focused on science and engineering fields.

The work of building and sustaining partnerships will continue in Period 3. We will leverage the capabilities of partners, like MIT's OEOP, Berkeley's BNNI, COINS, TAP and the College of Engineering, UCLA's CCCP and the California statewide office of MESA. See also Section *V.2d*.

The Center will continue to seek additional funding opportunities to support the new programs and students, should opportunities arise.

VII. MANAGEMENT

1a. Organizational Structure and Underlying Rationale

The organizational structure of the Center for E^3S has been designed to provide leadership and support to its members in pursuit of research, as well as the programmatic goals of education, diversity, and knowledge transfer in an environment that spans disciplinary and institutional boundaries. The current organizational chart is presented in **Appendix G**.

- Executive Committee: The Center is led by a leadership team, the Executive Committee (EC), which is chaired by the Center Director (and Principal Investigator), **E. Yablonovitch** (*Berkeley*), and co-chaired by the Deputy Center Director, **J. Bokor** (*Berkeley*). Other EC members are: **D. Antoniadis** (*MIT*), **C. Chang-Hasnain** (*Berkeley*), **E. Fitzgerald** (*MIT*), **T.J. King Liu** (*Berkeley)*, **H.-S. P. Wong** (*Stanford*), **M.C. Wu** (*Berkeley*), **J. Yuen** (Executive Director), and **S. Artis** (Director of Education and Outreach). Several EC members have been assigned to provide timely and focused EC support to the management team. E. Yablonovitch, as the Center Director, provides oversight to the entire team, and in particular, he serves as the supervisor to J. Yuen, Executive Director. C. Chang-Hasnain, in the role of Associate Education Director, and J. Bokor, in the role of Associate Diversity Director, provide guidance and support to S. Artis, Education and Outreach Director. As part of her Education responsibility, S. Artis provides guidance and support to the Graduate Student and Postdoc Council.

- Administration and Programmatic Team: The Center has a team with full-time personnel who are responsible for the Center's operations. This team, led by **J. Yuen**, Executive Director, added two additional full time positions and one part-time position in Period 2.

  J. Peng joined the Center as Administrative Manager, bringing a strong and extensive record in financial and grants management, and knowledge of the processes of the lead institution.

  S. Artis, who holds a Ph.D. in Industrial and Systems Engineering from Virginia Tech, assumed the position of Director of Education and Outreach, responsible for facilitating the delivery of Education and Diversity outcomes. She brings to this new position over thirteen years of experience working with education and outreach programs in engineering. Prior to joining the Center, S. Artis was a Postdoctoral Research Fellow in the Ohio State College of Engineering's Office of Diversity and Outreach and the Engineering Education Innovation Center. In this position, she led research initiatives focused on the development and implementation of engineering education pedagogies with an emphasis on engaging underrepresented groups including women and minorities. Previously, she spent nine years at Virginia Tech providing program and student support for the Center for the Enhancement of Engineering Diversity.

  C. Jones, Administrative Assistant, provides part-time support to the Center. Her efforts have included logistics support for the Center's Education and Diversity programs.

  While the team has the requisite skills to manage the Center and execute on its programs, the Center is challenged by the workload. Thus, the Center is recruiting for a Program Coordinator, who will devote 70% effort to support Education and Diversity programs and 30% effort to organizing other Center events. The Center is also expected to hire a Diversity Manager who will work under the supervision of S. Artis.

1b. Performance Metrics

Objective	Metrics	Frequency
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly
Leadership	Annual Surveys:	
	• Perception Survey – Students / Postdocs	Yearly
	• Perception Survey – Co-PI's	Yearly
	• External Advisory Board Survey	Yearly
Ethical Conduct	Survey on fairness in authorship	Yearly
	Survey on plagiarism	Yearly
	Spot checks on laboratory notebooks	Yearly

1c. Performance Against Metrics

Objective	Metrics	Targets	Period 2 Results
Strategic Plan	Assessment of goals, objectives, and outcomes		*Yearly*
Leadership	Annual Surveys:	3 or higher on Likert Scale	
	• Perception Survey – Students / Postdocs		Average: 3.89 (See **Appendix M**)
	• Perception Survey – Co-PI's		*In Progress*
	• External Advisory Board Survey		Strategic Plan = 4.18 Center Status = 4.01
Ethical Conduct	Survey on fairness in authorship	Period 2: Baseline	*Part of co-PI survey**
	Survey on plagiarism		*Part of co-PI survey**
	Spot checks on laboratory notebooks		*Process being planned*

*Survey of students and postdocs on ethical conduct will be administered in Period 3.

1d. Problems Encountered

The Annual Centerwide Retreat and Student and Postdoc Retreat, which are two key events to enable coordination and communication, did not have full on-site participation from MIT because inclement weather on the East Coast disrupted travel. Only three MIT graduate students were able to travel to the meeting. All MIT Center faculty participated via videoconferencing. Consequently, the planned breakout sessions for each Theme at the Annual Retreat did not take place. One training session of the Student and Postdoc Retreat had to be postponed.

2. Management and Communications systems

At the core of Center's management philosophy is the establishment of a culture in the Center that transcends physical and institutional boundaries. The Center's leadership team is dedicated to inspiring and leading the Center for E^3S based on the following values:

- Inclusiveness
- Teamwork

- Open and timely communications
- Agility
- Focus on Performance

Establishing such a culture must start with the Executive Committee. In Period 2, the Executive Committee established a governance structure to enable the desired culture in the Center. The Executive Committee adopted the following as part of the Center's governance:

- Executive Committee By-Laws
- Code of Conduct
- Regular Executive Committee meetings with pre-announced agendas and post-meeting minutes
- Annual proposal process for next period funding

Copies of the first three items are given in **Appendix H**, **Appendix I**, and **Appendix J**.

The following is a list of EC meetings that were held via videoconferencing and a list of topics discussed at the meetings.

EC Meeting Dates	Agenda Topics
March 1	Integration of Themes; By-laws
May 18	Financials, By-laws, Code of Conduct, Review of Education Program, Project Evaluation, E^3S Symposium
July 5	Code of Conduct, Financials, Center Synergy, Center's Value Add
August 30	Debriefing of the Annual Meeting, Discussion of the input by Industrial Research Board, Internal Proposal Review Process
November 4	Review of Proposals for Period 3 Funding
December 15	Preparation for NSF Site Visit

Outside the scheduled meetings, the EC consider 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 addition, the entire Center's communication system has gradually become more formalized.

- Center's Website: The website, www.e3s-center.org, which is built on the existing backend platform of another UC Berkeley STC, TRUST, serves as a communication tool for internal and external communication and has been customized to provide a unique E^3S look and feel. The website offers information about the Center and regularly updated information on future and past events on its public pages. The private intranet serves as a collaborative tool with capabilities to archive publications, presentations, and meeting materials and provides access to e-mail lists. Most Center participants have set up individual accounts and membership in multiple workspaces.

- Center's Annual Retreat: The 2nd Annual Retreat that was held on August 29-30 at UC Berkeley had the theme of "Building an Integrated and Collaborative Center." The agenda for the centerwide meeting included presentations of the Center's research projects and education programs, a discussion panel on Integrative Research that was aimed at identifying ways to increase the value-add as a Center, breakout sessions for each Theme, a working session for the Education and Outreach Director to engage partners, a Center Management session, as well as an awards and recognition ceremony during the Retreat dinner. Because inclement weather on the East Coast resulted in the Center's members from MIT participating via videoconference, the breakout sessions for the Themes had to be cancelled. Instead, there was one Research breakout session where the members from different Themes gathered to discuss cross Theme collaborations. During the Center Management session, E. Yablonovitch, Center Director, and J. Yuen, Executive Director, emphasized the need for teamwork in the Center and rolled out the Code of Conduct and the Annual Proposal Process. See **Appendix K** for the Center's Annual Retreat agenda.

- Annual Student and Postdoc Retreat: The Graduate Student and Postdoc Council organized an annual retreat for the Center's students and postdocs; see **Appendix L** for agenda. Besides research discussions and ethics training (see Section *III* for more information), the attendees were given an opportunity to complete a survey of their impression of the Center and its leadership. During the Center Management session on the second day of the Annual Retreat, A. Mutig, a Postdoc of the Center, presented the survey results that can be found in **Appendix M**.
- Regularly Scheduled Research Seminars: Since the inception of the Center in Fall 2010, the Center has used research seminars as a vehicle for its members to share and learn about the Center's research activities. There were 6 seminars that discussed the Center's research to date in Period 2. We expect additional Research Seminars in the last two months of this Period. As Research Seminars are also education venues, additional information can be found in Section *III*, Education.
- Regularly Scheduled Theme Meetings: In Period 2, there was an increase in the use of regularly scheduled meetings to communicate, plan, coordinate, and brainstorm among the faculty and graduate student/postdoc researchers.
  - Theme IV, which initiated regular theme meetings at the inception of the Center, has continued to meet regularly during the semester at a frequency of about once per month for two hours. Typical attendance is three faculty members and 8-10 students. Each meeting has focused deeply on one of the projects, with multiple presentations from different students/postdocs working on that project, followed by extended discussion, planning and brainstorming.
  - Theme II held meetings at a frequency of about once every 2-3 months during the academic year. The meetings have typically been attended by all faculty members and graduate student/postdoc researchers. Recent progress of each project is presented at each meeting. The meetings have included suggestions and discussion of ideas on future work and possibilities for collaboration. There were four meetings to date in Period 2.
  - Theme I meetings started at the end of Period 1. In Period 2, biweekly theme meetings are held with participations by faculty and students from participating institutions. Typical attendance has been four faculty members and about 8 graduate student/postdoc researchers. The emphasis to date has been presentation by students and postdocs on their research projects.

3. *Internal and External Advisory Bodies*

The primary sources of advice and guidance for the Center for E^3S are two groups: the External Advisory Board and the Industrial Research Board. This section presents the Period 2 activities for each group.

- External Advisory Board (EAB): In Period 2, the E3S Executive Committee formally adopted a charter that defines the roles and responsibilities of the EAB. The charter recognizes the primary mission of the EAB is to offer an independent assessment of E3S goals, plans, and accomplishments for research, education, diversity, knowledge transfer and center management. In addition, the charter identifies the responsibilities to include an annual evaluation report on the Center, the findings of which will be shared the E3S Executive Committee, as well as the Vice Chancellor of Research at the E3S lead institution, UC Berkeley. The EAB charter is presented in **Appendix N.**

The Executive Committee appoints EAB members so that the entire EAB will have the diversity of skills and experiences that will complement each other, enabling the Center to benefit from the broad range of experience and perspectives necessary to support the breadth of the Center's mission. In Period 2, the Executive Committee expanded the membership of the EAB. While this action was initiated by the need to address the change in availability of the original set of members, the goal is to increase the size of the EAB over time to maximum of ~12 members. A larger EAB will not only allow a diversity of viewpoints but also will minimize the burden on any one EAB member. New members are appointed by the Executive Committee through a ballot process. A candidate for membership in the EAB must be nominated by a member of the Executive Committee. Majority vote, as defined in the Executive Committee By-Laws, is required for appointment to the EAB. The Period 2 EAB members, their affiliations, and their primary expertise are listed in the table below.

			Research	Education	Diversity	Knowledge Transfer	Center Management
Nick Alexopoulous	Broadcom		x			x	
Peter Delfyett	U of Central Florida		x	x	x		x
Katherine Dunphy-Guzman	Sandia			x	x		
Jonathan Heritage	UC Davis		x	x			
Mark Lundstrom	Purdue U		x	x			
Luigi Colombo	Texas Instruments		x			x	
Elizabeth Weitzman	Semiconductor Research Corp.		x			x	x

In compliance with the charter, the first annual meeting of the EAB took place on November 2 at UC Berkeley. Six out of seven of the individuals identified in the above table attended. Unfortunately, N. Alexopoulous could not attend as his travel to the meeting was interrupted by inclement weather. The members in attendance appointed J. Heritage to serve as the chairperson of the EAB for this year. The output of the meeting is an assessment report that is made up of two parts, a qualitative assessment and a quantitative assessment, both of which are presented in **Appendix O** and **Appendix P**. The Executive Committee has reviewed the assessments. The assessments have also been shared with all funded faculty members in the Center and with the Vice Chancellor of Research of UC Berkeley.

- Industrial Research Board (IRB): The Center for E^3S is fortunate to have received strong support from four leaders in the semiconductor industry even before its inception. IBM, Intel and Hewlett-Packard are working toward the goal of energy efficient electronics science and, as noted above, have agreed to perform parallel research in their own laboratories and, in time, assign their staff to participate in the research as part of the Center. Lam Research has gifted two major process modules to UC Berkeley that are used by E^3S researchers. The IRB monitors, advises and participates in the Center's research, education and knowledge transfer goals. IRB members and their affiliations are listed in the table below.

	Name	Affiliation
1	Paolo Gargini	Intel
2	David Hemker	Lam Research
3	Ghavam Shahidi	IBM

4	Stan Williams	Hewlett-Packard

The Industrial Research Board convened its annual meeting with the Center's Executive Committee when the representatives of the member companies attended the Center's Annual Retreat. The company participants at the IRB meeting were:

	Company	**2011 IRB Meeting Attendees**
1	IBM	Paul Solomon, representing Ghavam Shahidi
2	Intel	George Thompson, representing Paolo Gargini
3	Lam Research	David Hemker

Even though Hewlett-Packard could not participate at the IRB meeting, S. Williams participated in the first day of the Annual Retreat and subsequently emailed his input to E. Yablonovitch.

4. *Changes in the Strategic Plan*

The Center for E^3S' Strategic Plan calls for the use of Period 2 to establish a baseline for many of our metrics and then to set goals for improvement in subsequent Periods. In doing so, we have found that some of our metrics need refinement (see Section *VII.1b* and *VII.1c*). In particular, some metrics are broken down to report on subsets, so that we will have better indicators of our progress. However, the strategic goals of the Center remain substantively unchanged.

VIII. CENTERWIDE OUTPUT

1a. Publications

1ai. Peer Reviewed (alphabetized by first author)

2010

S. H. Kim, S. Agarwal, Z. A. Jacobson, P. Matheu, C. Hu and T.-J. K. Liu, "Tunnel field effect transistor with raised germanium source*," IEEE Electron Device Letters*, Vol. 31, No. 10, pp. 1107-1109, 2010.

2011

R. Chen, T.-T. D. Tran, K. W. Ng, W. S. Ko, L. C. Chuang, F. G. Sedgwick and C. Chang-Hasnain, "Nanolasers grown on silicon," *Nature Photonics 5*, 170-175, March 2011.

L. C. Chuang, F. G. Sedgwick, R. Chen, W. S. Ko, M. Moewe, K. W. Ng, T.-T. D. Tran, and C. Chang-Hasnain, "GaAs-Based Nanoneedle Light Emitting Diode and Avalanche Photodiode Monolithically Integrated on a Silicon Substrate," *Nano Letters 11*, 385-390, February 2011.

H. Fang, M. Madsen, C. Carraro, K. Takei, H. S. Kim, E. Plis, S.-Y. Chen, S. Krishna, Y.-L. Chueh, R. Maboudian, A. Javey, "Strain engineering of epitaxially transferred, ultrathin layers of III-V semiconductor on insulator," *Applied Physics Letters*, 98, 012111, 2011.

A.C. Ford, C. W. Yeung, S. Chuang, H. S. Kim. E. Plis, S. Krishna, C. Hu, and A. Javey, "Ultrathin body InAs tunneling field-effect transistor on Si," *Applied Physics Letters*, Vol. 98, Issue 1, pp. 113105 - 113105-3, March 2011.

K. Ganapathi and S. Salahuddin, "Heterojunction Vertical Band-to-Band Tunneling Transistors for Steep Subthreshold Swing and High ON Current", *IEEE Electron Device Letters*, Vol. 32, No. 5, pp. 689-691, 2011.

X. Guan, D. Kim, K.C. Saraswat, and H.-S. P. Wong, "Complex Band Structures: From Parabolic to Elliptic Approximation," *IEEE Electron Devices Letters*, Vol. 32, No. 9, pp. 1296 – 1298, 2011.

M.-K. Kim, A. M. Lakhani, and M. C. Wu, "Efficient waveguide-coupling of metal-clad nanolaser cavities," *Optics Express*, vol. 19, no. 23, pp. 23504-23512, November 2011.

S. H. Kim, Z. A. Jacobson, P. Patel, C. Hu, and T.-J. K. Liu, "Tunnel FET-based pass-transistor logic for ultra-low-power applications," *Annual Device Research Conference*, Santa Barbara, California, USA, June 2011.

B. Lambson, D. Carlton, and J. Bokor, "Exploring the Thermodynamic Limits of Computation in Integrated Systems: Magnetic Memory, Nanomagnetic Logic, and the Landauer Limit," *Physical Review Letters*, vol. 107, Jul 2011.

A. M. Lakhani, M.-ki Kim, E. K. Lau, and M. C. Wu, "Plasmonic crystal defect nanolaser," *Optics Express*, vol. 19, no. 19, pp. 18237-18245, 2011.

M. Madsen, K. Takei, R. Kapadia, H. Fang, H. Ko, T. Takahashi, A. C. Ford, M. H. Lee, and A. Javey, "Nanoscale Semiconductor "X" on Substrate "Y" – Processes, Devices and Applications, " *Advanced Materials*, vol. 23, issue 28, pages 3115-3127, July 2011.

A. Murarka, S. Paydavosi, T. Andrew, J. H. Lang and V. Bulovic; "Printed MEMS membranes on silicon"; Proceedings: *IEEE International Conference on Micro Electro Mechanical Systems*, Paris, France, January 29 -February 2, 2012.

S. Paydavosi, F. M. Yaul, F. Niroui, A. Wang, T. Andrew, V. Bulovic and J. H. Lang, “MEMS switches employing active metal-polymer nanocomposites,” Proceedings: *IEEE Workshop on Micro Electro Mechanical Systems*, Paris, France, January 29 - February 2, 2012.

P.M. Solomon, I. Lauer, A. Majumdar, J.T. Teherani, M. Luisier, J. Cai, and S.J. Koester, “Effect of Uniaxial Strain on the Drain Current of a Heterojunction Tunneling Field-Effect Transistor,” *Electron Device Letters*, IEEE, vol. 32, no. 4, pp. 464-466, 2011.

K. Takei, S. Chuang, H. Fang, R. Kapadia, C.-H. Liu, J. Nah, H. S. Kim, E. Plis, S. Krishna, Y.-L. Chueh, and A. Javey, "Benchmarking the performance of ultrathin body InAs-on-insulator transistors as a function of body thickness," *Applied Physics Letters*, 99, 103507, 2011.

K. Takei, H. Fang, S. B. Kumar, R. Kapadia, Q. Gao, M. Madsen, H. S. Kim, C.-H. Liu, Y.-L. Chueh, E. Plis, S. Krishna, H. A. Bechtel, J. Guo, and A. Javey, "Quantum Confinement Effects in Nanoscale-Thickness InAs Membranes," *Nano Letters*, 2011.

Y. Yoon, D. E. Nikonov, and S. Salahuddin, “Role of Phonon Scattering in Graphene Nanoribbon Transistors: Nonequilibrium Green’s Function Method with Real Space Approach,” *Applied Physics Letters*, vol. 98, p. 203503, 2011.

Y. Yoon, D. E. Nikonov, and S. Salahuddin, “Scaling Study of Graphene Transistors”, *Proceedings of IEEE Nano*, Portland, OR, USA, August 15-18, 2011.

Submitted/Accepted for Publication

S. Agarwal and E. Yablonovitch, “Pronounced Effect of pn-Junction Dimensionality on Tunnel Switch Sharpness,” submitted to Proceedings of the IEEE on 9/1/2011.

J. T. Heron, M. Trassin, K. Ashraf, M. Gajek, Q. He, S.Y. Yang, D. E. Nikonov, Y-H. Chu, S. Salahuddin, and R. Ramesh, “Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure,” accepted for publication in *Physical Review Letters*, 2011.

H. Kam, T.-J. King Liu, and E. Alon, “Design Requirements for Steeply Switching Logic Devices,” accepted for publication in *IEEE Transactions on Electron Devices*.

K. Takei, M. Madsen, H. Fang, S. Chuang, H-S. Kim, C.-H. Liu, E. Plis, R. Kapadia, J. Nah, S. Krishna, Y.-L. Chueh, J. Gui, A. Javey, “Nanoscale InGaSb heterostructure membranes on Si substrates for high hole mobility transistors,” Submitted, 2011.

J. T. Teherani, W. Chern, D. A. Antoniadis, J. L. Hoyt, L. Ruiz, C. D. Poweleit, and J. Menendez, “Extraction of Large Valence Band Energy Offsets and a Review of Deformation Potentials in Strained-Si/Strained-Ge Type II Heterostructures on Relaxed SiGe Substrates,” submitted to *Physical Review B* on 10/6/2011.

1aii. Other Non-Peer Reviewed (alphabetized by first author)

C. Hu, P. Patel, A. Bowonder, K. Jeon; S. H. Kim, W-Y. Loh, C. Y. Kang, J. Oh, P. Majhi, A. Javey, T-J. K. Liu, and R. Jammy, "Prospect of tunneling green transistor for 0.1V CMOS", Invited paper, *2010 IEEE International Electron Devices Meeting (IEDM),* pp. 16.1.1 - 16.1.4, December 2010.

T.-J. K. Liu, S. H. Kim, and Z. A. Jacobson, “Ge-source TFETs for ultra-low-power electronics,” Invited paper, *219th ECS Meeting, Symposium E3,* Montreal, Quebec, Canada, May 2011.

T.-J. K. Liu, P. Matheu, Z. Jacobson, and S. H. Kim, “Steep-subthreshold-slope devices on SOI,” Invited paper , *2011 IEEE International SOI Conference*, Tempe, Arizona, USA, October 2011.

H.-S. P. Wong, "Nanoscale Electronic Devices," Invited paper, *The 39th Annual Electronic Materials Symposium,* Santa Clara, CA, USA, April 15, 2011.

1b. Conference Presentations (in chronological order)

T.-J. K. Liu, J. Jeon, R. Nathanael, H. Kam, V. Pott and E. Alon, "Prospects for MEM-relay logic switch technology," IEEE International Electron Devices Meeting, San Francisco, CA, USA, December 2010.

J. Teherani, "Band-to-band tunneling in silicon diodes," *MTL Annual Research Conference (MARC)*, USA, January 2011.

N. Antler, R. Vijay, C. Weis, E. Levenson-Falk, T. Schenkel, and I. Siddiqi, "Observation of Collective Strong Coupling between a Superconducting Resonator and Bismuth Dopants in Silicon," *APS March Meeting 2011*, Dallas, TX, USA, March 2011.

C. Hu, "Semiconductor Technology for Low Power ICs," Keynote Presentation, *China Semiconductor Technology International Conference (CSTIC)*, Shanghai, China, March 2011.

M. Trassin, J.T. Heron, K. Ashraf, M. Gajek, Q. He, S.Y. Yang, D.E. Nikonov, Y.-H. Chu, S. Salahuddin and R. Ramesh, "Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure," *MRS Spring 2011*, San Francisco, CA, USA, April 2011.

F. Lu, T.-T. D. Tran, W. S. Ko, K. W. Ng, R. Chen and C. J. Chang-Hasnain, "InGaAs Nanopillar Lasers Monolithically Grown on MOSFET-Si," *Spring Meeting of Material Research Society*, San Francisco, CA, USA, April 25-29, 2011.

F. Lu, T.-T. D. Tran, W. S. Ko, K. W. Ng, R. Chen and C. J. Chang-Hasnain, "Nanolasers on Si-MOSFET: A Monolithic Integration," *Conference on Lasers and Electro-Optics (CLEO)*, paper CMO2, Baltimore, MD, USA, May 2011.

T.-J. K. Liu, S. H. Kim, and Z. A. Jacobson, "Ge-source TFETs for ultra-low-power electronics," *219th ECS Meeting, Symposium E3*, Montreal, Quebec, Canada, May 2011.

K. Ganapathi, Y. Yoon and S. Salahuddin, "Monolayer MoS2 Transistors - Ballistic Performance Limit Analysis," *69th Device Research Conference*, UC Santa Barbara, CA, USA, June 2011.

Y. Yoon and S. Salahuddin, "Performance Assessment of Partially Unzipped Carbon Nanotube Field-Effect Transistors*", IEEE / ACM International Symposium on Nanoscale Architectures (NanoArch),* San Diego, CA, USA, June 8-9, 2011.

Y. Yoon and S. Salahuddin, "Role of Optical Phonon in Graphene Nanoribbon Tunnel Transistors: Strategy for Abrupt Switching from Material's Point of View," *Electronic Materials Conference (EMC),* Santa Barbara, CA, USA, June 22-24, 2011.

N. Antler, K. W. Murch, R. Vijay, S. Weber, C.D. Weis, D. Budker, T. Schenkel, and I. Siddiqi, "Measuring Spin Ensembles with Superconducting Circuits," *Les Houches Summer School*, Les Houches, France, July 20, 2011.

W.S. Ko, K. Li, K.W. Ng, R. Chen, S. Hertenberger, G. Koblmueller, G. Abstreiter and C. Chang-Hasnain, "Site-Controlled Growth of Nanopillar Laser on Silicon Substrate*," International Nano-Optoelectronics Workshop*, St. Petersburg, Russia and Wurzberg, Germany, July 24 – August 5, 2011.

N. Antler, K. W. Murch, R. Vijay, S. Weber, C.D. Weis, D. Budker, T. Schenkel, I. Siddiqi, "Readout and Control of Spin Systems with Superconducting Circuits", Invited Talk*, 26th International Low Temperature Physics Conference*, Beijing, China, August 13, 2011.

X. Guan, D. Kim, K. C. Saraswat, H.-S. P. Wong, “Analytical Approximation of Complex Band Structures for Band-to-Band Tunneling Models,” *2011 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD),* Osaka, Japan, September 8-10, 2011.

X. Shen, S. Chong, D. Lee, R. Parsa, R. T. Howe, and H.-S. P. Wong, “2D Analytical Model for the Study of NEM Relay Device Scaling*,” 2011 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD)*, Osaka, Japan, September 8-10, 2011.

M. Eggleston, A. Lakhani, L. Zhang, E. Yablonovitch, and M.C. Wu, “Optical Antenna Based nanoLED,” *IEEE Photonics Society (IPS) Meeting*, Arlington, VA, USA, October 2011.

R. Going, T. J. Seok, A. Lakhani, M. Eggleston, M.-K. Kim, and M. C. Wu, “Optical Antenna Design for Nanophotodiodes,” *IEEE Photonics Society (IPS) Meeting*, Arlington, VA, USA, October 2011.

T.-J. K. Liu, P. Matheu, Z. Jacobson, and S. H. Kim, “Steep-subthreshold-slope devices on SOI,” *2011 IEEE International SOI Conference,* Tempe, Arizona, USA, October 2011.

J.T. Heron , M. Trassin, K. Ashraf, M. Gajek, Q. He, S.Y. Yang, D.E. Nikonov, Y.-H. Chu, S. Salahuddin and R. Ramesh, “Electric-Field-Induced Magnetization Reversal in a Ferromagnet-Multiferroic Heterostructure,” *MRS Fall 2011*, Boston, MA, USA, November-December 2011.

M. Trassin, J.T. Heron, K. Ashraf, M. Gajek, Q. He, S.Y. Yang, D.E. Nikonov, Y.-H. Chu, S. Salahuddin and R. Ramesh, “Transverse electric field induced magnetization reversal using multiferroics”, *MRS Fall 2011*, Boston, MA, USA, November-December 2011.

M. Trassin, “Electric-field induced magnetization reversal using multiferroics,” *APS March Meeting 2012*, Boston, MA, March 2012.

1c. Other Dissemination Activities (in chronological order)

C. Hu, "Very low voltage tunneling green transistor", Invited presentation at Intel Corp., Oregon, USA, November 17, 2010.

T.-J. K. Liu, “Sustaining the Silicon Revolution: Challenges and Opportunities,” Invited seminar, *EE Department seminar,* University of California at Los Angeles, Los Angeles, California, USA, January 10, 2011.

T.-J. K. Liu, “Mechanical Computing Redux: Relays for IC Applications,” Invited seminar, *IEEE Electron Devices Society Santa Clara Chapter seminar*, Santa Clara, California, USA, January 11, 2011.

E. Yablonovitch, “Energy Efficient Electronics;: Searching for the milli-Volt Switch,” Invited talk, Tuskegee University, Alabama, USA, March 21, 2011.

E. Yablonovitch, “Nano-Photonic Silicon Circuits as a Commercial Technology,” Invited talk, *GOMACTech-11 Conference*, Orlando, Florida, USA, March 22, 2011.

E. Yablonovitch, “Energy Efficient Electronics; Searching for the milli-Volt Switch,” Invited talk, *UCLA Electrical Engineering Department Seminar*, Los Angeles, California, USA, April 5, 2011.

T.-J. K. Liu, “Sustaining the Silicon Revolution: Challenges and Opportunities,” Invited seminar, *Electrical and Computer Engineering Department seminar*, Lehigh University, Bethlehem, Pennsylvania, USA, May 10, 2011.

E. Yablonovitch, “Energy Efficient Electronics; Searching for the milli-Volt Switch,” Invited talk, Berkeley Nano-Seminar Series, Berkeley, California, USA, August 26, 2011.

C. Hu, "Future low power transistors," *Seminar* at University of Illinois, Urbana-Champaign, August 31, 2011.

J. Teherani, Presented paper on the MOS-capacitor valence band offset extraction of s-Si/s-Ge heterojunctions, *MTL Annual Research Report*, August 2011. (This report is shared with industry partners).

H.-S. P. Wong, Participated in *DARPA ISAT study on future electronic systems*, Spring to Summer, 2011 (organizers: Subhasish Mitra, Stanford University and Kerry Bernstein, IBM).

E. Fitzgerald, "Epitaxial Growth of Heterojunctions for Density-of-States Switching Devices via MOCVD," *Materials Processing Center Research Review Poster Session*, October 18th, 2011.

E. Alon, "Circuit and System Driven Requirements for Digital Logic Devices" Invited talk, *2nd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, California, USA, November 3-4, 2011.

J. Bokor, "Concepts for Spin Communication and Logic," Invited talk, *2nd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, California, USA, November 3-4, 2011.

T.-J. K. Liu, "The Path Toward Efficient Nano-Mechanical Circuits and Systems," Invited talk, *2nd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, California, USA, November 3-4, 2011.

H.-S. P. Wong, "Emerging Memories: Are They Energy Efficient Enough?" Invited talk, *2nd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, California, USA, November 3-4, 2011.

M. C. Wu, "Nanophotonic Devices for Energy Efficient Optical Interconnect," Invited talk, *2nd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, California, USA, November 3-4, 2011.

E. Yablonovitch, "Tunnel Transistor Mechanism Based on Density of States Switching," Invited talk, *2nd Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, California, USA, November 3-4, 2011.

E. Yablonovitch, "Searching for the milli-Volt Switch - New NSF STC Center," Invited talk, *CIFAR NanoElectronics Program Meeting*, Napa, CA USA, November 14, 2011.

E. Yablonovitch, "Replacing the Transistor; Searching for the Milli-Volt Switch," Invited talk, *IAS HKUST Distinguished Lecture*, Hong Kong, November 21, 2011.

2. *Awards & Honors*

Recipient	**Reason for Award**	**Award Name**	**Sponsor**	**Date**	**Award type**
Elad Alon(co-recipients)	Best Paper	2010 Jack Raper Award for Outstanding Technology – Directions	IEEE	February 2011	Industry
Trisha Andrew	Career contributions of young women researchers in the life and	2011 L'Oreal USA Fellowships for Women in Science	L'Oreal	April 2011	Fellowship

	physical/materials sciences (1 of 5 women scientists selected)				
Sharnnia Artis	Future contributions to engineering education research	2011 Apprentice Faculty Grant	Educational Research and Methods Division, American Society for Engineering Education (ASEE)	June 2011	Education
Connie Chang-Hasnain	Pioneering contributions to vertical cavity surface emitting laser (VCSEL) arrays and tunable VCSELs	2011 IEEE David Sarnoff Award	IEEE	February 2011	Scientific
Eugene Fitzgerald (co-recipient)	Strained silicon/SiGe	2011 IEEE Andrew Grove Award	IEEE	December 2011	Scientific
Judy Hoyt (co-recipient)	Strained silicon/SiGe	2011 IEEE Andrew Grove Award	IEEE	December 2011	Scientific
Chenming Hu	Outstanding American scientists, engineers and corporate leaders with Asian ethnicity with exceptional contributions in their fields of expertise	Distinguished Lifetime Achievement Award	Chinese Institute of Engineers – USA (CIE-USA)	February 2011	Scientific
Chenming Hu	Distinguished Service to the University	Berkeley Citation	University of California, Berkeley	April 2011	Education
Chenming Hu	exemplary research and significant contributions to the advancement of the electronics industry and our national economy	University Research Award	Semiconductor Industry Association	May 2011	Industry
Chenming Hu	Outstanding	Distinguished	National Taiwan	Novembe	Other

	Achievements	Alumni Award	University	r 2011	
Chenming Hu	Distinguished contributions to education on electron devices	Education Award	IEEE Electron Devices Society	Decembe r 2011	Education
Ali Javey	For creative research on nanomaterials and nanotechnologies for electronic applications	Early Career Award in Nanotechnology	IEEE	August 2011	Scientific & Industry
Tsu-Jae King Liu	Research accomplishments	2011 Callinan Award	Electrochemical Society	May 2011	Scientific & Industry
Tsu-Jae King Liu (co-recipients)	Best Paper	2010 Jack Raper Award for Outstanding Technology – Directions	IEEE	February 2011	Scientific & Industry
Wai Son Ko	Best Poster	Best Poster Award, Honorable Mention	International Nano-Optoelectronics Workshop	August 6, 2011	Scientific
H.-S. Philip Wong	International scientific excellence of research works and long-standing collaborations with institute and French research community	Honorary Doctorate Degree	Grenoble Institute of Technology (Institut Polytechnique de Grenoble), France	February 10, 2011	Scientific
Ming C. Wu	Leadership and contribution in photonics	Nortel Networks Distinguished Professorship Endowed Chair	Nortel Networks and UC Berkeley	July 1, 2011 through June 30, 2016	Education & Scientific
Eli Yablonovitch	Pioneering contributions to photonic crystals, the photonic bandgap and photonic bandgap engineering	2012 IEEE Photonics Award	IEEE	August 2011	Scientific
Eli Yablonovitch	Distinguished achievements and contributions	Honorary Doctorate in Engineering	The Hong Kong University of Science and Technology (HKUST)	Novembe r 18, 2011	Scientific

Matthew Spencer, Rhesa Nathanael, Jaeseok Jeon, Hei Kam, Vincent Pott, Tsu-Jae King Liu, Elad Alon	Best Paper	2010 ISSCC Jack Raper Award for Outstanding Technology Directions Paper	IEEE International Solid-State Circuits Conference	February 2, 2011	Scientific

3. *Graduates*

Students:

Name	Degree(s)	Years to Degree	Placement
Alexandra Ford	Ph.D.	5	Sandia National Lab
Qing He	Ph.D.	7	ALS, LBNL
Frank Yaul	M Eng EECS	1.5 (M Eng)	MIT EECS Ph.D. Program

Postdocs:

Name	Placement
Pouya Hashemi	IBM, Yorktown

4a. *General Outputs of Knowledge Transfer Activities*

Patent Name	Inventors/Authors	Number	Application Date	Receipt Date (leave empty if pending)
Electronically-Controlled Squishable Composite Switch	T. Andrew, V. Bulovic, J.C. Grossman, J.H. Lang, A. Murarka, F. Niroui, S. Paydavosi, F. Yaul and A. I. Wang	MIT patent disclosure - Case # 14594	Disclosed in December 2010; patent filed on November 7, 2011	

Licenses: none to report

Startup companies: none to report

4b. *Other Outputs of Knowledge Transfer Activities*

Tsu-Jae King Liu conducted regular teleconference presentations and discussions (held on 4/8/11, 5/13/11, 5/20/11, and 5/27/11, 7/1/11, 7/20/11, 7/27/11, 8/5/11, 8/19/11, 8/26/11) with researchers at Intel Corporation on relay devices and technology.

5a. Participants

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
19	Faculty	11	Berkeley	15	E.E.	16	M	0	Hearing Impairment	0	Hispanic or Lantino	0	American Indian or Alaskan Native	16	US Citizens
		6	MIT	3	Mats Sci	3	F	0	Visual Impairment	14	Not Hispanic or Latino	7	Asian	3	Permanent Resident
		1	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	4	Decline to State	0	Black or African American	0	Other non-US Citizen
		1	Tuskegee					0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								15	None			9	White	0	Not Available
								4	Decline to State			3	Decline to State		
								0	Not Available			0	Not Available		
16	Post-Docs	12	Berkeley	12	E.E.	14	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	3	US Citizens
		2	MIT	0	Mats Sci	2	F	0	Visual Impairment	16	Not Hispanic or Latino	12	Asian	2	Permanent Resident
		2	Stanford	4	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	11	Other non-US Citizen
		0	Tuskegee					0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								14	None			3	White	0	Not Available
								2	Decline to State			1	Decline to State		
								0	Not Available			0	Not Available		
42	Graduate Students	28	Berkeley	31	E.E.	32	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	22	US Citizens
		8	MIT	7	Mats Sci	10	F	0	Visual Impairment	38	Not Hispanic or Latino	25	Asian	1	Permanent Resident
		5	Stanford	5	Physics			0	Mobility/Orthopedic Impairment	3	Decline to State	1	Black or African American	18	Other non-US Citizen
		1	Tuskegee	0	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								39	None			10	White	1	Not Available
								2	Decline to State			5	Decline to State		
								1	Not Available			1	Not Available		
12	Undergraduate Students	1	Berkeley	4	E.E.	7	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	5	US Citizens
		0	MIT	1	Mats Sci	5	F	0	Visual Impairment	10	Not Hispanic or Latino	6	Asian	5	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	2	Black or African American	0	Other non-US Citizen
		2	Tuskegee	6	Other			0	Other	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					8	None			1	White	2	Not Available
		1	CCC					2	Decline to State			2	Decline to State		
		7	Other					2	Not Available			1	Not Available		
6	Staff	5	Berkeley		E.E.	0	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	5	US Citizens
		0	MIT		Mats Sci	6	F	0	Visual Impairment	5	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford		Physics			0	Mobility/Orthopedic Impairment		Decline to State	3	Black or African American	0	Other non-US Citizen
		1	Tuskegee	6	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								4	None			1	White	1	Not Available
								1	Decline to State			0	Decline to State		
								1	Not Available			0	Not Available		

5b. Affiliates

	Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship
4	Faculty	2	Berkeley	2	E.E.	2	M	0	Hearing Impairment	2	Hispanic or Lantino	0	American Indian or Alaskan Native		US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	1	Not Hispanic or Latino	1	Asian		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	Tuskegee	2	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					3	None			1	White	1	Not Available
		1	CCC					0	Decline to State			1	Decline to State		
		0	Other					1	Not Available			1	Not Available		
1	Visiting Faculty	0	Berkeley	1	E.E.	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	0	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	Tuskegee	0	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	Other					0	None			0	White	1	Not Available
								0	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
1	Research Scientists	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	Tuskegee	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		
5	Post-Docs	4	Berkeley	2	E.E.	4	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	0	US Citizens
		1	MIT	1	Mats Sci	1	F	0	Visual Impairment	2	Not Hispanic or Latino	2	Asian	1	Permanent Resident
		0	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	0	Black or African American	2	Other non-US Citizen
		0	Tuskegee					0	Other	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								2	None			1	White	2	Not Available
								1	Decline to State			0	Decline to State		
								2	Not Available			2	Not Available		
14	Graduate Students	12	Berkeley	10	E.E.	13	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	3	US Citizens
		2	MIT	2	Mats Sci	1	F	0	Visual Impairment	6	Not Hispanic or Latino	3	Asian	0	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	3	Other non-US Citizen
		0	Tuskegee	1	Other			0	Other	8	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								6	None			3	White	8	Not Available
								0	Decline to State			0	Decline to State		
								8	Not Available			8	Not Available		
38	Pre-College Students	0	Berkeley	0	E.E.	22	M	0	Hearing Impairment	9	Hispanic	1	American Indian or Alaskan Native	0	US Citizens
		0	MIT	0	Mats Sci	16	F	0	Visual Impairment	0	Not Hispanic or Latino	8	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	9	Black or African American	0	Other non-US Citizen
		0	Tuskegee	0	Other			0	Other	29	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	38	N/A			0	None			4	White	38	Not Available
		0	CCC					0	Decline to State			0	Decline to State		
		38	Other					38	Not Available			16	Not Available		
8	Staff	5	Berkeley	1	E.E.	4	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	8	US Citizens
		2	MIT	0	Mats Sci	4	F	0	Visual Impairment	6	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	Tuskegee	7	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								6	None			3	White	0	Not Available
								2	Decline to State			1	Decline to State		
								0	Not Available			0	Not Available		

6. *Center Partners*

	Organization Name	Organization Type	Address	Contact Name	Type of Partner	160 hours or more?
1	Intel	Company	Santa Clara, CA	Paolo Gargini	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	Army Research Laboratory	Federal Government		Brian Bennett	Research	N
6	University of New Mexico	University	Albuquerque, NM	Sanjay Krishna	Research	N
7	Technical University of Munich	University	Munich, Germany	Markus-Christian Amann	Research	N
8	Texas Tech University	University	San Marcos, TX	Ravi Droopad	Research	N
9	Purdue University	University	West Lafayette, IN	Mathieu Luisier	Research	N
10	UC Santa Barbara	University	Santa Barbara, CA	David Awschalom	Research	
11	UC Berkeley – Transfer Alliance Project	University	Berkeley, CA	Keith Schoon	Education	N
12	UCLA Center for Community College Partnerships	University	Los Angeles	Alfred Herrera	Education	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)	12
3	the total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC)	$45,000

4	the number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF) .	95

8. *Media Publicity of Center*

The Center received media publicity for the 2nd Berkeley Symposium on Energy Efficient Electronic Systems, which is discussed in detail in Section *IV.2a*.

The Science section of US News carried an article about the Center in Fall 2011; see http://www.usnews.com/science/articles/2011/11/29/designing-better-transistors.

The Center also received media publicity in Electronics Design, Strategy, News (EDN.com); see http://www.edn.com/article/520180-Driving_toward_millivolt_electronics.php.

IX. INDIRECT/OTHER IMPACTS

The Center's engagement in international activities includes:

- T.J. King Liu, M.C. Wu and J. Yuen participated in a meeting with a delegation of Taiwan University Deans visiting UC Berkeley
- J. Yuen secured international participation in the Organizing Committee and international speakers at the 2nd Berkeley Symposium on Energy Efficient Electronic System
- E. Yablonovtich hosted a seminar by F. Guistino, Oxford University
- C. Hu received the Distinguished Alumni Award from National Taiwan University (Hu)
- J. Hoyt hosted an undergraduate of Mexican citizenship, but who is an international student in Texas, to do 9 weeks of research (J. Hoyt) under MSRP sponsorship. (No funds from the Center for E^3S were used).
- E. Yablonovitch accepted an Honorary Doctorate in Engineering from Hong Kong University of Science and Technology.
- E. Yablonovitch gave the IAS HKUST Distinguished Lecture in Hong Kong.

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XI. APPENDICES

Appendix A: Biographical Information of New Faculty

Appendix B: Research Seminars and Journal Club

Appendix C: Tuskegee's Letter of Support

Appendix D: UC Berkeley Joint Recruitment Schedule

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Appendix F: Program of the 2nd Berkeley Symposium on Energy Efficient Systems

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Appendix Q: Center Website Visits