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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 3, 2012
Reporting period	March 1, 2012 – February 28, 2013
Name of the Center	Center for Energy Efficient Electronics Science (E^3S)
Name of the Center Director	Eli Yablonovitch
Lead University	University of California, Berkeley
Contact Information	
Address	267M Cory Hall Berkeley, CA 94720-1770
Phone Number	510-642-6821
Fax Number	510-666-3409
Email Address of Center Director	eliy@eecs.berkeley.edu
Center URL	https://www.e3s-center.org

Participating Institutions

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

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

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

Institution Name	Tuskegee University Shaik Jeelani
Address	101 James Center Tuskegee, AL 36088
Phone Number	334-727-8970
Fax Number	334-724-4224
Email Address of Center Director	jeelanis@tuskegee.edu
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
Address	2600 Mission Bell Drive San Pablo, CA 94806
Phone Number	510-235-7800 x 4527
Fax Number	510-236-6768
Email Address of Center Director	ssidharta@contracosta.edu
Role of Institution at Center	Contra Costa College is an education and outreach partner to encourage greater minority participation in engineering.

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

1b. *Biographical Information of New Faculty*

No new faculty members were 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
Address	552 Sutardja Dai Hall, Berkeley, CA 94720
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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 [1]. Rapid growth of energy consumption for information processing is a direct result of the spectacular success of the information technology industry largely fueled by the exponential growth in electronics functionality enabled by Moore's law scaling of integrated circuit (IC) 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 is the recognition that the energy consumption of an IC imposes its own limit on scaling. As more and more transistors are packed onto a chip with fixed dimensions of a few tens of mm^2, the power dissipated during dynamic operation of transistors as well as the standby power dissipated even when transistors are not in operation tends to grow almost linearly with the number of transistors (which itself grows exponentially). There is a fundamental limit to the amount of power dissipation that can be tolerated in an IC due to limits in heat extraction.

The confluence of these trends is of critical importance. The rapid growth in the demand for information processing within the economy is 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 needed be in an ideal system.

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 of the energy consumption required to process information [2]. This goal represents a potential reduction from current energy levels, per operation, by 6 orders of magnitude.

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 comprises four Themes:

I. Nanoelectronics with a focus on solid state millivolt switching

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

III. Nanophotonics focused on few-photon communication

IV. Nanomagnetics that has the potential of achieving the lowest energy.

Themes I, II and IV each pursue different approaches 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 System Integration research targeted to provide detailed specifications for the new devices from a circuit perspective. These will enable future ultra-low energy information systems to be built and integrated using elements of each of these approaches.

Nanotechnology offers the potential for continuing the exponential growth in capabilities beyond the energy-imposed scaling limits of current CMOS technology, but laying the foundation for radically new approaches requires research among the basic disciplines (physics, nanomaterials, nanodevices) in a coordinated matrix fashion.

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 (TFETs) continues to be a key approach in the Nanoelectronics Theme. Even though the concept has been in research for many years, TFET experiment results have been disappointing, and simulation predicting phenomenal device performance and experiment faring far worse. The lack of a sound scientific foundation has impeded achieving promising results. The Center is the first concerted effort to focus on the elucidation of the physics of energy bandgap sharpness both theoretically and experimentally. Moreover, the concept of the TFET itself is still in flux, with various mechanisms proposed. In Period 3, the Nanoelectronics Theme's focus has expanded to include the Work-Function induced Bilayer TFET, as it shows considerable promise. In the Nanomechanics Theme, the Center focuses efforts on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of conventional transistors. Prior research on micro/nano-electro-mechanical (M/NEM) switches 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 Nanomechanics Theme investigates both contact and non-contact approaches in mechanical switching. Optical interconnects research efforts generally claim performance and lower power consumption as goals. The Nanophotonics Theme's target on nanoscale ultra-efficient active optical components for on-chip application differentiates from the many R&D optoelectronics efforts in industry which have concentrated on optical backplanes. A DARPA funded silicon photonics research program, Ultraperformance Nanophotonic Intrachip Communications (UNIC) has much of its focus on optical transceivers and the integration of passive components. The goal of the Nanomagnetics Theme is to evaluate the fundamental limits of energy dissipation in magnetic logic devices and switches. 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 focused 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 students 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. At the preparation of this Period 3 Annual Report, the Center has completed approximately 24 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 given in the Center's Strategic Plan. The metrics were established to help track our performance in the various areas that make up our mission. There are also metrics for Center Management. While not an element in our mission, how we manage our Center will impact the climate of the Center.

Objective	Metric	Targets	Period 3 Results
Research	Multi-PI projects	Period 5: 30%	67% (14)
	Multi-Institutional projects	Period 5: 30%	10% (2)
	Unplanned research projects	Period 3: 1	4
	New joint research funding opportunities	Mid-Period 3: 1 proposal	1
	Publications with authors from multiple institutions	Period 3: 12	1
Education	Number of Center graduates who have completed E^3S training	Period 3: 50%	3 (17%)
	Number of publications with	Period 3: 9	0

	student and postdoc authors who have published previously in other themes		
	Number of students and postdocs participating in education and diversity programs	Period 3: 60%	48 (52%)
	Number of students and postdocs serving in leadership roles in the Center	Period 3: 15%	11 (19%)
Diversity	Number of women participating in the Center's research programs	Period 3: 5% increase (27%)	15 (25%)
	Number of underrepresented minorities participating in the Center's research programs	Period 3: 15% increase	1 (2%)
	Number of diversity program participants from groups underrepresented in STEM	Period 3: Baseline	93 (82%)
	Number of pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline	31 (68%)
	Number of community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Period 3: 5%	3 (100%)
	Number of undergraduates who pursue advanced degree in science and engineering	Period 3: 5%	0 (0%)
Knowledge Transfer	Website hits & unique visitors	Period 3: 20% increase	Website Hits: 240% (27,298) Unique Visitors: 267% (16,338)
	Number of contacts with industry: • General • Presentations by industry	 Period 3: 36 Yearly: 2	 Period 2: 66 Period 3: 20 Average: 43 2
	Center publications	Per Year: 18	16 plus 1 accepted and 4 under review
	External citations of publications	Period 3: 10	178

	Patent disclosures	Period 3: 3	0
	Students hired into relevant industries	Period 5: 50% Period 10: 50%	Students: 64% Postdocs: 33%
	Technology development attributable to Center's research	Period 10: 1	n/a in Period 3
	Number of events leading to external articles on Center	Period 3: 100% increase	0
Center Management	Centerwide communications	1 newsletter Annual Retreat Annual NSF Review Updated Website	June 2012 August 21-22, 2012 January 9-10, 2012 Continuously
	Number of disputes	Annual decrease	0
	Annual Surveys:	3 or higher on Likert Scale	
	• Students /Postdocs		Average: 4.04
	• Co-PIs		Leadership: 4.46 Collaboration: 3.25
	• External Advisory Board Survey		Strategic Plan: 4.07 Accomplishments: 3.96
	Authorship disputes	20% decrease annually	0
	Plagiarism		Faculty Ethics Survey: 4.39
	Assessment of goals, objectives, and outcomes – Strategic Plan Review	Yearly	December 19, 2012

Research

Center's Faculty: In Period 3 (March 2012 through February 2013), the Center has 22 faculty researchers at four partner institutions. These researchers bring expertise in materials synthesis, device physics and processing, and theory and modeling. They are:

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

The research of the Center for E^3S continues to be 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 wires in an integrated circuit; these wires are also often referred to as 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.

The Center's four research Themes effort are made up of multiple projects addressing different aspects and/or utilize different approaches that will help the Center make progress toward its goals.

Over-arching these four Themes is the System Integration research, where the outcomes will include a common set of metrics for each of the themes and a circuit perspective that will enable future ultra-low energy information systems to be built and integrated using elements of each of these approaches. In addition, there are Theme specific collaborations as Themes seeks insights from a system perspective.

Center Synergy: The faculty and their research groups are taking advantage of the collaborative environment offered by the Center. The following summary of the status of the research program will show that most projects are collaborative efforts among faculty researchers. Moreover, as the Center and in particular, the Themes, are evolving into communities, informal collaborations also abound.

Faculty members have reported that they highly value Theme meetings where colleagues share issues and approaches and vet each other's ideas. By comparing and discussing the evolving approaches of the teams in the same Theme, some researchers have reported that they develop new understandings of the fundamentals and thus, have been able to evolve their approaches more rapidly and effectively. In addition to Theme meetings, seminars and annual retreats are additional venues for students and postdocs to get to know each other and each other's research. These interactions are building and enhancing the foundation for team science.

Here are specific examples of collaborative activities in Period 3. Many of them evolved organically and involve two member institutions. These collaborative examples bear testimony that through the Center's activities, an E^3S community is being built.

- Upon conceptualing the device with the new Bilayer TFET concept, the **E. Yablonovitch** group at *Berkeley* received valuable feedback from the *MIT* team of **D. Antoniadis** and **J. Hoyt**. The teams from the two institutions jointly analyzed the prospects of the device. By collaboratively analyzing the device we were able to quickly obtain a realistic expectation of its limits and potential performance.
- The interactions within the Center between **E. Yablonovitch** and **A. Javey** at *Berkeley* on characterization of 2-D InAs membranes have led to consideration of a new physical concept: quantum unit of optical absorption.
- The group of **J. Wu** of *Berkeley* is sharing its capability and know-how for synthesis and transfer of high-quality graphene with **H.-S.P. Wong**'s group at *Stanford*.

- The group of **J. del Alamo** at *MIT* learned from the work on nanopillar LEDs of **M.C. Wu**'s group at *Berkeley*, as the *MIT* group began their work to fabricate vertical nanowire by Reactive Ion Etching.
- The **M.C. Wu** group of *Berkeley* has begun discussions with **J. Hoyt** of *MIT* on the feasibility of a collaboration to grow epitaxial germanium on silicon for the Nanophotodetector project.
- Theme II continues to have a project that brings together the disparate fields of nanomagnetics and nanomechanics to address surface adhesion. This collaboration between **J. Bokor** and **T.-J. King Liu** *(both Berkeley)*, which began towards the end of the previous reporting period, was conceived as a result of proactive discussions on Integrative Research within the Center.

Goals and Objectives: The Center's faculty researchers and their groups are working together to achieve the Center's research goals, which have not changed since the inception of the Center. 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 mS/μm; i.e., a 1μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in mS/μm of conductance versus what that is typically assumed in the traditional unit of milli-Amps/μm, reflecting the Center's target operating voltage of significantly less than the 1 Volt.)

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

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 [2]. Nevertheless, since the inception of the Center, we have identified a near-term application of magnetics in mechanic switching, and we also expect that there are potentially near-term goals employing magneto-resistive switching.

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 3:

All research Themes in the Center are making good progress in this reporting period, but there are changes that we consider significant to be worth noting here : (i) One unplanned project in Theme I is the Bilayer TFET that potentially will greatly simplifies the material strategy; (ii) Theme II modified its strategy to place greater emphasis on non-contacting switching mechanisms in mechanical relays as we learned more about the difficult issue of surface adhesion, alternatively known as stiction; (iii) The project on metal-insulator transition (MIT) in the correlated oxide VO_2, initiated as a seed project in Period 2 without a targeted application, joined the Theme II portfolio as a phase transition approach towards mechanical actuation; (iv) Theme III consolidated its emitter efforts in the nano-LED project, largely because of experimental successes achieved in this period; and (iv) Theme IV is concentrating on fundamental verification and experimental studies of logic devices, having decided to de-emphasize its spin diffusion communications project.

Below is an expanded summary of each area of research in Period 3.

- *System Integration Research*: Detailed specification of the research goals of the Center is itself an ongoing research effort. In Period 3, **E. Alon** of *Berkeley* continued to work with the four Themes to elucidate circuit- and system-level requirements for new switching and interconnection technologies. We built on last period's research by developing a generalized framework for analyzing I_{on}/I_{off} analysis that includes the effects of variability. The analysis points to the need for new metrics to capture the effect of variability, and that threshold variability in mV can be a misleading quantity for steep devices. Specifically, this absolute variability (in mV) must be compared against a composite of the local steepness measures (Soff and Son) in order to predict its final effect on energy-efficiency. Collaborative projects between the System Integration effort and Themes II & III have revealed fundamental limitations and the tradeoffs for these Themes.

- *Theme I - Nanoelectronics*: Theme I comprises **E. Yablonovitch,** Theme Leader, and 10 other faculty from *UC Berkeley*, *MIT* and *Tuskegee*. This Theme has been focusing on alternative mechanisms, particularly switching mechanisms, to make Field Effect Transistors (FET) to turn on with a few milli-Volts. A large part of the effort that involves 8 faculty (**Antoniadis**, **Das**, **Fitzgerald**, **Hoyt**, **Hu**, **Javey**, **Rangari**, and **Yablonovitch**) is devoted to switching via tunneling by using:

    - 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.

    - Heterostructure with 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 [3].

  Other approaches aimed at achieving a steep-subthreshold swing in a III-V FET in Theme I are: (i) the use of a Superlattice Nanowire to form a minigap in the density of states at the source that effectively cuts off the thermal tail responsible for the subthreshold current in an FET (**del Alamo**); and (ii) the use of composite gate dielectric stacks, including ferroelectric gates, to provide "transformer" action boosting the gate voltage seen by a channel of a MOSFET (**Salahuddin** and **Hu**).

  Noteworthy is that the Theme I researchers have made great strides experimentally in the past year, and we have added a switch with a new tunneling mechanism, the Bilayer TFET, into the mix of research projects.

  - We have demonstrated the key building blocks that are needed to build a 2D-2D Density of States switch:

      - **C. Hu,** in collaboration with **A. Javey**, (*both Berkeley*) have fabricated a gate controlled InAs (quantum well) on a GaSb tunnel diode, and achieved successful demonstration of strong MOS gate control of multiple Negative Differential Resistance (NDR) steps in a quantum well tunnel diode. This success is built on newly developed processing technologies: E-beam T-gate technology and low-resistance contact technology for forming a low series resistance self-aligned gate TFET, a technique of making MOS high-k dielectric and metal gate stack, and a well-controlled selective etching process to etch away the GaSb source while keeping the InAs/AlGaSb tunnel junction intact.

      - **A. Javey** of *UC Berkeley* has successfully completed the XOI platform [4] for both n- and p-type semiconductors studies for ultra-thin films of InAs and InGaSb, laying the experimental foundation for 2D-2D p-n junctions. From the optical study of 2-D InAs the role of quantum confinement has been understood. The onset of shifts to higher energies with thickness reduction indicating bandgap increases with downscaling of the thickness due to quantum confinement. Clear steps in absorption depict the optical transitions between 2D subbands, and the spacing between the subbands increases with thickness reduction. These results provide insights in future designing of InAs/GaSb TFETs.

  - **E. Fitzgerald** of *MIT* has demonstrated functional diodes made from InAs/GaSb heterostructures grown by MOCVD, establishing the Center with its own material growth capability. This demonstration is built on the identification of various links between process parameters (such as temperature, V/III ratio, and interface gas switching sequence, growth order) and heterostructure properties (such as interface abruptness, dislocation densities, top surface roughness). We have made progress in suppressing intermixing to achieve the sharpest possible interface for tunneling between device layers.

- **A. Javey** of *UC Berkeley* has achieved new successes in chalcogenides based monolayer semiconductors, a solution to overcome the problem of quantum well thickness variation. In the last reporting period, we began research on monolayer semiconductors drawn from the chalcogenide class of materials. Now, in Period 3, using the XOI platform [4], we have successfully demonstrated top gated WSe_2 FETs with ~60 mV/dec Subthreshold Swing (SS) and ~250 cm^2/V.s effective mobility, and van der Waals heterojunctions InAs/WSe_2 diodes.

- The experimental verification of negative capacitance in ferroelectric ceramics by **S. Salahuddin** *(Berkeley)* furthers the application of a concept that he pioneered in earlier theoretical work [5]. Extensive work was undertaken to establish an understanding of how substrate strain and crystal structure are relevant to negative capacitance, leading to the experimental observation of negative capacitance in three different material systems: the original STO/PZT bi-layer (>200˚C), (LAO/BSTO bi-layer at >200˚C), and STO/PTO bi-layer (>100˚C); and finally, in LAO/BSTO superlattices at room temperature.

- The effort of **J. del Alamo** *(MIT)* to demonstrate a prototype Superlattice Nanowire FET in the InAlAs/InGaAs system is advancing. The demonstration of sub-10nm nanowire diameter structures with aspect ratios better than 10:1 is an important experimental milestone towards the fabrication of the entire FET.

- Investigations of a new Bilayer TFET concept were initiated by **E. Yablonovitch**, **D. Antoniadis** and **J. Hoyt**, a joint effort between *Berkeley* and *MIT*. The bilayer TFET comprises a free standing semiconductor film as an undoped homojunction. The thin semiconductor film has opposite gate stacks on either side. The Work Function difference creates a 2D electron channel on one side and a 2D hole channel on the other side. Alternately, a static external potential can provide the internal electric field which aligns the valence band on one side with the conduction band on the other side. This homojunction structure has many advantages relative to the Type III heterojunction Density of States switch that has been under investigation. The tunneling probability is adjustable by the thickness of the film and will be high due to the large tunneling area and 2D-2D tunneling current. The tunneling is between a 2D valence band channel and a 2D conduction band channel. The 2D-2D case is known to result in a favorable step-function I-V response. There is no doping and therefore, there are no heavy doping effects. Rather than the unique GaSb/InAs Type III band alignment case, a simple film of InAs could fulfill the material requirement.

However, the effort to obtain experimental data on the bandedges of InAs/GaSb backward diodes bandedge sharpness is taking longer than expected. In the course of fabricating InAs MOS structures, an intermediate step, **D. Antoniadis** and **J. Hoyt** of *MIT* encountered very large interface trap densities. Nevertheless, in response, we have developed a hybrid model for interface traps that allows the extraction of the interface trap distribution from experimental CV data. This model will help guide process optimization for its reduction. The novelty of the technique is that it only requires one calculation of the computationally intensive quantum mechanical simulations of the MOS capacitor structure.

- *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 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, led by **T.-J. King Liu** *(Berkeley)*, and includes six other faculty from Berkeley, MIT and Stanford **,** 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.

  During Period 3, the Theme II research portfolio is a collection of five projects, each pursuing an approach that mitigates surface adhesion (stiction) by: (i) minimizing the real contact area, (ii) avoiding contact by utilizing tunneling current in the ON state, (iii) counteracting stiction, e.g., with a repulsive magnetic force, or (iv) by a switching mechanism that does not require breaking a contact.

  During Period 3, the analytical and experimental studies conducted at Berkeley led to the conclusion that voltage (and size) scaling will be fundamentally limited by contact adhesive force. The analytical study was a collaboration between of **E. Alon** of System Integration and **T.-J. King Liu** and the experimental results were obtained by the **T.-J. King Liu**'s group. Based on this conclusion, Theme II began to place greater emphasis in non-contact/tunneling approach to switching, and the portfolio evolved to consist of:

  - Three projects pursuing switching concepts where the two plates in the mechanical relay are not in direct contact with each other: (i) a nonlinear mechanical tunneling gap (**T.-J. King Liu**, *Berkeley*); (ii) modulation of tunneling through a compressible material that is made of a self-assembled monolayer of molecules (**V. Bulović**, **J. Lang** and **T. Swager**, *MIT*); (iii) actuation due to a mechanically induced phase change in the VO_2 that is placed between the plates (**J. Wu**, *Berkeley*); and

  - Two projects pursuing a switching mechanism that requires contact: (i) relays with graphene beams and carbon coated contacts (**H.-S. P. Wong**, *Stanford*), (ii) mechanical relays with magnetic elements to provide a repulsive force to break the contact (**J. Bokor**, *Berkeley*).

  Since the inception of the Center, the Theme II research at MIT has focused on non-contacting actuation for mechanical relays; i.e., a mechanical switch that operates via modulation of tunneling through a compressible material, a switch concept that the MIT researchers have dubbed a "squitch". At the beginning of Period 3, **T. Swager**, a synthetic organic chemist, joined **V. Bulović** and **J. Lang** to pursue the approach of controlling the gap with a mechanical spring formed by attaching sparsely-spaced insulating organic molecules between the two electrodes in the form of a self-assembled monolayer (SAM) or a deposited thin film. The molecules bend and compress as the gap closes. In Period 3, we achieved an experimental proof of concept by fabricating and characterizing two-terminal tunneling devices, one with an active layer of hexaethylene glycol dithiol and another with an active layer of mercaptopropyl –trimethoxysilane. Switching occurs at 1.7 V and 2.8 V respectively. The experimental effort has been complemented by an analytical evaluation of the theoretical performance limits of the squitch in terms of minimum actuation voltage, switching energy and switching time as a function of the Young's modulus of the SAM. The results of this analysis indicate that a Young's modulus below approximately 1 MPa allows a minimum actuation voltage in the milli-Volt range, a switching energy less than 10 keV and nanosecond switching time, confirming that this switching concept has the potential to meet the E^3S objectives. Thus, efforts to achieve the target Young modulus by controlling the density of SAM's are in progress.

Two projects, Graphene Beam Relay project of **H.-S.P. Wong** and the Mechanically Controlled Tunneling gap of **T.-J. King Liu,** are aiming for device demonstration. Device fabrication is in progress for both projects with characterization expected to begin before the end of the Period. The remaining two projects, the magnetic assisted switching of **J. Bokor** and the VO_2 phase transition project of **J. Wu** are highly exploratory and their concept feasibility assessment phase will continue into the next reporting period.

- *Theme III - Nanophotonics*: The goal of the Theme III team, which is led by **M. C. Wu**, and includes **C. Chang-Hasnain** and **E. Yablonovitch** (all of *Berkeley),* is to reduce *both* energy efficiency and sensitivity by orders of magnitude in the emitters and detectors, and miniaturize the components to sizes comparable to state-of-the-art transistors. By virtual of the radical reduction of the dimensions of the components, Theme III researchers can apply photonic phenomena that are applicable only in nanoscale dimensions, to overcome the fundamental trade-off between energy efficiency and sensitivity. To achieve the ultimate goal of approaching quantum-limited sensitivity (20 photons/bit) with an energy efficiency of 20 aJ/bit, we seek the following:

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

    In Period 3, Theme III's technical strategy has two elements.

    - Coupling of optical antennas to nanoscale emitters and photodetectors: For emitters, we utilize the Spontaneous Hyper Emission (SHE) that results from such a design to enhance bandwidth and efficiency. 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 [6]. By attaching optical antennas to the photodetectors, we can enhance the quantum efficiency of the nano-photodetector, while preserving the small capacitance.
    - Integration to minimize capacitance: Integrating the photodetector directly to a transistor can eliminate the parasitic capacitance that result from interconnecting wires between the photodetector and the amplifying transistor, i.e., forming a phototransistor.

    Significant experimental progress has been made on two of the three Theme III projects:

    - SHE Nano-LEDs: The group of **M.C. Wu** *(Berkeley)*, in collaboration with the group of **E. Yablonovitch** *(Berkeley),* has successfully demonstrated the first optical antenna-coupled nano-LED with unambiguous proof of spontaneous emission rate enhancement [7]. By comparing a bare emitter to an emitter coupled to a 400nm long antenna, an increase of 35x in photoluminescence polarized parallel to the antenna has been observed. This increase can be directly attributed to the increase of spontaneous emission rate.
    - Phototransistors and III-V/Si Integration: The group of **C. Chang-Hasnain** *(Berkeley)*, in collaboration with the group of **E. Yablonovitch** *(Berkeley),* has assessed the feasibility of different phototransistor design based on JFET, MOSFET and BJT. Using a previously developed growth process of single-crystalline (In)GaAs nanopillars on silicon at CMOS compatible growth temperature, we first fabricated and tested the quality of various pn diodes. We learned that it is best to keep the junction inside the nanopillar to maximize performance. As

a result, we adopted a floating base bipolar junction phototransistor design with the emitter, base and collector regions all integrated into the nanopillar body.

In addition, the Nanophotodetector, another project in the group of **M.C. Wu** *(Berkeley)*, is nearing the end of the design phase. A design for a germanium based photodiode which is directly integrated with silicon photonics components, such as silicon waveguides has been achieved. This design took into account the restriction of using only CMOS compatible materials (e.g., no gold). We developed two primary optical cavity designs which strongly enhance the absorption of light from a waveguide into a subwavelength germanium cavity for high responsivity from an extremely small photodiode. Fabrication activities will begin before the end of the period.

- *Theme IV – Nanomagnetics:* Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that could possibly approach the Landauer limit [2], or perhaps even surpass it via reversible logic [8]. In Period 3, most of the Theme IV research, led by **J. Bokor** *(Berkeley)***,** has been directed towards understanding switching dynamics and basic spin logic physics.

One of Theme IV projects is one very fundamental, Experimental Verification of the Landauer Energy Limit. This project, led by **J. Bokor**, seeks to provide an experimental verification of the scientific basis of this Theme. Landauer's famous theory predicted a minimum of exactly kTln2 of energy being dissipated in erasure of a single nanomagnetic bit (Landauer's limit) [2], and Bennett has indicated 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 [8]. Neither of these theoretical predictions has been directly experimentally demonstrated and they remain controversial. Indeed, in Period 3, we achieved one key milestone, the experimental measurement of energy dissipation during nanomagnet erasure over a range of temperatures. The measured results are consistent with the Landauer Limit. However, improved measurement precision is needed to definitively test the theory. Once this precision is reached, we will be able to make further studies of fundamental energy dissipation in magnetic systems, including tests of reversible logic which could go below Landauer's limit.

Two Theme IV projects have the goal of achieving magnetic structures that will allow us to study switching dynamics at room temperature. One approach, led by **R. Ramesh** *(Berkeley)* is focused on reducing the voltage for full magnetization reversal of a ferromagnet magnetization in contact with the multiferroic material $BiFeO_3$ (BFO). Efforts have been made to control leakage which is believed to be the main cause. Work is continuing on improving and optimizing the device structure, by investigating the use of La doping of BFO, reducing thickness of the films and improving material quality. A parallel approach, led by **J. Bokor**, is investigating a device structure with a magnetostrictive ferromagnet on a piezoelectric material. The magnetostrictive ferromagnet of choice is Terfenol-D, an engineering alloy of rare earths that exhibits large magnetostriction coefficient at room temperature. Composite magnetoelectric film stacks involving PZT or PMN-PT piezoelectrics and Terfenol-D have been grown and characterized. We find that for 30 nm thickness Terfenol-D films, the preferred magnetization direction develops an out-of-plane component, which is highly advantageous for magnetoelectric switching.

An rf SQUID magnetometer with arrays of nano-scaled high-Q resonators has been in development by **I. Siddiqi** *(Berkeley)* for the purpose of studying spin dynamics and relaxation times. Enhancements were made to the magnetometer to increase bandwidth and flux sensitivity. We have also developed the crucial ability to selectively position nanomagnets in close proximity of our sensor by either using hydrophobic molecules to guide the particles, which are in a solution, or by placing individual nanoparticles that have an electric dipole using a biased magnetic force microscopy cantilever.

Education and Diversity

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

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

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 attend university and graduate programs in technical disciplines that will contribute to low energy electronics; and
- promote continued interest in the E^3S research areas among Center participants and alumni.

To meet these goals, the Center for E^3S offers ongoing training on energy efficient electronics topics and professional development opportunities for its graduate students and postdocs; these efforts are described in this Annual Report's Section II, Education. 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 this Annual Report's Section VI, Diversity.

In Period 3, training on energy efficient electronics topics is embedded in many Center activities.

- Third Annual Retreat included research presentations, review of Center's progress, discussions of competitive research, education and outreach overview, online education, and poster presentations,
- Second Annual Graduate Student and Postdoc Retreat allowed the participants to share research and learn from each other,
- Research Seminars series and Journal Club held a total of 15 sessions in 2012, and
- Theme meetings have been held regularly, ranging from biweekly to once every two months

Other training included:

- EE 290: Advanced Topics in Solid State Devices, a course developed and taught by E. Yablonovitch, Center Director. This course was taught at UC Berkeley and offered to members at all institutions through videoconferencing and online posting of course material.

- Ethics training that was conducted as part of the New Member Orientation at the Graduate Student and Postdoc Retreat;
- A workshop entitled, *Science Communication*, co-presented by **Carol Lynn Alpert** and **Karine Thate**, from the *Museum of Science, Boston*, on effective strategies to communicate technical research to an interdisciplinary and non-technical audience;
- A workshop entitled, *Understanding Innovation and Intellectual Property Protection*, presented by, **J. Yuen**, Executive Director, on perspectives on innovation to enable an understanding of what it is, why it is important, and some of its important attributes;
- Project management and mentor training conducted by **S. Artis** for mentors in summer research programs for undergraduates and high school students.

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,
- Participation at the STC Director's Meeting as Student or Postdoc Representatives of the Center,
- Serving as leaders on laboratory tours,;
- Serving as poster reviewers for the Center's Research Experiences for Undergraduates Poster Session,
- Mentoring undergraduate and high school students doing research at the Center, and
- Serving on the selection committee for applicants to undergraduate summer research program *(postdocs only)*.

To cultivate a pipeline of students at the undergraduate level, the Center had four programs, including two new programs established in Period 3.

- E^3S Internship (ETERN) supports undergraduate students at the member institutions to do research throughout the year with the Center's faculty. Six undergraduates joined the Center at *Berkeley*, *Stanford* and *Tuskegee* in Period 3.
- E^3S Research Experiences for Undergraduates program (E^3S REU) at *Berkeley* and *MIT* had 11 rising juniors and seniors. The students conducted 9 weeks of research, each hosted by an E^3S faculty (**J. Bokor**, **V. Bulović**, **C. Chang-Hasnain**, **C. Hu**, **T.-J. King Liu**, **J. Lang**, **R. Ramesh**, **S. Salahuddin**, **T. Swager**, **M.C. Wu**, and **E. Yablonovitch**). In addition, the students participated in enrichment activities, including ethics training and a leadership day where the undergraduates were panelists sharing their experience as undergraduate researchers with lower-division undergraduates and community college students.
- Transfer-to-Excellence (TTE) program's goal is to inspire California community college students to pursue baccalaureate STEM degrees through research (TTE REU) or cross- enrollment (TTE X-Enroll) at Berkeley. This population 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. The TTE REU had 5 participants who participated in an 8-week research experience hosted by E^3S co-PIs, **T. J. King**, **C. Hu**, and **J. Wu**, and E^3S Education Affiliates, **A. C. Arias** and **O. Dubon**, and mentored by their graduate students and postdocs. 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 Center hosted one TTE X-

Enroll student from Napa Valley College. An additional critical program element is year-long transfer advising and support that continues even after the participants' completion of the summer programs. These services are delivered through partners at Berkeley and UCLA.

- New in Period 3, the E^3S Hands On Practical Electronics Summer Research Workshop (E^3S HOPE SRW) hosted eight lower-division undergraduates, including 3 community college students, for a 1-week of intense lectures on electronics, hands-on build projects, lab tours, and research presentations. This is a bridge program to stimulate interest in research.

Another new program in Period 3 is the E^3S Research Experience for Teachers (E^3S RET). E^3S faculty **J. Wu** hosted one faculty member from Los Angeles Trade-Technical College for an eight-week research experience. The RET Fellow was mentored by a postdoc. Targeting community college teachers has synergy with our community college focus. Before returning to the community college, the teacher already has developed plans to use a journal club with the Science Club that he mentors to introduce new scientific and engineering concepts. He is also exploring the feasibility of introducing 2-dimensional materials to laboratory experiments.

The Center's pre-college programs are targeting rising 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);
- Minority Introduction to Engineering and Science (MITES) program; and
- MIT Online Science, Technology, and Engineering Community (MOSTEC)

The pre-college programs promote student's early interest in science and engineering careers, particularly among female and students from under-represented groups. 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 Summer High-school Apprenticeship Program (SHARP) in Period 3 included funding of three rising high school seniors (two females and one under-represented minority), who successfully completed the research program in an E^3S faculty member's research group (**C. Chang-Hasnain** and **E. Yablonovitch**), and mentor training by S. Artis, the Center's Education and Outreach Director.

The E^3S impact on the two MIT programs includes funding the electronics elective for 12 high school students in the MIT Minority Introduction to Engineering and Science (MITES) program. In addition, we are one of the founding sponsors of the MIT Online Science, Technology, and Engineering Community (MOSTEC), an online enrichment program for high school seniors that includes an electronics workshop. MOSTEC, now in its second year, also provides a weeklong conference at MIT and assists the participant during the college application process.

In addition to the operational programs, the Center's has focused on active recruitment of a diverse pool of applicants. **S. Artis** and **J. Yuen** recruited this fall for the Center's diversity programs. Targeting upper division undergraduates, together, they attended 2 diversity and graduate fair conferences and conducted graduate preparation workshops and information sessions at 17 universities. For the Center's community college programs, **S. Artis** and **J. Yuen** presented at 3 conferences and 4 information sessions at community colleges.

The Center also supports outreach for current undergraduates at member institutions. **S. Artis** 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). She also served as a cluster facilitator for LeaderSHAPE©, an intensive, energizing, six-day educational experience designed to equip college students with the necessary qualifications to become extraordinary leaders.

Knowledge Transfer

In Period 3, we have clarified the wording, but did not change the substance, of the Center's Knowledge Transfer goals. The 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 ways to prepare workers at all levels to participate in the new opportunities. As such, Knowledge Transfer includes the transfer of new-found knowledge that is relevant to the Center's research as well as programmatic activities. We think of Knowledge Transfer as cross-fertilization that would go in both directions, up and down the food chain. Knowledge transfer is envisioned to be through the following channels:

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

The main venue for disseminating the Center's research results is through established technical publications and professional conference and workshop. In Period 3, the Center's faculty, students and collaborators had 13 technical publications. Two papers have been accepted for publication, including a paper that documents results from collaborative research collaboration between Berkeley and MIT.

We continue to utilize the Center's industry members to be knowledge transfer venues. Representatives from the member companies attended the Center's 2012 Annual Meeting. Two seminars by representatives from two member companies helped the Center's researchers understand industry research in nanoelectronics and opportunities for innovation in the semiconductor industry.

In Period 3, we also utilized co-sponsorship of conferences and workshops to help the Center's meet its Knowledge Transfer goals.

- Co-sponsorship of International Nano-Optoelectronics Workshop (iNOW) enabled this annual forum to expand its scope to add 3 technical sessions that are relevant to the Center's Themes I and III research and included talks from two E^3S faculty. A panel that featured the CTO's from three companies addressed the potential of Optical Interconnects in Supercomputers and Data Centers.
- Co-sponsorship and participation at the two US workshops of the Guardian Angels (GA) Project of the European Union provided a forum for four E^3S faculty to present the Center's research. This consortium has, as part of its goals, research of zero power consumption in smart systems. This Knowledge Transfer opportunity also built relations for international collaborations.

- Co-sponsorship of the Nanovation symposium, organized by the IEEE San Francisco Bay Area Nanotechnology Council, was intended to be a professional development opportunity for our students and faculty to increase their understanding of translating nanotechnology research outcomes to commercial use. This symposium brought together the unique perspectives of researchers, entrepreneurs, and investors.
- Co-sponsorship of four seminars by external academic researchers given as part of UC Berkeley's Solid State Seminar series provided infusion of knowledge to the Center, particularly for Themes I and III researchers.

For transfer of knowledge related to Education and Diversity, **S. Artis**, E^3S Education and Outreach Director, has focused on building a community for knowledge sharing among the Education and Diversity professionals of all active STC's.

- She served as the co-chair of the planning committee on an all-day Education and Diversity workshop.
- She is continuing to organize quarterly teleconferences and provide leadership to bring together Education and Diversity personnel of all active STC's. This forum is intended to enable sharing of information and best practices.
- The Center for E^3S has assumed responsibility the joint STC website, replacing the Center for Embedded Networked Sensing, another STC that has graduated.

External Partnerships

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 E^3S' two-way knowledge transfer strategy. The education and diversity plans in the proposal also calls for leveraging established programs to add value. The key goal for the Center is to continue to execute and enhance its partnership strategy to deliver the programs and activities in its plans.

In Period 3, 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. In Period 3, Applied Materials joined the Center as an industry member, increasing the number of industry members to five. The Center used the opportunity to formalize the membership process. We executed a membership agreement and a confidential agreement with Applied Materials. We also asked the other four industry members that have been with the Center since its inception to execute confidential agreements.
- *Research Partnerships*: Industry research partnerships in the form of parallel research are highly valued by the Center. The research collaboration with Intel on the nanophotodetector project of Theme III is progressing. One Theme III project has leveraged the long-term relationship of M.C. Wu with a material grower at Bell Labs, Alcatel Lucent. Theme I has four material growth collaborations and one on TFET modeling. The newest research partnership on material growth is with National Chiao-Tung University in Taiwan. This international partnership will include a student/postdoc from Taiwan spending time at Berkeley. The Center has continued to explore international partnerships, leveraging the relationship that was established in 2011 at the 2^{nd} Berkeley Symposium on Energy Efficient Electronic Systems, a symposium of the Center. Towards that end, E. Yablonovitch, Center Director, was the invited speaker at a symposium of the Japanese Green Electronics Center and at a workshop of the STEEPER project of Europe. He

also gave talks at EPFL, Switzerland and IBM Zurich Labs; both are participants of the STEEPER project.

- *Education and Diversity Partnerships*: Partnerships with established programs that are external to the Center, but mainly internal to Center's member institutions, have been a key factor that has contributed to the successes of the Center's Education and Diversity endeavors. We have continued to partner with MIT's Office of Engineering Outreach Programs and Berkeley's Nanoscience and Nanoengineering Institute to offer electronics education and research opportunities to high school seniors, respectively. The TTE REU program for community college students is built on a partnership with two other NSF funded centers, COINS and SynBERC, Berkeley's Transfer Alliance Project and the Scholars Program of UCLA's Center for Community College Partnerships. In Period 3, to support an expanded cohort of community college REU interns, we have also established new off-campus partners, California MESA and BFOIT. We worked with MESA to recruit community college REU candidates and with Berkeley Foundation for Opportunities in Information Technology (BFOIT) for leadership development experience for the community college interns.

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
- Ethical Conduct

The Center's leadership is the Executive Committee that has the responsibility to enable the Center's culture. In Period 3, the Executive Committee continued to operate in accordance to the management processes that were established in Period 2. These processes include Executive Committee By-Laws, Code of Conduct, regular Executive Committee meetings with pre-announced agendas and meeting minutes, and an annual process to determine the funding of research and programmatic activities for the following period. To ensure the Center has a culture that transcends physical and institutional boundaries, Center members evaluate the Center's leadership team annually.

The Center measures the effectiveness of its management and communication systems primarily through two perception surveys of the faculty, postdocs and graduate students. Of key interest is the Center's leadership ability to instill what it espouses to value into the organization. The *Co-PI's Perception of Center's Collaboration, Ethics, and Leadership Team Survey* was administered at the end of Period 2. The survey asked information about faculty perceptions related to the degree of collaboration with others at the Center, the leadership and ethical behavior exhibited by the Center leadership and colleagues, and their self-rating about their own contribution in terms of leadership and ethical behavior. Overall, the results of the faculty survey indicate that the Center has created a strong culture for leadership, collaboration, and ethics. On a scale from 1-5, with 5 being the highest anchor, average faculty rating for leadership, collaboration, and ethics were 3.25, 4.46, and 4.39, respectively. The *Student and Postdoc Perception of Center's Leadership Team Survey* was administered at the Second Annual Student and Postdoc Retreat in Period 3 to elicit students and postdocs' perceptions about the Center's leadership, including research experience, diversity, inclusiveness, communication, collaboration, ethics, decision making, and performance. Results of the survey concluded that students and postdocs agreed or strongly agreed that the Center is making progress in these areas. On a scale from 1-5, with 5 being the highest anchor for strongly agree, the average rating across all survey questions was 4.04.

The Center's potential is maximized when its members are coordinated to achieve synergy. Timely communication among its faculty, postdocs, students and staff is key in enabling this outcome. The Center's communication has been facilitated by the following:

- Center's website with public pages and an intranet for collaboration
- Center's Annual Retreat
- Graduate Students and Postdocs Retreat
- Regular Research Seminars and Journal Club meetings
- Regular Theme Meetings, and
- Center's newsletter

Center Output

Publications		
	Peer Reviewed Publications	16
	Accepted/Submitted for Publication	5
	Non-Peer Reviewed (Invited) Publications	0
Conference Presentations		34
Other Dissemination Activities		14
Awards and Honors		34
Ph.D. and M.S. Graduates		11
Postdoc Alumnus		6
Patents Disclosures		0

PLANS FOR PERIOD 4

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

The Research portfolio will continue to have four Themes and the System Integration effort. Themes I, II and III are expected to pursue the projects that are in place in the later part of Period 3. Theme IV will add two new projects, and the System Integration effort will explore ways for collaborative projects with Theme IV.

- 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 4 **E. Alon** of *UC Berkeley* will continue collaborative efforts with Themes II and III. Moreover, we will also explore the opportunities provided by magnetics-based devices at the front-end in communication applications. Although their I_{on}/I_{off} may be low, their potential capability to switch at very low voltages makes such devices attractive for analog amplification.

- Theme I will continue to pursue these six key areas.
  - The groups of **C. Hu**, **A. Javey** and **E. Yablonovitch** at *Berkeley* and **D. Antoniadis** and **J. Hoyt** at *MIT* will work interactively to elucidate the science of and demonstrate InAs/GaSb TFETs. One key experimental goal is the demonstration of tunnel transistors based on InAs/ GaAlSb system that will have I_{on}~100μA/μm, I_{off}~0.1nA/μm at power supply voltage less than 300mV, an effort that will be led by C. Hu, in collaboration with A. Javey. We also expect to obtain measurements of bandedges to help elucidate the fundamental barriers to abrupt switching.
  - The groups of **E. Yablonovitch** and **A. Javey** and **D. Antoniadis** and **J. Hoyt** will work together in Period 4 to elucidate the science of bilayer tunneling transistors, but there will be complementary approaches. The team at Berkeley will focus an electron hole bilayer transistor in InAs. The groups of E. Yablonovitch and A. Javey will determine bandedge sharpness and other key scientific questions arising from the overlap of valence and conduction bands in InAs field induced bilayer. The groups of D. Antoniadis and J. Hoyt will study a Si bilayer transistor. Even though earlier simulation studies have indicated that III-V's is the material system of choice, the researchers expect to encounter fewer complexities by studying the tunneling physics of a Si bilayer device.
  - The group of **J. del Alamo** at *MIT* will fabricate and electrically characterize two-terminal Superlattice Nanowire structures and will seek evidence of 1D transport and miniband/minigap structure of the superlattice. The MIT team will consult with **C. Hu** and **A. Javey**, as they develop ohmic contact and gate technology.
  - The main goal for **S. Salahuddin** of *UC Berkeley* is to fabricate a Negative Capacitance MOSFET and perform materials optimization to develop a three-terminal device platform. The challenge is the fact that conventional device processing techniques are not directly applicable to complex oxides. He will work, in collaboration with **C. Hu**, to design new techniques and will be evaluating and optimizing them in the coming year.
  - The focus on 2D materials and devices will solely be on van der Waals heterojunctions devices where the junctions are made by mixing and matching 2-D III-Vs and/or 2-D layered chalcogenides. This effort is led by **A. Javey**. We are hopeful that **V. Rangari** and **K. Das** of *Tuskegee* will contribute to the synthesis and characterization of applicable chalcogenides.
  - The MOCVD growth capability, led by **E. Fitzgerald** of *MIT*, will strive to be an internal resource for the Center, collaborating with the Theme I researchers on their materials needs. In addition, research on the fundamental growth issues of additional material systems like heterovalent Ge/III-V will be explored.
- Theme II: Three of the five projects will increase their emphasis on demonstration of devices with milli-Volt operation. Through the device demonstration efforts we will continue to enhance understanding of the underlying materials science and will address fabrication challenges.
  - The Graphene Beam Relay project, led by **H.-S. P. Wong** of *Stanford*, will seek to demonstrate a three-terminal device after the successful demonstration of a two-terminal device. In collaboration with **J. Wu** of *UC Berkeley*, this project will broaden its choice of ultra-thin structural materials to novel 2D materials, like metal dichalcogenides (MX_2).

- The Tunneling Relay project of *Berkeley*, led by **T.-J. King Liu,** will demonstrate the device concept in two steps: 1) a prototype device with 0 hysteresis and a sub 60mV/dec swing; and 2) redesigned tunneling relays to demonstrate lower operating voltage and improved on-state resistance.

- The Tunneling Squitch at MIT, a joint project of **V. Bulović**, **J. Lang** and **T. Swager**, is aiming to demonstrate three-terminal switch actuated at well below 1 V. This will involve the development of appropriate SAMs and fabrication strategies, the reduction in size of all three switches, and the fabrication and testing of all three switch designs that they are considering in Period 3.

The remaining two projects, Switching with Magnetic Elements, led by **J. Bokor** of *Berkeley*, and Solid State Switching with Phase Transitions, led by **J. Wu,** will make an assessment of their exploratory approaches, to determine whether to proceed with device demonstrations in the second half of the next reporting period.

- Theme III: All three experimental projects will have a strong device demonstration focus. In addition, Theme III researchers will continue to work with **E. Alon** *(Berkeley)* to identify schemes to minimize the input capacitance of an ultimate low-energy optical receiver.

  - SHE Nano-LED: The main goal is to develop electrical injection nano-LED. The basic structure of the proposed nano-LED is similar to that of a FIN-FET except the channel is replaced by III-V emitter, the gate metal is replaced by optical antenna, and the source/drain are replaced by electron and hole injectors. **M.C. Wu** of *Berkeley* plans to reach out to the group at Intel for potential collaboration on nano-FIN-LED.

  - Nanophotodetector with Ultra-Low Capacitance: The group of **M.C. Wu** will focus on fabricating the developed photodiode design. In addition, the photodiode will be integrated directly into existing silicon photonics processes previously developed within the group. By fabricating the nanophotodiode using CMOS compatible processes and measuring its low capacitance and high efficiency, we take the first step in demonstrating such an ultra-low energy photoreceiver. Discussions of collaboration on epitaxial growth of germanium with **J. Hoyt** *(MIT)* will continue.

  - Phototransistors and III-V/Si Integration: The group of **C. Chang-Hasnain** at *Berkeley* will develop fabrication techniques to demonstrate a working single nanopillar based HBT on silicon substrate. We will then optimize the structure to improve sensitivity and electrical characteristics to show >10 GHz operation with low photon operation. Further optimization of the design of the device structure will be in collaboration with **E. Yablonovitch**.

- Theme IV: The main Period 4 focus is experimental studies of logic devices, while the experimental verification of the fundamental limits of nanomagnetic logic energy dissipation is completed by **J. Bokor's** group. **R. Ramesh** and **J. Bokor** (both of *Berkeley*) will continue to lower voltage magnetic switching. Two new topics will be added.

  - Topological Insulator for High MR Ratio: The typical scheme to readout the state of magnetic switches is through magnetic tunneling junction (MTJ) devices. The magnetoresistance ratio of MTJ devices is very low, particularly in the context of the goals the Center has set for a switch. **R. Ramesh** will initiate a project that will investigate Pyrochlore Iridate and Perosvskite Iridate MTJ devices. The initial studies will focus on understanding transport at interfaces and the effects of doping.

  - Ultrafast Magnet Switching: Conventional magnetic switching is limited by precessional dynamics to a minimum switching time of ~100ps. Ultrafast laser experiments, on the other hand, have demonstrated deterministic magnetic switching is possible on the sub-10 psec time scale using femtosecond laser excitation of a highly non-equilibrium hot electron distribution. **J. Bokor** will test the feasibility of similar dynamics being initiated by purely electrical excitation in magnetic hot-electron Schottky diode devices.

In Period 4, future plans for education and diversity include the following:

- Refine and formalize the E^3S Professional Development Program (E^3S PDP),
- Expand the venues for dissemination information on E^3S research;
- Streamline our diversity programs, and
- Further improve the E^3S website to enable a high quality visit for the visually impaired.

The Center's E^3S PDP model provides a variety of professional development activities in the areas of: mentoring, outreach, leadership, teaching, proposal writing, science communication, and entrepreneurship. In addition to hands-on practical activities, we plan to refine the program to include educational modules in these areas to share theoretical frameworks and best practices.

The Center will accelerate its efforts to provide broader dissemination of its research via online access. In the next period, the Education and Outreach Director will work closely with Co-PIs to develop videos to educate the external technical community as well as the general public about the importance of energy efficient electronics devices and the need for more scientists and engineers to pursue career opportunities in this field. The Center will also explore the application of social media to disseminate the Center's research to the general public.

In Period 4, we will complete the implementation of a Period 2 decision to move away from localized programs, a decision made in recognition that the Center must cast the widest net to broadening student participation in energy efficient electronics science. We will continue to refine our programs so that they can be easily integrated into other educational infrastructure. The programs will include an implementation guide that documents the framework of our programs, including program goals, objectives, learning outcomes, and targeted audience; application and selection material and procedures; recruitment calendar, flyer, and presentations; curriculum and/or training calendar and modules; and formative and summative evaluation questionnaires.

Since establishing the E^3S website, we have been mindful that we should provide access to visitors who are visually impaired. Building on the encouraging assessment of the E^3S website by the *Web Accessibility Team* at *Berkeley* in Period 3, the Center, in Period 4, will address issues raised in the assessment including the field label and flyout menu issues.

Partnerships with industry will continue to be the key strategy in Knowledge Transfer. For the existing industry partners, the Theme III team will sustain and expand its parallel research engagement with Intel Research Labs. Another emphasis will be to expand the Center's industry partnership to include additional companies, particularly mid-size companies. We plan to organize the Berkeley Symposium on Energy Efficient Electronic Systems again in Period 4.

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 mS/μm; i.e., a 1μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in mS/μm of conductance versus what that is typically assumed in the traditional unit of milli-Amps/μm, reflecting the Center's target operating voltage of significantly less than the 1 Volt.)

Power consumption by electrical interconnects, used for both off and on-chip communication, have also been increasing. Today, off-chip electrical interconnects use ~1 pJ/bit of energy to communicate, while the energy for on-chip interconnect is ~100fJ/bit. Optical interconnects have the potential to be a low power consumption alternate and the Center' high level goal of the optical interconnects is to achieve close to quantum limit detection (20 photons/bit) and atto-Joule/bit communication (~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 [2].

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	Targets
Integrative Research	Multi-PI Projects	Yearly	Period 2: 30% Period 5: 30%
	Multi-Institutional Projects	Yearly	Period 2: 10% Period 5: 30%
	Unplanned research projects	Yearly after Period 2	Mid Period 3: 1 Mid Period 4: 3
	New joint research funding opportunities	Beginning in Period 3	Mid Period 3: 1 proposal
	Publications with authors from multiple institutions	Yearly beginning in Period 2	Period 3: 12

1c. Problems Encountered

The situations in Period 3 identified as problems mainly fall into the following categories: i) projects or Themes that have changed directions due to what have been learned; and ii) challenges with unanticipated level of difficulty encountered in research projects that will require additional time to resolve.

Theme I:

In Period 3, the research projects of Theme I have generally progressed as planned. One exception is the delay in obtaining experimental data on the bandedges of InAs/GaSb backward diodes, a key objective of the groups of **E. Yablonovitch** *(Berkeley)*, **D. Antoniadis** *(MIT)* and **J. Hoyt** *(MIT)*. These research groups failed to achieve functioning diodes with their designs of InAs/GaSb heterostructures and thus, were delayed in their band-edge measurements. Nevertheless, the MIT researchers developed additional insights on the very large interface trap densities that they encountered in the course of fabricating InAs MOS structures, a first step towards fabricating diodes. While for the ultimate TFET devices structure we are continuing to search for an optimal process for InAs using analysis such as XPS, TEM, and CV measurements in conjunction with the hybrid model for trap density extraction from our fabricated devices (see Section *II.2aii*), the MIT team is now pursuing the band alignment investigation using a Schottky diode method that should be insensitive to interface states. Also, for the TFET structure the group is investigating the ternary material system, $In_xGa_{1-x}As/GaAs_{1-y}Sb_y$, in order to allow the growth of a InP capping layer which has been shown to decrease the trap density at the high-K / semiconductor surface.

Another disappointment is the research program at Tuskegee which has continued to make relatively less progress. This program was hampered by the need to recruit an alternate graduate student researcher. A new graduate student joined Tuskegee's Materials Science program at the beginning of the Fall 2012 semester. Faculty participation in the biweekly Theme I meetings also has not been at a sufficient level to build good linkages with the rest of the Theme.

Theme II:

A major thrust under Theme II is to achieve milli-Volt device operation through device miniaturization. Previously, a theoretical study indicated that, if contact adhesive force continues to scale down with the area of the contact dimple regions, then sub-10 milli-volt operation should be feasible with a planar, electrostatically actuated 3.5um-long × 83nm-wide × 40nm-thick cantilever beam. During Period 3, experimental results obtained by the Theme II team at UC Berkeley indicated that, although contact adhesive force is reduced, it does not seem to scale linearly with contact dimple area. In parallel, additional analytical studies, conducted to understand ultimate limits of relay-based integrated circuit, concluded that surface adhesion ultimately will limit relay scaling. These findings altered the strategy of Theme II during Period 3. During Period 3, the Berkeley team transitioned to investigations on a non-contacting relay design to circumvent surface adhesion. To further mitigate risk, a fifth project was added under Theme II to explore another switching mechanism, namely stress-induced phase transition. This change means that only two of the five Theme II projects are pursuing contacting mechanical switch designs.

The Theme II plans at Stanford included investigations of partial-energy-recycling relay operation and the three-terminal relay with a feedback resistor to dynamically reduce gate overdrive, thereby achieving contact-less relay operation. In-depth theoretical studies were completed for both approaches. For the energy-reversible operation, the study showed that relay based logic could suffer from a glitch issue (related to logic hazard) if the glitch signal has a certain range of glitch width. The study on dynamic feedback to reduce gate overdrive and thereby achieve contact-less relay operation found the approach to have a rather narrow design window, so that it may be difficult to implement in practice. (This finding is yet to be published.) Therefore, these complexities led to the decision to consider these approaches to be of lower priority. Instead, the Stanford team is putting its full focus on the Graphene Beam Relay project.

Theme III:

In Period 3, the type of problems encountered by the Theme III researchers can be considered typical of research projects. None were so major that caused a shift in technical direction.

Theme IV:

Since the inception of the Center, the Theme IV portfolio has included a mix of projects that addresses switching and communications. The project, Spin Diffusion for Spin Logic, has the goal of providing a spin-based communication scheme to maximize energy efficiency by mitigating the impedance mismatch between spintronic logic devices and the communication link. The approach is to use magnetic multilayers that can be used to inject spins into copper channels, and perturbations in the magnetization on one side of the channel are 'visible' to the other side. The key point is that spin diffusion needs no voltage between the magnets. During Period 3, the device structures were fabricated with a number of variations, however a non-local spin voltage has not yet been detected. We believe that the problem is interface contamination. This project will be on hold until a UHV e-beam evaporation capability is available. So for the remainder of Period 3 and likely into Period 4, Theme IV's will not address the potential of a spin base circuit.

Another project that encountered delays is the project, Electric Field Control of Nanomagnets. In Period 2, we reported the successful demonstration of full magnetization reversal at room temperature of a ferromagnetic in contact with $BiFeO_3$ induced by using 7 volts. The significance of this result is verification that a room temperature device can be capable of writing and rewriting the state of magnetization with the application of only an electric field and that reading the state with a simple electron transport measurement is achievable. The next step is to reduce voltage to < 1 volt. However, our approach to voltage reduction by reducing the thickness of the $BiFeO_3$ layer is hampered by current leakage through the layer. Efforts to reduce the leakage have taken longer than expected. In Period 3, to mitigate risk, we initiated a parallel approach for Electric Field Control of Nanomagnetics. The new approach uses a magnetostrictive ferromagnet material on piezoelectrics.

2a. *Research Thrusts in Period 3*

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

V. Nanoelectronics with a focus on solid state millivolt switching

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

VII. Nanophotonics focused on few-photon communication

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

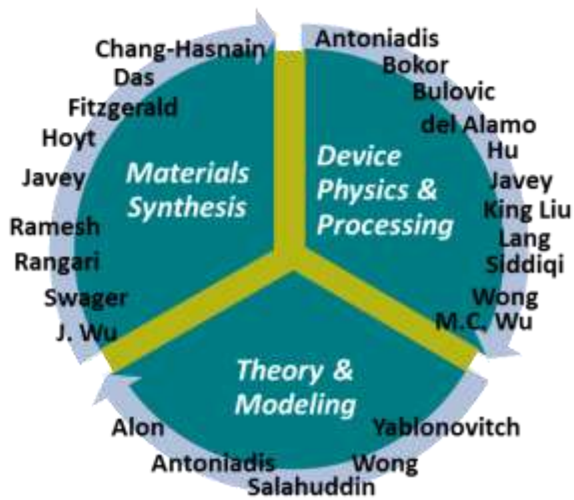
The most challenging aspect of electronic energy efficiency is internal communication in processors. Indeed the main function of the electronic switch is to drive signal currents and voltages along the internal wire in an integrated circuit; these wires are often referred to as interconnects. Themes 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 system integration research, where the outcomes will include a common set of metrics for each of the themes and a systems perspective that will enable future ultra-low energy information systems to be built and integrated using elements of each of these approaches. In addition, there are Theme specific collaborations as a Theme seeks insights from a systems perspective.

In Period 3, the Center funded 22 faculty members in four member institutions. Off the 22 faculty, two were added at the beginning of Period 3 and their resumes were given in the Period 2 annual report. There are no plans to add new faculty in Period 4.

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

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



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

Institution	Faculty	System Integration	Theme I	Theme II	Theme III	Theme IV
UC Berkeley	Alon	*x*	*x*	*x*	*x*	
	Bokor			*x*		*x*
	Chang-Hasnain				*x*	
	Hu		*x*			
	Javey		*x*			
	King Liu	*x*		*x*		
	Ramesh					*x*
	Salahuddin	*x*	*x*			*x*
	Siddiqi					*x*
	J. Wu			*x*		
	M.C. Wu	*x*			*x*	
	Yablonovitch		*x*		*x*	
MIT	Antoniadis		*x*			
	Bulović			*x*		
	del Alamo		*x*			

	Fitzgerald	*x*	
	Hoyt	*x*	
	Lang		
	Swager		*x*
Stanford	Wong		*x*
Tuskegee	Das	*x*	
	Rangari	*x*	

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

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

In Period 3, specific examples of collaborative outcomes are:

- Upon conceptualizing the Bilayer TFET concept, the **E. Yablonovitch** group at *Berkeley* received valuable feedback from the *MIT* team of **D. Antoniadis** and **J. Hoyt**. The teams from the two institutions jointly analyzed the prospects of the device. By collaboratively analyzing the device we were able to quickly obtain a realistic expectation of its limits and potential performance.
- The interactions within the Center between **E. Yablonovitch** and **A. Javey** at *Berkeley* on characterization of 2-D InAs membranes have led to consideration of a new physical concept: quantum unit of optical absorption.
- The group of **J. Wu** of *Berkeley* is sharing its capability and know-how for synthesis and transfer of high-quality graphene with **H.-S.P. Wong**'s group at *Stanford*.
- The group of **J. del Alamo** at *MIT* learned from the work on nanopillar LEDs of **M.C. Wu**'s group at *Berkeley*, as the MIT group began their work to fabricate vertical nanowire by Reactive Ion Etching.
- The **M.C. Wu** group of *Berkeley* has begun discussions with **J. Hoyt** of *MIT* on the feasibility of a collaboration to grow epitaxial germanium on silicon for the Nanophotodetector project.
- Theme II continues to have a project that brings together the disparate fields of nanomagnetics and nanomechanics to address surface adhesion. This collaboration between **J. Bokor** and **T.-J. King Liu** *(both Berkeley)*, which began towards the end of the previous reporting period, was conceived as a result of proactive discussions on Integrative Research within the Center.

2ai. System Integration Research

The System Integration effort, led by **E. Alon** (*Berkeley)*, is a close collaboration with the Theme Leaders. In Period 3, there were three key goals, one with applicability across the Themes, while the remaining two are investigations specific to Themes II & III. Here we will report on the goal with more general application, while the Theme specific efforts will be report in the Theme specific sections of this report.

The research to understand the impacts of device variability, which was started in Period 2, has general applicability. The goal is to expand the initial analysis than was done Period 2 into a generalized device-analysis framework. This will enable us to provide predictions of required variability levels for any CMOS-like device. We have completed a preliminary expansion of our general I_{on}/I_{off} analysis framework to include the effects of variability. The analysis points to the need for new metrics to capture the effect of variability, and that threshold variability in mV can be a misleading quantity for steep devices. Specifically, our analysis derives a variability "penalty factor" (which we refer to as "pf") that captures the increase in the leakage current and reduction in performance caused by variability. This pf is super-exponentially dependent upon the ratio of the absolute variability (in mV) to the local steepness measures (S_{off} and S_{on}). To first-order, the minimum energy per operation is proportional to $(S_{eff}*pf)^2$, where S_{eff} is the effective steepness measure, whereas without variability it was simply proportional to $(S_{eff})^2$ Thus, even though a steep turn-on device may have lower S_{eff} than a MOSFET, with a fixed absolute threshold variability in mV, the super-exponential increase in pf may dramatically outweigh the potential energy benefit one would have expected to gain without considering variability.

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

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

The recognition that TFETs have the potential to be an alternative to ordinary transistors is not new, given the body of prior TFET research. There have been many attempts to experimentally implement a TFET, but the results have been disappointing, with simulation predicting phenomenal results and experiment faring far worse [9] [10]. 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.*1a*), has been elusive. In most cases the switching mechanism has been tunnel barrier thickness modulation which is not expected to result in high conductance density while simultaneously satisfying the other two requirements.

The inception of the Center allowed the Theme I Research team to focus on a different mechanism, "Density of States" switching, which has the potential to achieve all three requirements simultaneously. In particular, we have been focusing on a material system with Type III band alignment, as in the lattice-matched p-GaSb/n-InAs heterostructure system that allows a very thin tunnel barrier for good on-state current at milli-Volt threshold voltages [11]. The n-InAs layer can be a thin quantum well, 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.

Theme I also has taken the approach that we need to increase the scientific understanding of the underlying physics, including the sharpness 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. 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.

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, e.g. WSe_2, 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.

Very thin n and p layers also require the ability to control interfacial quality and abruptness during material growth. The material growth parameters can influence tunneling and thus the device characteristics. Investigations of derivatives of the GaSb/InAs system can elucidate the effect of the heterovalent interfaces on tunnel characteristics.

The GaSb/InAs Type III band alignment is unique, and clearly there are concerns over the limitations that this uniqueness brings. In Period 3, we introduced an alternate TFET design to Theme I. It is a bilayer structure with a n-p homojunction that is created by opposite gate stacks on either side, a device concept first presented by Lattanzio *et al.* a few months earlier [12]. The tunneling is between a 2D valence band channel and a 2D conduction band channel. The bilayer device should have many advantages relative to the Type III heterojunction Density of States switch that has been under investigation. The tunneling probability is adjustable by the thickness of the film. By taking advantage of the 2D-2D tunneling and the large tunneling area, the need for a heterojunction to get a high tunneling current is eliminated. The homojunction will avoid the possibility of traps that arise from lattice quality at the interface of heterojunction. There is no doping and therefore, no heavy doping effects will be applicable. Rather than the unique GaSb/InAs Type III band alignment case, a simple film of InAs could fulfill the material requirements.

Theme I is also exploring other approaches to suppress the subthreshold regime for a steep-subthreshold swing in a FET. One approach is to create a mini-gap in the density of states at the source that effectively cuts off the thermal tail responsible for the subthreshold current in an FET [13] [14]. This, in essence, suppresses the high energy source electrons that are far above the energy barrier with the channel. A way to accomplish this suppression is to use a superlattice to create mini-bands in the source of a nanowire field-effect transistor, resulting in a mini-gap above where no states are allowed. 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.

Another way to achieve a steep-subthreshold swing in a FET can to use a composite gate dielectric that incorporates a ferroelectric material to provide “transformer” action 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 conventional MOSFET be changed, it can also be complementary to tunneling action and if successful, the two effects will multiply, significantly increasing the device performance.

In Period 3, the Theme I researchers made great strides experimentally. We have demonstrated the key building blocks that are needed to build a 2D-2D Type III Density of States switch. The demonstration of InAs/GaSb diode by **C. Hu,** in collaboration with **A. Javey**, both of *UC Berkeley*, the successful completion of the XOI platform for both n- and p- type semiconductors studies for ultra-thin films of

InAs and InGaSb by **A. Javey**, and the demonstration of functional diodes made from InAs/GaSb heterostructures grown by MOCVD by **E. Fitzgerald** of *MIT* are laying the foundation for the future device work with this material system. The first demonstrations, utilizing the XOI platform [4], of top gated WSe_2 FETs with ~60 mV/dec Subthreshold Swing (SS) and ~250 cm^2/V.s effective mobility, and of van der Waals heterojunctions InAs/WSe_2 diodes by **A. Javey** offer new possibilities of 2D materials. The experimental verification of negative capacitance in ferroelectric ceramics by **S. Salahuddin** of *UC Berkeley* furthers the application of a concept that he pioneered in earlier theoretical work [5].

- *GaSb/InAs Tunneling Field Effect Transistors*

  This project is made up of a collection of subprojects, one of which is at MIT and two at Berkeley. We have taken the strategy of parallel and complementary efforts, recognizing the complexities and the many unknowns in the device physics and materials science associated with the GaSb/InAs material system. Here we report the progress of two efforts.

  - *Experimental Realization of Devices*

    C. Hu, in collaboration with **A. Javey**, *(both Berkeley)*, has focused on eliminating all extrinsic deleterious effects in device processing, in recognition of the need for a well-controlled fabrication process for device fabrication. Our approach for a GaSb structure that has a normal-to-gate 3D to 2D tunneling takes into account the relationship between device attributes and processing. In particular, we addressed the need for reduced series resistance with self-aligned to T-shape gate, source/drain doping and contact process optimization. We strived for large gate voltage coupling ratio by layer thickness and doping optimization, and we sought to minimize junction leakage and gate leakage by p+ material under n+ drain etched away, and near zero V_t.

    The key accomplishments in Period 3 are:

    - As an intermediate step toward a tunnel transistor, we have fabricated a gate controlled InAs (quantum well) on a GaSb tunnel diode. We achieved successful demonstration of multiple Negative Differential Resistance (NDR) steps in a quantum well tunnel diode (Figure 1a).
    - We also achieved successful demonstration of strong MOS gate control of NDR (Figure1b).

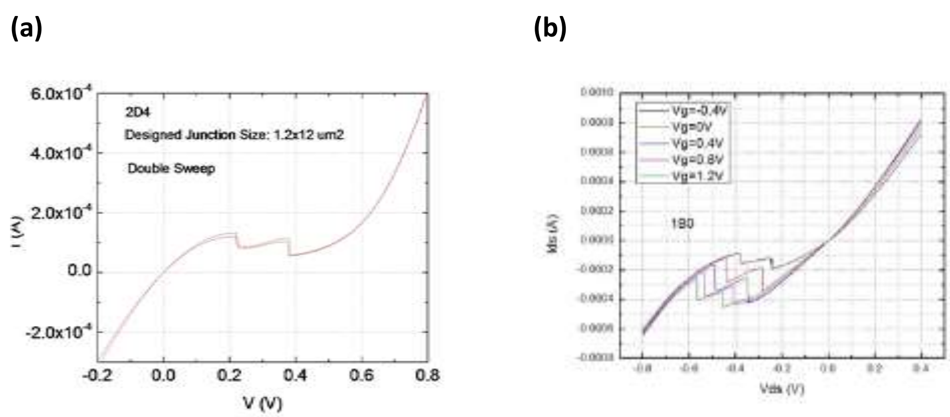


Figure 1: (a) The I-V Curve of thin InAs quantum well on a GaSb Easki diode showing a double NDR step reflecting two quantun levels in InAs. (b) The Esaki diode shows a strong gate control.

The GaSb tunnel diode demonstration was made possible by the following developments.

Center for Energy Efficient Electronics Science

- E-beam T-gate technology and low-resistance contact technology for forming a low series resistance self-aligned gate TFET. This technology will also be used to produce low-voltage high current TFET, for which the low resistance is important (Figure 2).
- Two techniques of making MOS high-k dielectric and metal gate stack. One is the dry etching process and the other is a lift-off technique: We found a lower density of states at the interface after dry etching than lift-off. Due to equipment limitations and reproducibility issues with dry etching, we have also established and used a working lift-off process; and

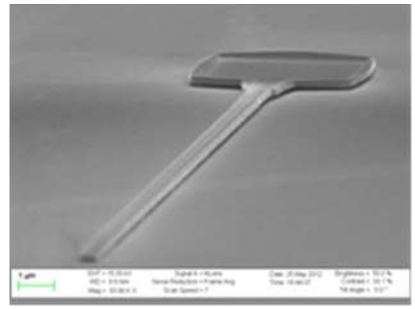


Figure 2: A SEM of the fabricated T-gate technology gate.

- A well-controlled selective etching process to etch away the GaSb source while keeping the InAs/AlGaSb tunnel junction intact.

The remainder of Period 3 will be spent on analyzing the data collected on these InAs/GaSb diodes.

- *Tunneling Physics - Experiments & Simulations*

Barriers to abrupt switching include phonon scattering, band-edge abruptness, the physics of tunneling barrier width modulation which limits the current slope steepness to very low current values, and the lack of practical three-terminal structures. To address some of these barriers, the groups of **D. Antoniadis** and **J. Hoyt** of *MIT* are complementing their work on simulation of devices with experiments on test structures. Key properties under analysis in Period 3 include effective band-gap, band alignment, and phonon coupling of electron and hole eigenstates. The goal as planned for Period 3 was to extract key aspects of tunneling physics in fabricated InAs/GaSb diodes. These Schottky-like diodes are used to extract band offsets between InAs and GaSb. Since tunneling current depends exponentially on the effective band-gap at the heterojunction, the effective band-gap (deduced from the band alignment) is critical in modeling the tunneling phenomena.

However, as mentioned previous in Section *1c*, many fabrication processes for InAs MOS structures result in very large interface trap densities. A key accomplishment of Period 3 is the development of a hybrid model for interface traps that allows the extraction of the interface trap distribution from experimental CV data. The novelty of the technique is that it only requires one calculation of the computationally intensive quantum mechanical simulations of the MOS capacitor structure. InAs MOS-capacitors were fabricated with a variety of surface treatments and dielectrics to determine the optimal fabrication process for low interface trap densities and low gate leakage. Analysis of the data using the hybrid model indicates that HfO_2 appears to result in lower interface trap density as compared to Al_2O_3. This method allows us to model the trap distribution as a function of energy. Trap states within the band gap contribute to the band edge steepness and so this modeling method provides us some insight into the steepness of the band edges when trap limited. We are continuing our search for an optimal process using analysis such as XPS, TEM, and CV measurements along with the hybrid model for trap density extraction from our fabricated devices, so that different dielectrics can be compared. We are also communicating with other groups in the Center to determine the best process for InAs MOS gate dielectrics.

We have also completed a process flow for and begun fabrication of laterally-contacted InAs/GaSb n-p tunnel diodes. This is a challenging structural design with an airbridge to enable study of 2D-to-2D tunneling. A fully suspended airbridge (Figure 3) with 10nm InAs thickness was recently demonstrated. We expect to have completed the fabrication of n-InAs/n-GaSb *Schottky-like* structures for CV analysis of band alignment by the end of this reporting period.

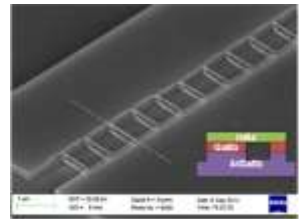


Figure 4: SEM picture of a fully-suspended airbridge on 10nm thick InAs.

To address the limitations resulting from interface traps, we have also transitioned to the ternary $In_xGa_{1-x}As/GaAs_{1-y}Sb_y$ in order to allow the growth of an InP capping layer which has been shown to decrease the trap density at the high-K/semiconductor surface. $In_xGa_{1-x}As/GaAs_{1-y}Sb_y$ vertical TFETs are being fabricated to study the impact of effective band-gap on tunneling current and switching abruptness. A thin InP layer will be grown on the $In_xGa_{1-x}As/GaAs_{1-y}Sb_y$ heterojunction in order to realize a high quality high-K/semiconductor interface, paramount to effective gate control. The effective band-gap will be varied by changing the alloy fraction of the semiconductors.

- *2D-2D Materials and Devices*

In Period 2, we reported the results of analytical studies of the group of **E. Yablonovitch** *(Berkeley)* that account the effect for the dimensionality on the density of states on either side of the p-n junction. The studies showed a 2D-2D junction has sharper turn-on and larger turn-on current at low voltages (Figure 4).

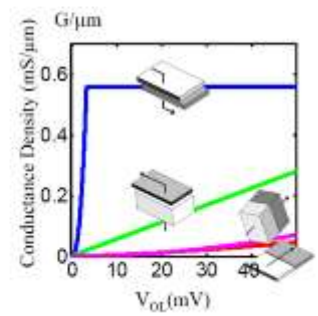


Figure 3: The conductance curves for junctions of various dimensionalities show that a 2D-2D junction has sharper turn-on and larger turn-on current at low voltages.

The experimental investigations of 2D materials and 2D-2D semiconductors are being pursued by the group of **A. Javey** *(Berkeley)* that has invented a novel materials platform, XOI, enabling the study of the fundamental materials properties of ultra-thin layers as well as the properties of the resulting devices [4]. Through this platform, we can study and utilize the drastic effects of quantum confinement in ultra-thin films of many materials systems.

The Period 3 studies comprise two materials systems and here we report the status of each sub-project.

- *Heterojunction Tunnel Field-Effect Transistors from III-V XOI*

In the last reporting period, we reported results from 2-D III-Vs on Si/SiO_2 (XOI) with free-standing, ultra-thin membranes of III-Vs, such as InAs and InGaSb. In the past year, we have successfully transferred InGaSb ultrathin epi-layer (down to 7 nm) from original growth substrate onto Si/SiO_2 substrate. Along with InAs XOI, this achievement completes the XOI platform for both n- and p- type semiconductors. In the course of the research, we have also achieved the following results.

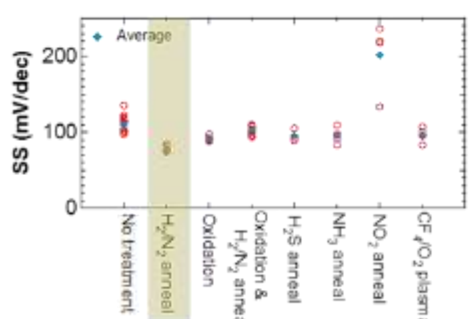


Figure 5: H_2/N_2 anneal at 170 ^oC after ZrO_2 deposition results in the best subthreshold slope (~75 mV/decade).

  - We have done a systematic surface treatment study to improve the interface properties of 2-D InAs. Figure 5 shows that anneal at 170

°C after ZrO_2 deposition results in the best SS (~75 mV/decade). This is important to enhance the transport properties of InAs.

- InGaSb is found to be easily oxidized in the air, as shown in Figure 6a. By using InAs capping layers from both top and bottom, InGaSb layer can be preserved un-oxidized, as shown in Figure 6b. This capping layer enables good transport behavior in the InGaSb channel, as shown in Figure 7.

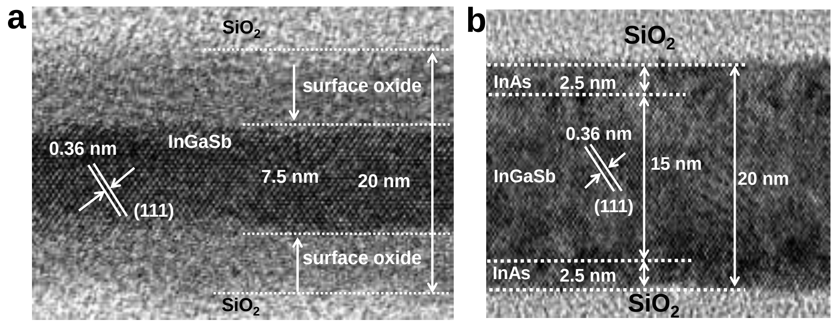


Figure 6: (a) A cross-sectional TEM image of an uncapped InGaSb XOI. (b) A cross-sectional TEM image of a InAs capped InGaSb XOI

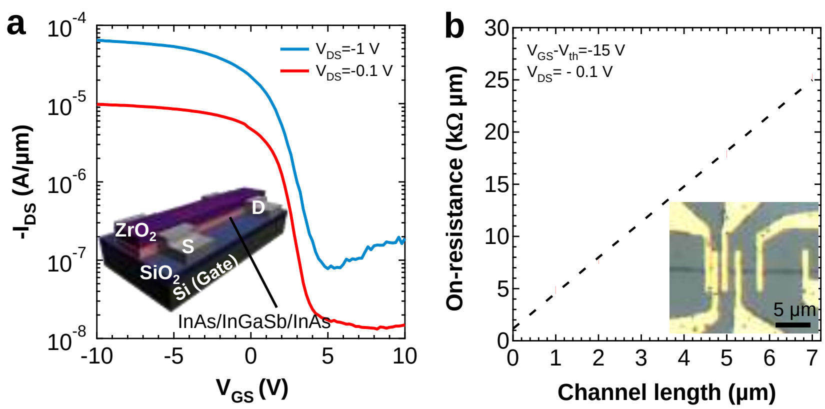


Figure 7: (a) The back gated InAs/InGaSb/InAs channel XOI FETs show p-type transfer characteristics. (b) Transmission line method shows that the contact resistance is ~580 Ω.µm.

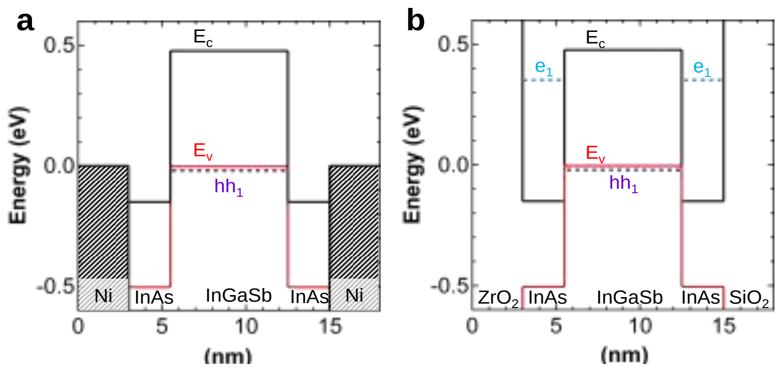


Figure 8: Band alignment of InAs/InGaSb/InAs with (a) Ni boundary, and (b) ZrO_2 boundary

- Transport and simulation study shows that with metal contact, the band alignment between InAs and InGaSb is type III, while with air or high-k boundary, the alignment is type II, as depicted by Figure 8. This change can be understood by the difference in the spatial confinement barrier and is essential in building InAs-GaSb based TFETs.
- From the optical study of 2-D InAs (Figure 9), the role of quantum confinement has been understood. The onset of shifts to higher energies with thickness reduction indicating bandgap increases with downscaling of the thickness due to quantum confinement. Clear steps in absorption depict the optical transitions between 2-D subbands. The spacing between the subbands increases with thickness reduction. This result is in distinctive contrast to ultra-thin Si, and will provide insights in future designing of InAs/GaSb TFETs. Moreover, we also found a quantum unit of absorptance in 2-D semiconductors. The optical absorptance due to interband transitions between the 2-D subbands is independent of thickness and band structure details. Simply, it is A_Q=8πα/(3nr) ~ 1.7%, where α is the fine-structure constant and n_r is the refractive index. Total absorptance is then A=M.A_Q.

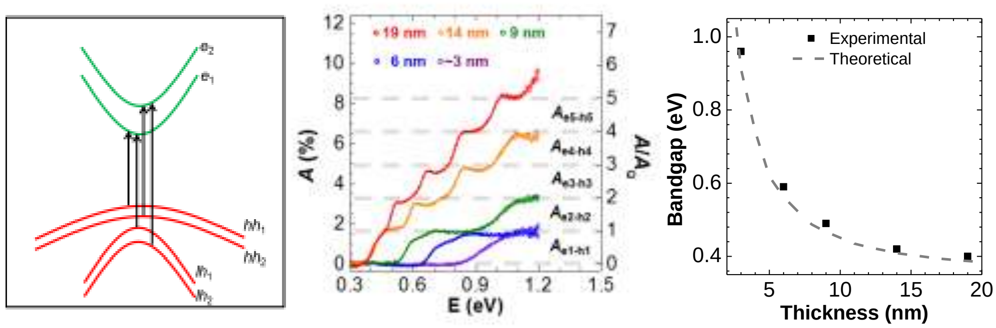


Figure 9: Optical measurement of InAs XOI; InAs on CaF2 substrate

- *2-D Layered Chalcogenides on Si/SiO2 (XOI)*

The need for ultra-thin n-p junctions also brings concerns for thickness fluctuations. We cannot rely upon the growth of quantum well with uniform thickness to provide reproducible device thresholds. Instead, the group of **A. Javey** is leading an effort to study the chalcogenide class of materials which are layered compounds, the most famous of which is *n*-MoS. There are other chalcogenides that tend to be p-type, and there might be combinations that form pn junctions with the desired band alignment.

As planned for Period 3, we expanded our investigation to include WSe_2 and MoS_2 on Si/SiO_2. Our top gated monolayer WSe_2 pFETs after contact resistance minimization demonstrate ~60 mV/dec subthreshold swing (SS) and ~250 cm^2/V.s effective hole mobility, which reflects the advantages of its fundamental layered structure, minimum surface roughness, lack of dangling bonds and surface defects at extremely thin body (~1 nm for single layer). We also achieved a first demonstration of a van der Walls heterojunction diode. Moreover, we have also accomplished the following:

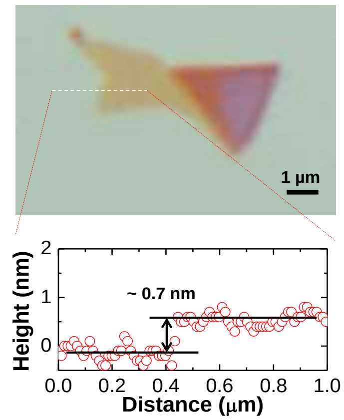


Figure 10: Single layer WSe_2 on Si/SiO_2

- Single layer of WSe_2 and MoS_2 has been achieved by mechanical exfoliation method. As shown in Figure 10, single layer WSe_2 has been exfoliated and transferred onto Si/SiO_2, which has thickness of ~ 0.7 nm.
- Metal to WSe_2 and MoS_2 contacts have been studied and optimized. As shown in Figure 11, Pd has been found to have smallest contact resistance (i.e. Schottky barrier height) to WSe_2.

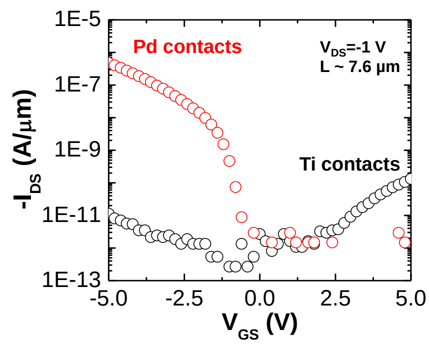


Figure 11: IDS-VGS characteristics of back gated WSe2 FETs with different metal contacts.

- Degenerate doping technique has been explored to further reduce the contact resistance. As shown in Figure 12, NO_2 gas has been found to have the strongest doping power. The top gated FETs after contact resistance minimization demonstrates ~60 mV/dec subthreshold swing (SS) and ~250 cm^2/V.s effective mobility.
- First demonstration of a diode based on a van der Waals heterojunctions, based on InAs/WSe_2. The diode shows clearly rectifying behavior as shown in Figure 13.

Our current focus is on reducing the contact resistance. For the rest of this reporting period, we will continue to investigate n-type doping and other doping technique to layered chalcogenides.

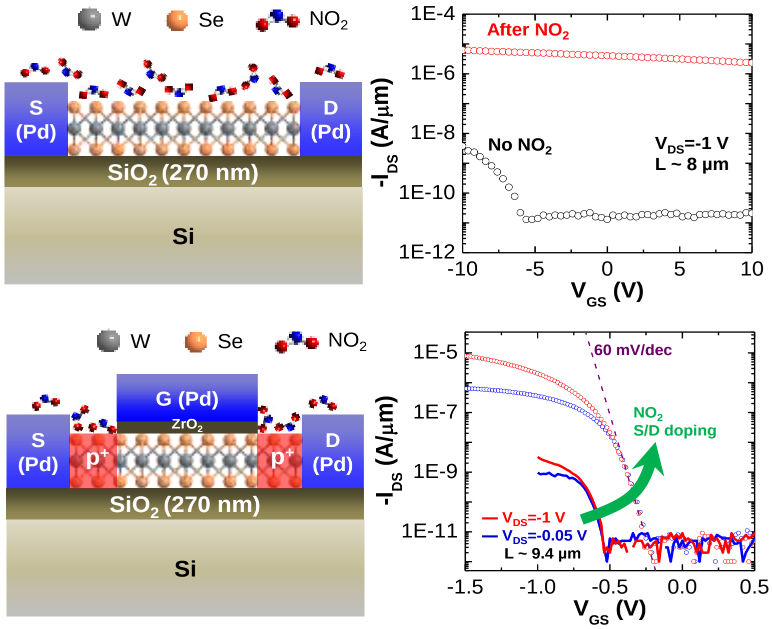


Figure 12: Degenerate doping by NO_2 to reduce the contact resistance.

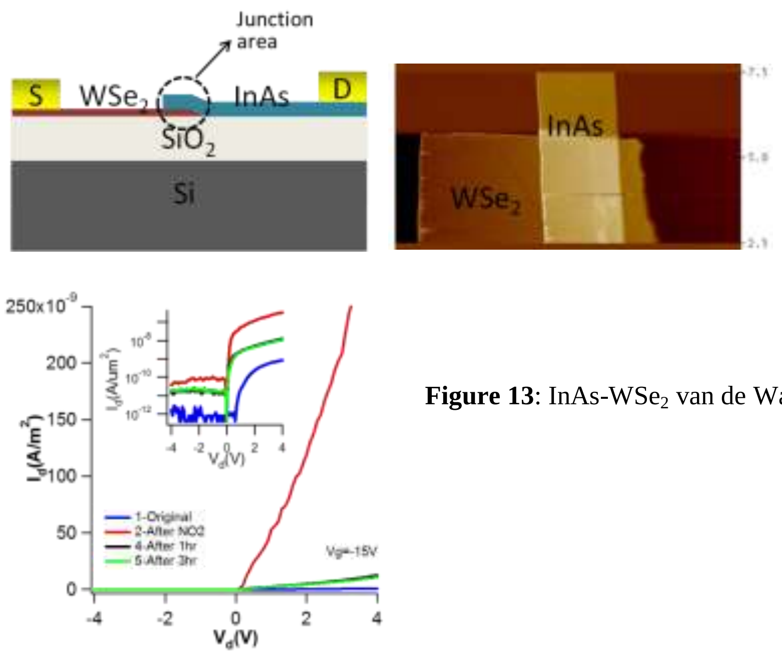


Figure 13: InAs-WSe_2 van de Waals diode

- *MOCVD Growth of Novel Heterostructures for Tunnel Devices*

  Another key Theme I goal is that the group of **E. Fitzgerald** of *MIT* establish a MOCVD growth capability for GaSb/InAs heterostructures. This research is intended to fulfill two needs:

- The ability to study the influence of growth parameters on device characteristics and eventually on device performance, and explore new materials system; and
- An internal material growth source to collaborate in the device and processing research projects of other Theme I researchers.

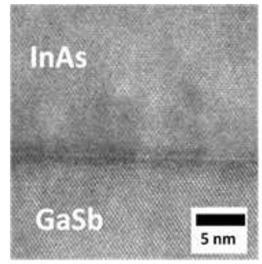


Figure 14: A cross-sectional TEM image of an InAs layer grownon a GaSb layer.

To date, research in steep-subthreshold switches have relied primarily on MBE growth, but MOCVD growth offers commercial advantage over the more commonly used MBE technique in that it is a more scalable technique, since it can handle much larger wafer sizes and greater throughput. The choice of pursuing MOCVD reflects the Center's long term focus on outcomes that are practical. It is a novel and important endeavor for the Center's co-PI's to understand the connection between MOCVD parameters, materials quality, interfacial quality, and device performance of novel material systems like GaSb/InAs, and derivatives like in which the GaSb hole-gas layer is replaced with Ge. The research in heterostructures with novel combinations of elements could evolve into a tunnel system in which all layers are made up of column IV elements except for the InAs electron gas layer.

In Period 3 we continued to research MOCVD growth of the GaSb/InAs system. Here is a list of accomplishments.

- We have developed the capability to grow InAs/GaSb heterostructures via MOCVD and we have identified various links between process parameters (such as temperature, V/III ratio, and interface gas switching sequence, growth order) and heterostructure properties (such as interface abruptness, dislocation densities, top surface roughness). We have made progress in suppressing intermixing to achieve the sharpest possible interface for tunneling between device layers (Figure 14).

Figure 15: A TEM image of a Ge layer grown on an InAs layer.

- We have developed an alternate heterostructure in which the GaSb layer is replaced with Ge. We have identified the effect on the dimensionality of grown Ge films (quantum dot growth vs film growth) due to growth parameters including temperature, time, and substrate off-cut, and we have used this information to successfully grow Ge thin films on InAs that can be used for devices (Figure 15).

- We have fabricated small-area mesa diodes down to 10 µm in diameter with dielectric passivation based on our grown InAs/GaSb heterostructures, and have observed negative resistance which corresponds to the band-edges of InAs and GaSb (Figure 16). This diode process can be used as a platform for studying the link between materials properties and electrical properties for these tunnel heterostructures.

- We have also designed alternative diode processes for utilizing Ge/InAs heterostructures, and for using organic passivation to suppress off-state leakage in these studies.

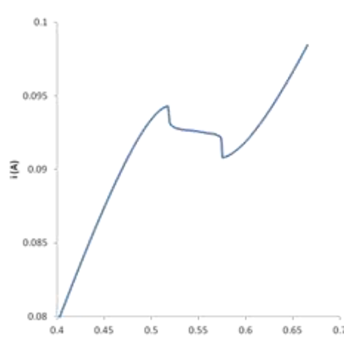


Figure 16: IV curve of an InAs / GaSb diode that is made from MOCVD grown heterostructures.

For the rest of this reporting period, we will complete the electrical characterization of InAs/GaSb devices, and relate these characteristics to different interface switching sequences and different dislocation densities. We also expect to study the impact of different growth order (InAs/GaSb vs. GaSb/InAs) before the end of this period.

- *Negative Capacitance Field Effect Transistors*

  S. Salahuddin of *UC Berkeley* is continuing to investigate the use of ferroelectric gates to achieve steep-subthreshold swing in a MOSFET, a concept that he has pioneered [5]. This concept hinges on the fact that the stored energy in the lattice of a ferroelectric material could be used to step up the surface potential in a MOSFET channel relative to the gate potential (voltage), which would in turn provide a sub-60 mV/decade subthreshold swing. When exploited in this manner, the ferroelectric material looks like a negative capacitance to the outside circuit; hence the name 'Negative Capacitance FET'.

  The main accomplishments in Period 3 are as follows:

  - Extensive work was undertaken to establish an understanding of how substrate strain changes the ferroelectric properties that are relevant to negative capacitance. Our studies have shown that the conventional polarization-strain linear coupling model may break down for Lead Zirconate Titanate (PZT), for which we demonstrated negative capacitance, once the tetragonality crosses a certain threshold (currently under review for publication in Physical Review B).
  - The work on strain also showed that the capacitance seen in partially relaxed ferroelectric materials has a significant contribution from extrinsic sources such as dislocations, defect formation etc.
  - The aforementioned study paved the way to reduce the temperature at which the negative capacitance effect was initially observed (>200˚C). We have now been able to see negative capacitance in three different material systems: Original STO/PZT bi-layer (>200˚C), (LAO/BSTO bi-layer at >200˚C) and STO/PTO bi-layer (>100˚C) (Figure 17). Finally, we have been able to observe negative capacitance at room temperature (for LAO/BSTO superlattices) (Figure 18).

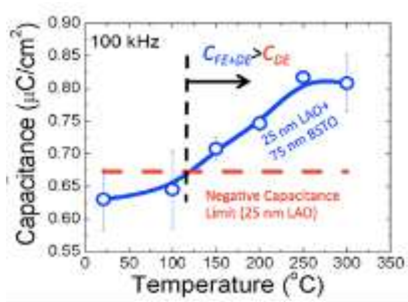


Figure 17: Capacitance vs. temperature characteristics of LAO (2.5 nm)/BSTO (7.5nm) x10times superlattice grown on DSO substrate.

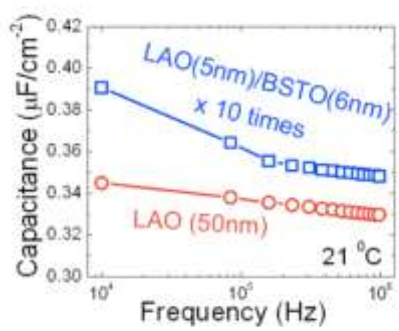


Figure 18: Capacitance vs. frequency characteristics of a LAO (5nm)/BSTO (6nm) x10 times on $GdScO_3$ substrate at room temperature (21 ^{0}C).

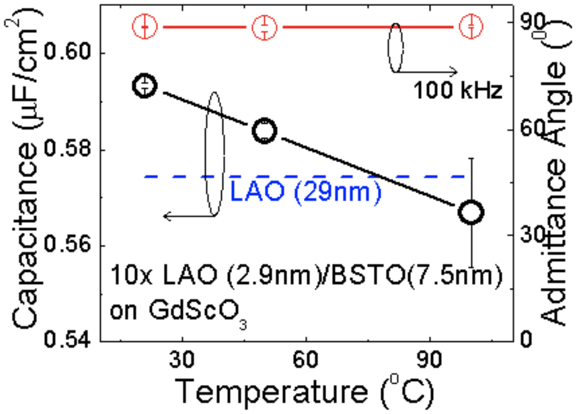


Figure 19: Capacitance and admittance angle of a LAO (2.9 nm)/BSTO (7.5 nm) x 10 times superlattice grown on GSO substrate as a function of temperature.

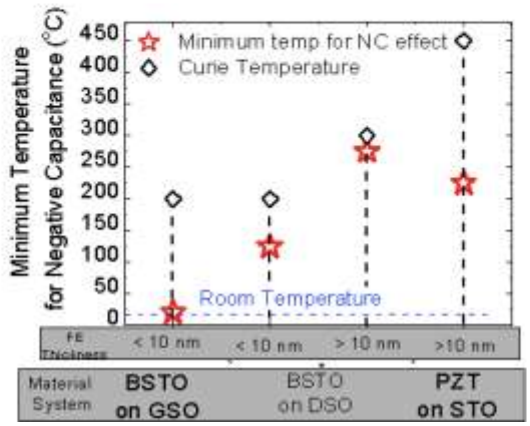


Figure 20: A comparison the lower temperature threshold for negative capacitance for BSTO and PZT materials for different thickness regimes and strain states.

- In addition, temperature characterization of these superlattices was performed. Figure 19 shows the capacitance vs. temperature characteristics of LAO (2.9 nm)/BSTO (7.5 nm) x10 times superlattice grown on GSO substrate. The capacitance of the superlattice becomes larger than that of the constituent dielectric LAO (29 nm) at room temperature. This capacitance enhancement decreases with increasing temperature and at above ~75 ^{0}C, the enhancement ceases to exist. This suggests that (1) the Curie temperature of BSTO grown on GSO is ~75 ^{0}C and (2) the addition of the LAO shifts the apparent Curie temperature of the bilayer to below room temperature. It is also important to note that in Figure 19, the admittance angle is close to 90^0, indicating that the sample is non-leaky and the contributions from extrinsic mechanisms are minimal. Figure 20 summarizes the temperature range of negative capacitance effect in BSTO and $Pb(Zr_{0.2}Ti_{0.8})O_3$ (PZT) for different thickness regimes and strain conditions.
- We have also been able to propose a technique and then directly measure the negative slope in a ferroelectric material using pulsed excitation.

In collaboration with **C. Hu** of *UC Berkeley*, we have initiated work on fabricating MOSFETs with these gate oxides. We are also collaborating with R. Droopad from Texas Tech University for initial template of STO on Si. Because of this collaborative work, E^{3}S students A. Khan and C.W. Yeung received the Qualcomm Innovation Award.

- *Superlattice Nanowire Field-Effect Transistor*

The group of **J. del Alamo** at *MIT* has been pursuing a transistor concept that provides a scheme to cut off the thermal tail that is responsible for the subthreshold current in an FET. The potential of a nanowire field-effect transistor with a superlattice source (SLS-NW FET) to achieve steep-subthreshold swing has been proposed by [13], and verified through simulations by Gnani *et al*. [14] With the proper design, the structure has a mini-band in the source creating a mini-gap above where no states are allowed. No current is possible until the top of the source mini-band 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.

The theoretical calculations of Gnani *et al*. [14] concluded that a variety of SL's can accomplish these goals in 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. Seven periods appear to be enough to accomplish the filtering action of the superlattice [14]. They also showed 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.

In the first year of this project, the accomplishments are as follows:

We have created a simulation environment for self-consistent Poisson-Schrodinger calculations of the band structure of 1D nanostructures containing superlattices. The model has been validated with literature data. It has also been used to design InAlAs/InGaAs/InP heterostructures that have been sent for epitaxial growth.

We have developed an electron-beam lithography-based technology for defining and dry etching 20 nm diameter vertical nanowires on InGaAs/InAlAs/InP heterostructures with a 10:1 aspect ratio. A digital etch technology has also been developed to smooth the sidewalls and to controllably thin the nanowires to ~10 nm diameter (Figure 21).

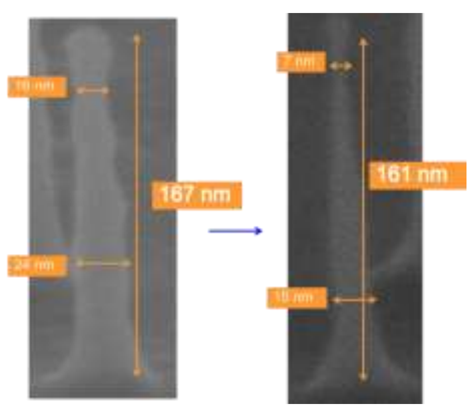


Figure 21: InGaAs/InAlAs/InP nanowire structures fabricated by RIE (left) followed by digital etching (right). Sub-10 nm nanowire diameter structures have been achieved with aspect ratios better than 10:1.

While we have demonstrated III-V nanopillars with high aspect ratio, achieving smooth vertical sidewalls and diameters in the few-nm range have proven to be very challenging. We have succeeded in demonstrating 10 nm diameter InGaAs/InAlAs nanopillars with 10:1 aspect ratio and smooth sidewalls. However, the process is not very reproducible. So, we are exploring various avenues to increase the repeatability of the results at the 10 nm diameter range.

Devising a strategy to sample the density of states in the 1D nanowire structure without having to fabricate a complete field-effect transistor is proving to also be quite challenging. We have come up with an approach that we believe we can fabricate without developing a full transistor process and that uses Ballistic Electron Emission from a STM tip. A device structure has been defined and most of the process has been developed. We are working towards a direct observation of the DOS structure of the 1D superlattice source using Ballistic Electron Emission Microscopy (BEEM) before the end of this reporting period.

- *Bilayer Tunneling Field Effect Transistors*

In Period 3, the group of **E. Yablonovitch** of *UC Berkeley* initiated a new TFET concept at the Center, a device concept first introduced by Lattanzio *et al.* [12]. It comprises a free standing semiconductor film with an undoped homojunction. The thin semiconductor film has opposite gate stacks on either side. The Work Function difference creates a 2D electron channel on one side and a 2D hole channel on the other side. Alternately, a static external potential can provide the internal electric field which aligns the valence band on one side with the conduction band on the other side.

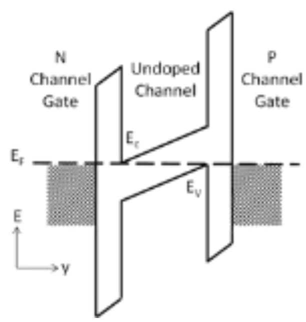


Figure 22: "Tilted H", an undoped homojunction in which band alignment is controlled by the Work Functions of the opposite gates, producing an n-p bilayer.

The homojunction structure, given in Figure 22, incorporates a n-p bilayer and has many potential advantages relative to the Type III heterojunction Density of State switch that has been under investigation. The tunneling probability is adjustable by the thickness of the film and will be high due to the large tunneling area and 2D-2D tunneling current. The tunneling is between a 2D valence band channel and a 2D conduction band channel. The 2D-2D case is known to result in a favorable step-function I-V response. There is no doping and therefore, there are no heavy doping effects. There are many semiconductors which could be employed, rather than the unique GaSb/InAs Type III band alignment case. A complementary device is easily made by reversing the electrical gating signal between opposite sides of the symmetrical channels. The tunneling current in the "tilted H" band diagram is controlled by gate modulation as in a conventional Field Effect Transistor, but the current path is different. Among the advantages of the n-p bilayer structure is that it can be propped up into a "Fin" allowing top down fabrication of the double-sided structure.

The groups of **D. Antoniadis** and **J. Hoyt** of *MIT* joined the Yablonovitch group to evaluate this device concept.

- Initial analytical studies and simulation with NextNano have been conducted. As in all transistors, there is a question of gate efficiency. The shift in the energy of the channel is invariably less than the applied voltage on the gate electrode. There is voltage divider action between the gate oxide, and the tunnel capacitance in the semiconductor. The quantum Capacitance, $C_{quantum}$, of filling the 2D density of states of the channel, tends to short out the electric field across the tunnel barrier. Owing to the higher effective mass of silicon, the Si gate efficiency is in the range 15%-25%.

- The studies also showed the 2D hole channel, and 2D electron channel, both sitting in triangular potential wells on either side of a 15nm InAs tunneling film. Owing to the quantum confinement, the applied electric field must produce a voltage difference equal to the bandgap energy + confinement energy. Analytic calculations indicate good on-state tunnel conductance ~1 mS/μm, and a reasonable gate efficiency of 60% for this case.

- Analysis of device design tradeoffs for this proposed bi-layer tunneling device structure was completed. We have established the theoretical relationships between semiconductor thickness, dielectric thicknesses, and total potential at eigenstate alignment and corresponding expected gate-channel leakage current. An optimal InAs based design was found. A joint MIT/UCB paper has been accepted by IEEE EDL for publication [15].

- Using a non-equilibrium greens function model, we numerically demonstrated that tunneling in a confined junction can result in higher on-state conductivity in a smaller device.

We are beginning to plan for experimental demonstration of bilayer FETs. Again, we will have two complementary efforts.

- The UC Berkeley Bilayer team that is being expanded to include the group of **A. Javey**, also of *UC Berkeley,* will address the fabrication of an InAs bilayer device.

- The MIT groups will address the fabrication of a Si bilayer device. The ability to have high quality dielectrics in a silicon FET will allow the study of tunneling physics with fewer complications from deleterious issues like traps.

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

Mechanical switches have zero off-state leakage and abrupt on/off switching behavior, which allows for aggressive supply voltage scaling for ultra-low active energy consumption (projected to be <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 was the first and continues to be the only major concerted effort to focus on achieving ultra-low-voltage mechanical switches with energy efficiency far superior to that of transistors. To be a viable low-energy alternative to transistors, a mechanical switch must operate at reasonable speed and have nanometer-scale dimensions. 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).

At the beginning of Period 3, the Theme II research portfolio of projects was focused on:

a. Investigating fundamental limits for achieving milli-Volt operation with a mechanical switch;

b. Investigating advanced structural materials and interfacial treatments to improve the energy efficiency and reliability of mechanical switches; and

c. Investigating alternative switch designs to mitigate the problem of stiction, which is crucial for low voltage operation.

d. Demonstrating milli-Volt operation of a mechanical switch.

During most of Period 3, Theme II research was organized as follows.

Project	Primary Focus in Period 3	Lead Faculty	Lead Institution
i. Technologies for Nanoscale and milli-Volt Relays	a, c, d	King Liu	UC Berkeley
ii. Low-Energy-Consumption NEM Relays with Carbon as a Structural and Interfacial Material	b, d	Wong	Stanford
iii. Nanomechanical Switch Based on Electrically Actuated Tunneling Gaps	c, d	Bulović, Lang & Swager	MIT
iv. Nanomechanical Relays with Magnetoelectric Switching Elements	c	Bokor	UC Berkeley
v. Electromechanical Switch with Sub-Nanometer Displacement utilizing Metal-Insulator Transition in VO_2	c	J. Wu	UC Berkeley

Collaborative interactions take place among the faculty, post-docs and students across all of the projects; these interactions include sharing of materials and process knowledge to problem-solving and brainstorming during Theme meetings.

As can be seen from the table above, each project is pursuing an approach that mitigates surface adhesion (stiction): (i) minimizing the real contact area, (ii) avoiding contact by utilizing tunneling current in the ON state, (iii) counteracting stiction, e.g., with a repulsive magnetic force, or (iv) by circumventing the need to break contact.

During Period 3:

- Project i started by investigating the dependence of contact adhesive force on apparent contact area for a conventional switch design (Figure 23). The results indicated that surface adhesion ultimately will limit relay scaling; therefore, the focus of the project was shifted toward a tunneling (i.e., non-contacting) switch design (Figure 27).
- Project ii focused on the fabrication of mechanical switches employing graphene as an ultra-thin structural (Figure 30), for reasons explained in Section *II.1c. Problems Encountered*.
- Projects iii investigated switching by modulating a tunneling gap between two plates (Figure 33).

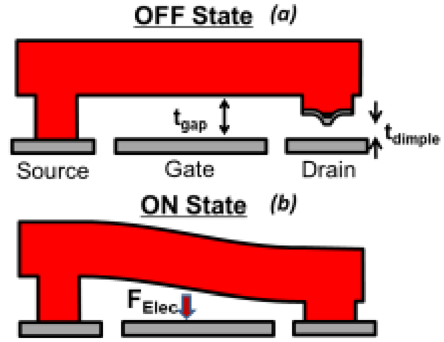


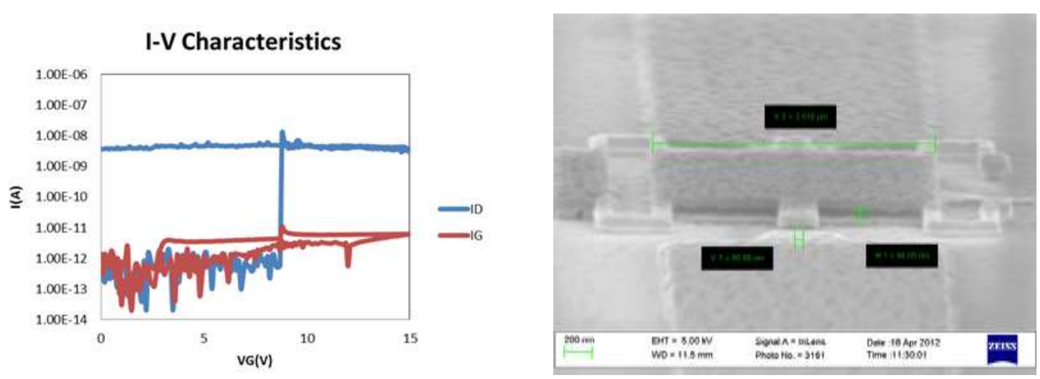
Figure 23: Schematic cross-sections of a conventional contacting mechanical switch (a) in the OFF state, and (b) in the ON state.

- Project iv investigated the range of repulsive magnetic force achievable for incorporation into a contacting relay design (Figure 43).
- Project v was added to investigate metal-insulator transition as a potential switching mechanism. As stated in the Period 2 annual report, research on metal-insulator transition in VO_2 was supported as a seed project beginning in the middle of Period 2 to allow the project to demonstrate initial results before identifying an application among the Center's Themes.

Progress made in each of these projects during Period 3 is detailed below.

- *Technologies for Nanoscale and Milli-Volt Relays*

  A theoretical study of relay scaling projected that sub-10 milli-Volt operation should be achievable with a 3.5μm-long × 83nm-wide × 40nm-thick suspension beam if contact adhesion scales down proportionately with the area of the contact dimple regions. Subsequently, scaled electrostatic relays (with 4μm by 4μm total footprint) comprising a 100nm-thick polycrystalline silicon-germanium (poly-$Si_{0.4}Ge_{0.6}$) structural film and 70nm-thick electrostatic actuation gap were successfully fabricated and characterized (Figure 24). The scaled structural film showed little out-of-plane deflection, indicating that strain gradient was sufficiently reduced through process optimization (addressing a problem that was encountered in 2011).



(a) (b)

Figure 24: a) Measured drain current and gate current as a function of the applied gate voltage, and b) A tilted scanning electron microscopy (SEM) view of a scaled electrostatic relay.

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Relays of various contact dimple areas (from 6um^2 down to 0.04um^2) were fabricated to investigate the dependence of contact adhesive force on apparent contact area.

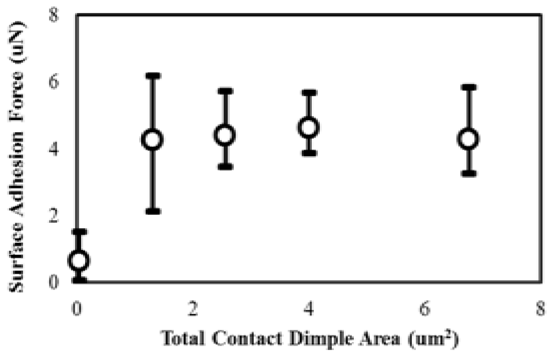


Figure 25: Extracted surface adhesive force as a function of apparent contact area in a relay.

The results (Figure 25) indicate that, although surface adhesion is lower for smaller contact dimple area, there is not a linear dependence so that stiction may be problematic for ultra-scaled relays. Finite-element-method (FEM) simulation of 3-dimensional nanoscale relays showed that voltage (and size) scaling will be fundamentally limited by contact adhesive force. That is, a relay which operates by making and breaking physical contact between metallic electrodes will be difficult to scale aggressively to sub-10mV operating voltage and sub-micron actuation area.

Analysis:

$$F_{spring} > F_{surf} \longrightarrow kg_d > F_{surf}$$

$$V_{DD}^2 = V_{pi}^2 = \frac{8}{27}\frac{kg_o^3}{\varepsilon_o A_{act}} > \frac{8}{27}\frac{\left(F_{surf}/g_d\right)g_o^3}{\varepsilon_o A_{act}}$$

$$V_{DD} > \sqrt{\frac{8}{27}\frac{F_{surf}}{\varepsilon_o}\frac{g_o}{g_d}}\left(\frac{g_o}{\sqrt{A_{act}}}\right)$$

Examples:

$$(1) F_{surf} = 4.0nN$$

$$\rightarrow V_{DD} > \left(\frac{g_o}{\sqrt{A_{act}}}\right) \cdot 14.17V$$

$$(2) F_{surf} = 0.4nN$$

$$\rightarrow V_{DD} = \left(\frac{g_o}{\sqrt{A_{act}}}\right) \cdot 4.48V$$

Figure 26: Analysis of minimum supply voltage for a relay as a function of surface force, and numerical examples of the derived minimum voltage with two representative values for surface force.

In parallel with the experimental effort, **E. Alon** of *UC Berkeley* was continuing the analytical studies on the ultimate limits of relay-based integrated circuit performance, area, and energy, in collaboration with **T.-J. King Liu** of *UC Berkeley*. An analysis of minimum switching energy and voltage of relay-based circuits as a function of surface forces was completed. As detailed in Figure 26, the analysis is based on the fact that in order for the relay to function correctly, its spring restoring force in the on state must exceed the attractive surface force exerted on the moveable structure. This analysis shows that given a certain surface force, the minimum voltage is set only by the ratio of actuation gap to actuation area. This implies that in the ultimate limits of scaling where both the actuation gap and the surface force are fixed, further dimensional scaling does not result in any further reduction in operating voltage.

Thus, during Period 3, the focus of this research project was shifted toward a non-contacting (i.e., tunneling) relay design for ultimate scalability (Figure 27). Non-contact has been the research direction for the MIT team since the Center's inception. This is an example of how the different PIs begin to influence the thinking of their peers through the Center activities.

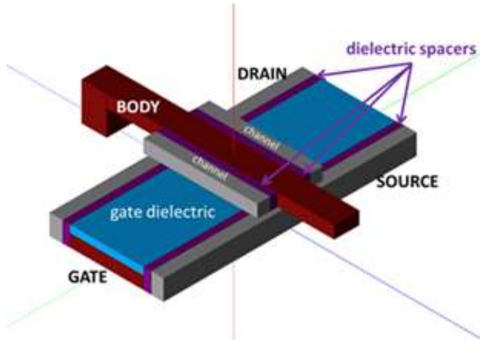


Figure 27: Schematic isometric view of the tunneling relay design being investigated.

Upon selective removal of the (ultra-thin) sacrificial oxide, the channel electrodes fall into contact with the source electrode. The contact gap (hence tunneling current) between the channel electrodes and the drain electrode is modulated by changing the voltage applied between the gate electrode and the (movable) body electrode to which the channel electrodes are attached via intermediary dielectric spacers. Based on the classical tunneling model, the contact gap in the on state must be close to 1 Å to achieve low on-state resistance (< 10 kΩ).

FEM simulation results for the tunneling relay design are given in Figures 28a and 28b. Figure 28a shows how the tunneling gap at the drain is reduced with increasing gate bias, while Figure 28b shows the relationship between displacement and force and the resulting effective spring constant k_{eff}; it can be seen that k_{eff} increases as the tunneling gap is reduced below ~3 Å (in Region III), so that the pull-in phenomenon is avoided. Figure 29 shows the calculated tunneling current as a function of the gate bias, based on the FEM simulation results.

(a) **(b)**

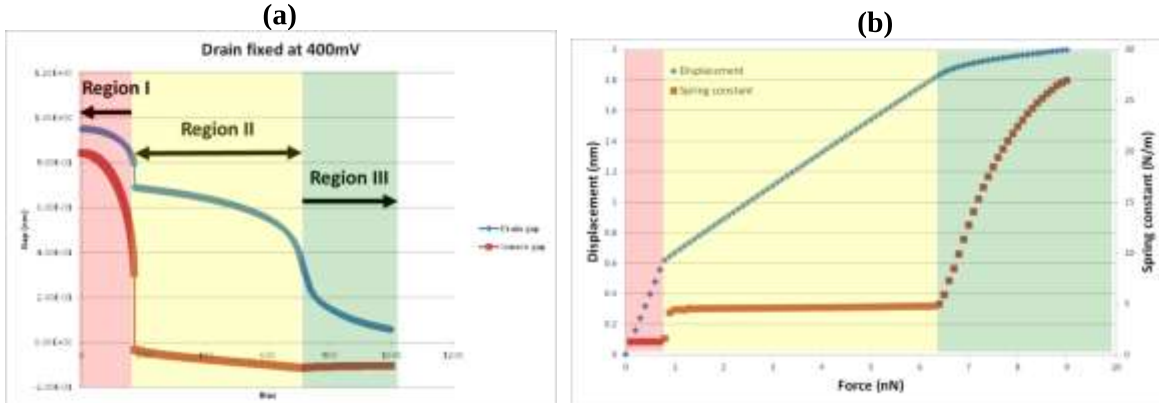


Figure 28: (a) Simulated contact gap thickness as a function of the applied gate bias; and (b) Displacement resulting from applied force at the drain electrode, and extracted effective spring constant.

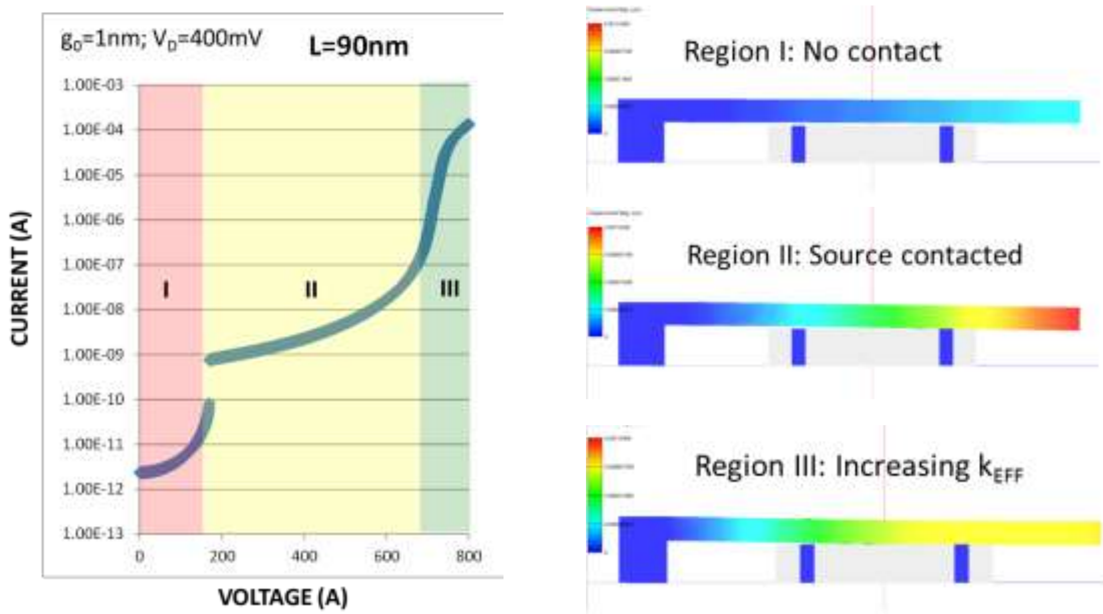


Figure 29: Calculated tunneling current (assuming total tunneling area = 50 nm^2) as a function of gate bias, based on the FEM simulation results in Figure 28.

Experimental work was initiated in Fall 2012 to demonstrate this new relay design which avoids the pull-in phenomenon to achieve ~1 Å tunneling gap. By the end of Period 3, process development for demonstration of prototype non-contacting relays is expected to be completed. A systematic study will be conducted to identify and optimize the relay design parameters.

- *Low-Energy-Consumption NEM Relays with Carbon as a Structural and Interfacial Material*

During Period 3, **H.-S. P. Wong** of *Stanford*, led a project that focused on one goal (refer to Section *II.1c. Problems Encountered*); namely, to demonstrate a three-terminal switch comprising a graphene beam and sub-10nm actuation gap, wherein the graphene serves as the movable source electrode.

Sub-10k_BT switching energy, 300 milli-Volt switching voltage, and 1ns switching delay are expected to be achieved with this small gap size and thin structural layer.

As the lateral dimensions (length L and width W) of an electrostatically actuated structure are scaled down, its thickness (h) also must be reduced proportionately in order to achieve low V_{PI}:

$$V_{PI} \propto \sqrt{\frac{k_{eff} t_{gap}^{3}}{\varepsilon_0 A}} \qquad \text{where} \qquad k_{eff} \propto \frac{Wh^3}{L^3}.$$

Additionally, the structural material should have very low strain gradient, to avoid significant out-of-plane deflection resulting in undesirable variation in the actuation gap thickness t_{gap}. Graphene is a promising candidate structural material that can meet these requirements for nanometer-scale relays; hence it is being investigated by the Theme II researchers at Stanford, with the goal to demonstrate conventional (contacting) mechanical switches that employ graphene as the structural material.

Progress was made during Period 3 as follows:

- Processes were developed to fabricate two-terminal and three-terminal graphene-beam switches with gap size ranging from 10 nm to 100 nm (Figure 30). Specifically, (i) bottom electrodes were patterned using a lift-off process on pre-patterned trenches of thermal oxide, (ii) nickel was used as a sacrificial layer to avoid stiction prior to the release process, and (iii) post-transfer processing methods were developed to avoid damaging the patterned graphene. Integrated process flows were developed using (i) a single trench process for patterning bottom electrodes with nickel sacrificial layer, and (ii) a bottom source structure with PMMA sacrificial layer. To expedite device fabrication, a 2-inch LPCVD furnace for graphene synthesis in-house was built. Efforts are underway to optimize the graphene synthesis process for mechanical switch application.

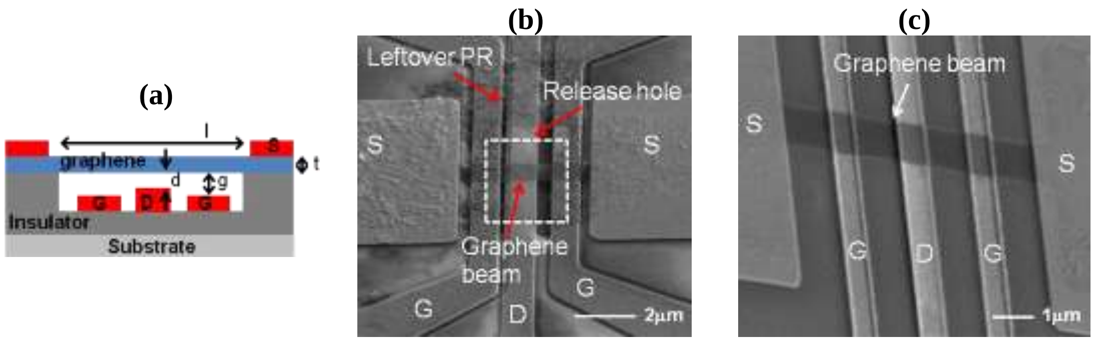


Figure 30: Three-terminal graphene-beam switch: (a) schematic device cross-section, (b) SEM image of a fabricated device for which wet etching was used for trench formation for the bottom electrodes, and nickel and thermal oxide were used as the sacrificial materials, and (c) SEM image of a fabricated device for which reactive-ion-etching was used for trench formation for the bottom electrodes, and nickel was used as the sacrificial material.

- Electrical characterization of two-terminal and three-terminal graphene-beam switches was performed. As can be seen from Figure 31, pull-in (turn-on) behavior was clearly observed. Off-state leakage and stiction (such that the switch does not turn off when the beam voltage is reduced to zero) are issues that require further investigation. The mechanical quality (initial bowing) of the suspended graphene beam and design space (beam dimensions, gap size, and structure type) will be characterized in detail.

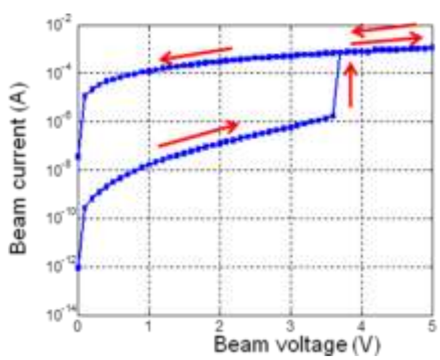


Figure 31: Electrical measurement of a two-terminal graphene-beam switch. Anchor-to-anchor distance is 1.5μm and the current compliance is 1mA. The pull-in voltage is observed to be 3.6V.

- The performance limit of graphene-beam switches, set by van der Waals force, was analyzed by applying a constant-sensitivity scaling strategy for minimizing the switching energy. This analysis shows that sub-10k_BT switching energy, 300mV switching voltage, and 1nsec switching time can be achieved with a cantilever beam comprising a single layer of graphene and actuation gap size of 10 nm. Also, theoretical analysis of the partial-energy-recycling operation scheme for a six-terminal (single-pole, double-throw) nano-electro-mechanical switch was completed. (This scheme allows for virtually zero switching voltage swing at the optimum design point – subject to noise margin requirements (Figure 32) – and hence can provide for milli-Volt operation, in principle.)

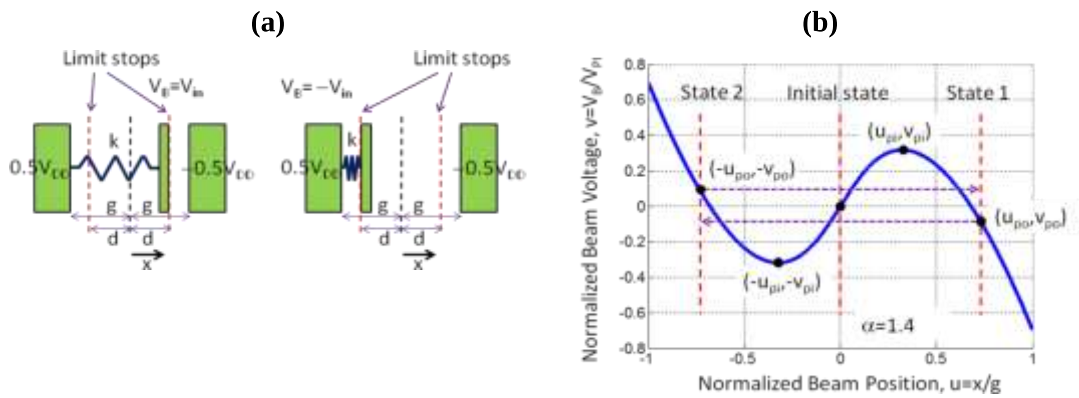


Figure 32: (a) Proposed partial-energy-recycling operation scheme. Two states are shown. V_{DD} is set to be larger than V_{PI} (pull-in voltage for single-throw operation), (b) Normalized beam voltage, $v=V_B/V_{PI}$, as a function of normalized beam position, $u=x/g$, for a given normalized bias voltage, $\alpha=V_{DD}/V_{PI}$ for the proposed partial-energy-recycling operation scheme. It can be shown that switching between the two states can be achieved only for negative V_{po}.

Successful demonstration of a two-terminal graphene-beam switch with low off-state leakage is targeted for the end of Period 3. Optimization of the graphene synthesis process and transfer process for device fabrication is underway, in collaboration with the group of **J. Wu**, another E^3S faculty (leading Project v under Theme II) at UC Berkeley.

- *Nanomechanical Switch Based on Electrically Actuated Tunneling Gaps*

In recognition of the contact reliability concern for mechanical switches, the Theme II research portfolio has included investigation of non-contact relay designs since the inception of the Center. This collaboration of **V. Bulović**, **J. Lang** and **T. Swager**, all of *MIT*, seeks to develop a mechanical switch that operates via modulation of tunneling through a compressible material. The switch is a planar structure, and its tunneling gap is delineated by two parallel metal electrodes as shown in Figure 33. To modulate conduction, the separation between the electrodes is actuated electro-mechanically (not shown in the figure). This separation should vary from 4-10 nm when open to 1-2 nm when closed. The gap is held open with a mechanical spring formed by attaching sparsely-spaced insulating organic molecules between the two electrodes in the form of a self-assembled monolayer (SAM) or a deposited thin film. The molecules bend and compress as the gap closes. Alkyl-thiols, for example, could serve as the elastic insulating SAM anchored between the electrodes. Since our concept is a squeezable switch, it is referred to within the Center as a "squitch".

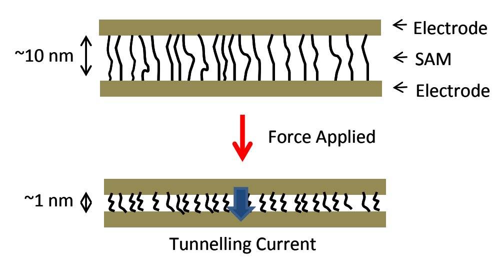


Figure 33: Schematic cross-sectional views of the tunneling gap in a "Squitch."

During Period 3, this project has focused on three aspects: performance modeling and design optimization; SAM material development; and squitch fabrication and testing. Each is described below.

- Performance Modeling and Design Optimization

According to the Simmons Model [15], the tunneling current through a molecular layer will increase exponentially with a decrease in tunneling distance. For example, for an initial off-state electrode gap of 4 nm, the tunneling current will increase by a factor of approximately 10^9 as the gap is closed to an on-state separation of 2 nm. This allows the squitch to exhibit the desired abrupt switching behavior. Assuming an electrode area of 1 μm^2 and a 70-nm-thick gold top electrode, the theoretical performance limits of the squitch in terms of minimum actuation voltage, switching energy and switching time are evaluated as functions of the Young's modulus of the SAM. The results of this analysis, summarized in Table 1, indicate that a Young's modulus below approximately 1 MPa allows a minimum actuation voltage in the milli-Volt range, a switching energy less than 10 keV and nanosecond switching time. This theoretical confirmation of the feasibility of the squitch concept to meet the E^{3}S objectives has led our team to propose and pursue three-terminal squitch designs such as those shown in Figure 34. In these designs, the SAM occupies the tunneling region between the drain and source. Electromechanical actuation is effected by a voltage between the gate and source electrodes. That gap is recessed to prevent gate-to-source tunneling for all source electrode displacements. Finally, for the lower design in Figure 34, if the two drains are not connected, then tunneling currents can flow from one drain to the source and back to the second drain. If the gate is similarly split into two sections, then electromechanical actuation of the tunneling gap can occur with a voltage applied between the two gates. In this way no connection needs to be made to the source. This greatly simplifies device fabrication, and results in a potentially more useful four-terminal squitch.

Young's Modulus [Pa]	Minimum Actuation Voltage [V]	Switching Energy [eV/μm^2] (Number of electrons/μm^2)	Switching Time [ns]
10^3	0.014	15 (1100 e⁻)	370
10^4	0.045	150 (3300 e⁻)	110
10^5	0.14	1500 (11,000 e⁻)	37
10^6	0.45	15,000 (33,000 e⁻)	11
10^7	1.40	1.5×10^5 (1.1×10^5 e⁻)	3.7
10^8	4.50	1.5×10^6 (3.3×10^5 e⁻)	1.1
10^9	14.0	1.5×10^7 (1.1×10^6 e⁻)	0.37

Table 1: Squitch Performance Limits

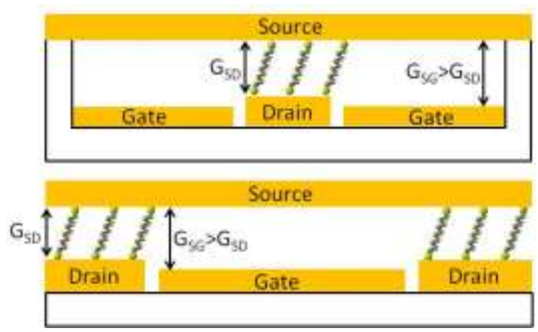


Figure 34: Three-Terminal Squitch Designs

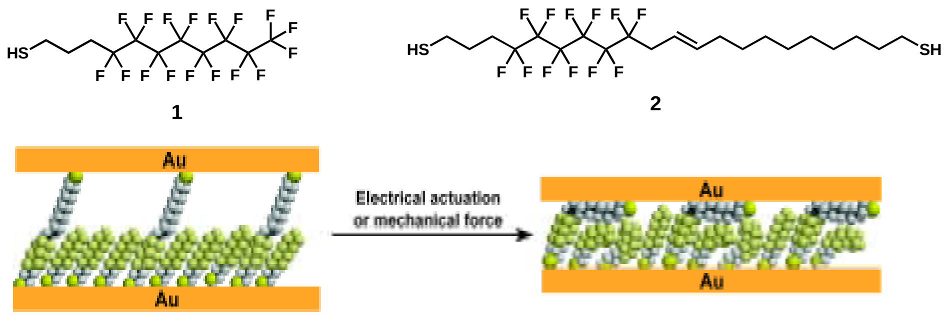


Figure 35: (A/*above*) Fluorinated thiol and semifluorinated dithiol for formation of a stable, compressible SAM with good recovery; and (B/*below*) a 2-terminal squitch device based on the fluorous/alkyl SAM.

- SAM Material Development

The SAM in the drain-source gap in Figures 33 and 34 is a critical component of the squitch. It is a compressible spacer that holds apart the gaps in the squitch. It prevents drain-source contact, and hence contact sticking, and it sets the spring constant of the squitch. It must also be electrically insulating. Initially we have focused on dithiol-alkyl- and PEG-based SAMs due to their commercial availability and their precedence for use in other metal-molecule-metal devices. However, rapid recovery coupled with facile compression, i.e., a low Young's modulus, is critical to an energy-efficient low-stiction squitch, and thus a custom-designed material is necessary. We are currently exploring two options for an advanced squitch material: a self-assembled monolayer based on fluorinated thiols and semifluorinated dithiols (Figure 35), and a dibenzocyclooctatetraene (Figure 36) which has significantly different electronic states based on its 3D conformation. The fluorinated-SAM option involves growing a monolayer comprising a mixture of thiols **1** and **2** in Figure 35A to create a SAM that is dense and fluorous at the bottom with a sparsely packed alkyl SAM at the top. The fluorous base will be rigid, stabilize the SAM, and promote self-assembly. The sparse alkyl portion will allow for compression as shown in Figure 35B. Alkyls and perfluoroalkyls have unfavorable intermolecular forces with each other, resulting in the extended off-state form being the thermodynamically favorable state and thus promote recovery. Dibenzocyclooctatetraene, dibenzoCOT **3**, in Figure 36A, is a small-molecule, which takes on a tub shape in its ground state to avoid an unfavorable antiaromatic system. However, dibenzoCOT can be forced to the flattened antiaromatic state in Figure 36B. This results in a change in dimension of approximately 50%, and a significant restoring force is generated due to the chemical instability of the antiaromatic system. DibenzoCOT also presents the opportunity of making a squishable material through charge injection, as the dianion of dibenzoCOT prefers the flattened state because the two extra electrons give rise to an aromatic compound (Figure 36B). Work towards fabrication of devices with the materials of Figures 35 and 36 is now underway.

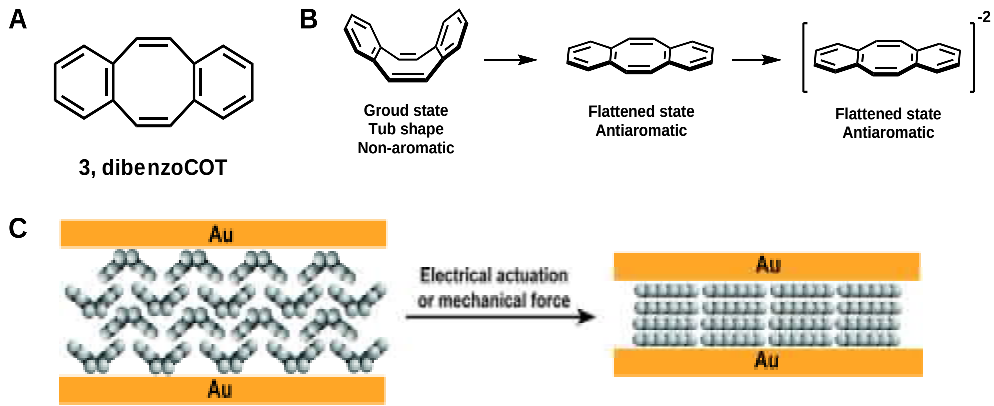


Figure 36: (A) dibenzocyclooctatetraene, and (B) its different conformational / electronic states; and (C) a two-terminal squitch based on the conformational changes of dibenzoCOT.

- Squitch Fabrication and Testing

Squitch fabrication, particularly fabrication of the upper electrode in Figures 33-36, is challenging. For this reason we are pursuing three squitch designs, each offering a different plan for fabricating a squitch like that shown in Figure 34. Since our focus now is on fabrication process development, a basic understanding of the electromechanical properties of the SAMs, and electrical tunneling through the SAMs, we have experimented primarily with two-terminal squitches to date. The first squitch has bottom electrodes on a substrate with SAMs grown on them. The upper electrode is then printed by transfer stamping. The second squitch is similar in style, but has an organic buffer layer above the SAMs to present a dense surface that captures evaporated metal without the metal passing through. The third comprises graphene-oxide sheets that have SAMs attached first. These functionalized sheets then self-assemble on to bottom electrodes; the sheets can serve as the upper electrodes or act as protection to the underlying SAM during metal evaporation.

The basic fabrication process flow for the first squitch, and a simpler two-terminal tunneling device, is shown in Figure 37. Briefly, the flow proceeds as follows. First, two gold electrodes, the primary external electrodes, are deposited on a clean glass substrate. Next, the SAM is grown on the electrodes. To guarantee the location of growth, the SAM molecules are terminated with thiol end groups which adhere preferentially to the gold electrodes. Third, a transfer pad is prepared for printing the upper suspended electrode. Finally, the upper electrode is transferred to the SAM layer resulting in a completed device as shown in Figure 37. Importantly, transfer stamping is a low-temperature process that does not affect the SAM. Note that this device differs slightly from that shown in Figure 33 in that this device has two tunneling gaps in series. The two-gap device is fabricated here for initial simplicity.

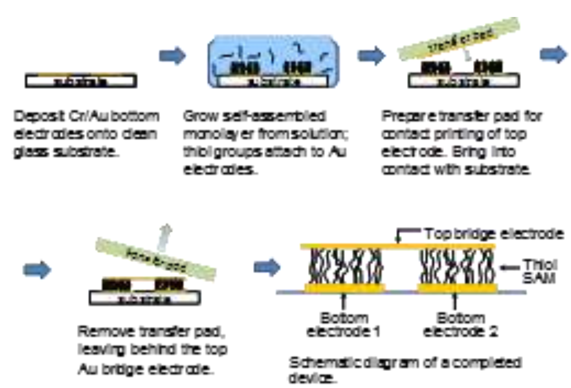
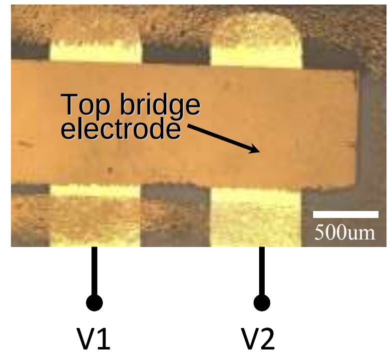


Figure 37: Squitch fabrication process.

A two-terminal tunneling device, fabricated as shown in Figure 37 is shown in top-view in Figure 38. The two bottom electrodes, labeled V1 and V2, as well as the suspended upper electrode, are all visible. Electrical contact is made via the more robust bottom electrodes rather than to the suspended upper electrode. The measured electrical conduction characteristics of two different two-terminal devices are shown in Figure 39. For the first data set, the SAM layer was formed from hexaethylene glycol dithiol (inset). The second data set shows similar behavior for a device with active layer composed of mercaptopropyl - trimethoxysilane (inset). This conduction data is characteristic of two-terminal tunneling devices up until punch-through at about 1.7 V and 2.8 V, respectively. The data demonstrates that the device can work as hoped, although the yield is low at present.

Figure 38: A fabricated two-terminal tunneling device



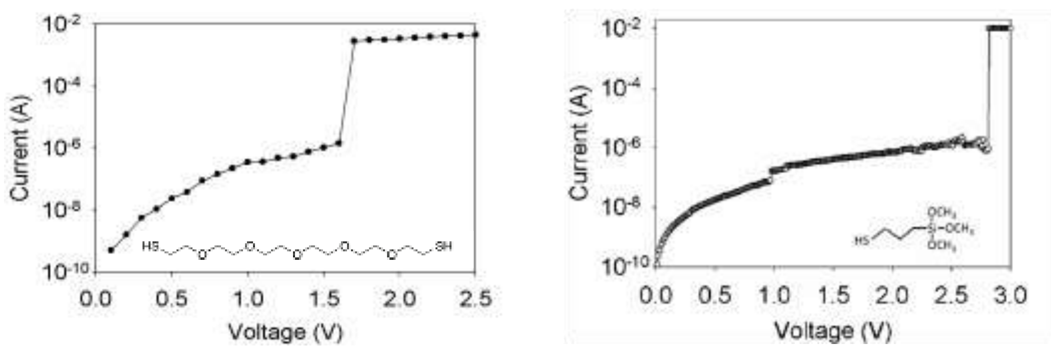


Figure 39: Measured current-*vs*.-voltage characteristics of the two-terminal tunneling device.

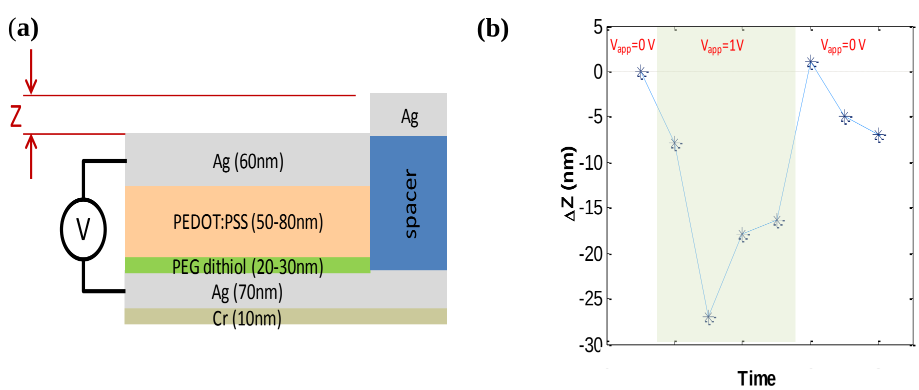


Figure 40: (a) a PEG-dithiol two-terminal squitch; and (b) optical interferometry measurements displaying apparent compression of the PEG-dithiol layer.

A schematic cross-section of the second squitch is shown in Figure 40a. The SAM is polyethylene glycol dithiol (PEG-dithiol) self-assembled on a silver electrode. Above the SAM is a layer of PEDOT:PSS to accept evaporation of the upper silver electrode; PEDOT:PSS is itself conducting. The squitch is fabricated adjacent to a SiO_2 spacer that provides a fixed reference relative to which motion of the silver electrode above the PEG-dithiol SAM can be measured. An optical interferometer is used to measure electrode motion and verify the electromechanical functionality of the squitch. Preliminary interferometry results (Figure 40b) suggest a compression of approximately 20 nm upon application of 1 V across the squitch. Further experimentation is underway to confirm the mechanical motion for various SAMs while correlating the measured motion to the applied electric pressure and the expected Young's modulus of the SAMs. The preliminary electrical characteristics of the squitch shown in Figure 40 are themselves shown in Figure 41. These characteristics resemble tunneling as expected. Further experimentation is underway to confirm the results and correlate them to the motion observed in Figure 40.

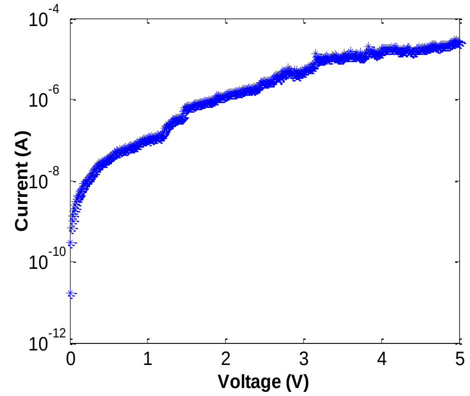


Figure 41: Measured current-vs.-voltage characteristics of the PEG-dithiol Squitch.

Two major challenges to the fabrication of a squitch have been the formation of sparse SAMs and the installation of the upper electrode on the organic SAMs. To simultaneously address both challenges, we have devised a new fabrication strategy based on chemically modified graphene-oxide (GO). Following this strategy, GO is covalently functionalized with alkyl thiol groups to yield thiolGO as shown in Figure 42A. The density of alkyl thiol groups can be varied by changing the conditions of the chemical reaction. This allows us to directly control the Young's modulus of the material. The thiolGO can be chemically reduced to yield a graphene upper electrode. Alternatively, GO can act as a shield to prevent shorting during evaporation of an upper electrode. The lower electrodes will be fabricated by e-beam lithography and the thiol-modified GO will be dropcast or dipcoated onto the bottom electrodes such that one sheet of GO, approximately 1 μm square, spans two bottom gold electrodes as shown in Figure 42B. We have prepared thiolGO **1** and **2**, and initial results show that **1** sticks to gold surfaces. Preliminary fabrication results show that further dispersion strategies are necessary to decrease clumping of the thiolGO sheets on the surface.

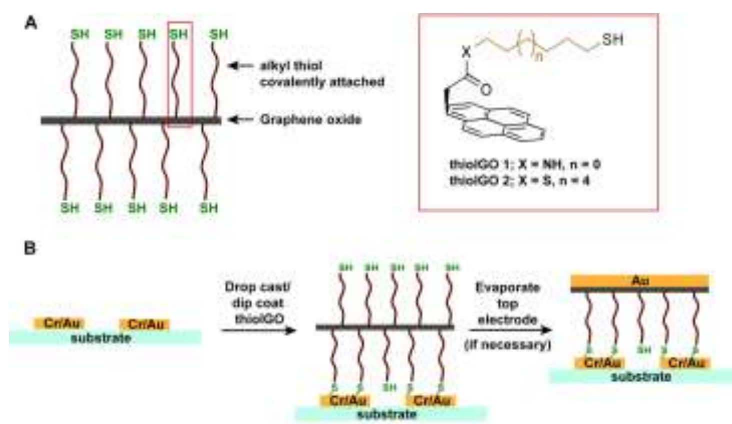


Figure 42: (A) Graphene-oxide (GO) covalently modified with alkyl thiol groups (thiolGO); (B) the anticipated self-assembling fabrication process for squitches using thiolGO.

Our primary objective for the end of Period 3 is to demonstrate a functioning three-terminal or four-terminal squitch, and to show that the functionality of the squitch is electromechanically and electrically consistent. Here, consistency means that the electrostatically induced pressure, the Young's modulus of the SAM, and the compression of the SAM, are self-consistent, and that the electrical drain-source current characteristics are consistent with the simultaneous compression of the SAM. We expect that such results will be most easily demonstrated with the first two squitch designs discussed above.

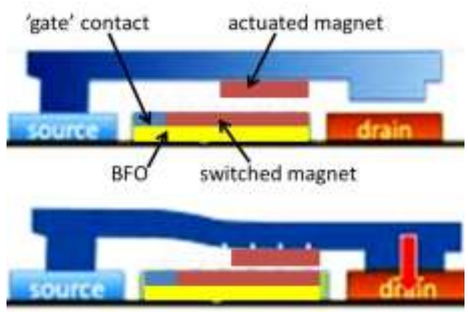


Figure 43: Schematic diagram illustrating the use of BFO switching of a ferromagnet in order to actuate the cantilever of a nanomechanical relay.

- *Nanomechanical Relays with Magnetoelectric Switching Elements*

This collaboration between Theme II and Theme IV, led by **J. Bokor** of *UC Berkeley*, is investigating the application of magnets to induce repulsive force to counter stiction in electro-mechanical relays. Previously, the Center's Theme IV researchers have demonstrated multiferroic coupling effect in bismuth iron oxide (BFO) to flip a nanoscale ferromagnet by 180° using voltage-only actuation [16]. The basic concept for the proposed magnetoelectric relay is shown in Figure 43. The plans are to place the magnetoelectrically switched magnet on a substrate, and then suspend a second ferromagnetic island on the underside of a cantilever above the switched magnet. By flipping the magnetization direction of the switched magnet, we produce a force between the two magnets that is either attractive or repulsive.

We can apply a simple array of parallel strips. Heron *et al.* [16] reported that using a thickness of 2.5nm CoFe actuated by BFO, a top magnet, 20nm thick, 20 nm gap, a force of 1.5 nN in a 1μm × 1μm area can be attained; a force that compares favorably with electrostatic actuation. A plot showing how the force scales with gap, d, is shown in Figure 44a. As the gap closes to 1nm, the force approaches 6 nN. A similar calculation for out-of-plane magnetization, Figure 44b, shows that the force is approximately doubled.

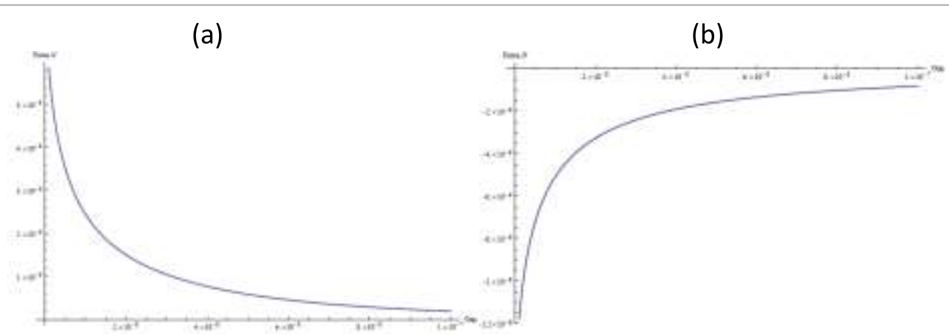


Figure 44: Calculated magnetic force for (a) in-plane magnets and (b) out-of-plane magnets, in a 1μm × 1μm area, as a function of magnet gap. The force curves are symmetric for attraction and repulsion, for both the in-plane and out-of-plane cases. Top magnet thickness = 20nm; bottom magnet thickness = 2.5 nm; B=2T (saturation magnetization for CoFe).

In addition to the simulation studies, we have defined a process flow for device fabrication and test structures. Device fabrication has begun and the expectation is that the first simple test structure for magnetically actuated cantilever will be completed by the end of Period 3.

- *Electromechanical Switch with Sub-Nanometer Displacement utilizing Metal-Insulator Transition in VO_2*

This exploratory project, led by **J. Wu** of *UC Berkeley*, is investigating the possibility of driving the metal-insulator transition (MIT) in VO_2 through mechanical strain induced by electrostatic force. Preliminary data [17] have shown that, by using ionic liquids as the gating medium, surface MIT can be triggered in single-crystal VO_2, which stabilizes a ultra-thin (~1nm), ultra-dense (~10^{15}cm^{-2}) electron system on the surface resulting in a reduction in resistivity by two orders of magnitude. As a seed project at the start of Period 3, it meant that this project had yet a well- defined device application, but during Period 3, the project evolved to be an investigation of its potential as a switching scheme for mechanical relays.

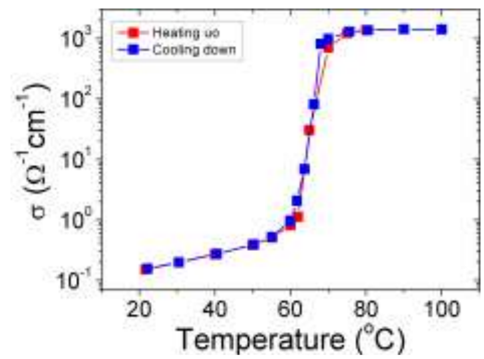


Figure 45: Measured conductivity of a VO_2 film. A transition to metallic phase occurs as the temperature goes above the phase transition point.

The project's progress is as follows.

- Growth of High-Quality VO_2 Films

  Employing pulsed laser deposition (PLD), we have successfully deposited VO_2 thin films on a wide range of substrates: sapphire, quartz, silica, and doped Si. These films show a textured crystal orientation even on amorphous silica surface, a high conductivity ON/OFF ratio across the phase transition (Figure 45), and a narrow hysteresis. Hall Effect, Raman and infrared reflection experiments are being carried out. We will continue to systematically characterize PLD-grown epitaxial VO_2 films (electrical, optical, thermal), in preparation for device fabrication in the next period.

- Electrostatic Gating of VO_2

  We have shown that by using an ionic liquid as the gating electrolyte, a VO_2 channel layer can be switched to a highly conductive state, akin to the thermally activated phase transition in Figure 46. The source-drain resistance of VO_2 is reduced by ~ 80 times at a gate voltage of 3V using liquid electrolyte. The ON/OFF ratio is nearly two orders of magnitude, much higher than any previously reported gating experiments on VO_2 (60% at the maximum*)* [18] [19]. We speculate that this is an electrostatically induced surface insulator-to-metal transition (within a depth of < 5nm), and are actively pursuing direct proof of this premise. We are continuing to elucidate surface effects of electrolyte-gated VO_2 with Auger and Raman techniques: surface phase transition, doping, corrosion, *etc*. The significance of these results is that if the surface phase transition is confirmed, this would be a direct proof of

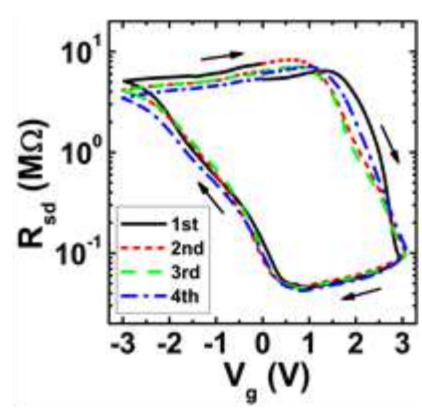


Figure 46: Measured source-drain resistance of VO_2 as a function of voltage.

concept for a gated Mott switch, opening opportunities for novel, energy-efficient electronic devices.

- Stress-Induced Phase Transition in VO_2

We have shown that at room temperature, compression force of ~ GPa (strain ~ 1%) along the rutile c-axis of VO_2 can drive the system into the metallic state [20]. Figure 47 presents promising preliminary experimental data obtained by conductive AFM, showing a resistance change of >100x for a VO_2 film upon application of pressure by the AFM tip, indicating a stress-driven Mott Insulator Transition at 30°C. At an elevated temperature such that the VO_2 is already in the metallic state, there is no such effect.

These preliminary results show promise for a new type of mechanical switch that does not require the making and breaking of a mechanical contact.

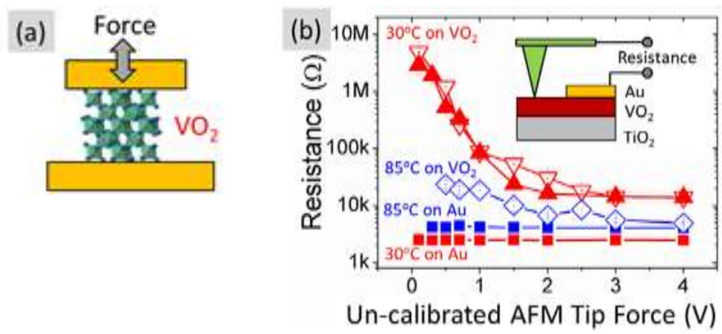


Figure 47: (a) Schematic illustration of a mechanically modulated conductivity change in VO_2; (b) initial measured data.

State of the art optical communication used in fiber interconnect at board and box-level a sensitivity of ~10^5 photons/bit and consumes energy of ~1 pJ/bit, involving discrete laser sources and Si photonics. Today's optical communication consumes more energy consumption than electrical interconnects for chip scale applications.

The goal of the Theme III team is to reduce *both* energy efficiency and sensitivity by orders of magnitude in the emitters and detectors, and miniaturize the components to sizes comparable to state-of-the-art transistors. By virtual of the radical reduction of the dimensions of the components, Theme III researchers can apply photonic phenomena that are applicable only in nanoscale dimensions to overcome the fundamental trade-off between energy efficiency and sensitivity. To achieve the ultimate goal of approaching quantum-limited sensitivity (20 photons/bit) with an energy efficiency of 20 aJ/bit (see Figure 48), we seek the following:

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

The research team in Theme III pursued the following strategies as in Period 3.

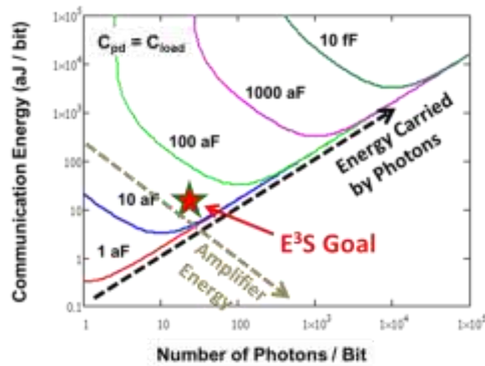


Figure 48: Energy efficiency (in J/bit) versus sensitivity (in photons/bit) for short-distance photonic links with various photodiode/load capacitance.

- Emitters / Sources:
  - To enhance bandwidth and efficiency, we began to couple optical antennas to nano-LEDs to achieve 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 [6].
  - In Period 3, we began to focus on one emitter project, Spontaneous hyper emission (SHE) nano-LEDs. That is, we pursued one less device project than was stated in the Period 3 Theme III plans as given in last annual report; page 64 of the Period 2 Annual Report. After successfully demonstrated the nano-patch laser, which is among the smallest semiconductor lasers ever realized in the infrared regime, we have decided to focus on nano-LED as an even-lower energy optical source for interconnect. While lasers have been the workhorse in optical communications, since the early days of implementation in telephony. However, lasers inherently require biasing above threshold before lasing occurs, while light emitting diodes (LEDs) emit light without a dc bias, as illustrated in Figure 49a. Moreover, laser bandwidth increases with bias; i.e., higher bandwidth requires higher bias, while the photons from LED are independent of bias as illustrated in Figure 49b. Conventional LEDs have not been the emitter of choice due to the lack of bandwidth. LEDs is a more energy efficient emitter, but its output must be enhanced to equal that of lasers; i.e., a 200x increase in bandwidth. The progress made in this current reporting period in enhancing the LED bandwidth has been very encouraging; see below in the section entitled Spontaneous hyper emission (SHE) nano-LEDs. This progress convinced the Theme III team to put its entire emitter focus on nano-LEDs for now, given the potential of nano-LEDs to be the ultimate energy-efficient emitter.

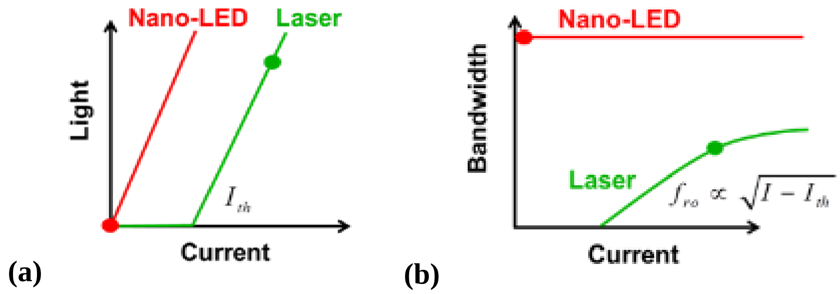


Figure 49: (a) Schematic of Output versus current for laser and nano-LED; (b) Schematic of bandwidth versus current for laser and nano-LED.

- Detectors / Receivers:
  - 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 ultra-small 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.
  - 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.

Below is the progress of Theme III in Period 3.

- *Analytical Studies of Short Distance Optical Communications*

  Building on the research that was initiated in the previous period, the Period 3 goals of this project that is led by **E. Alon,** in collaboration with **M.C. Wu,** both of *UC Berkeley*, are to:

  - Complete a comprehensive framework for the design of low-energy photonic links including noise constraints as well as energy/bit versus throughput tradeoffs.
  - Establish a generalized framework as general by abstracting the device-level details into a small set of critical parameters.
  - Develop complete transmitter and receiver circuits tailored to exploit the advantages of the new photonic devices being proposed and developed within the center.

  Figure 50 is the schematic of the basic photonic link model on which the analytical studies have been based.

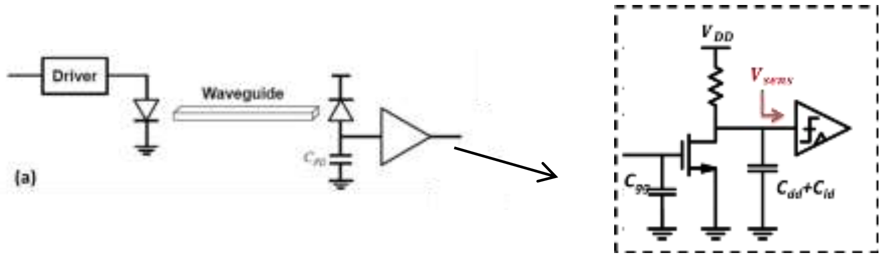


Figure 50: a) Schematic of a photonic link; and b) Schematic of the receiver circuit.

The initial study of the minimum energy dissipation of photonic links did not include the effects of thermal and/or shot noise in the receiver circuitry, and instead set a specification on the required voltage swing at the output of the receiver.

The following relationship

$$E_{bit,opt} = 2\sqrt{2\pi V_{sense} V_{TX} C_{load}}\left(\sqrt{V_{DD} V_{eff} C_{pd}} + \sqrt{P_{bias}/\omega_T}\right)$$

helped to identify two key tradeoffs:

– Number of photons versus receiver sensitivity, as given in Figure 51a; and

– Amortizing transmitter overhead versus receiver bandwidth, as given in Figure 51b.

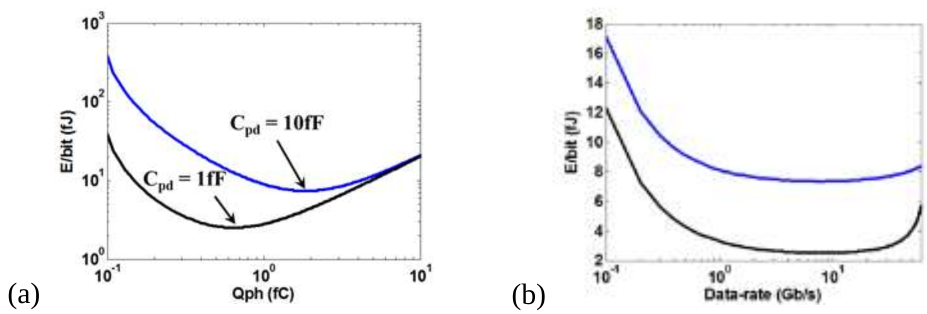


Figure 51: (a) *Photonic link optimal energy per bit as a function of photodetector parasitic capacitance; (c) Photonic link optimal energy per bit as a function of data rate.*

Further investigation in Period 3 showed that with currently known receiver topologies and devices, the capacitance at the receiver's input would be dominated by the number capacitance of the (minimum sized) transistors connected to this node.

Conventional receiver designs often require multiple gain stages with additional circuitry for offset cancellation and clocking. A minimum-sized CMOS transistor has ~200-300aF and ~100-200mV of ΔV_{th}. To achieve an ultra-sensitivity receiver, can an optical receiver be simplified and can we really get to ~1fF or even less receiver input capacitance?

We assessed what it would take to achieve a receiver circuit, where the total capacitance is small enough to achieve a ~100-200mV voltage swing at the photo-diode, and the digital output occurs after a single stage amplifier or comparator. Assuming a sensitivity of 100 photons/bit with a 100% quantum efficiency, the total capacitance will have to be <160 aF. A medium-sized transistor is a single stage receiver circuit would likely use up the entire capacitance budget. Given the difficulty in accommodating a capacitance budget of <160aF, we proposed several schemes to attain and perhaps even reduce the input capacitance of such a photonic receiver. In particular, we explored an approach by which an additional circuit (Figure 52) was placed at the input of the receiver in order to actively generate the equivalent of a negative capacitance. However, a detailed analysis of this approach showed that although one could indeed reduce the effective input capacitance – and hence allow the transmitter to send fewer photons per bit – the energy spent by the active circuit generating this negative capacitance outweighed this benefit.

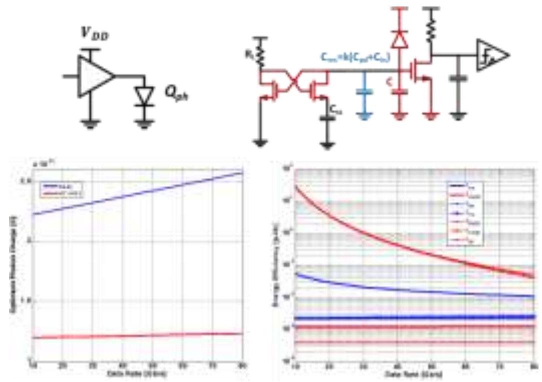


Figure 52: (Top) Photonic link utilizing the proposed negative capacitance circuit to reduce the effective input capacitance of the receiver. (Bottom) Optimum transmitted photon charge and energy breakdown of the complete transceiver for a photonic link with and without the negative capacitance circuit.

- *Spontaneous Hyper Emission (SHE) Nano-LEDs*

This project, led by **M.C. Wu**, in collaboration with **E. Yablonovitch**, both of *UC Berkeley*, involves the design and fabrication of a nanoscale LED coupled to an optical antenna designed for high modulation bandwidths. Antenna enhanced spontaneous emission has been demonstrated with dye molecules [21], however dye molecules cannot be modulated at high speed. The goal of this project is to create a semiconductor nanoLED capable of modulation bandwidths greatly exceeding tens of gigahertz with room temperature electrical injection that can be integrated with silicon transistor technology. This will allow for use as energy-efficient on-chip optical interconnects.

During this reporting period, the primary goal of this project has been to more accurately measure the spontaneous emission enhancement from our fabricated structures of nano-LEDs that are coupled with optical antennas. In the previous reporting period, the structures contained excess gain material that was poorly coupled to our optical antennas; this poor coupling gave lower than expected enhancement numbers. During this period, great effort was put towards removing excess material to more deeply understand the antenna-semiconductor interaction and get a more clear indication of the enhancement that was being achieved. In addition, care was taken to eliminate all physical mechanisms that could give false enhancement numbers during measurement, most notably light trapping. Light trapping is often overlooked in literature, leading many researchers to mistake enhanced light extraction for enhanced spontaneous emission rate. Being able to separate these two mechanisms is necessary to truly understand and study rate enhancement effects.

During the past year, we have successfully demonstrated the first optical antenna-coupled nano LED with unambiguous proof of spontaneous emission rate enhancement [7]. Our devices consist of an InGaAsP nano-ridge (35nm width, 35nm height, 150nm length) that is covered by an arch dipole antenna (Figure 53). The substrate is completely removed to eliminate light trapping effects which allows for direct comparison of bare and antenna clad ridges to determine spontaneous emission rate enhancement. Secondly, by removing almost all active semiconductor material except in the very near vicinity of the antenna, uncoupled emission was effectively eliminated.

By comparing a bare ridge to an antenna coupled ridge (Figure 54), an increase of 35x in photoluminescence polarized parallel to the antenna is seen when the emitter is coupled to a 400nm long antenna (Figure 54c), which is directly attributed to the increase of spontaneous emission rate. The spectrum of emitted light also largely depends on the antenna length, with shorter antennas enhancing shorter wavelengths. In all cases, the photoluminescence emitted from the ridges polarized perpendicular to the antenna stays mostly constant (Figure 54b). This is expected since this polarization is orthogonal to the antenna mode, further confirming the antenna induced rate enhancement. Such large rate enhancements make these devices excellent candidates for high-speed nano-emitters in ultra-low power applications.

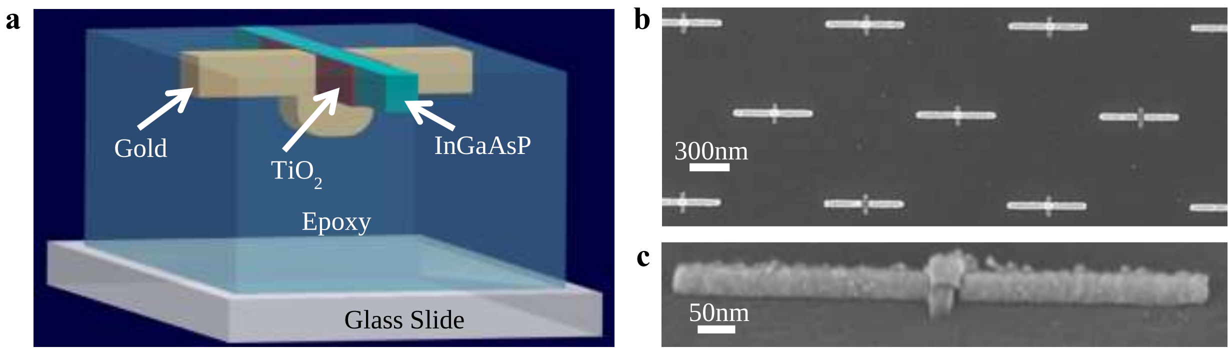


Figure 53: a - Perspective view of nanoLED structure after being bonded to glass with epoxy; b - SEM of antenna arrays before flip-chip bonding; c - Perspective SEM of single optical antenna. Antennas are 500nm long and 50nm wide; InGaAsP ridges are 35nm wide and 150nm long.

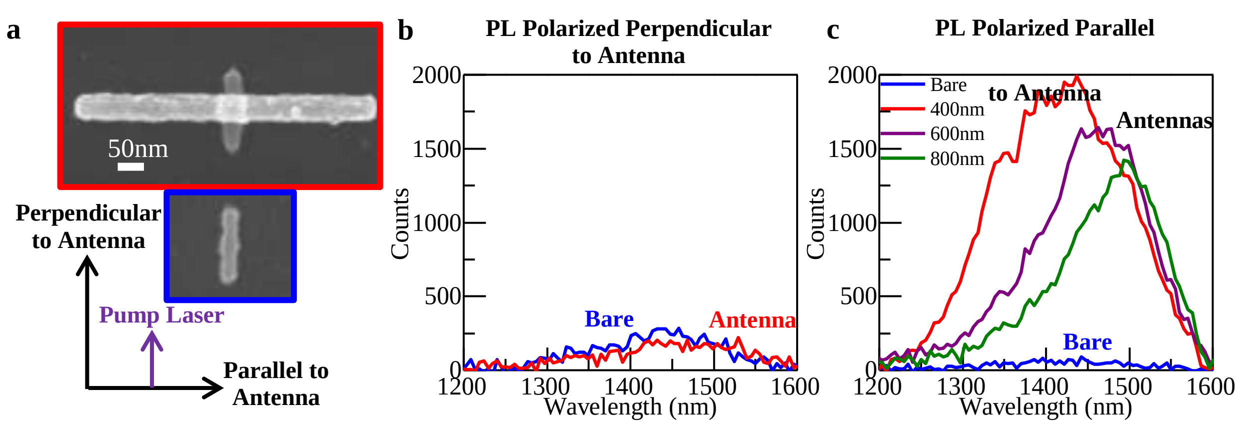


Figure 54: a - SEM micrographs of a bare InGaAsP ridge (blue) and an antenna coupled ridge (red); b - Photoluminescence (PL) of the ridges for light emitted polarized perpendicular to the antenna; and c - PL of the bare ridge and three different length antennas for light emitted polarized parallel to the antennas.

Theoretical work has also been performed to model the amount of rate enhancement that should be expected. Previous enhancement predictions were based off of complicated and time consuming computer simulations which did not allow for intuitive insight into how the antennas should be designed. We have shown that the increase in emission rate with an antenna is equal to $\frac{1}{4}(L/d)^2$, where L is the length of the antenna and d is the gap spacing [22]. This result agrees very well with experimental results and provides a very simple and intuitive way to predict antenna enhancement.

Nevertheless, during this period, we have determined optically injecting carriers significantly limits the output power and uniformity of our devices. When antenna coupled ridges are optically pumped, the antenna effectively shields near-by semiconductor from being pumped resulting in carriers only being generated far from the high enhancement regions of the optical antenna, requiring carriers to diffuse a great distance in order to radiatively recombine. Due to high surface recombination, the diffusion length of carriers is short and therefore the carrier transport is inefficient. This severely limits the power output of the devices and causes enhancement rates to be under-estimated. Electrical injection will solve this problem, allowing for higher output powers at greater efficiencies as well as more uniform carrier excitation levels in bare and antenna coupled structures.

- *Nanophotodetector with Ultra-Low Capacitance*

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 [23] [24] [25]. During this report period, the group of **M.C. Wu** of *UC Berkeley* has successfully shown through simulation that a Ge absorber when coupled with a silver antenna can have absorbing efficiency as high as 75%.

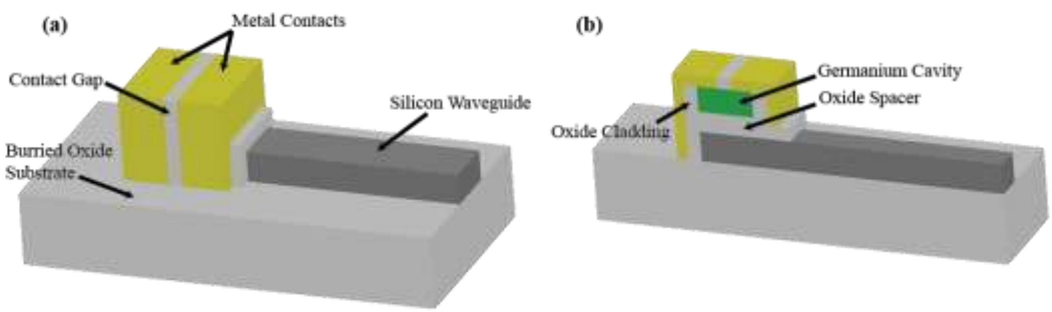


Figure 55: (a) Design of the germanium on oxide photodiode, showing the metal contacts creating the cavity coupled to a silicon waveguide. (b) Side cut shows the interior germanium on oxide.

Building on that understanding, the main goal of the current reporting period is to design and fabricate a low capacitance photodiode which can be integrated with a waveguide.

Indeed, a design for a germanium based photodiode which is directly integrated with silicon photonics components, such as silicon waveguides, has been achieved. This design took into account the restriction of using only CMOS compatible materials (e.g., no gold). We developed two primary optical cavity designs which strongly enhance the absorption of light from a waveguide into a subwavelength germanium cavity for high responsivity from an extremely small photodiode. The first design assumes the germanium is present on oxide, and creates a cavity where aluminum metal serves as both a reflector for the cavity, and as contacts for a metal semiconductor metal (MSM) photodiode with 180 aF capacitance [26]. The simulations showed absorption efficiency upwards of 38% from light incident in the waveguide. The designed structure is shown in Figure 55.

The second design assumed germanium epitaxially grown on silicon, but otherwise utilized the same optical mode and similar dimensions. That design (Figure 56) assumes the aluminum surrounding the cavity electrically contacts the germanium from the top and the photocurrent flows downward and is collected from the waveguide itself. The simulations show upwards of 51% absorption efficiency with less than 90aF of capacitance.

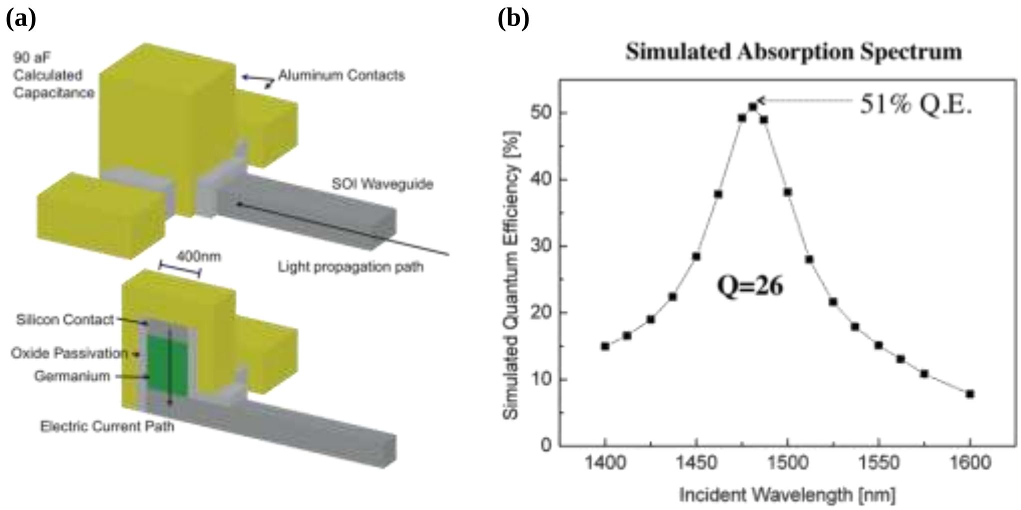


Figure 56: (a) Design of the germanium on silicon photodiode, showing metal cavity, electrical contacts, current path, and scale bar. (b) Simulated absorption efficiency spectrum showing high quantum efficiency and broadband enhancement.

Both designs utilize the same single mode resonance, which can be seen in Figure 57. The primary distinction between the designs has more to do with fabrication, and how the germanium is integrated with the silicon substrate. The first design, which utilizes germanium on oxide (GOI), the germanium can be obtained using the rapid melt growth (RMG) technique [27], which is used by IBM for their silicon photonics integration [28], and is something we are currently adding to our capabilities. The second design requires the much more difficult epitaxial growth of germanium on silicon, but allows more flexibility for electrical device designs. Since the vertical doping profile can be altered in-situ while growing, and there are heterojunctions between germanium and silicon, the possibility exists for a phototransistor integrated directly with the optical cavity needed for enhanced absorption.

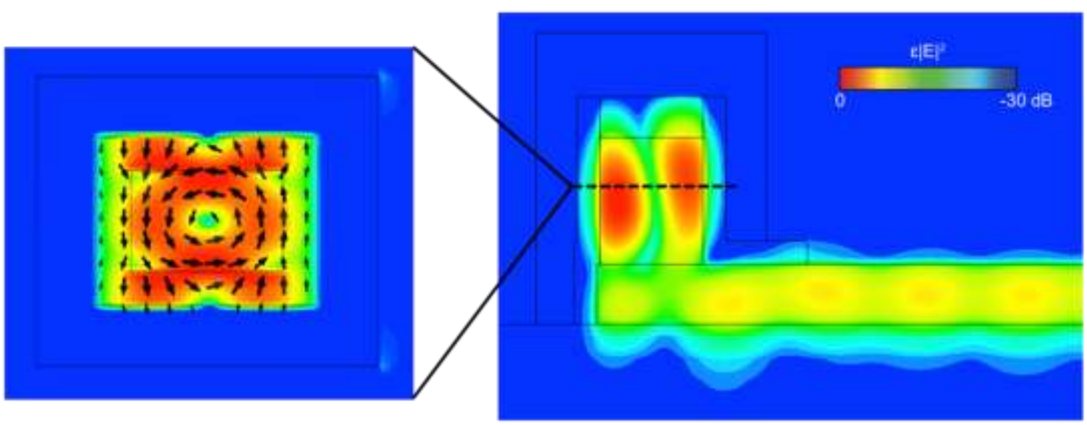


Figure 57: Electric energy density plot, showing strong field enhancement in the germanium and little field in the metal. The inset shows the electric field orientation of the 'doughnut' mode.

The majority of the year has been spent on theory and simulation to understand the necessary requirements for an ultra-low energy photodetector and on developing a good design for a device satisfying those requirements. Having developed a promising and realistic design, we are now transitioning to fabrication of the device to characterize it.

In creating the photodiode cavity, the largest hurdle was in creating two independent contacts for the photodiode while maintaining the performance of the cavity in general. The solution was to create a split in the metal down the middle and sides of the structure, which produces good theoretical results, but will be difficult to fabricate. The total efficiency is still only 36%, and could likely be doubled to near 70%. Both of these issues can be resolved by further optimization of the structure, but at the moment experimentally verifying the 36% figure is a more important priority. In order to address the issue with having a split in the cavity, a second design was developed, which from simulations has an efficiency of over 51% and could likely be improved further with optimization. However the second design requires that germanium be grown epitaxially on silicon, which is significantly more complex than germanium-on-insulator, a capability available at Berkeley. To address this, we have begun discussions with **J. Hoyt** of *MIT* in Theme I to possibly grow germanium in collaboration with us, as well as assessing the capabilities of outside vendors.

We expect that preliminary photodiodes will be fabricated before the end of Period 3. These diodes are not expected to have good performance, but will serve as pilots to identify problems in the fabrication process.

- *Phototransistors and III-V/Si Integration*

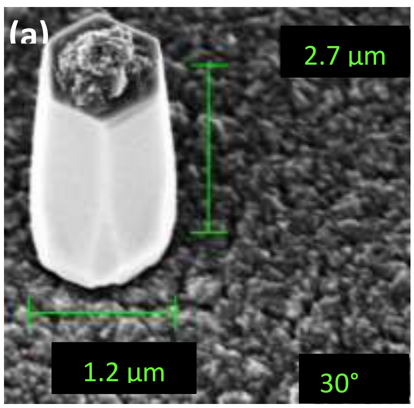
To achieve low energy operation and high speed operation, the capacitance of the detector needs to be very small to increase photo-voltage Q/C and reduce RC time delay. The capacitance can be made very small by making the detector nano-size. To further reduce the need for amplifying a weak signal, nanoscale III-V material with high optical absorption should be used to create highly sensitive, nano-sized photodetector. The major challenge then becomes integrating high quality III-V material onto silicon with CMOS compatible processes. To overcome such a challenge, the group of **C. Chang-Hasnain** of *Berkeley* has developed a novel catalyst-free, metastable growth of single-crystalline (In)GaAs nanopillars on silicon at CMOS compatible growth temperature [29] [30].

At the end of Period 2, the last reporting period, using the new growth technique, the group of **C. Chang-Hasnain** of *Berkeley* demonstrated a low power, highly efficient, ensemble GaAs nanopillar avalanche photodetector monolithically grown on silicon substrate with external QE > 11,000% at -5 V bias. However, such a sensitive photodetector still requires a power hungry pre-amp to convert the photocurrent into useful photovoltage to drive logic circuits. To eliminate the need of a separate pre-amp, we evolved the Period 3 goal building a highly sensitive III-V avalanche photodetector into building a highly sensitive III-V phototransistor. With the more integrated approach, the total capacitance of the detector and pre-amp circuit can be further reduced, thus, increasing the sensitivity and energy efficiency of detector circuit. Since III-V materials offer some of the best optical absorption, such a phototransistor can be made very small to further increase the sensitivity and energy efficiency by decreasing the capacitance.

In Period 3, collaborating with **E. Yablonovitch**, also of *Berkele*y, we began designing and concept testing different phototransistor design based on JFET, MOSFET and BJT transistor structures. To test the feasibility of the different transistor structures, we first fabricated various pn diodes using n-doped nanopillars on p-doped silicon substrates to test the junction quality between nanopillar and silicon substrate. During the design phase of the phototransistor, we tested the pn junction quality between the n-doped nanopillar and p-doped silicon substrate to evaluate whether we could use the nanopillar and silicon interface to create a high quality pn junction. However, we learned that the junction quality was not good enough to give us the performance that we need, and it is best to kept inside the nanopillar to maximize performance. As a result, we adopted a floating base bipolar junction phototransistor design with the emitter, base and collector regions all integrated into the nanopillar body.

After choosing a transistor design, we proceeded in designing the layer thickness and doping concentration with Sentaurus device simulator. Since the cylindrical shape of the nanopillar restricts depletion region growth, emphasis was placed in ensuring that base region would not be fully depleted under normal operation. A fully depleted base region is undesirable because it makes the collector current less controllable by the photovoltage applied to the base.

A.



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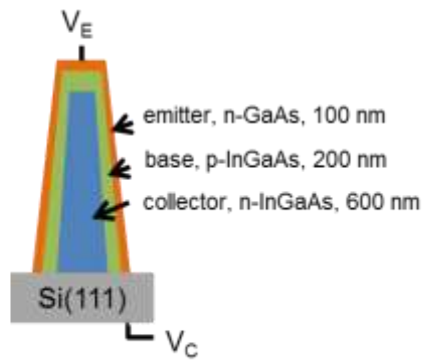

Figure 58: (A) As-grown GaAs/InGaAs based nanopillar phototransistor. (B) Cross-sectional schematic showing the three layers that makes up a nanopillar phototransistor.

With a phototransistor design, we proceeded in growing the nanopillars with integrated bipolar junction phototransistor layers inside (Figure 58). We are currently developing fabrication recipe to fabricate these nanopillars into HBT devices. This device is highly promising to fulfill the goals of this thrust, with ultrahigh sensitivity and speed.

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

Nanomagnetic/spintronic devices appear to offer an attractive option for building practical devices that can approach the Landauer limit [2], or perhaps even surpass it via reversible logic as predicted by Bennett [8]. The goal of Theme IV is to first establish experimentally the scientific basis for this Theme, while in parallel build test structures to learn the dynamics of magnetic logic devices. Eventually, we will build prototype devices that operate as close as possible to the fundamental limits of energy dissipation. This Theme is the most futuristic and forward looking of the Center's research themes.

Since the inception of the Center, Theme IV's research has been directed towards experimental verification of the fundamental limits of energy dissipation in magnetic logic, because, to our knowledge, neither one of the theoretical predictions of Landauer and Bennett has been experimentally verified. This project provides the fundamental basis that underlies the overall goals of Theme IV. In Period 3, we have focused on exploring switching dynamics and basic spin logic physics.

The following choices have the potential for achieving ultra-low energy devices.

- *Electric Field Control of Nanomagnets*

  The goal is to achieve magnetic structures that will allow us to study switching dynamics at room temperature. Such devices are projected to operate with sub-100 mV, and at ~20nm, can achieve sub-aJ switching energy. In Period 3, we are working with two material systems.

  – $BiFeO_3$ Multiferroic Heterostructures

  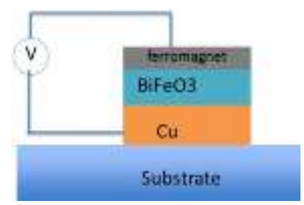

  Figure 59: Schematic of a $BiFe0_3$ Multiferroic Heterostructure.

  In Period 2, the group of **R. Ramesh** at *Berkeley* reported the application of 7 volts to enable full magnetization reversal in a BFO multiferroic structure (schematic given in Figure 59) at room temperature. Subsequently, we created a CoFe-BFO heterostructure using a combination of laser MBE (for the BFO) and UHV sputtering for the CoFe layer. Anisotropic magnetoresistance **(**AMR) measurements of the CoFe layer showed that the magnetization state in the CoFe layer switched by 180° when the ferroelectric state in the BFO is switched with an out-of-plane voltage of 7V.

  In Period 3, characterization of the devices continued. Through detailed imaging studies using scanning electron microscopy polarization analysis (SEMPA), we have ascertained that the ferromagnetic moment in the CoFe couples to the canted moment in the BFO layer. We also used phase field and OOMMF computation that was developed by **S. Salahuddin** to explore the fundamental origins of the interface coupling.

  However, the main Period 3 focus has been on the reduction of voltage required to accomplish switching to below 1V (possibly 0.5V). We believe that leakage is the underlying issue that has impeded progress. The research team, led by R. Ramesh, is continuing to work on improving and optimizing the device structure, by investigating the use of La doping of BFO, reducing thickness of the films and improving material quality.

  Our studies have shown that the ferroelectric switching voltage for BFO can be systematically tuned by La substitution in the Bi site, Figures 60a and 60b. For example, pulsed polarization measurements Figure 60b clearly show that a significant amount of the polarization can be switched at 3V in a 10%La –BFO in contrast to pure BFO. Our studies also showed that reducing the film thickness will correspondingly lower the switching voltage. We have shown the existence of robust ferroelectricity in films only a few nanometer thick. Figure 60c shows piezoforce microscopy data for a 5nm thick film. We also have inserted magnetic impurities into the Fe site in an attempt to enhance the canted moment in the BFO. Preliminary work, Figure 60d, shows that this may indeed be possible, with the bulk moment being enhanced by ~3-4X over the canted moment of pure BFO.

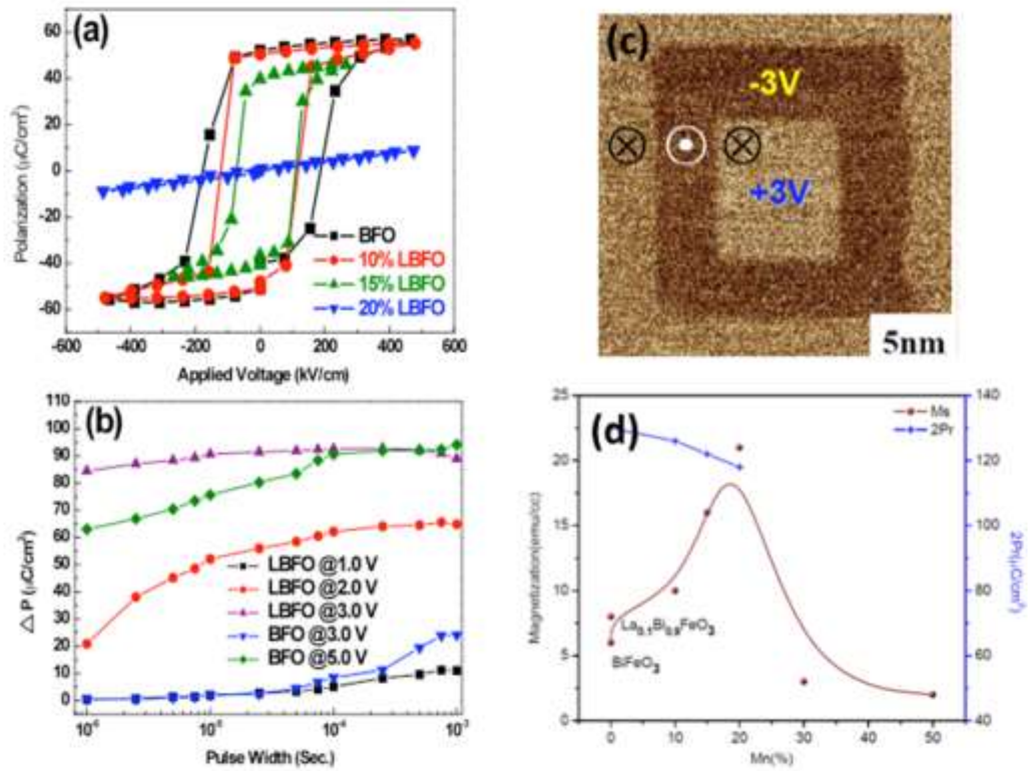

Figure 60: (a) Ferroelectric switching voltage for BFO with various amount of La substitution; (b) Polarization in BFO with various La substitution levels that can be switched at various voltage; (c) Piezoforce microscopy data for a 5nm thick film; (d) Magnetization with various La substitution levels in BFO.

– Composite Magnetoelectric Heterostructures

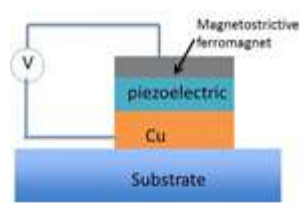

Figure 61: Schematic of a composite magnetoelectric heterostructure.

As indicated earlier in Section *1c*, this project was initiated during Period 3. **J. Bokor** of *Berkeley* is leading an effort to investigate a device structure that is made up of a magnetostrictive ferromagnet on a piezoelectric layer (Figure 61). The magnetostrictive ferromagnet of choice is Terfenol-D, an engineering alloy of rare earths that exhibits large magnetostriction coefficient at room temperature. We are including two piezoelectrics in our investigation: lead zirconium titanate (PZT) and lead magnesium niobate-lead titanate (PMN-PT).

Composite magnetoelectric film stacks involving PZT or PMN-PT piezoelectrics and Terfenol-D have been grown and their magnetic properties characterized. We find that for 30 nm thickness Terfenol-D films, the preferred magnetization direction develops an out-of-plane component, which is highly advantageous for magnetoelectric switching.

(a) **(b)**

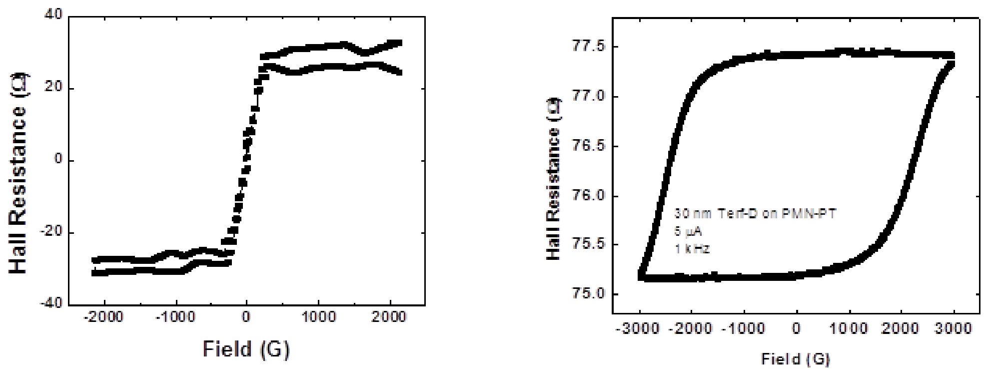

Figure 62: a) 10 nm of Terfenol-D on Si. Field direction is out of plane while measuring the anomalous Hall effect. The saturation implies that in this sample an easy axis is only oriented in-plane. The out-of-plane field of the measurement cants the moment till it is saturated in either direction; and b) 30 nm of Terfenol-D deposited on PMN-PT. Measurement is performed in the same manner as in a). In this figure the hysteresis loops indicates an easy axis out-of-plane.

- *Time Resolved Coherent Spin Detection using Magnetometry*

An rf SQUID magnetometer with arrays of nano-scaled high-Q resonators has been in development by **I. Siddiqi** of *Berkeley* for the purpose of studying spin dynamics and relaxation times. Enhancements were made to the magnetometer to increase bandwidth and flux sensitivity. Many of the nanomagnetic devices we wish to study must be operated in a static biasing magnetic field. Accordingly, a full 3-axis set of field coils has been incorporated into the apparatus. The tolerance of the SQUID sensors to this bias field has been characterized. The measurements establish that the rf SQUIDscan be operated in a parallel DC magnetic field up to 50 mT, sufficient for biasing nanomagnets of interest. As part of establishing the limits of the magnetometer, we have identified flux trapping in the ground plane as the limiting factor when operating in a parallel magnetic field. Also, pulse tube cooler vibrational noise may be another limiting factor on the performance of our nanobridge SQUID magnetometer at high magnetic fields. We have mitigated this problem at low fields by triggering our measurements in synchronization with the pulse tube. We expect to solve the problem at intermediate fields using active feedback on the magnetometer with our fast flux line. At high fields we may need to explore other options, including active cancellation of the pulse tube vibration using a piezoelectric actuator, a technology developed by the S2 Corporation.

We have also developed the crucial ability to control the placement of magnetic nanoparticles. In particular, we are able to selectively position nanomagnets in close proximity of our sensor by either using hydrophobic molecules to guide the particles, which are in a solution, or by placing individual nanoparticles that have an electric dipole using a biased magnetic force microscopy cantilever.

The Period 3 studies for nanoSQUID magnetometer were focused on the study of semiconductor spin ensembles of diamond NV and Bi impurities in isotopically purified ^{28}Si. These systems are of interest for room-temperature, non-ferromagnetic spin-ensemble-based classical logic devices. We have not yet successfully coupled the Bi impurities in 28Si to our superconducting resonator, although the Bismuth implants are active as verified with ESR. We believe this problem is due to extremely long relaxation times at low temperatures, so we will attempt to solve it using an LED below the bandgap of silicon to excite the spins and mitigate the effects of spin saturation. We will continue to focus on Bi impurities in ^{28}Si for the remaining of this reporting.

- *Experimental Verification of the Landauer Energy Limit*

The goal for this project, which is led by **J. Bokor** of *Berkeley*, is to provide an experimental verification of the scientific basis of Theme IV. Landauer's famous theory predicted a minimum of exactly kTln2 of energy being dissipated in erasure of a single nanomagnetic bit (Landauer's limit), [2] and Bennett has 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 [8]. Neither of these theoretical predictions has been directly experimentally demonstrated and they remain controversial.

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 adiabatic (non-precessional) Landauer erasure in a nanomagnet with uniaxial shape anisotropy, two magnetic field components are utilized, 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.

In the previous reporting period, we have numerically solved the Landau-Lifschitz-Gilbert equation to calculate the hysteresis loops and found that values are in essentially exact agreement (subject only to thermal broadening) with the Landauer limit, kT ln2. In Period 3, we set out to measure the hysteresis loops to test the results from our simulation. Our approach is to measure the hysteresis loops when the magnetic fields are applied in a specific sequence. The measurements were done with 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. We carefully measured the hysteresis loops for arrays of identical nanomagnets and we extracted 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 to achieve a sufficiently large signal. This is an entirely new and unique approach for testing Landauer's principle.

In this fashion, we have succeeded in measuring energy dissipation during nanomagnet erasure. We have measured the temperature dependence of heat dissipation during Landauer erasure of nanomagnets. According to Landauer's Principle, heat dissipation during bit erasure scales linearly with temperature as kTln2. Experimental results are shown in Figure 63a and 63b. External magnetic fields were used to erase the information stored in each nanomagnet. A method for quantitatively calibrating the magnetization was found, thus making the measurement absolute.

Currently, the signal/noise ratio in our apparatus is such that our result is consistent with the kTln2 value, but the error bar is about 8kT (Figure 63c).

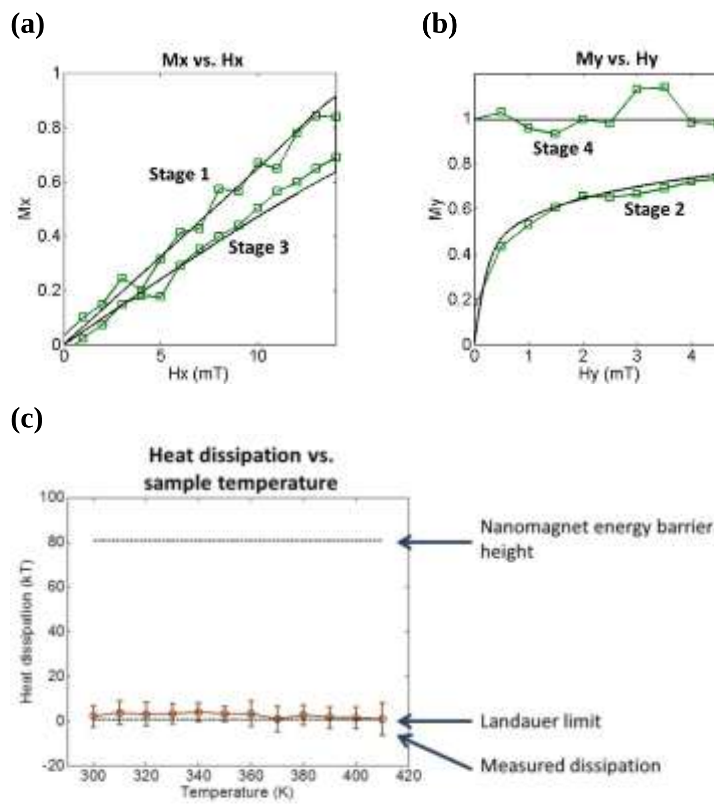

Figure 63: The measurements (in green) versus predictions of the stochastic LLG equation (in black) of (a) X-axis and (b) Y-axis hysteresis loops of a nanomagnet during the 'restore to one' operation at 300K; (c) Measurements of the dissipated heat over a range of temperatures.

In order to make a more precise measurement, we need to improve our signal to noise ratio. Careful noise analysis of our apparatus has identified several sources that can be reduced. These include using a lower noise photodetector and amplifier, and reducing mechanical vibration in the optical setup. We have also identified methods of optimizing our sample design to increase signal. This work will continue for the remaining of this reporting period. Preliminary results are encouraging.

2b. Performance Against Metrics

Objective	Metrics	Targets	Period 3 Results
Integrative Research	Multi-PI Projects	Period 2: 30% Period 5: 30%	67% (14)
	Multi-Institutional Projects	Period 2: 10% Period 5: 30%	10% (2)
	Unplanned research projects	Period 3: 1 Period 4: 3	4
	New joint research funding opportunities	Mid Period 3: 1 proposal	1
	Publications with authors from multiple institutions	Period 3: 12	1

2c. Research in Period 4

The Center's four Themes and the System Integration research effort will continue in Period 4. The projects in Themes I, II and III will continue. However, Theme IV will initiate two new projects.

2ci. System Integration Research

The principal goal of the project in Period 4 will continue to be to explore the implications of actual communication and computation circuits/systems on the design, optimization, and requirements of the emerging device technologies being explored in the rest of the center. We further aim to 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 the next period, we plan to continue our activities in these key areas:

- Develop new receiver circuit topologies enabling ultimately low-energy photonic links. In addition to exploring circuit topologies that require an absolute minimum number of devices connected directly to the photo-detector (in order to minimize parasitic capacitance), we will complete an analysis of the fundamental energy penalties (relative to SNR*kT) required for such an optimized receiver design. This study will also explore the potential opportunities offered by steeply switching electronic devices to improve the energy-efficiency of these communication links.
- 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.
- Explore the opportunities provided by magnetics-based devices as the front-ends for communication applications. Although their I_{on}/I_{off} may be low, their potential capability to switch at very low voltages makes such devices attractive for analog amplification.

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

In Period 4, the Theme I researchers at UC Berkeley and MIT will work collaboratively together to achieve the following goals.

- *InAs/GaSb Tunneling FETs*

  The groups of **C. Hu**, **A. Javey** and **E. Yablonovitch** at *Berkeley* and **D. Antoniadis** and **J. Hoyt** at *MIT* will work together in Period 4 to elucidate the science of and demonstrate InAs/GaSb TFETs.

One key experimental goal is the demonstration of tunnel transistors based on InAs /GaAlSb system that will have I_{on}~100µA/µm, I_{off}~0.1nA/µm at power supply voltage less than 300mV, an effort that will be led by **C. Hu**, in collaboration with **A. Javey**. This combination of performances will be achieved with low series resistance, low leakage, and large gate-voltage coupling ratio. Self-aligned gate and source/drain metal will minimize the series resistance as will optimized source/drain doping and a low contact-resistance metallization process. The p+ material under the n+ drain will be etched away to minimize the junction leakage. The threshold voltage will be near zero so that the gate leakage is minimized. In addition, material layer composition, thickness and doping concentration are all to be optimized for a large gate-voltage coupling ratio. The fabrication of such a tunnel transistor will be completed in the early months of Period 4. Based on the results obtained by characterizing and analyzing the new transistor, an improved tunnel transistor design will be developed.

The elucidation of the fundamental barriers to abrupt switching include phonon scattering, band-edge abruptness, and the physics of tunneling which limit the current versus gate voltage slope steepness to very low current values will continue. To address some of these barriers, **D. Antoniadis** and **J. Hoyt** are pursuing an approach which includes simulation of devices as well as experiments on test structures. We have chosen InGaAs/GaAsSb due to its direct bandgap, effective bandgap at the heterointerface which can be tuned (by varying the alloy composition) between ~ 0 and 300 eV, and relatively small lattice mismatch. We will use material from different sources, including the Naval Research Laboratory (Dr. Brian Bennett) and IQE, Inc.

The experimental team of **C. Hu** will also make materials and data for analysis by the groups of **E. Yablonovitch**, **D. Antoniadis** and **J. Hoyt**.

- *Bilayer Tunneling FETs*

The concept of an electron-hole bilayer tunneling transistor is a new concept initiated in the Center in Period 3. The groups of **E. Yablonovitch** and **A. Javey** of *UC Berkeley* and **D. Antoniadis** and **J. Hoyt** at *MIT* will work together in Period 4 to elucidate the science of bilayer tunneling transistors. We will have complementary approaches. The team at Berkeley will focus on electron hole bilayer transistor in InAs. The group of **E. Yablonovitch** will determine bandedge sharpness arising from the overlap of valence and conduction bands in a nano-device, InAs/GaSb quantum wells, InAs field induced bilayer, or a double quantum dot device. We will investigate whether this information can be learned more readily from the tunnel spectroscopic sharpness of individual levels in a double quantum dot device. The group of **A. Javey** will also contribute in answering some of the key scientific questions using a thin double-gated InAs layer.

The groups of **D. Antoniadis** and **J. Hoyt** will study a Si bilayer transistor. Even though earlier simulation studies have indicated that III-V's is the material system of choice, the researchers expect to encounter less complexity in studying the tunneling physics of a Si bilayer device. We will also interact with M. Luisier (ETH Zurich) on atomistic simulations of these structures.

- *Superlattice Nanowire FETs*

The group of **J. del Alamo** of *MIT* will investigate Superlattice Nanowire FETs with focus of enhancing the fundamental understanding of the switching mechanism and achieving the first experimental demonstration.

In the next year, we plan to carry out fundamental experimental studies of the density of states of nanowires with a superlattice structure (SLS-NW). The nanowires will be characterized using the BEEM technique. The data will be compared with the data from the P-S simulation environment that was created in Period 3. To our knowledge, this type of study has never been done before.

We will fabricate and electrically characterize two-terminal SL-NW structures. We will seek evidence of 1D transport and miniband/minigap structure of the superlattice.

A key goal is to demonstrate a working device late in 2013 or early in 2014. Thus, we will develop process technology to fabricate vertical SLS-NW FETs with 10-50 nm in diameter. Specifically, we will develop ohmic contact and a gate technology. Achieving a technology for gates with a high-k MOS gate stack that will wrap around the vertical nanowire just above the superlattice is critical. We will consult with **C. Hu** and **A. Javey** of *Berkeley* to leverage their experience in GaSb TFETs.

- *Negative Capacitance FETs*

Following the demonstration of negative capacitance in a variety of ferroelectric ceramics in Period 3, the groups of **S. Salahuddin** and **C. Hu** at *Berkeley* will establish methods for mitigation of the fundamental research/technology barriers. Fundamental barriers include (i) the need to optimize the gate stack, (ii) the integration of the ferroelectrics materials with Si and/or III-V semiconductors, and (iii) device fabrication.

We have worked extensively on (i) in the past years, and the research activities on (ii) and (iii) were initiated in Period 3. The challenge is the fact that conventional device processing techniques are not directly applicable to complex oxides. We are currently designing new techniques and we will be evaluating and optimizing them in the coming year.

In Period 4, our main goal is to fabricate a Negative Capacitance MOSFET and to perform materials optimization in that three-terminal platform. For that, we have already designed a process for self-aligned gate and silicide contacts. In this process, the negative capacitance gate stack will be first combined with Si or III-V. Next optical and e-beam lithography will be used to pattern the gate. In the next step a physical etching method will be used to define source and drain. At this moment, our plan is to use both Ar milling and reactive ion etching for this purpose. We anticipate that significant efforts will be needed to obtain this process as etching methods for complex oxides are underdeveloped and selectivity with Si is relatively unknown. Once source and drain are defined, we shall evaporate Pt electrode and perform a rapid thermal annealing so that Pt dopants can diffuse into Si, thereby giving a doped source and drain. These steps are critical for fabricating negative capacitance MOSFETs. We are targeting to obtain the first set of three-terminal device characteristics from the negative capacitance MOSFET in Period 4.

- *Chalcogenide Materials and Devices*

In Period 4, the focus on 2D materials and devices will solely be on van der Waals heterojunctions devices where the junctions are made by mixing and matching 2-D III-Vs and/or 2-D layered chalcogenides. This effort is led by **A. Javey** of *Berkeley*.

The first goal is to explore the fundamental physics and electron transport across the interface of 2-D to 2-D van der Waals junctions by mixing and matching 2-D III-Vs and/or 2-D layered chalcogenides. We will develop transfer processes that enable fabrication and characterization of devices from mixed 2-D to 2-D heterostructures. The first step would be to fabricate atomically sharp p-n junctions, such as InAs(n)-WSe_2(p). We expect that in the course of the research, one milestone is the demonstration of van der Waals rectifying diodes of mixed 2-D to 2-D heterostructures.

To further exploit the potential of the XOI platform (where X could be either III-Vs or layered chalcogenides) [4] for the development of novel devices, as well as for the control of electronic and optical properties of these devices, the second goal is to develop heterojunction TFETs based on WSe_2-$SnSe_2$ material system, which exhibits a Type III band offset. In Period 4, we will fabricate and characterize tunnel diodes and potentially TFETs based on WSe_2-$SnSe_2$. Experimental work will be carried out along with device simulations.

The team of **V. Rangari** and **K. Das** at *Tuskegee* will accelerate their efforts to identify new chalcogenide compounds that are potential candidates for van der Waals transistors. Bulk chalcogenides will be synthesized by microwave and characterized by a variety of microscopy, optical and X-ray techniques. Electrical characterization of thin films is also planned. The thin films will be prepared by printing with nanaparticulate emulsions of the chalcogenides as inks on oxidized Si wafers with a pre-deposited film of Au to provide a back contact. A number of metals with different workfunctions (Al though Pt) will be utilized to form the top contacts. This approach is likely to establish ohmic and rectifying contacts, also the conductivity type may be determined by noting the polarity for high current for a rectifying contacts.

- *MOCVD Growth of Novel Heterostructures*

  The scope of the MOCVD growth project that is led by **E. Fitzgerald** of *MIT* will expand in Period 4. We will continue to utilize our diode process for InAs/GaSb heterostructures to study and eventually to suppress interdiffusion. Inherent to the favorable band-alignment of the InAs/GaSb system is a tendency for interdiffusion, which results from the high electron affinity of the InAs. In addition, we will begin investigations of a derivative of the GaSb/InAs system in which the GaSb hole-gas layer is replaced with Ge. We are interested in the effect of the heterovalent Ge/III-V interface on tunnel characteristics.

  We plan to collaborate with **D. Antoniadis** and **J. Hoyt** at *MIT* to utilize a unique technique based on capacitance-voltage characteristics to measure the band alignment of our heterostructures and to identify any ability to control the band alignment using process parameters for both InAs/GaSb and InAs/Ge heterostructures.

  We will accelerate our collaboration with the group of **J. del Alamo** at *MIT* on superlattice source transistors. We plan to grow lattice-matched InGaAs/InAlAs superlattices and to optimize interface sharpness and material quality to allow for devices to be fabricated in the del Alamo group that exhibit a highly sharp bandstructure tailored by the superlattice structure and optimized for steep subthreshold.

  In Period 4, we will strive to be a material source internal to the Center, by providing material to other Theme I collaborators, particularly to strategically enhance the flexibility and throughput of research within the Center with regards to research involving Sb-based materials.

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

All five projects from Period 3 will continue into Period 4; we do not expect to add new switching device concepts to the Theme II research portfolio. Three of the five projects will increase their emphasis on demonstration of devices with milli-Volt operation, while the remaining two projects will make an assessment of their exploratory approaches, to determine whether to proceed with device demonstrations in the second half of the next reporting period. Through the device demonstration efforts we will continue to enhance understanding of the underlying materials science and address fabrication challenges. In the following description of future activities, we have slightly modified the names of some projects to reflect their switching approach and have re- ordered the project list for the sake of clarity.

- *Novel Structural Materials*

  With the expectation that a two-terminal graphene-beam switch will be successfully demonstrated with zero leakage current and sub-1V operation by the end of Period 3, the main goal in Period 4 for the **H.-S. P. Wong** group at *Stanford* is to demonstrate a three-terminal graphene-beam relay with zero leakage current and sub-1V operation. As part of this activity, we will establish an optimized graphene synthesis recipe and transfer process through comparative studies of relays fabricated using our in-house recipe and other collaborators' recipes including that of **J. Wu** (Berkeley), who is part of the Theme II team. In parallel, the fabrication process will be refined (to achieve gap size control with a few nm accuracy, small electrode width, electrode alignment, etc.) and a design optimization study (beam dimensions, gap size, structure type) will be performed. AFM studies will be also performed for characterizing the spring constant of graphene beams and bowing, in collaboration with Prof. Laurent Montes group in Grenoble MINATEC, France.

To broaden the choice of ultra-thin structural materials, we will investigate metal dichalcogenide (MX_2) materials at Stanford and other alternative beam materials in collaboration with MIT. MX_2 materials are two-dimensional layered materials similar to graphene which have good mechanical properties. One promising candidate, MoS_2 has Young's modulus as high as 270GPa (vs. 1 TPa for graphene) and yield strength reaching 6-11% (vs. 13% for graphene).

- *Tunneling Relay*

In Period 4, this *Berkeley* project of **T.-J. King Liu** is to demonstrate a device with sub-0.1V operation and on/off current ratio > 1000. We expect that an ultra-thin structural material is necessary to achieve short yet compliant beams for low actuation voltage. Therefore, highly compliant structural films (e.g., sub-100nm-thick amorphous metal) will be investigated. Tunneling relays with various structural beam (body) dimensions (width, length, location of anchor relative to actuating gate electrode, etc.) will be systematically characterized to identify the optimal design for minimizing the operating voltage. Refinements to the structural film and integrated process flow will be conducted. There will also be additional quantitative modeling for tunneling current in the sub-nm regime (accuracy, domain of validity, etc.). Device demonstration is planned to be two steps: 1) a prototype device with 0 hysteresis and a sub 60mV/dec swing; and 2) redesigned tunneling relays to demonstrate lower operating voltage and improved on-state resistance.

- *Squitch*

The long term goals for the "squitch" project, a collaboration of **V. Bulović**, **J. Lang** and **T. Swager** *(MIT)*, include an on/off conduction ratio exceeding 10^6, a switching energy of 1-10 keV, a switching voltage near 0.1 V, and switching time approaching 1 ns. The analysis summarized in Table 1 given above indicates that a scaled squitch can meet these objectives. In Period 4, the goal is to demonstrate a device operating well below 1V. To enable that goal, this project will focus on the continued development of all three designs described above until one becomes clearly superior. This will involve the development of appropriate SAMs and fabrication strategies, the reduction in size of all three switches, and the fabrication and testing of all three switches.

The first key milestone is to confirm the experimentally observed gap compression and tunneling, and to show that the observed functionality of the two-terminal devices is electromechanically and electrically consistent. Here, consistency means that the electric pressure applied through the gate voltage, the Young's modulus of the SAM, and the compression of the SAM, are self-consistent, and that the electrical drain-source characteristics are consistent with the compression of the SAM. Next, we will transition to the fabrication and testing of three-terminal switches, all fabricated with nanometer-scale gaps consistent with the performance reported in Table 1. Throughout Period 4 we anticipate fabricating devices that continue to exhibit micrometer to hundreds-of-micrometer lateral dimensions. While these devices must exhibit nanometer-scale gaps to tunnel and switch at low voltages, there is no initial compelling need to have small lateral dimensions. That fabrication complexity will be addressed in future years. Again, we will seek to show that the observed functionality of the three-terminal devices is electromechanically and electrically consistent. Finally, we plan to demonstrate a three-terminal switch actuated at well below 1 V. This will necessitate the development of SAMs with a low Young's modulus as discussed previously.

- *Magnetically Actuated Switch*

For this project that is led by **J. Bokor** *(Berkeley)*, the initial goal is to complete the concept feasibility assessment. With the availability of test structures at the end of Period 3, testing will take place in Period 4. The magnetic forces in the structure will be characterized and the magnetic repulsion will be compared with the contact adhesive force to confirm that the repulsion can be larger.

If this concept can be proven out, the project will move into device fabrication. Magnets will first be incorporated in to the relay structures of cantilever design to provide a built-in static repulsive force which can supplement the spring restoring force of the cantilever. Fabrication of fixed beam relays with magnet-assisted actuation is also being considered. This can be of dramatic impact on overcoming stiction, which is the key factor that limits scaling of the actuation voltage. Repulsive magnetic force can lower the actuation voltage significantly.

- *Solid-State Mechanical Switch*

This project, led by **J. Wu** *(Berkeley)*, continues to be in the concept assessment phase. The initial focus to complete a systematic study of stress-induced phase transition in VO_2 using an AFM tip. We will measure the resistance change, its temperature dependence, hysteresis, and On/Off ratio, etc. We will also be theoretically analyzing the physics and energetics of these processes. Upon satisfactory verification of the potential of this phenomenon, we will seek to demonstrate electromechanical switches involving motion with only sub-nanometer displacements. The device demonstrated must be preceded by achieving a scheme for mechanically controlled metal-insulator transition (MIT) in epitaxial VO_2 thin films. We expect that the moving electrode, which would be always in physical contact with the active material, needs to move by less than 1 nm to achieve the switch. This would enable a low-power switch free of surface damage, material fatigue and stiction. When made into a three-terminal device, the subthreshold slope is expected to be steeper than that of MOSFET because of the distinct switching mechanism based on a first-order MIT (VO_2).

Depending on the progress of the VO_2 investigations, we may also work on a similar device configuration yet with completely different physics using a layered wide-bandgap semiconductor, MoS_2. Due to the van der Waals inter-layer coupling (and thus soft elastic modulus perpendicular to the layer), the tunneling resistance across the few layers of MoS_2 can be exponentially modulated by a relatively low compression force. We have plans to explore this material system for risk mitigation. A high OFF resistance is expected from the wide bandgap of MoS_2.

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

All three experimental projects will continue in the next reporting period. The Theme III researchers will continue to work with **E. Alon** (System Integration faculty) to identify schemes to minimize the input capacitance of an ultimate low-energy optical receiver.

- *Spontaneous Hyper Emission (SHE) Nano-LEDs*

The main goal in Period 4 is to develop electrical injection nano-LED. All previous research with the nanoLED has been with optical pumped devices. This project continues to be led by **M.C. Wu**, in collaboration with **E. Yablonovitch**, both of *Berkeley*.

Electrical injection devices are essential for practical on-chip and short-distance optical interconnects. They are also important for us to gain more fundamental understanding of the spontaneous hyper emission (SHE). In optically pumped device, the optically generated carriers are created in the semiconductor area outside the optical antenna region. The short diffusion length in such nano devices (due to surface recombination) limits the amount of electrons and holes in the active area underneath the optical antenna. As a result the emission intensity is low. Electrical injection device will overcome this limitation, enabling high concentration of electrons and holes to be directly injected into the active region. The key technological challenges for electrical injection devices include: (1) low-resistance electrical contacts to the nano emitter; (2) tight control of doping profile; (3) design of optical antenna compatible with electrical contacts.

We will perform detailed design and simulation of electrically pumped nano-LEDs. The basic structure of the proposed nano-LED is similar to that of a FIN-FET except the channel is replaced by III-V emitter, the gate metal is replaced by optical antenna, and the source/drain are replaced by electron and hole injectors. We plan to develop the nanofabrication process for such nano-FIN-LED. First, we will develop the doped epitaxial structures suitable for electrical injection. Dopant diffusion and degradation of photoluminescence are key considerations. Next, we will develop Ohmic contacts for both electron and hole injectors. Low contact resistance is essential to minimize heat generation in such nano devices. Self-aligned electron/hole injector can greatly reduce the series resistance. We plan to leverage on the advances in III-V FIN-FETs with InGaAs channels recently reported by Intel. We also plan to reach out to the group at Intel for potential collaboration on nano-FIN-LED.

- *Nanophotodetector with Ultra-Low Capacitance*

The primary goal of Period 4 of this project that is led by **M.C. Wu** at *Berkeley* is to fabricate and characterize the nanophotodiode designed in Period 3. The small dimensions of the designed photodiode result in an extremely low capacitance, which makes the photodiode very sensitive. By creating an optical cavity to mitigate the optical effects of shrinking the photodiode, and integrating with receiver circuitry, it is possibly to communicate optically with fewer than 1000 photons/bit. The simulation results from this period described a nanophotodiode integrated directly to a silicon waveguide with 180aF capacitance and 36% quantum efficiency. Using the germanium RMG technique, we will focus on fabricating the photodiode design that was completed in Period 3 and fully characterizing it. In addition, the photodiode will be integrated directly into existing silicon photonics processes already developed within our group to minimize the complexity of the fabrication. By fabricating the nanophotodiode using CMOS compatible processes and measuring its low capacitance and high efficiency, we take the first step in demonstrating such an ultra-low energy photoreceiver.

In Period 4, we will continue to assess the possibility of a collaboration **J. Hoyt** of *MIT* (Theme I faculty) on growth of germanium on silicon for the second device that we designed, which promises higher performance than the germanium on oxide device.

- Phototransistors and III-V/Si Integration

For the coming year, the group of **C. Chang-Hasnain** at *Berkeley* will develop fabrication techniques, such as electron beam lithography, to make contact to such nanopillar to demonstrate a working single nanopillar based HBT on silicon substrate. Once we demonstrate a working HBT, we will optimize the structure to improve sensitivity and electrical characteristics to show > 10 GHz operation with low photon operation. 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, and to increase sensitivity. Further optimization of the design of the device structure will be in collaboration with **E. Yablonovitch** at *Berkeley*.

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

In Period 4, while completing the experimental verification of the fundamental limits of nanomagnetic logic energy dissipation, Theme IV will focus on experimental studies of logic devices: switching at lower voltage, increase of magnetic switching speed, and increasing magnetoresistance ratio for device readout. The last two topics are new to Theme IV.

The following is the list of projects planned for Period 4.

- *Experimental Verification of the Landauer Limit*

  To complete the experimental verification of the fundamental limits of nanomagnetic logic energy dissipation, this project, under **J. Bokor**, will continue to reduce the measurement error to be small compared to kTln2 by improving the signal/noise ratio in MOKE measurements of nanomagnet erasure. We will measure temperature dependence for further confirmation of Landauer's principle. The studies will be extended to verify energy dissipation for reversible logic. A new sample structure and measurement protocol for a reversible logic function will be developed for these additional experiments.

- *BFO Multiferroic Switching at Lower Voltage*

  The near-term goal of this project continues to be the reduction of the voltage required for magnetization reversal to less than 1 Volt. In Period 4, the group of **R. Ramesh** will also enhance robustness of the BFO-CoFe heterostructure with respect to repeated switching events (fatigue and imprint).

  The approach to voltage reduction will be based on La substitution in BFO, reduction of BFO film thickness and insertion of magnetic impurities into the Fe site in an attempt to enhance the canted moment in the BFO, as discussed in Section *2aiv*.

  In parallel, we will initiate two additional areas of research that will be of direct relevance to this project. The first is the integration of such heterostructures on Si, using an approach that we pioneered in the past. This approach uses a STO template on a Si wafer to create epitaxial BFO films, as illustrated in Figure 64.

  The second area will be to explore the switching of individual nanodots, located within a single domain of the BFO. This is illustrated in Figure 65. The switching of the BFO will be accomplished using a PFM while the magnetic state will be probed using a combination of MFM and PEEM.

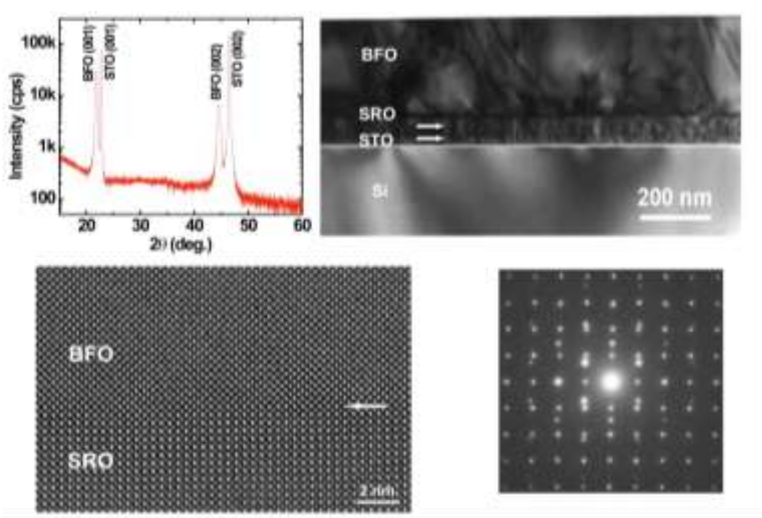

Figure 64: Epitaxial film of BFO using SRO template on a Si wafer.

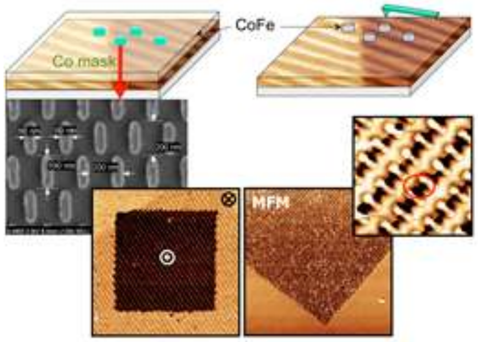

Figure 65: Illustration of using nano-dots within a single domain of BFO for switching.

- *PZT/Terfenol Composite Multiferroic*

  The key goal for this project in the **J. Bokor** group is establish a proof of concept with the fabrication and testing of composite magnetoelectric structures using thin-film piezoelectric materials. The key concept to be tested is the effects of "substrate clamping" on magnetic actuation. With sufficient understanding, we will continue to design a completed device incorporating magnetic tunnel junction (MTJ) readout.

- *Diamond NV Classical Logic*

  Diamond arrays are prime candidates for room temperature magnetic logic. **I. Siddiqi** and his group will use the nanoSQUID to investigate mechanisms responsible for information loss in densely packed arrays. We plan to place our commercially available nano-diamonds, which have NV centers, in close proximity to the magnetometer. Our nanobridge magnetometer's superior sensitivity will enable us to dispersively couple to the spins of the NV centers, and this with an ensemble of several hundred spins, as opposed to the requirement of other superconducting circuit systems of ~10^{17} spins.

- *Topological Insulator for High MR Ratio*

  The typical scheme to readout the state of magnetic switches is through magnetic tunneling junction (MTJ) devices. The magnetoresistance ratio of MTJ devices are very low, particularly in the context of the goals the Center has set for a switch, as given in Section *1a*. In 2008, Ikeda *et al.* [31] established a record in magnetoresistance ~600% (i.e., 6x) at 300°K in $Co_xFe_{80-x}B_{20}$ MTJs. More recently, Tominaga *et al.* reported a surprising result of ~2000% (i.e., 20x) for magnetoresistance ratio in $GeTe/Sb_2Te_3$ superlattice structures [33].

  In light of the latest encouraging result and given prior experience in magnetoresistance and iridates, **R. Ramesh** decided to initiate a project that will investigate Pyrochlore Iridate and Perosvskite Iridate MTJ devices. The initial studies will focus on understanding transport at interfaces and the effects of doping.

- *Ultrafast Magnet Switching*

  J. Bokor's group will begin to address switching speed, one of the key issues with magnetic switching for logic devices. Conventional magnetic switching is limited by precessional dynamics to a minimum switching time of ~100ps. Ultrafast laser experiments [34] [35] [36], on the other hand, have demonstrated deterministic magnetic switching is possible on the sub-10 psec time scale using femtosecond laser excitation of a highly non-equilibrium hot electron distribution. The question is whether similar dynamics can be initiated by purely electrical excitation. This project will attempt to answer the question by fabricating and testing magnetic hot-electron Schottky diode devices.

III. EDUCATION

1a. Goals and Objectives

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

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

The focal point of the Center is research. Therefore, the Center's leadership has made 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. Because of a strong emphasis on including female and students from under-represented groups, there are strong education efforts to cultivate a pipeline of students from secondary school to college; these efforts are presented in Section *VII. Diversity*.

In this section, we are reporting the following of the Center's programs:

- • Program status;
- • Internal E^3S education and professional development activities for Center members;
- • External E^3S education activities for general public and K-12; and
- • Center's philosophy of integrating education and research with internal and external education activities.

New in Period 3 is an emphasis on professional development activities, as we implement the E^3S Professional Development Certificate for the Center's graduate students and postdocs. The new professional development activities augmented the activities that are continuing from previous reporting periods.

1b. Performance Metrics

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

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

		Period 3	
	Number of publications with student and postdoc authors who have published previously in other research themes	Every 2 years beginning in Period 4	Period 3: 9 Period 5: 12
	Number of students and postdocs participating in education and diversity programs	Yearly beginning in Period 3	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 3	Period 2: Baseline Period 3: 15% Period 5: 20%

1c. Problems Encountered

Two primary problems were encountered during this reporting period: 1) difficulty in engaging Tuskegee University; and 2) expanding educational courses across all partner locations. The Center has not fully leveraged the partnership with Tuskegee University. With Tuskegee University being a minority-serving institution, the Center expected to work closely with Tuskegee to cultivate a pipeline of under-represented undergraduate and graduate students to pursue research opportunities at Berkeley, MIT, and Stanford. In addition, the Center expected students and postdocs from Berkeley, MIT, and Stanford, to do research presentations at Tuskegee or participate in Tuskegee's mentoring conference, to further enhance their experience working on diverse teams. In Period 3, E^3S fell short in meeting these expectations.

To engage students at Tuskegee, there is a great need for Tuskegee to promote these opportunities. It has been difficult for the Center to fully engage Tuskegee Co-PIs in the Center's education programs. The Center has made several attempts to engage Tuskegee by visiting to host an information session to introduce students for E^3S research opportunities, inviting Co-PIs and students to participate in bi-weekly research seminars and summer journal clubs, and sending program opportunities emails to Co-PIs to post widely for students at Tuskegee. To increase participation from Tuskegee, the Center will continue promoting education opportunities, but will also be more assertive by creating an agreement between the Center and Tuskegee to meet expectations to receive Center funding.

In Period 3, the Education and Outreach Director has focused the majority of her efforts on developing diversity programs so it has been difficult to expand the portfolio of E^3S educational courses. This focus on diversity has abbreviated the time available to work closely with the Co-PIs to adapt educational material to include applications relevant to E^3S research. During this period, the Center planned to offer a course on Innovation and Commercialization to provide Center members knowledge about the process of innovation, entrepreneurship and the transition of research results to commercially-viable products. However, this course was not fully developed so it was replaced with two other educational activities: a workshop offered on innovation and commercialization at the Second Annual Student and Postdoc Retreat, and the Nanovation symposium, organized by the IEEE San Francisco Bay Area Nanotechnology Council focused, on bringing together the unique perspectives of researchers, entrepreneurs, and investors on the applications of nanotechnologies. These perspectives included that of **E. Yablonovitch** who shared case studies of his inventions.

2a. Internal Educational Activities

Activity Name	E^3S Course – EE 290B: Advanced Topics in Solid State Devices

Led by	**E. Yablonovitch** (Berkeley), **S. Agrawal** (Berkeley)
Intended Audience	All Center Members
Approx Number of Attendees (if appl.)	Total – 7 Graduate Students: 6 Berkeley, 1 MIT

One of the Center's goals for its members is to receive formal training in technical topics that are applicable to the Center. **E. Yablonovitch,** Center Director, developed EE 290: Advanced Topics in Solid State Devices, a UC Berkeley course to be the key training venue. This course was first taught in Fall 2010, at the inception of the Center. In Fall 2012, **E. Yablonovitch** updated and taught EE 290 again, assisted by **S. Agarwal,** an E^3S postdoc. This course covers the following topics: solid-state switching devices that operate in the milli-Volt regime, nano-transistor options with steeper sub-threshold slope, nano-optical links, novel nano-scale impedance matching transformers, including plasmonics, new forms of amplification using giant magneto-resistance and other spintronic effects, nano-mechanical switching elements that are capable of very low voltage operation, low-temperature electronics, and electro-chemical switching elements. This course was taught at UC Berkeley and offered to members at all institutions through videoconferencing technology and online posting of course material. The enrollment count for this course was 25, including 7 E^3S participants from Berkeley and MIT; and 18 non-E^3S participants, one of whom is from Stanford.

Activity Name	Third Annual Retreat
Led by	**E. Yablonovitch** (Berkeley)
Intended Audience	Faculty, Staff, Students, Postdocs, and Partners
Approx Number of Attendees (if appl.)	Total – 25 Graduate Students: 11 Berkeley, 6 MIT Postdocs: 5 Berkeley, 2 MIT, 1 Stanford

The Annual Retreat was an education event as well as venue to communicate to graduate students and postdocs and build sense of community across the member institutions. This two-day event enables the participants to learn about the Center's research directions and status through presentations and discussions, and present their own results to the Center, including the Center's industry partners. In addition, they also learn about the Center's Education and Outreach mission and programs. In Period 3, online access to training was a featured topic, presented by **I. Porro**, Outreach Programs Officer for MIT's Office of Engineering Outreach Programs. More details about the Annual Retreat are given in Section *VII. Management*.

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 – 19 Graduate Students: 8 Berkeley, 5 MIT Postdocs: 4 Berkeley, 1 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 21 posters at the 2012 Annual Retreat, including a poster presented by a RET fellow from LATTC, one of the Center's education partners; see **Appendix C**.

Activity Name	Second 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 – 20 Graduate Students: 8 Berkeley, 6 MIT Postdocs: 3 Berkeley, 2 MIT, 1 Stanford

In August, the Center hosted its 2nd Annual Student and Postdoc Retreat for graduate students and postdocs (see **Appendix D**). 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 professional development training and a one-hour new member orientation for new students and postdocs; see description in Section *III.2b*, Professional Development Activities.

Activity Name	E^3S Research Seminars
Led by	**A. Khan** (Berkeley), **J. Carter** (Berkeley), **R. Iutzi** (MIT)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	**Appendix E: Seminars and Journal Club**

Research Seminars is a regularly scheduled center-wide activity that was originally initiated within weeks of the start of the Center. It is a vehicle to educate and communicate the research being undertaken at the Center across research themes and member institutions, as well as an educational forum. The E^3S seminars mainly feature graduate students and postdocs, where they share the progress of their research. However, it also has served as a venue for the faculty to share information about their new projects. Occasionally, industry partners also use this forum to present their technical direction and views of topics that are relevant to the Center. Period 3 is expected to conclude with 11 seminars; **Appendix E** gives a list of the scheduled seminars for the first 10 months of Period 3.

Activity Name	Journal Club
Led by	**J. Carter** (Berkeley) and **R. Iutzi** (MIT)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	**Appendix E: Seminars and Journal Club**

A Journal Club was initiated by the GSPC as a vehicle to learn about relevant research undertaken outside the Center in summer 2011. In Period 3, **J. Carter** (Berkeley) and **R. Iutzi** (MIT), E^3S graduate students, coordinated this activity. In the summer of 2012, we focused on learning and assessing the research efforts external to the Center but are relevant to the Center. We had four meetings, one devoted to each Theme, when we discussed papers published by other laboratories. There was faculty participation in the selection of papers and at the Journal Club meetings; see **Appendix E**.

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.)	Total – 6 Undergraduate Students: 4 Berkeley, 1 Stanford, 1 Tuskegee

The E^3S Internship (ETERN) program is the newest education activity, initiated in January 2012. The ETERN program is an academic-year program for undergraduates at all of the Center's institutions. The primary goal is to attract students to energy efficient electronics science by providing research experiences to lower-level undergraduate students of member institutions, with the goal of enhancing the pipeline of students interesting in graduate studies in the science and engineering disciplines of relevance to the Center. This first cohort of ETERN scholars began their research in E^3S faculty groups in January 2012. In Period 3, we had 6 participants. These students were supervised by E^3S faculty and mentored by E^3S graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs.

2b. Professional Development Activities

- *Activities for the Entire Center*

Activity Name	Graduate Student and Postdoc Council (GSPC)
Led by	**W. Ko** (Berkeley)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 20 Graduate Students: 8 Berkeley, 6 MIT Postdocs: 3 Berkeley, 2 MIT, 1 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. In this Period, the GSPC meeting was chaired by **W. Ko**, a graduate student at Berkeley, and mentored by S. Artis, Education and Outreach Director. 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 Perception Surveys as part of Section *VII. Management*). The majority of the students and postdocs expressed interest in formalizing the professional development opportunities. During their meeting they finalized the E^3S Professional Development Program, including the program overview and requirements for certificate of completion (see **Appendix F**). It was suggested that the Center have graduate student and postdoc representation on the Center's Executive Committee. Students and postdocs also provided insight on education and outreach activities. They expressed interest in focusing more on undergraduate programs and engaging graduate students and mentors in the selection process for the undergraduate research programs. The GSPC also met with E. Yablonovitch, Center Director to provide an update on student and postdoc participation and express any Center concerns. Resolutions to their concerns were also discussed.

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

The Center offers many education programs that students and postdocs can engage in throughout the academic year. Some of these programs are internal to the Center, while others are external for outside stakeholders such as the general public, k-12, and undergraduates at other universities. These programs also vary in length, ranging from a one-time event for one hour to a nine-week program requiring a 40-hour commitment. Given the dynamics of these education opportunities, in Period 3, the Center focused on formalizing the education programs so students and postdocs are familiar with the programs, understand how these programs can develop their professional skills, and are motivated to participate in the E^3S programs. To formalize our programs, the Center launched the E^3S Professional Development Program (E^3S PDP). At the Second Annual Student and Postdoc Retreat, **S. Artis** and **Graduate Student and Postdoc Council (GSPC)** developed the E^3S PDP. The goal of the program is to offer opportunities for students and postdocs to make a strong start on professional development while part of the Center. The program provides a variety of professional development activities in the areas of: mentoring, outreach, leadership, teaching, proposal writing, science communication, and entrepreneurship. The Center expects that all of our education programs will fit into one of these training areas. To date, this program has formal, yet flexible requirements. For a certificate of completion, students and postdocs must complete: 1) at least one education activity in the area of outreach or mentoring; and 2) at least one education activity in three other training areas (leadership, teaching, proposal writing, science communication, and entrepreneurship).

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

At the 2012 Annual Student and Postdoc Retreat, **S. Artis**, trained new students and postdocs on scientific ethic during the new member orientation. The ethics training covered the following topics: scientific standards, history of scientific ethic codes, types of research misconduct. After completing the ethics training, students and postdocs were sent an electronic copy of the book, *On Being a Scientist: Responsible Conduct in Research*, as an additional resource on scientific ethics.

Activity Name	Professional Development Seminar: *Science Communication Workshop*
Led by	**Carol Lynn Alpert and Karine Thate** (Museum of Science, Boston)
Intended Audience	All Graduate Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 20 Graduate Students: 8 Berkeley, 6 MIT Postdocs: 3 Berkeley, 2 MIT, 1 Stanford

At the 2012 Annual Student and Postdoc Retreat, the Center hosted a workshop titled, *Science Communication.* **Carol Lynn Alpert** and **Karine Thate**, science communication facilitators from the Museum of Science, Boston, provided a guide for effectively communicating technical research to an interdisciplinary and non-technical audience. The speakers provided science communication strategies for slide and poster presentations and job interviews. This workshop included advice, resources, and practice with peers. The session concluded with time for questions and answers.

Activity Name	Professional Development Seminar: *Understanding Innovation and Intellectual Property Protection Workshop*
Led by	**J. Yuen** (Executive Director)
Intended Audience	All Graduate Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 20 Graduate Students: 8 Berkeley, 6 MIT Postdocs: 3 Berkeley, 2 MIT, 1 Stanford

At the 2012 Annual Student and Postdoc Retreat, the Center hosted a workshop titled, *Understanding Innovation and Intellectual Property Protection.* **J. Yuen** (Executive Director) provided an overview of innovation and intellectual property protection. This workshop shared perspectives on innovation to enable an understanding of what it is, why it is important, and some of its important attributes. As intellectual property creation and protection is an important element in innovation, its role in competitiveness and the ways to protect this asset are also covered in this workshop. The workshop concluded with students and postdocs able to share their views and own understandings with their peers.

Activity Name	Project Management and Mentor Training
Led by	**S. Artis** (Berkeley)
Intended Audience	Graduate Student and Postdoc mentors
Approx Number of Attendees (if appl.)	Total – 8 Graduate Students: 6 Berkeley Postdocs: 2 Berkeley

As part of the Center's objective to provide leadership experiences, graduate students and postdocs who served as mentors in the Center's summer undergraduate and precollege programs participated in a project management and mentor training. Students and postdocs received 1.5 hours of mentoring and project management training and then over 360 hands-on training in mentoring, supervisory skills, communication, and leadership. 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. 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 for Postdocs*

Activity Name	REU Selection Committee
Led by	**S. Artis** (Berkeley)
Intended Audience	All Graduate Students and Postdocs at Berkeley
Approx Number of Attendees (if appl.)	Total – 4 Graduate Students: 1 Berkeley Postdocs: 3 Berkeley

Special emphasis is given to secure postdocs to serve on the selection committee for the E^3S Research Experience for Undergraduates. Should there be vacancies, then graduate students are invited to participate. Each member of the selection committee reviews the application, personal statement, transcript, and letters of recommendations of ~6 applicants. Based on the review, the postdocs and graduate students provided a list of applicants that should be considered for placement in a summer research project.

- *Other Individual Activities*

Activity Name	Graduate Student and Postdoc Council (GSPC) Event Coordinator
Led by	**W. Ko** (Berkeley)
Intended Audience	All Students and Postdocs of the Center
Approx Number of Attendees (if appl.)	Total – 20 Graduate Students: 8 Berkeley, 6 MIT Postdocs: 3 Berkeley, 2 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 Berkeley EECS Department's Visit Day for prospective graduate students, the summer journal club, and the 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	REU Poster Review
Led by	**S. Artis** (Berkeley), **J. Peng** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx Number of Attendees (if appl.)	Total – 4 Graduate Students: 3 Berkeley Postdoc: 1 Berkeley

The Center hosted two REU programs, one for upper division undergraduates and another for community college students that was in conjunction with a REU site award. These programs concluded with a joint poster session of all REU participants. This offered a professional development opportunity for graduate students and postdocs to be reviewers. In Period 3, the four graduate students and postdocs who participated in this activity included 3 who are not members of the Center, but are electrical engineering or materials science graduate students and postdocs. Their inclusion reflects the leverage the Center offers to its host institution. Members of this review panel were asked to provide a quantitative assessment based on the following criteria: understanding of scientific principles and applications, energy efficient electronics science, research process; critical thinking; and creativity. Two members of the review panel evaluated each student. At the conclusion of the poster session, assessments were anonymously shared with the REU intern to provide them feedback on their performance. All of the students were rated above average or well above average on these criteria.

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

While all four themes have Theme meetings, two themes rely on graduate students to organize the meetings. For example, **J. Carter**, a graduate student of Berkeley, the coordinator has been the key coordinator of the 15 1-hour Theme I meetings in 2012. His responsibilities have included arranging for the logistics of scheduling and setting up a virtual meeting across institutions as well as securing speakers for each meeting.

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

N. Antler, a Ph.D. student at Berkeley, and **R. Iutzi**, a Ph.D. student at MIT, served as student representatives at the STC Director's Meeting. Both students participated in the student breakout sessions and the poster session. This was a great opportunity for them to network with students from other STCs and to further cultivate their leadership skills as co-chairs on the Graduate Student and Postdoc Council.

Activity Name	Ana G. Méndez University System Research Symposium (AGMUS)
Led by	**S. Artis** (Berkeley)
Intended Audience	Undergraduate researchers
Approx Number of Attendees (if appl.)	Total – 2 Undergraduate Students: 1 Berkeley REU Program, 1 MIT REU Program

The Center strongly encourages summer research interns to disseminate their research to larger audiences through conferences and publications. To help promote this professional development opportunity, E^{3}S provides a travel award to cover expenses associated with attending technical conferences. For the Ana G. Méndez University System Research Symposium (AGMUS), the abstracts of **F. Bennett** of *Norfolk State* and **D. Drew** of *Virginia Tech*, two of the Center's REU student in summer 2012, were selected for the 2012 Research Symposium in San Juan, Puerto Rico. This conference targets students from underrepresented ethnic groups with an interest in pursuing a graduate degree in science and engineering. **F. Bennett** presented a technical presentation titled, *Dynamic Graphical Representation of Vertical Cavity Surface Emitting Lasers*. This research was completed in C. Chang-Hasnain's research group at *Berkeley*. **D. Drew** presented a poster presentation titled, *Creation of a Voltage-Actuated Switch for MEMS using a Piezoresistive Polymer Composite*. This research was completed in J. Lang and V. Bulović's research groups at MIT. **D. Drew** also received a best poster award at this conference. F. Bennett's attendance to the AGMUS Conference was funded by the Center.

Activity Name	Society for Advancement of Chicanos and Native (SACNAS) National Conference
Led by	**S. Artis** (Berkeley)
Intended Audience	Undergraduate researchers
Approx Number of Attendees (if appl.)	Total – 1 Undergraduate Students: 1 MIT REU Program

The Center strongly encourages summer research interns to disseminate their research to larger audiences through conferences and publications. To help promote this professionally development opportunity, E^{3}S provides a travel award to cover expenses associated with attending technical conferences. The abstract of **D. Drew**, one of the Center's summer 2012 REU students, was selected for the 2012 SACNAS National Conference in Seattle, Washington. This conference targets students from underrepresented ethnic groups with an interest in pursuing a graduate degree in science and engineering. **D. Drew** presented a poster presentation titled, *Creation of a Voltage-Actuated Switch for MEMS using a Piezoresistive Polymer Composite*. This research was completed in J. Lang and V. Bulović's research groups at MIT. He also received a best poster award at this conference. D. Drew's attendance to the SACNAS Conference was partially funded by the Center.

2c. *External Educational Activities*

Activity Name	Cal Day

Led by	**J. Bokor** (Berkeley) and **J. Yuen** (Berkeley)
Intended Audience	High school seniors with admission offers from Berkeley and their families
Approx Number of Attendees (if appl.)	~130

Each April, UC Berkeley invites 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. Bokor** gave a separate talk about nanoelectronics, Moore's law and energy efficient electronics entitled: "What's Nano about my iPod?" **J. Yuen** gave a talk about the need for the Center for E^3S and the nanotechnology aspects of the research program, and shared the availability of the ETERN program to support undergraduate research at the Center.

Activity Name	Berkeley EECS Annual Research Symposium (BEARS) – Open House
Led by	**J. Yuen** (Berkeley), **J Peng** (Berkeley)
Intended Audience	Industry in the Bay Area
Approx Number of Attendees (if appl.)	10

UC Berkeley's Electrical Engineering and Computer Sciences Department (EECS) fosters close cooperation with industry in the Bay Area through the Berkeley EECS Annual Research Symposium (BEARS). Each February, BEARS, a day-long research conference, features a variety of informative talks and laboratory open houses offered by distinguished faculty members and advanced graduate students. During BEARS, the Center sponsored an Open House to give industry members a look at the very latest exciting work being carried out by the Center. E^3S graduate students and postdocs participated in the poster session that was part of the Open House.

Activity Name	Berkeley EECS Visit Day – Open House and Coffee Hour
Led by	**S. Artis** (Berkeley), Graduate Student and Postdoc Council (GSPC)
Intended Audience	Admitted Graduate Students
Approx Number of Attendees (if appl.)	30

Each spring, UC Berkeley's Electrical Engineering and Computer Sciences Department (EECS) hosts a Visit Day for admitted graduate students. Some admitted students travel to the Berkeley campus with their minds already made up: Berkeley is where they are going to enroll. Others who have not made up their minds come to experience what it's like to live and learn at Berkeley before they decide. For both groups, the EECS faculty, students, and staff organize a two-day schedule with panels, speakers, lab tours, project overviews, and interviews with professors. This March, the Center hosted two events: 1) Open House for admitted students interested in physical electronics and E^3S research; and 2) Coffee Hour for admitted students interested in meeting members from Women in Computer Science and Engineering (WICSE), Black Graduate Engineering and Science Students (BGESS), and Latino Association of Graduate Students in Engineering and Science (LAGSES). Center faculty, graduate students, and postdocs participated in these events as poster presenters, speakers, or hosts, and in one-on-one meetings with the visiting students. Both events provided the opportunity for admitted students to learn about the Center's cutting-edge research and the education and outreach programs.

Activity Name	Marvel Nano Fabrication Lab Tour for Tau Beta Pi's Overnight Stay and Engineering Open House

Led by	**S. Artis** (Berkeley), **J. Carter** (Berkeley)
Intended Audience	High School Students in Bay Area
Approx Number of Attendees (if appl.)	90

Tau Beta Pi, UC Berkeley's general engineering honor society, hosted an overnight stay program for high school students from November 16-17, 2012. Ninety high school students registered for the event, which included an opportunity for students to experience college life with a current UC Berkeley student in the residence halls. The Engineering Open House included a look at Berkeley's engineering program through: guided lab tours, panels with industry professionals, panels with current undergraduates, and student organization fairs. The Center provided students a tour of the Marvell Nanofabrication Laboratory, which was led by **J. Carter**, a Berkeley graduate student. He also provided students an overview of how the lab fits into the design of devices the Center is investigating.

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 Undergraduate and Teacher Research	• Research on energy efficient electronics	• Graduate student as mentors: Education to enhance mentoring

Programs	science topics	and project management skills of graduate students
Summer High-School Apprenticeship Program (SHARP)	• Research on energy efficient electronics science topics	• Graduate student as mentors: Education to enhance mentoring and project management skills of graduate students
Minority Introduction to Engineering and Science (MITES) MIT Online Science, Technology, & Engineering Community (MOSTEC)	• Application of energy efficient electronics science topics	• Graduate student as instructors: Education to enhance curriculum development and teaching skills of graduate students

*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 VII. Diversity.

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

In alignment with the goals of the E^3S program, MIT's Minority Introduction to Engineering and Science (MITES) has built upon changes made last year. The course instructor continued to integrate energy efficient concepts into MITES' Electronics curriculum. The concept of energy and power in the context of electronics was introduced earlier in the course, with homework problems explicitly exploring conservation of energy integrated into introductory circuit analysis work. Conservation of energy, energy efficiency, and other related concepts were all covered throughout the course, with many lectures (approximately 75%), having an energy section now included to tie the concepts learned on that particular day back to energy and power related ideas. Changes made to the labs to add new investigations and guided calculations into of energy and power were maintained.

A completely new lab, Lab 8, was developed for the summer of 2012 that focused on E^3S concepts. In particular, Lab 8 focused on using solar cells to harvest radiant energy, and then storing and utilizing that energy to illuminate an LED. Students made calculations on energy storage, and the lab proved to be probably the most popular of the summer. We intend to streamline and expand it for summer of 2013, and potentially expand it to two full sessions, because of the popularity, not just of the lab but also of the topic of solar energy and energy efficiency in general.

Several student groups had a significant portion of their final project address energy efficiency concepts. One group, which designed and developed a mobile security system, spent quite a bit of time calculating battery life estimates of their system, which led to quite a few learning opportunities and discussions on these concepts with the teaching staff. A second group constructed a model solar-power house, which also spent significant time looking into energy-focused concepts.

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. Students in the Electronics course toured the cleanrooms at the MIT Microsystems Technology Laboratories (MTL) with a presentation by **J Teherani,** a graduate student co-advised by **J. Hoyt** and **D. Antoniadis**. The two-hour discussion and lab tour were very well received by both MITES students and teaching staff. The students really became engaged and enjoyed the presentation. It was also a professional development opportunity for the graduate student presenter, who did a great job of conveying ideas about Integrated Circuits and why a cleanroom is required to make them. More importantly he conveyed his enthusiasm for the research work done at MTL.

2e. *Performance Against Metrics*

During this reporting period, the Center has compared the education programs against the baseline established in Period 2. The table below displays this data and future metrics to measure education success

Objective	Metrics	Targets	Period 3 Results
Education	Number of Center graduates who have completed E^3S training	*Period 2: 0 Period 3: 50% Period 5: 100%	2 (20%)
	Number of publications with student and postdoc authors who have published previously in other themes	Period 3: 9 Period 5: 12	0
	Number of students and postdocs participating in education and diversity programs	*Period 2: 42 (52%) Period 3: 60% Period 5: 75%	48 (52%)
	Number of students and postdocs serving in leadership roles in the Center	*Period 2: 9 (11%) Period 3: 15% Period 5: 20%	11 (19%)
	Number of events leading to external articles on Center	*Period 2: 1 Period 3: 100% increase Period 5: 50% increase	0 (0%)

*Baseline

2f. *Education Activities in Period 4*

- *Internal Education Activities*

In Period 4, E^3S will continue to refine and formalize the E^3S Professional Development Program (E^3S PDP) and expand the number of courses E^3S offers. The existing E^3S PDP model provides a variety of professional development activities in the areas of: mentoring, outreach, leadership, teaching, proposal writing, science communication, and entrepreneurship. In addition to hands-on practical activities that fall under these training areas, the professional development program will include educational modules in these areas to share theoretical frameworks and best practices. In Period 4, the program will be refined to develop these modules, which will center on specific learning objectives and outcomes.

The Center will also continue to formalize existing programs. For example, the Center plans to formalize the mentor training for postdocs and mentors. The current training, a 90 minutes training at the beginning of the summer research program will be developed into a more comprehensive mentor training program with identified training objectives and metrics to ensure mentors are meeting the training objectives. To meet some of the objectives, the training will be expanded to include speakers on critical mentoring competencies and weekly meetings to develop a community of mentors to utilize for support from their peers and further develop their mentoring skills. Mentors will also have the opportunity to engage in other training areas through the program by leading REU program activities such as organizing the REU BBQ, being a facilitator in the science communication workshop, and judging posters and presentations.

In Period 4, the Center will expand the E^{3}S course portfolio. With the hiring of personnel to assume some of the diversity and outreach responsibilities being carried out by the Education and Outreach Director, the Center shift focus to course development. The Education and Outreach Director will work closely with Co-PIs on course development and creating an infrastructure for offering online courses for Center members.

- *External Education Activities*

  In Period 4, the Center will further 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 will also use the World Wide Web and social media to disseminate the Center's research to the general public. Plans to put videos online are underway. These online videos will include short videos highlighting the Center's research presentations and hands-on demonstrations. This effort will target multiple audiences, including other researchers, potential industry partners, students interested in exploring energy efficient electronics science, and the general public interested in how the Center's research impact society. The Center will also use online postings for brief discussions and informational topics to communicate the Center's science to a broader audience.

IV. KNOWLEDGE TRANSFER

1a. Goals and Objectives

In Period 3, we have clarified the wording, but did not change the substance, of the Center's Knowledge Transfer goals. The 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 ways to prepare workers at all levels to participate in the new opportunities. As such, Knowledge Transfer includes the transfer of new-found knowledge that is relevant to the Center's research as well as programmatic activities. We think of Knowledge Transfer as cross-fertilization that goes in both directions, up and down the food chain. For Research, the scope will include device researchers at the leading electronics companies, circuit designers, CAD software writers, all the way to manufacturing workers in the semiconductor equipment industry. For Education and Diversity, the scope will include other educators and potential employers. Thus opportunities will be created at all levels, from community college students up to Ph.D. graduates from research universities. Knowledge transfer is envisioned to be through the following channels:

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

1b. Performance Metrics

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

	articles on the Center	beginning in Period 3	Period 3: 100% increase Period 5: 50% increase

1c. Problems Encountered

The public pages of the Center's website continue to be the primary vehicle for external communications. Online dissemination of research results has been in the form videos and slides from the 2nd Berkeley Symposium on Energy Efficient Electronic Systems. These materials are suitable for the technical community but not the general public. Expanding the Center's online outreach to the general public has been delayed. Despite this delay, we have seen a large increase in internet traffic to our website. Our analysis of the monthly traffic led us to surmise that the increase is partly driven by external interest in the Center's Education programs.

2a. Knowledge Transfer Activities

Outcomes of the Center's activities include knowledge that covers research results as well as what we learn as we execute education and diversity programs. The Center's knowledge transfer activities include transfers out, transfers in, as well as two-way transfers. The target of knowledge transfer can be the Center, the technical and education communities, and other research and education centers.

The main venue for disseminating the Center's results is the established technical journals and professional conferences and workshops.

Dissemination of the Center's Research Results in Technical Publications		
Led by	E^3S Faculty	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, CA

In Period 3, the Center's faculty, students and collaborators had 13 technical publications; 12 from Berkeley, and one each from MIT. In addition, 2 papers have been accepted for publications; 1 paper on results from collaborative research collaboration between Berkeley and MIT has been accepted for publication and 1 paper from Stanford. Two papers from Berkeley are being reviewed for publication.

Dissemination of the Center's Research at Conferences, Workshop and Meetings		
Led by	E^3S Faculty	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, CA

In Period 3, there were 23 technical talks and 8 posters at conferences and workshops, including 1 talk and two posters from two students from the 2012 REU programs at Berkeley and MIT. There were also 14 invited talks given by the faculty.

As in previous periods, we continued to share information with the Center's industry members in the Center's Annual Meeting, and through the Center's industry members, we learn about the approaches and directions of industry.

E^3S Annual Retreat		
Led by	**E. Yablonovitch** (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Palo Alto, CA
4.	Tuskegee University	Tuskegee, AL
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 with its industry members. The attendees from industry: A. Brand, Applied Materials; J. Cook, Lam Research; and P. Solomon, IBM. P. Gargini, Intel, participated by videoconference. The attendees were also invited to a poster session which included 21 posters by students and postdocs. For the first time, a teacher from the Center's education partner, LATTC, **M. Diaz**, also had a poster on the research he undertook as a RET fellow.

Seminars by Industry Partners		
Led by	**E. Yablonovitch** (Berkeley), **D. Antoniadis & J. Hoyt** (MIT)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, CA

The Center strives to sponsor seminars with speakers from relevant industries. In Period 3, we had two seminars by the Center's industry partners. K. Schuegraf, Applied Materials, gave a seminar, entitled *Innovation to Advance Moore's Law - Room for Core Technology Revolution*, in March 2012. P. Solomon, IBM, gave a seminar, entitled *Is there Life after CMOS?* in October 2012. The former seminar was given at UC Berkeley, while the latter was given at MIT. Nevertheless, there was centerwide participation via videoconference. The total attendance was 60 and 31, respectively.

In Period 3, we used a strategy of co-sponsorship to enable knowledge transfer.

iNOW 2012 - Added Focus on Energy Efficient Photonics & Electronics	
Led by	**C. Chang-Hasnain** (Berkeley) & **E. Yablonovitch** (Berkeley)
Organizations Involved	

	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

International Nano-Optoelectronics Workshop (iNOW) is an annual forum that rotates yearly among locations in Europe, Asia and the US. In 2012, the workshop took place in the US with two E^3S faculty serving on the organizing committee. The Center was a co-sponsor to enable the workshop to expand its scope to include energy efficient photonics as well as electronics. The E^3S co-sponsorship enabled the organizers to add 3 technical sessions that are relevant to the Center's Themes I and III research. Included in these sessions are talks by two E^3S faculty, **E. Yablonovitch** and **M.C. Wu**, and a paper given by a researcher from one of the Center's industry member, IBM. The panel featured the CTO's from three companies who talked about Optical Interconnects in Supercomputers and Data Centers, providing systems and component perspectives. The entire workshop had 134 participants; 88 of whom are students and 13 are from industry. This is a two-way transfer activity.

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

The Center utilizes an established venue to learn more about research that may have relevance to our research programs. In Period 3, we sponsored four seminars by academic researchers. The sponsored talks, relevant to the Center's Themes I and III research, are one-way knowledge transfers to the Center. Typical attendance at the Solid State Seminars is 40-45, some of whom are members of the Center at Berkeley.

Guardian Angel (GA) Workshops in the US - International Collaborations		
Led by	**E. Yablonovitch** (Berkeley), Other E^3S Faculty, and **J. Yuen** (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, CA

The Guardian Angels (GA) Project is scientific consortium in the European Union that has, as part of its goals, the research of zero power consumption in smart systems. The consortium comprises 66 partners: 29 universities, 16 research organizations, and 21 companies. Together, they stem from 16 different European countries. The consortium is coordinated by EPF Lausanne and ETH Zürich. The Center supported the outreach efforts of the GA Project in the US. Two GA workshops were held, first at San Francisco in March 2012 and again, at Boston in November, 2012. Two E^3S faculty, **E. Yablonovitch** and **H.-S.P. Wong,** served on the Scientific Committee of the San Francisco workshop which featured three E^3S faculty on its agenda (**E. Alon**, **E. Yablonovitch** and **T.-J. King Liu**). The Center staff also provided publicity and registration support to the San Francisco workshop. The Boston workshop included a talk by E^3S faculty, **D. Antoniadis**. Both workshops, which had about 40 attendees each, were two-way transfer activities.

Nanovation – Commercialization of Nanotechnology		
Led by	**J. Bokor** (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

The Nanovation symposium, organized by the IEEE San Francisco Bay Area Nanotechnology Council, focused on bringing together the unique perspectives of researchers, entrepreneurs, and investors on the applications of nanotechnologies. E^3S faculty, **E. Yablonovitch**, was a speaker. The Center co-sponsored this event as a professional development opportunity for our students and faculty; i.e., a one-way transfer activity of the Center. There were 67 participants, most of whom are not members of the Center.

The Center considers knowledge transfer related to education and diversity to be an important mandate. As such, in Period 3, we initiated community building to ensure we will have partners to work with. The initial target is other STCs.

NSF STC Director's Education and Diversity Meeting Planning Committee		
Led by	**S. Artis** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

The 2012 STC Directors' Meeting was preceded by an all-day Education and Diversity workshop. **S. Artis** served as the co-chair of the workshop's planning committee. She was responsible for identifying topics and speakers, leading planning teleconferences, and assisting with logistics of the meeting. As an information sharing venue among all STCs, we consider this a two-way transfer activity. Thirty attendees attended the Education and Diversity workshop before the STC Directors' Meeting. A result of this meeting is further collaborations between E^3S and two other STCs in the class of 2010, Emergent Behavior of Integrated Cellular Systems (EBICS) and Center for Dark Energy Biosphere Investigations (C-DEBI). In September, E^3S and EBICS partnered to recruit for STCs at the Ana G. Méndez University System Research Symposium (AGMUS), University of Puerto Rico at Mayaguez and University of Puerto Rico at Rio Piedras. S. Artis and EBICS Diversity Manger Olanda Bryant co-presented on their Center's research programs during these recruitment activities. In September and October, **S. Artis** met with Stephanie Schroeder, C-DEBI's Education Director, to provide best practices and lessons learned designing a summer research program for community college students. **S. Artis** provided C-DEBI an implementation guide and the framework of the Transfer-to-Excellence Program, including program goals, objectives, learning outcomes, and targeted audience; application and selection material and procedures; recruitment calendar, flyer, and presentations; curriculum and/or training calendar and modules; and formative and summative evaluation questionnaires.

Quarterly Education and Diversity Teleconference	
Led by	**S. Artis** (Berkeley)

Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

S. Artis organizes and provides leadership teleconferences that bring together Education and Diversity personnel of all active STCs. This quarterly forum is intended to enable community building and sharing of information and best practices. Each teleconference is typically attended by 15 people from the 17 active STCs. During this period the following topics were covered:

- Summer Research Programs - Executing an Effective Research Experiences for Undergraduates (REU) and Research Experiences for Teachers (RET)
- Evaluation and Assessment of Education and Outreach Programs
- STC-LSAMP REU Fellowships - Creating partnerships by collaborating around our collective REU goals
- Create a Writing Plan - "telling our stories" as best or promising practices
- Professional Development - identifying/sharing professional development strategies; e.g., remaining marketable
- Utilize our STC Colleagues - collaborating on resource development and problem solving

E^{3}S Website		
Led by	**J. Yuen** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, 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 K**. During the Science Communication session at the 2012 Graduate Student and Postdoc Retreat, the participants discussed how to improve the Research section of the website. Suggestions at and following the workshop are being incorporated into the next release of the research pages.

NSF STC Website		
Led by	**S. Artis** & **J. Yuen** (Berkeley)	
Organizations Involved		
	Name	*Address*
1	U of California, Berkeley	Berkeley, CA

In Period 3, the Center for E^{3}S assumed the responsibility of the joint STC website. Previously, the site was hosted by the Center for Embedded Networked Sensing, a center that is graduating from the STC program. The site has been successfully moved to a Berkeley host server. We are planning updates to be implemented before the end of this reporting period.

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.

2c. Performance Against Metrics

Objective	Metrics	Targets	Period 3 Results
Knowledge Transfer	Website hits & unique visitors	Period 2: Baseline Period 3: 20% increase	Website Hits: 240% (27,298) Unique Visitors: 267% (16,338) (see **Appendix K**)
	Number of contacts with industry • General • Presentations by industry	Period 2: 18 Period 3: 36 Yearly: 2	Period 2: 66 Period 3: 20 Average: 43* 2
	Center publications	Yearly: 18	16 plus 1 accepted and 4 under review
	External citations of publications	Period 3: 10 Period 5: 100	178
	Patent Disclosures	Period 3: 3 Period 5: 8	0
	Students hired into relevant industries	Period 5: 50% Period 10: 100%	Students: 64% Postdocs: 33%
	Technology development attributable to Center's research	Period 10: 1	n/a

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

2d. Transfer Activities in Period 4

In Period 4, the Center will organize the 3rd Berkeley Symposium on Energy Efficient Electronic Systems. Greater efforts will be applied to develop effective mechanisms for disseminating research results to the general public. For online multimedia communications, the Center will accelerate its plans to implement blogs and 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 E^3S' two-way knowledge transfer strategy. The education and diversity plans in the proposal also call for leveraging established programs to add value. The key goal for the Center is to continue to execute and enhance its partnership strategy to deliver the programs and activities in its plans.

1b. Performance Metrics

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

1c. Problems Encountered

Even before its inception, the Center for E^3S established agreements to collaborate on research with groups around the world. However, those agreements did not mature into striving collaborations. In Period 2, we began to cultivate new relationships with programs with goals more similar to the E^3S goals. This partnership development effort continues in Period 3.

2a. Activities in Period 3

In Period 3, the Center has been engaged in four different categories of partnership activities:

i. Industrial Partnerships: Foremost in the Center's knowledge transfer goals, as noted above, is 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, H-P, IBM, Intel, Lam Research, supported the proposal to NSF to fund the Center for E^3S and has continued to participate in the Center's Industrial Research Board. In Period 3, Applied Materials joined the Center as an industry member. The Center used the opportunity to formalize the membership process. We executed a membership agreement and a confidential agreement with Applied Materials. We also asked the industry members that have been with the Center since inception to execute confidential agreements; 3 out of 4 have completed the agreement.

ii. Industry Research Partnerships: Theme III has utilized industry partnerships to complement the Center's research activities. (i) There is an active research partnership with the Silicon Photonics group at Intel. Our contacts are: Drs. Hai-Feng Liu and Botros Youssry. Intel's interest is in the potential impact of nanophotonic devices. They have provided matching support for the nano-photodetector project of $60K. This is part of Intel's university programs on "Silicon Photonic Devices for High BW Low Power Optical Interconnects". **M.C. Wu**, the responsible faculty, and his group have interacted with the researchers from Intel's Si photonics group regularly. (ii) The SHE Nano-LED project has used MOCVD grown III-V materials structure from Dr. Liming Zhang of Bell Labs, Alcatel Lucent. Alcatel Lucent is not an industry member of the Center, but the Center is benefiting from M.C. Wu's long-term relationship with Dr. Zhang.

iii. International Research Partnerships:

- We are continuing to leverage the relationships with the international researchers who served on the organizing committee of the 2nd Berkeley Symposium on Energy Efficient Electronic Systems. (i) **E. Yablonovitch** was a speaker at the International Symposium on Development of Core Technologies for Green Nanoelectronics in Toyko at the invitation of N. Yokoyama, the head of the Green Nanoelectronics Center (GNC), the organizer of the conference. This conference featured the research of the GNC, which is a research center that is funded Japan's FIRST Program and is a part of Japan's National Institute of Advanced Industrial Science and Technology. Through this visit, the Center for E^3S learned more about research that has relevance to Theme IV. (ii) The Center for E^3S continued to work with A. Ionescu, the project coordinator of STEEPER, a European research consortium with a focus on "steep subthreshold slope switches for energy efficient electronics". **E. Yablonovitch** was an invited speaker at the STEEPER workshop in France. He also gave talks at EPFL, Switzerland and IBM Zurich Labs; both are participants of the STEEPER project.

- **J. Yuen** provided marketing and registration support to the Guardian Angel (GA) Workshop on Zero Power Technologies for Autonomous Smart Systems in San Francisco. This San Francisco workshop and another in Boston were organized by the Guardian Angel Consortium, an EU organization, in collaboration with the Consulate of Switzerland. Four E^3S faculty were speakers at the San Francisco and Boston workshops; see Section *IV. Knowledge Transfer*. Potentially, there can be synergy between the Guardian Angel project and the Center.
- **C. Hu** has initiated a research partnership with E. Chang, a professor at National Chiao-Tung University in Taiwan, who support the Theme I GaSb TFET project with material growth and characterization. In addition, it is expected that a student or postdoc from the Chang group will come to Berkeley to participate in the device fabrication efforts. This was the result from a visit by a delegation of deans from Taiwan in 2011; an event that was reported in the Center's Period 2 annual report.

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

- Material Growth for Theme I: B. Bennett, Army Research Laboratory; S. Krishna, University of New Mexico; and R. Droopad, Texas Tech University
- TFET Modeling for Theme I: M. Luisier, ETH, Zurich

v. Education and Diversity Partnerships: Partnerships with established programs that are external to the Center, but internal to Center's member institutions, have been a key factor that has contributed to the successes of the Center's Education and Diversity endeavors.

- *Continuing Partnerships*
  - 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 **D. Antoniadis** and **V. Bulović** being involved in Period 2's diversity programs. This partnership has remained intact and has strengthened through monthly teleconferences with **I. Porro**, Outreach Programs Officer for the OEOP, and OEOP's participation in the Center's Annual Retreat. In Period 3, I. Porro was the featured speaker on online education at the Center's retreat; see Section *VII.2*. **S. Artis** also participates in quarterly teleconferences with **M. Orta**, Assistant Director, Diversity Initiatives and MIT Summer Research Program. To further the collaboration between E^3S and MSRP and to enhance the selection process for placing E^3S summer research interns at MIT, E^3S and MSRP developed a joint application this year for the summer research program.
  - Berkeley: The Center has leveraged partnerships with several organizations at Berkeley. While the following paragraphs provide information on the activities with the partners, it must also be recognized that as the Center's staff continues to receive invaluable advice, help

and information from individuals in the partner organizations have accelerated the ramp up of the Center's Education and Diversity efforts.

a. 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.

b. Center of Integrated Nanomechanical Systems (COINS): In Period 2, the Education Director of this NSF-funded NSEC, **M. Erol**, was instrumental in helping the Center start its first REU program. During Period 3, we have continued to partner with COINS in various capacities. E^3S and COINS partnered in recruitment efforts for prospective graduate students and summer research interns, professional development seminars and lab tours for the REU programs, and hosting students in the TTE REU program. In addition, they both attended the *Implementation of Research Experience for Undergraduates Science Communication Workshop (iREU Science Communication Workshop)* sponsored by the Museum of Science, Boston. The purpose of the 4-day train-the-trainer program was to train REU program directors on how to implement and facilitate the Research Experience for Undergraduates Science Communication Workshop (REU-SCW) that are designed to: encourage students to explore the broader context of their research; guide them in developing professional science communication skills; enhance their confidence in pursuing careers in science and in speaking about science in a variety of settings. After the workshop, **M. Erol** and **S. Artis** teamed up as co-presenters of the topic of science communication to share their experience with Berkeley's Coalition for Education and Outreach.

c. Transfer Alliance Project (TAP): The Center partners with TAP for the Transfer-to-Excellence (TTE) programs for 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 Berkeley have been admitted. In 2010, nearly 300 TAP students were admitted to 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 transfer advising help to one TTE-REU student who lives in Southern California. 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. This year, **S. Artis** participated in CCCP's Summer Intensive Transfer Experience (SITE LITE) and Fall Saturday Academy as an invited speaker to present on transferring to a 4-year university and applying for summer research internships. Section *VI.2a* – Diversity provides details.

- *New Partnerships*

During Period 3, the Center continued to seek new partners based on the needs of our Education and Diversity programs. We established four new partnerships, three of which are at Berkeley. At Berkeley, the Center partnered with the Berkeley Foundation for Opportunities in Information Technology (BFOIT) and two NSF-funded centers, Synthetic Biology Engineering Research Center (SynBERC) and The Team for Research in Ubiquitous Secure Technology (TRUST). The Center also formalized a partnership outside of Berkeley with Mathematics, Engineering, and Science Achievement (MESA).

- Berkeley Foundation for Opportunities in Information Technology (BFOIT): BFOIT is a project of Berkeley's International Computer Science Institute that supports historically underrepresented ethnic minorities and women in their desire to become leaders in the fields of computer science, engineering and information technology. The intent is to provide youth with knowledge, resources, practical programming skills and guidance in their pursuit of higher education and production of technology. This summer, E^{3}S partnered with BFOIT during their Summer Institute for Future Computer Scientists at Berkeley**.** The summer institute is a two-week technology training program designed to train students in the process of inventing technologies and computer programming. During this program, students hear from many professionals about options open to them when they enter university and the work world. This summer, **S. Artis** was invited to be a speaker for the institute. She presented a talk tilted, *Perfecting Your Elevator Pitch for Admissions to Berkeley*. The Center also partnered with BFOIT for the Transfer-to-Excellence Program's (TTE) Leadership and Service Day. The TTE summer interns organized a science and engineering panel for 25 participants in the BFOIT Summer Institute for Future Computer Scientists at Berkeley. The event started with an icebreaker where the high school and community college students each shared personal experiences about their family, goals, and interest in science and engineering. Then the community college students served as panelists, sharing their experience in science and engineering with the high school students.

- Synthetic Biology Engineering Research Center (SynBERC): In Period 2, E^{3}S teamed up with SynBERC and COINS, a NSF-funded NSEC, to submit a REU Site proposal to expand the existing TTE REU program from 5 community college students to 15 students. In Period 3, the Center was awarded the REU Site with COINS and SynBERC, formalizing a three-center REU Site, where students could be hosted by faculty in E^{3}S, COINS, and SynBERC. This partnership allowed us to attract students from a broad range of science and engineering disciplines. Under the leadership of **T.-J. King Liu** and **S. Artis**, the education directors of each center jointly plan and oversee the TTE REU program. The partnership has led to joint lab tours, professional development seminars, final presentations and poster session.

- The Team for Research in Ubiquitous Secure Technology (TRUST): In Period 2, E^{3}S had a strong partnership with TRUST, another NSF-funded, for center management. In Period 3, this partnership extended to the Center's education and diversity efforts. E^{3}S and TRUST partnered on lab tours, professional development seminars, and GRE preparation course. In addition, TRUST hosted a community college student that participated in the TTE REU Site program, of which S. Artis is the project coordinator.

- Mathematics, Engineering, and Science Achievement (MESA): MESA is a nationally recognized program for engaging thousands of educationally disadvantaged students so they can excel in math and science and graduate with math-based degrees. For over 40 years, California MESA has partnered with all segments of California higher education as well as K-12 institutions. MESA has a proven track record in producing math-based graduates by providing support such as classes, hands-on competitions, counseling, transfer support and a community environment to students from middle school through four-year college. The

Center partners with MESA to recruit talented community college students for the TTE programs. This year, **S. Artis** and **J. Yuen** participated in California MESA's Spring and Fall Student Leadership Conference as invited speakers to present on transferring to a 4-year university and applying for summer research internships. Section *VI.2a* – Diversity provides details.

2b. *Outcomes and Impact*

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

2c. *Performance Against Metrics*

Objective	Metrics	Targets	Period 3 Results
Knowledge Transfer	Number of contacts with industry	Period 2: 18 Period 3: 36	Period 2: 66* Period 3: 20* Average: 43**

* 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.

** The number of contacts with industry is highly influenced by the activities of the Center, as by the Center's Symposium on Energy Efficient Electronic Systems. We think that a running average may be a better reflection of our performance.

2d. *Partnerships Plans for Period 4*

Partnerships with industry will continue to be the key strategy in Knowledge Transfer. The Theme III team will sustain and expand its parallel research engagement with Intel Research Labs. Another emphasis will be to expand the Center's industry partnership to include additional companies, particularly mid-size companies. We will continue to develop international research collaborations.

As the Center accelerates its online education and outreach activities, partnering with experts in online teaching platforms and multimedia tools will help jump start the Center's efforts.

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 attend university and graduate programs in technical disciplines that will contribute to low energy electronics; and
- promote continued interest in the E^3S research areas among Center participants and alumni.

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. Given the Center's existing demographics, enhancing the diversity of the participants in the Center's programs that will grow the pipeline of these aforementioned underrepresented groups is a critical focus. Accordingly, many of the Center's educational programs also have a strong diversity focus. The diversity activities being pursued involve and/or impact many levels: postdocs, graduate students, undergraduate students, and high school students.

Since its inception, the Center's diversity strategy includes initiating new pipeline programs as well as collaborating 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. E^3S programs practice the approach of challenging the participants as well as providing a supportive environment that recognizes and enhances individual professional aspirations.

One distinctive focus of the Center is community colleges in California, which is an educational destination of choice for many ethnic minorities, women, and first generation college students in the state. In addition, the California community college system is the largest in the US. The Center's focus in community colleges is currently reflected by two California community colleges, Contra Costa College and LA Trade-Technical College being education partners of the Center. In Period 2, we started new programs to service community college students. Another focus is to develop programs to address gaps in the pipeline. In Period 3, we have designed and implemented a program to provide gateway experiences to students who otherwise, are unlikely to be candidates for E^3S programs.

Beginning in fall 2012, the Center has also committed significant resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. We believe this approach ensures that these programs will have access to competitive candidates and highly qualified participants, regardless of race, color or gender.

Period 2 was the start of the Center's Diversity endeavors, while in Period 3 E^3S has fully implemented these plans and is beginning to see positive outcomes from these efforts.

In this section, we are reporting the following of the Center's programs:

- Program status, if it has not been reported previously in the Education section;
- The diversity profiles of all programs;
- The Center's value add to pre-existing programs;
- Outcomes of program alumni, should they be available; and
- The Center's recruiting efforts.

1b. Performance Metrics

At the end of Period 2, we recognized the need to refine our targets to better track the progress of the Center's diversity programs. Thus, the targets for some of the diversity performance indicators are revised and here are the metrics in the Center's current Strategic Plan.

Objective	Metrics	Frequency	Targets
Diversity	Number of underrepresented minorities participating in the Center's research programs	Annually	Period 2: Baseline Period 3: 15% increase Period 4: 5% increase Period 5: 5% increase
	Number of women participating in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 5% increase Period 5: 5% increase
	Number of diversity program participants from groups underrepresented in STEM	Annually	Period 3: Baseline
	Number of pre-college students who pursue a bachelor's degree in science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 10% Period 5: 15%
	Number of community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 10% Period 5: 15%
	Number of undergraduates who pursue advanced degree in science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 10% Period 5: 15%

1c. Problems Encountered

This is the second year offering the Transfer-to-Excellence Cross-Enrollment program (TTE X-Enroll) for California community colleges in the Bay Area. The program enables community college students to take a science, math or engineering course at Berkeley. Tuition is free for the student, who also receives a stipend for books and transportation at the start of the course, tutoring, if necessary, and an incentive stipend upon completion of the course with a grade of B+ or better. In our first year, we only had one participant. In Period 3, the second year of the program, we again, had only one participant. As a result of the low number of applicants and participants, the Education and Outreach Director met with community college faculty, advisors, and students to learn more about student's interest in taking courses at a 4-year institution. During these meetings, the Center learned a couple of reasons for these opportunities are not attractive to students. One reason is that some students are intimidated by the courses at Berkeley and do not want to lessen their chances of getting admitted into a 4-year institution by possibly receiving a low grade in a Berkeley course. Second reason is that some students prefer to work during the summer. With this new information in hand, in Period 4, we will consider whether the TTE X-Enroll program can be revamped to make it more attractive to community college students. We will seek input from local community colleges as we consider how to increase enrollment in TTE X-Enroll.

2a. Development of US Human Resources

In Period 3, the Center has focused on refining and formalizing the process and implementation of existing diversity programs. The Center plans to maximize its education and research programs by including a strong current diversity focus. The Center continues to partner with 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 has further developed 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. The Center continues to lead on-going strategic planning meetings with representatives from diversity programs at Berkeley, MIT, Contra Costa College, Los Angeles Trade-Technical College, Mathematics Engineering Science Achievement (MESA), Berkeley's Transfer Alliance Project (TAP), and UCLA's Center for Community College Partnerships (UCLA CCCP) 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 Berkeley's Summer High-School Apprenticeship Program (SHARP), MIT's Minority Introduction to Engineering and Science (MITES) and MIT Online Science, Technology, & Engineering Community (MOSTEC) programs. 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 12th grade high school students
Approx Number of Attendees (if appl.)	Total: 3 Females: 2, URM: 1

SHARP: The Summer High-School Apprenticeship Research Program (SHARP) was launched in 2007 at Berkeley by C. Chang-Hasnain who is currently the Associate Director of Education of the Center for E^{3}S. In this program, a high school student spends four weeks conducting hands-on scientific investigations at 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 80 SHARP participants (SHARPies) have completed the program and all have enrolled in 4-year universities. About 85 graduate students from 20+ laboratories and 10 departments at Berkeley have participated as mentors. SHARP participants have included 45% female and 15% underrepresented minorities. In 2012, SHARP admitted a group of 12 rising seniors selected from an applicant pool of about 250 from ninety high schools spread throughout the U.S., with the cohort representing 9 schools in the SF Bay Area and New England.

E^{3}S' Impact on SHARP: In Period 3, the Center's focus is to support participation by high school students who are women and/or from under-represented communities. Three SHARPies out of the 12 in the 2012 class were designated as E^{3}S interns. Each SHARPie successfully completed the research program in an E^{3}S faculty member's research group (**C. Chang-Hasnain** and **E. Yablonovitch**) and presented an oral research progress report with an accompanying PowerPoint presentation. Another contribution of E^{3}S to the SHARP program is formal training of the mentors in mentoring and project management led by S. Artis. This past summer is the second summer that **S. Artis** has provided such training to graduate student mentors in the SHARP program.

Activity Name	MIT Minority Introduction to Engineering and Science (MITES) - Electronics Elective
Led by	**S. Young** (MIT), **S. Artis** (Berkeley),
Intended Audience	Rising 12th grade high school students
Approx Number of Attendees (if appl.)	Total: 12 Females: 5, URMs: 11

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 2,000 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, 43 of the 80 students (61%) in the MITES 2011 class were accepted to MIT and 34 of those students are currently freshmen at MIT.

E^{3}S' Impact on MITES: Summer 2012 was the fifth time that the electronics course was offered in MITES. The course is a typical 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% males and 42% females. Among this class, 92% of the students were from underrepresented minority groups. Per a post-program survey, students that participated in this Electronics course expressed a considerably higher interest in majors in Engineering, Computer Science and Mathematics, than for the whole MITES group. 83% of the Electronics students are very interested in a major in engineering, versus 64% for the entire group, 58% are very interested in a major in Computer Science and 42% in Mathematics to be compared with 38% and 31% respectively for the overall MITES group.

The instructors for this course were students at *MIT*; **J. Steinmeyer**, a Ph.D. student in Electrical Engineering, **B. Wu**, undergraduate student in electrical engineering, and **H. Li**, undergraduate student in material science.

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**S. Young** (MIT), **S. Artis** (Berkeley),
Intended Audience	Rising 12th grade high school students
Approx Number of Attendees (if appl.)	Total: 82 Females: 53, URMs: 66

The MIT Online Science, Technology, and Engineering Community (MOSTEC) program was initiated by MIT's OEOP. During the Center's Period 2, the Center increased funding to MIT's OEOP to be one of the founding contributors of the program. Now in its second year, MOSTEC is 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 complete online coursework and projects in science, engineering, and technical writing during the summer Academic Phase (July – August). When the summer ends, students enter the Enrichment Phase (August – January) and continue to learn more about science and engineering, interact with college faculty and staff, and receive online mentorship from undergraduates, graduate students, and industry professionals. In addition, in August 2012, 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.

The Center supported 82 students participated in the electronics workshop at the MOSTEC Conference. The electronics workshop was composed of 35% males and 65% females. Among this group, 80% of the students were from underrepresented minority groups. This workshop was adapted from newly created material for the MITES electronics course, leveraging the Center's earlier efforts. Results from evaluation show that of students reported a very positive impact of the workshop in helping them understand engineering and electrical engineering better (80%), in making them consider an engineering major in college (65%), and in strengthening their confidence in being successful in this effort (60%). In the fall, 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 3, 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 Berkeley to undertake a science or engineering research project hosted by a 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 Berkeley. Tuition is free for the student, who also receives a stipend for books and transportation at the start of the course, tutoring, if necessary, and an incentive stipend upon completion of the course with a grade of B+ or better.

While at 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 Berkeley's 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), **T. J. King** (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	Total: 5 Females: 1, URMs: 3

TTE REU: In summer 2011, the Center hosted 2 community college students in the TTE REU program. These two students are now juniors at a 4-year institution. One student is a joint major in electrical engineering and computer sciences and material and science engineering at Berkeley. The second student is majoring in biochemistry at UCLA.

Our 2011 experience with community college students exposed us to the need to expand the breadth of technical disciplines in REU opportunities, because many community college students are still exploring their niche within the wide world of STEM majors. Thus, in Period 2, the Center initiated a novel collaboration with two NSF-funded centers at Berkeley, Center of Integrated Nanomechanical Systems (COINS), a Nanoscale Science and Engineering Center; and Synthetic Biology Engineering Research Center (SynBERC), an Engineering Research Center, to offer a wider range of energy-related REU opportunities. Besides three NSF funded centers, the collaboration also includes Berkeley's Transfer Alliance Project (TAP) to provide transfer-advising support. E^3S faculty and staff, **T.-J. King Liu** and **S. Artis**, as PI and Co-PI respectively, submitted a REU Site proposal to NSF. In Period 3, NSF awarded a REU Site to serve California community college students. This additional funding augments the Center's own funding, increasing the Transfer-to-Excellence REU program's participant capacity and more importantly, the variety of available research opportunities focused on the grand challenges in energy.

This summer (2012), the Center at Berkeley hosted 5 of the 14 community college students in the TTE REU program. These students completed eight weeks of research in the labs of the Center's faculty **(T.-J. King Liu, C. Hu,** and **J. Wu)** and E^3S Education Affiliates **(A. C. Arias** and **O. Dubon)**. Education Affiliates are not part of the Center's funded 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, to give us an even wider range of research experiences to community college students. Moreover, with the large number of summer education and diversity programs hosted by the Center and the small number of Center faculty at 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. **A. C. Arias,** an Associate Professor of Electrical Engineering is in her second year as an Education Affiliates of the Center, while **O. Dubon,** an Associate Professor of Materials Science, and the Associate Dean of Equity and Inclusion, College of Engineering joins the Center as an Education Affiliate in Period 3; both are with Berkeley.

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. In addition to research, TTE participants were trained on scientific ethics, technical presentations, and science communication, and 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. At the conclusion of the TTE REU, the students presented a technical talk to their peers, graduate students and postdoc mentors, and faculty; and participated in the poster session. After completion of the summer program, TTE continues to provide students with transfer-advising support. Northern California students receive support from a TAP counselor, while the LA-based student receives support from UCLA CCCP. The support given by UCLA CCCP is in the form of formal enrollment into CCCP's Scholars' Program.

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

TTE X-Enroll: This program at Berkeley is initially targeted at community colleges in the Bay Area. In the first year, we utilized the partnership with Berkeley TAP, recruiting from the community students that TAP has been mentoring.

In summer 2011, the Center hosted 1 community college student in the TTE X-Enroll program. This student is now a junior majoring in Chemical Engineering at Berkeley. He also is recipient of the Regents' and Chancellor's Scholarship, the most prestigious scholarship awarded by the University of California, Berkeley, to entering undergraduates.

This summer (2012), one student from Napa Valley College participated in TTE X-Enroll, successfully completing a 4-credit lower division chemistry 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 Berkeley's 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.

Summer Research Programs for Undergrads from 4-Year Institutions: The Center hosts a Summer REU program at Berkeley and MIT and a Summer Research Workshop at Berkeley. The primary goal of our programs 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^3S Research Experiences for Undergraduates at Berkeley (E^3S REU)
Led by	**S. Artis** (Berkeley), **E. Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx Number of Attendees (if appl.)	Total: 11 Female: 3, URMs: 4

The Center's summer research program received over 100 applications. Nine of these students were matched with Center faculty at Berkeley and two were matched with faculty at MIT. At Berkeley, successful completion of the 9-weeks, hands-on research on an E^3S project at the laboratory of an E^3S faculty (**J. Bokor, C. Chang-Hasnain, C. Hu, T.-J. King Liu, R. Ramesh, S. Salahuddin, M.C. Wu,** and **E. Yablonovitch**) enabled the students to earn one Berkeley academic credit. At MIT, successful completion of the 9-weeks, hands-on research on an E^3S project with a team of E^3S faculty (**V. Bulović, J. Lang,** and **T. Swager**) enabled the students to earn a certificate of completion. 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) completed a two-hour science communication training; (iii) participated in a designated Leadership Day, where students served on a panel to share their research experience with prospective undergraduate researchers. 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.

Activity Name	E^3S Hands On Practical Electronics Summer Research Workshop (E^3S HOPE SRW)
Led by	**S. Artis** (Berkeley), **J. Bokor** (Berkeley)
Intended Audience	1st and 2nd year undergraduate students
Approx Number of Attendees (if appl.)	Total: 8 Female: 4; URMs: 5

In Period 3, the Center introduced a new program, the E^3S Hands On Practical Electronics Summer Research Workshop (E^3S HOPE SRW). The goal of the E^3S HOPE SRW is to prepare lower-division undergraduates, including community college students, for future research opportunities. This program was designed to meet the needs of students who do not have research opportunities at their undergraduate institution. The one-week residential program at Berkeley: provides hands-on laboratory experience, exposes participants to the field of and careers associated with energy efficient electronics science, shares information on where and how undergraduates can secure summer research opportunities, and motivates students to set their academic goals to pursue graduate studies in science and engineering.

This summer, we had 8 participants (50% females, 50% URMs) in the E^3S HOPE SRW. The workshop included four days of intense learning led by instructor, **S. Soleyman**, an undergraduate student in EECS at Berkeley. The curriculum included modules on: electronic circuits, capacitors and signals, and semiconductors. These modules were supplemented with hands-on application. The students designed a running bug and power amplifiers. The students also participated in daily lunch and learn activities. **J. Yuen** presented on the Center's research themes projects. The students also had a question and answer session with **E. Yablonovitch** to learn more about the science of low-energy electronic devices. The students participated in two lab tours. They toured the Marvell Nanofabrication Laboratory, which was led by **W. Ko**, a Berkeley graduate student E^3S. Berkeley graduate student, **H. Fang**, led a tour of the Javey Research Lab, where students learned about two-dimensional materials for electronic applications. At the conclusion of the program, the students participated in a workshop to prepare for undergraduate research, met with students in our E^3S REU to learn more about their research projects, and attended a Poster Session that featured the energy related research projects of the E^3S and TTE REU interns.

- *Teacher Programs*

Activity Name	E^3S Research Experiences for Teachers (E^3S RET)
Led by	**J. Yuen** (Berkeley) and **S. Artis** (Berkeley)
Intended Audience	Community college professors
Approx Number of Attendees (if appl.)	Total: 1 URM: 1

With the Center's focus on creating a pipeline of community college students to pursue a baccalaureate degree in science and engineering, it is imperative for the Center to engage community college faculty. These are individuals that can further integrate E^3S science and research findings into the community college curriculum, which will increase community college students' awareness and knowledge about low-energy electronic devices. In Period 3, the Center hosted **M. Diaz**, a chemistry professor from Los Angeles Trade-Technical College, for an eight-week research experience, in our E^3S Research Experiences for Teachers program (E^3S RET). The professor completed a research project in the laboratory of **J. Wu,** an E^3S Materials Science Faculty, and was mentored by a postdoctoral fellow in the J. Wu Group, and developed plans on introducing his experience into classroom teaching at his home institution. To support the development of education transfer plan, the E^3S RET fellow joined a cohort of 11 other in-service teachers who were also doing research at Berkeley through three other programs. This cohort was supported by a coach from Industry Initiatives for Science and Math Education (IISME), a non-profit consortium that seeks to transform teaching and learning through industry-education partnerships. The coach provided a process and met with the teacher fellows as they develop plans to adapt what they learned at Berkeley into their teaching. Upon return to the community college, the E^3S RET fellow is expected to incorporate journal clubs in the existing curriculum, and introduce 2-dimensional materials to laboratory experiments, subject to availability of equipment.

- *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, E^3S collaborated with another NSF-funded Center, COINS, and Berkeley's College of Engineering to recruit for the Center's diversity programs targeting students at 4-year institutions. Among the three organizations, 24 universities were visited and 5 diversity conferences were visited (See **Appendix G: Joint Recruitment Calendar**). For the university visits, **S. Artis** and **J. Yuen** conducted graduate preparation workshops and information sessions. These activities were typically one-hour presentations on the Center's research themes and diversity programs and on how to prepare for graduate school. At the diversity conferences, the Center sponsored a booth at the graduate fairs for prospective undergraduate and graduate students to meet Center members and to learn about the Center's research areas and opportunities for undergraduate and graduate students and postdocs.

For the Center, **S. Artis** and **J. Yuen** visited 17 universities: California State University at Fullerton, California State University at Long Beach, City College of New York, Hampton University, Montclair State University, Morgan State University, New Jersey Institute of Technology, Norfolk State University, Rutgers University, UC Davis, UC Irvine, UCLA, University of Maryland, University of Puerto Rico at Mayaguez, University of Puerto Rico at Rio Piedras, University of Southern California, and Virginia Tech. Among this list, 7 of these universities are minority-serving institutions. In addition, E^3S partnered with several organizations to host these university visits: Emergent Behaviors of Integrated Cellular Systems Center (EBICS), a NSF-funded Science and Technology Center; Louis Stokes Alliances for Minority Participation (LSAMP), a NSF-funded research program; Minority Access to Research Careers (MARC), a NIH-funded research program; American Institute of Chemical Engineers (AIChE); Institute of Electrical and Electronics Engineers (IEEE); and National Society of Black Engineers (NSBE). The Center also sponsored booths at two diversity and graduate fair conferences: National Society of Black Engineers (NSBE) and Society of Women Engineers (SWE). For a complete list of these recruitment and public outreach events, see **Appendix H: Summary of Diversity-Enhancing Activities**.

In Period 3, the Center increased its recruitment efforts for the Transfer-to-Excellence (TTE) programs targeting community college students (See **Appendix I: E^3S Transfer-to-Excellence Recruitment Calendar)**. **S. Artis** and **J. Yuen** were invited speakers at the following events: UCLA Center for Community College Partnerships' Summer Intensive Transfer Experience (SITE LITE) and Fall Saturday Academy, and Mathematics, Engineering, Science Achievement (MESA) Student Leadership Conference. They both led hands-on interactive workshops engaging students on topics related to strategies for being competitive applicants for transferring to a baccalaureate program in science and engineering. They also hosted information sessions about the TTE programs at Berkeley for Bay Area community college students and 3 California community colleges: Chabot College, Contra Costa College, and Sacramento City College.

S. Artis was also invited to speak to undergraduate students in 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 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, 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 2013).

The Berkeley Edge conference provided an opportunity to increase the number of master's and doctoral degrees granted to minorities at Berkeley. Berkeley Edge is designed to give prospective minority graduate students, and other students who find the program beneficial, an opportunity to visit Berkeley and the Bay Area and receive an overview of the graduate degree programs. In October 2012, 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 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 (October 2013).

In January, **S. Artis** is scheduled to be a cluster leader for Berkeley's College of Engineering's LeaderShape© Institute. The LeaderShape© Institute is an intensive, energizing, six-day educational experience designed to equip college students with the necessary qualifications to become extraordinary leaders. Each session of The LeaderShape© Institute has approximately 60 students from diverse backgrounds. As a cluster facilitator, S. Artis, will serve as the group's resource, catalyst and coach. This opportunity allows the Center to foster stronger relationships with Berkeley's Engineering Student Services and undergraduate leaders who can participate in the Center's research programs and courses.

- *Other Outreach and Diversity Activities*

Berkeley's Coalition for Education and Outreach (CEO): Our Center's administrative and programmatic staff is part of the larger community of Berkeley's employees with responsibilities in education and outreach. As indicated in previous discussions on the Center's activities, we constantly seek to collaborate with and leverage the effort of our campus colleagues. In Period 3, we participated and co-sponsored three events of Berkeley's Coalition for Education and Outreach (CEO). We are reporting two of them here as they relate to outreach and diversity. The third is reported in Section *IV. Knowledge Transfer*.

- The success of our undergraduate REU programs rests in a large part on the interest of the faculty to serve as hosts and advisors. Once again, in Period 3, Berkeley's Coalition of Educators hosted a panel on Broadening Participation to help junior faculty understand how they can use education and outreach to enhance the competitiveness of their proposals, particularly to NSF. **S. Artis**, E^3S Executive Director, and Kate Spohr, Education Manager of SynBERC, a NSF funded Engineering Research Center, jointly organized this panel. **J. Yuen**, E^3S Executive Director, and E^3S faculty, **S. Salahuddin**, were among panelists on last April's panel.

- The Center co-sponsored a CEO event where three individuals representing three university colleges, the College of Chemistry, Engineering, and Letters and Science, talked about the diversity strategies of their colleges. Two of the representatives were associate deans, including the Associate Dean of Equity of College of Engineering, the college that is hosting our Center.

E^3S Website: The Center disseminates information about all its education and diversity programs on its website. With respect to diversity, it is important for the Center to lead by example. As we have aspirations to target students with disabilities to participate in the Center's programs, we strive to design 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. In Period 3, the system administrator for the E^3S website has been working with the newly-established Web Accessibility Team at Berkeley, a team that promotes electronic environments that are welcoming and responsive to everyone, particularly individuals with disabilities. The team is led by Lucy Greco, the newly appointed "Web Access Analyst" at the campus' Technology Services organization. Ms. Greco, who is a visually-impaired activist for the disabled, and who uses assistive technology to navigate the Internet, recently assessed the E^3S website for access by the visually impaired.

- One key finding from the assessment is that the E^{3}S site was in better shape than many other sites. The positive elements include webpages that have adequate white space in the layout and distinctive sections for the electronic reader, called "Jaws", to be able to logically follow the content. Further, the Education section received extra points for having excellent navigation and heading structure. The team also commented favorably on availability of image descriptions in the form of alt tags.
- There were also, of course, areas for improvement. In particular, the electronic reader cannot “see” the 'fly-out menus' used in the navigation scheme of the website. Another issue is the use of vertical lines as separators between page links in navigational scheme at the bottom of every page. The electronic reader’s announcement of every vertical line it “sees” at the bottom every page, over and over again, is overwhelming to the user and should be corrected. Also, the search window lacks something called a 'field label', without which the reader does not know how to interpret the underlying javascript, resulting in the search capability being unavailable to the user.

Women in Engineering Proactive Network (WEPAN) Committee: **S. Artis** has continued to serve on the Women in Engineering Proactive Network (WEPAN) conference committee, as the local events co-chair and chair of the 2013 Annual WEPAN Conference. As local events co-chair, she was responsible for coordinating, organizing, hosting welcome dessert reception, local academic and industry tours, and dinner discussion groups. As chair of the conference, she is responsible for leading the conference committee to organize conference sessions, speakers, and entertainment and implement a successful annual meeting. WEPAN is a national non-profit organization that works to transform culture in engineering education to attract, retain, and graduate women. With a clear focus on research-based issues and solutions, WEPAN helps its members develop a highly prepared, diverse engineering workforce for tomorrow. **S. Artis’** involvement in this national position provides national exposure for the Center for E^{3}S and positions the Center to network and promote our opportunities to Women in Engineering Programs across the U.S.

First Take/Second Look: Exploring Unconscious Bias Workshop: **S. Artis** attended this workshop sponsored by Multicultural Education Program of Berkeley. The purpose of this workshop is to raise awareness through discussions of behaviors that might be problematic for others, as well as actions to be taken in response to bias behaviors. The outcomes of the workshop were to: 1) understand what Unconscious Bias is; 2) reveal the impacts and consequences of Unconscious Bias; 3) review how Unconscious Bias happens here on campus; and 4) be able to take actions in response to Unconscious Bias. **S. Artis** plans to use this training to develop diversity modules that will be integrated in the E^{3}S Professional Development Program.

2b. Impact on the Center’s Diversity

In Period 3, the Center has committed significant resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. We believe this approach ensures that these programs will have access to competitive candidates and highly qualified participants, regardless of race, color or sexual orientation. As a result, we are beginning to see positive outcomes from these efforts.

The Center has been able to successfully develop a pipeline of students at the pre-college and undergraduate level that have been exposed to energy efficient electronics science through research or lecture. Approximately, 82% (93) of our participants in the diversity programs come from underrepresented groups, including women and underrepresented minorities. Among the students who participated in our pre-college programs, approximately 68% (31) are pursuing a bachelor's degree in science and engineering.

For our upper-division undergraduate programs for juniors and seniors, the Center has had one student who graduates with a Bachelor's degree, who is now employed by a government research laboratory. The remaining students are still pursuing their bachelor's degree in science and engineering. This fall, over 50% of our E^{3}S REU alumni will be applying to graduate school this fall so we expect to see a significant number of our former REU participants pursing graduate study in science and engineering and science in Period 4. For our undergraduate programs targeting community college students, we've seen a significant impact on diversity. All of the alumni from the Transfer-to-Excellence (TTE) programs have transferred to a 4-year institution. Two former TTE students are currently enrolled in EECS/MSE and Chemical Engineering at Berkeley and one student is majoring in biochemistry at UCLA.

As shown in this section of the report, the Center put a high priority on diversity in Period 3. The Center leveraged existing partnerships nationally recognized pre-college and higher education programs and has formed new alliances to collectively tackle the challenge of building a diverse pipeline of students who will eventually contribute to a diverse workforce.

2c. Performance Against Metrics

In Period 3, 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 3 Results
Diversity	Number of underrepresented minorities participating in the Center's research programs	*Period 2: 2 (2%) Period 3: 15% increase Period 4: 10% increase Period 5: 5% increase	1 (2%)
	Number of women participating in the Center's research programs	*Period 2: 13 (22%) Period 3: 5% increase Period 4: 5% increase Period 5: 5% increase	15 (25%)
	Number of diversity program participants from groups underrepresented in STEM	Period 3: Baseline	93 (82%)
	Number of pre-college students who pursue a bachelor's degree in science and engineering	*Period 2: 20 (22%) Period 3: 5% Period 4: 10% Period 5: 15%	31 (68%)
	Number of community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	*Period 2: 0 (0%) Period 3: 5% Period 4: 10% Period 5: 15%	3 (100%)
	Number of undergraduates who pursue advanced degree in science and engineering	*Period 2: 0 (0%) Period 3: 5% Period 4: 10% Period 5: 15%	0 (0%)

*Baseline

2d. Plans in Period 4

In Period 4, the Center will streamline our diversity programs by following through on plans that we have made. In Period 3, the Center examined all diversity programs to ensure that the Center's portfolio was aligned with the vision and goals identified in the strategic plan. One of the major questions during this review was, *where could the Center have the greatest impact on diversity?* Given the Center's strong interest in broadening the participation of students interested in and aware of energy efficient electronics science, the Center decided to move away from localized programs and focus efforts on programs that are open to students across the country. This decision is resulting in replacing Summer High School Research Program (SHARP), a Bay Area research program, with MIT Online Science, Technology, and Engineering Community (MOSTEC), a national program for students from all over the nation. In Period 4, E^3S will have a larger role in the development of curriculum for MOSTEC.

As the Center moves toward streamlining our diversity programs, we will also focus on ensuring that our programs are scalable and transferable to member institutions as well as other universities. To provide programs that can be easily integrated into other educational infrastructure, the Center will design implementation guides that documents the framework of our programs, including program goals, objectives, learning outcomes, and targeted audience; application and selection material and procedures; recruitment calendar, flyer, and presentations; curriculum and/or training calendar and modules; and formative and summative evaluation questionnaires. The Center will analyze the programs to identify the lessons learned and translate these lessons into best practices that we can share through talks at conferences and publications in science and engineering education journals.

As the Center updates the E^3S website, we will take into account the findings of the assessment by the Berkeley *Web Accessibility Team* during Period 2. We will make changes to our navigation system and other identified issues to enable a higher quality visit for the visually impaired.

VII. MANAGEMENT

1a. Organizational Structure and Underlying Rationale

In Period 3, the Center is organized similarly as in the previous reporting period. **Appendix A** gives the current organizational chart. The Center's leadership team comprises the following:

- Executive Committee: The Center is led by a leadership team, the Executive Committee, 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.

  During 2012, M.C. Wu was on academic leave and was excused from his duties as an Executive Committee member. The committee made decisions based on a 9 member board.

- Administrative and Programmatic Team: The Center has a team of full-time personnel who are responsible for the Center's operations and programmatic activities. This team, led by **J. Yuen**, Executive Director, includes three additional full time positions and one part-time position in Period 3. One full time position continues to be vacant; see *Section VII.1d*.

- Theme Leaders: Each Research Theme is led by a Theme leader.
  - Theme I: **E. Yablonovitch**
  - Theme II: **T.-J. King Liu**
  - Theme III: **M.C. Wu**
  - Theme IV: **J. Bokor**

In Period 3, **E. Yablonovitch**, as the Center Director, met with Themes II and IV to guide the Theme's future direction and technical approaches. While M.C. Wu was on academic leave in 2012, he continued to play the role of the Theme Leader of Theme III.

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly	Yearly
Center Management	Centerwide Communications	Yearly	1 newsletter Annual Retreat Annual NSF Review Updated website
	Number of disputes	Yearly	Period 2: Baseline Annual decrease
	Annual Surveys:	Yearly	3 or higher on Likert

	• External Advisory Board		Scale
	• External Advisory Board		
	• External Advisory Board		
	Authorship disputes	Yearly	Period 2: Baseline 20% decrease annually
	Plagiarism	Yearly	

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

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

Student and Postdoc Perception of Center's Leadership Team: The student and postdoc survey (**Appendix L**) was administered for the second time at the Annual Student and Postdoc Retreat in Period 3. The survey asked about students and postdocs' perceptions about the Center's leadership, including research experience, diversity, inclusiveness, communication, collaboration, ethics, decision making, and performance. We also used this survey to measure the understanding the postdocs and students have of the Center's mission.

Co-PIs Perception of Center's Collaboration, Ethics, and Leadership Team: The faculty survey (**Appendix M**) was administered at the end of Period 2 and completed in Period 3. The survey asked about faculty perceptions related to the degree of collaboration with others at the Center, the leadership and ethical behavior exhibited by the Center management, and their self-rating about their own contribution in terms of leadership and ethical behavior. Results of the survey are reported for three key areas in the strategic plan: leadership, collaboration, and ethics.

1c. Performance Against Metrics

Objective	Metrics	Targets	Period 3 Results
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly	Dec 19, 2012
Center Management	Centerwide Communications	1 newsletter Annual Retreat Annual NSF Review Updated website	June 2012 Aug 21-22, 2012 Jan 9-10, 2012 Continuously
	Number of disputes	Period 2: Baseline Annual decrease	0
	Annual Surveys:	3 or higher on Likert Scale	

Center for Energy Efficient Electronics Science

	• Students / Postdocs		Average: 4.04
	• Co-PIs		Leadership: 4.46 Collaboration: 3.25
	• External Advisory Board		Strategic Plan: 4.07 Accomplishments: 3.96
	Authorship disputes	Period 2: Baseline 20% decrease annually	0
	Plagiarism		Ethics Survey: 4.39

The results from the Student and Postdoc Survey and the Co-PIs Survey were reviewed by the Executive Committee and reported to the Center members at the Annual Retreat. Areas of improvement and recommendations were discussed for implementation. Next year, the Center will administer this survey with slight modifications and compare results from Period 3 and 4, looking for improvement trends.

- *Student and Postdoc Perception of Center's Leadership Team:* The results from the Period 3 survey are given at the end of **Appendix L**. We also analyzed the data by comparing results of the Period 3 survey with the results from Period 2.

  To assess the students and postdocs' research experience, the students and postdocs were asked three questions about the Center's research. Majority of the students and postdocs agreed or strongly agreed that the Center is making progress in its research and identifies concepts and scientific principles that will enable fundamentally new and different science for digital information. Similar results were concluded about their understanding of how their project fits into the goals and vision of the Center. Compared to Period 2, Period 3 results show that students have a better understanding of the Center's research portfolio and how the projects fit into the big picture of achieving a radical reduction in energy consumption in electronics devices.

  For diversity and inclusiveness, the Center members were in strong agreement that the Center educates a diverse generation of scientists and engineers and provides a research environment that is inclusive of different institutions, research themes disciplines, and individual differences. In Period 3, more students and postdocs strongly agreed to these statements on diversity and inclusiveness.

  The survey also assessed the students and postdocs' perception of the Center's culture of communication and collaboration. Most of the students and postdocs agreed or strongly agreed that the Center keeps members well informed through clear and timely communications and provide a collaborative environment that crosses disciplinary and institutional boundaries. Similar to other areas evaluated, in Period 3, there was an increase in the number of students and postdocs stating that they strongly agree.

  For ethics and responsible conduct of scientific research, the majority of the students agreed that the Center promotes good behavior. The students and postdocs rated the Center's leadership as effective and agile in making decisions on behalf of the Center. They also agreed or strongly agreed that the Center's leadership team promotes a culture that permeates the Center's relationships, process, and activities that recognizes and values performance and avoids possessiveness. These results were similar in Periods 2 and 3.

- *Co-PIs Perception of Center's Collaboration, Ethics, and Leadership Team:* See **Appendix N** for the executive summary for the faculty survey.

  Overall, the results of the faculty survey indicate that the Center has created a strong culture for leadership, collaboration, and ethics. For leadership, the faculty indicated strong support for Center management. They felt that the management exhibited ethical behavior and made decisions that were in the best interest of the Center's aims and goals. Respondents indicated that they received communication in a timely manner from the leadership team and that the leadership team created an environment that valued teamwork. In terms of being evaluated, faculty felt that they were being rated on a performance-based evaluation system and that the leadership team recognized their efforts. With regard to the degree of collaboration among Center partners, data reveals that there are 'pockets' of interaction and collaboration. Faculty seemed to cooperate with one another and share ideas, especially within theme areas. For ethical behavior, faculty indicated they received adequate training in ethical behavior and standards. Faculty rated themselves highly with regard to their own ethical decision making. They also felt they contributed to a work environment that encourages cooperation and communication, valuing these aspects of the workplace.

1d. Problems Encountered

The hiring of a program manager to support diversity initiatives has been delayed, despite significant recruiting efforts. Nevertheless, this vacancy has not impeded the Center's fulfillment of its Education and Diversity objectives. As shared in the Period 2 annual report, the Center has the requisite skills to support its Education and Diversity programs. In Period 3, the Center's Executive Director and Administrative Manager have continued to share some of the Education and Outreach responsibilities with the Education and Outreach Director.

Our search to fill this vacancy, Manager of Diversity Programs, is continuing. We expect that this position will be filled by the end of the current reporting period.

2. Management and Communications Systems

The Center's potential will be maximized when its members is coordinated to achieve synergy. Timely communication among Center faculty, postdocs, students and staff is key in enabling this outcome. Activities of the Center enable information sharing, common understanding, coordination, planning and decision making. We complement the activities with a website and a newsletter. Figure 66 provides a 12-month view of Center's communications, coordination and decision making venues in 2012.

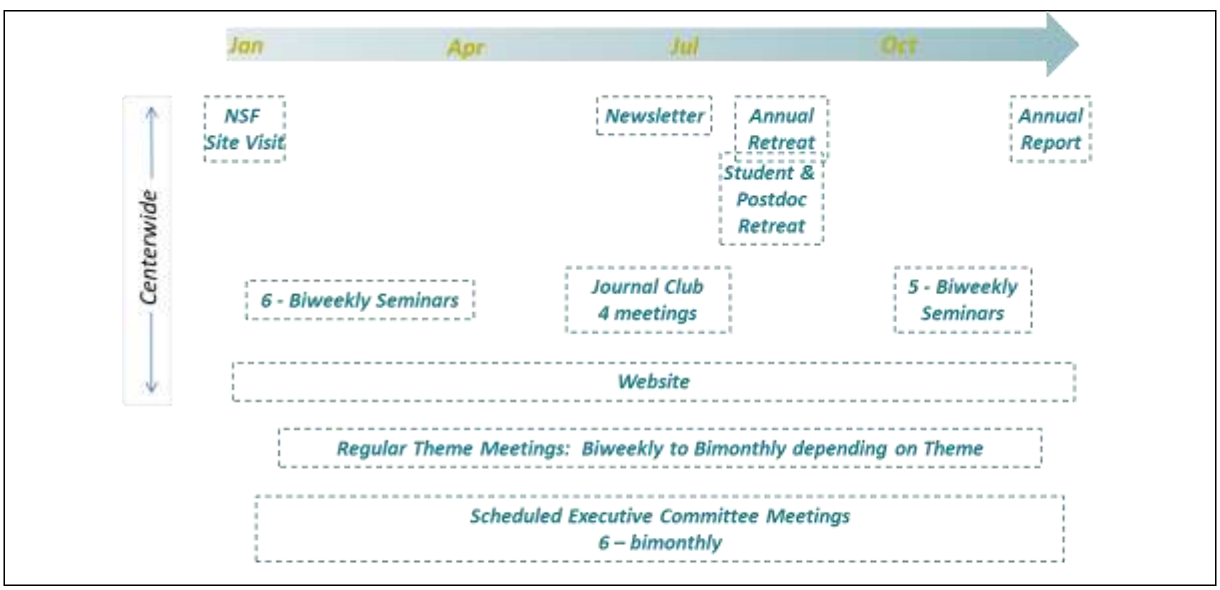

Figure 66: A 12 month view of the Center's venues to enable communications, planning and decision making.

Executive Committee Meetings: In Period 3, the Executive Committee continued to operate in accordance with the management processes that were established in Period 2. These processes include Executive Committee By-Laws, Code of Conduct, Regular Executive Committee meetings with pre-announced agendas and meeting minutes, and an annual process to determine the funding of research and programmatic activities for the following period. These processes were shared previously in the Period 2 annual report.

The following is a list of six Executive Committee meetings that were scheduled in Period 3. All meeting are held via videoconferencing.

Executive Committee – Period 3 Meetings	
Meeting Dates	**Agenda Topics**
April 12	*New*: E^3S Faculty Survey Results, External Advisory Board Membership, International Collaboration, Broadening MSI participation
May 15	*New*: Period 3 Budget Review, Review of the 2012 Education and Diversity Programs, Conference Sponsorship Policy, Policy on Spending Authority of Center Director and Deputy Center Director *Carry Over*: Broadening MSI Participation
July 2	*New*: Review of Research, Strategies for Increasing Student Participation in Programmatic Activities, ETERN Program Policy *Carry Over*: External Advisory Board Membership, Broadening MSI Participation
August 30	*New*: Annual Meeting Debriefing, Review of Industrial Research Board Input, Engaging Industry Members
October 8	*New*: Review of Proposals for Period 3 Funding
December 17	*New*: Review of Strategic Plans and Results, Review of External Advisory Board Report, Preparation for NSF Site Visit *Carry Over*: Broadening MSI Participation

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

Newsletter: In Period 2, as we reviewed the results from the postdoc and student perception survey, we recognized that the opportunity for improvement is communications. Thus, we decided to add a newsletter to our arsenal of communication venues. The first issue of the newsletter (**Appendix J**) was released at the end of June 2012.

Center's Annual Retreat: The 3rd Annual Center-wide Retreat was held on August 21-22 at MIT with the theme of "Midpoint Review"; the agenda is given in **Appendix B**. The two-day meeting was attended by the Center's faculty, postdocs, graduate students, staff, education and diversity partners and industry members. The first day was devoted to research presentations and discussions, while the second day was devoted to internal assessment of the Center's progress and discussions of the competitive landscape. The meeting also offered the opportunity for the industry members who make up the Center's Industrial Research Board to provide input to the Center, as well as for the Education Committee to meet. The

Retreat included a recognition ceremony when the Center's faculty, postdocs and students were thanked for their support of the Center's programmatic activities.

Seminars and Journal Club: The E^3S seminars and the Journal Club are both communication as well as education venues. As they are also vehicles for education, they have been discussed in Section *III. Education*.

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 3 activities for each group.

- *External Advisory Board (EAB)*: In Period 3, the E^3S External Advisory Board continued to be governed by a charter that was adopted by the E^3S Executive Committee in 2011; see page 156 of the Period 2 Annual Report. In Period 3, the E^3S Executive Committee appointed four new EAB members and excused one member who could no longer serve due to research collaborations with the Center. A larger EAB will not only allow a diversity of viewpoints but also will minimize the burden on any one EAB member. The Period 3 EAB members, their affiliations, and their primary expertise are listed in the table below. The asterisk next to the name indicates a new member.

			Research	Education	Diversity	Knowledge Transfer	Center Management
Nick Alexopoulous	Broadcom		x			x	
Samuel Bader *	Argonne National Labs		x	x			x
John Chen *	Nvidia		x			x	
Peter Delfyett	U of Central Florida		x	x	x		x
Luigi Colombo	Texas Instruments		x			x	
Katherine Dunphy-Guzman	Sandia			x	x		
Jonathan Heritage	UC Davis		x	x			
Witek Maszara *	Global Foundries		x			x	
Daniel Radack *	Institute for Defense Analysis		x				x
Elizabeth Weitzman	Semiconductor Research Corp.		x			x	x

In compliance with the charter, the annual meeting of the EAB took place on October 16 at Berkeley, with J. Heritage serving as the chairperson of the EAB for the second 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 will be made available at the January 2013 NSF Site Visit. The Executive Committee is scheduled to review assessment at its meeting on December 19, after which the assessments will be shared with all funded faculty members in the Center and with the Vice Chancellor of Research of 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. The IRB monitors, advises and participates in the Center's research, education and knowledge transfer goals. In Period 3, we expanded the Industrial Research Board to reflect the addition of a new industry member; see Section *V.1c*. The Period 3 board's membership is as follows.

	Name	**Affiliation**
1	Paolo Gargini	Intel
2	David Hemker	Lam Research
3	Ghavam Shahidi	IBM
4	Stan Williams	Hewlett-Packard
5	Klaus Schuegraf	Applied Materials

At the Center's Annual Retreat in August, the Industrial Research Board met with the Center's Executive Committee. The company participants at the IRB meeting were:

	Company	**2012 Industrial Research Board Meeting Attendees**
1	IBM	Paul Solomon, representing Ghavam Shahidi
2	Lam Research	Joel Cook, representing David Hemker
3	Applied Materials	Adam Brand, representing Klaus Schuegraf

4. Changes in the Strategic Plan

On December 19, 2012, the E^3S Executive Committee reviewed the Center's Period 3 performance against the metrics that are defined in the Strategic Plan. Besides analyzing the results and defining actions for improvement, the Executive Committee also reviewed the Strategic Plan and the goals. Some metrics did not have quantitative measures for every period. We added targets for every period per the suggestion of the External Advisory Board. Changes to the Strategic Plan and the goals and reason for change are presented in the table below. Blue indicates either a new or revised metric or goal. The finalized version of the revised Strategic Plan will be posted on the E^3S website at the beginning of Period 4.

Objective	Metric	Targets	REVISED Targets	Reason for Change
Integrative Research	Multi-PI projects	Period 5: 30%	Period 5: 75%	
	Multi-Institutional projects	Period 5: 30%	Period 5: 30%	
	Unplanned research projects	Period 3: 1 Period 4: 3	Period 3: 1 Period 4: 3 Period 5: 0	

	New joint research funding opportunities	Mid-Period 3: 1 proposal	Period 3: 1 Period 4: 2 Period 5: 2	
	Publications with authors from multiple institutions	Period 3: 12	Period 3: 12 Period 4: 3 Period 5: 5	
	Publications with authors from multiple departments		Period 4: 2 Period 5: 4	New - This metric was added per the suggestion of the 2012 Site Visit Team.
Education	Number of Center graduates who have completed E^3S training	Period 3: 50% Period 5: 100%	Period 3: 50% Period 4: 50% Period 5: 50%	
	~~Number of publications with student and postdoc authors who have published previously in other themes~~	~~Period 3: 9~~		Eliminated - Upon review of the current situation, we concluded that this metric is more appropriate for the second five years of the Center.
	Number of students and postdocs participating in education and diversity programs	Period 3: 60% Period 5: 75%	Period 3: 60% Period 4: 70% Period 5: 75%	
	Number of students and postdocs serving in leadership roles in the Center	Period 3: 15% Period 5: 20%	Period 3: 15% Period 4: 20% Period 5: 25%	
Diversity	Number of women participating in the Center's research programs	Period 3: 5% increase Period 4: 5% increase Period 5: 5% increase	Period 3: 5% increase Period 4: 30% Period 5: 30%	
	Number of underrepresented minorities participating in the Center's research programs	Period 3: 15% increase Period 4: 10% increase Period 5: 5% increase	Period 3: 15% increase Period 4: 5% Period 5: 10%	

	Number of diversity program participants from groups underrepresented in STEM		Period 3: Baseline Period 4: 80% Period 5: 80%	
	Number of pre-college students who pursue a bachelor's degree in science and engineering	Period 3: 5% Period 4: 10% Period 5: 15%	Period 3: Baseline Period 4: 70% Period 5: 70%	
	Number of community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Period 3: 5% Period 4: 10% Period 5: 15%	Period 3: 5% Period 4: 80% Period 5: 80%	
	Number of undergraduates who pursue advanced degree in science and engineering	Period 3: 5% Period 4: 10% Period 5: 15%	Period 3: 5% Period 4: 30% Period 5: 35%	
Knowledge Transfer	Website hits & unique visitors	Period 3: 20% increase	Period 3: 20% increase Period 4: 10% Period 5: 10%	
	Number of contacts with industry: • General • Presentations by industry	Period 3: 36 Per Period: 2	Per Period: 36 Per Period: 2	
	Number of research collaboration with industry		Period 4: 1 Period 5: 2	New - This metric was added to measure the quality of industry interactions.
	Center publications	Per Year: 18	Per Year: 18	
	External citations of publications	Period 3: 10 Period 5: 100	Period 3: 10 Period 4: 100 Period 5: 100	
	Patent disclosures • Disclosure/Provisional	Period 3: 3 Period 5: 8	Period 4: 3 Period 5: 5	This metric was divided into two categories to provide clarity.

	• Patent Application Filed		Period 4: 0 Period 5: 3	
	Students hired into relevant industries	Period 5: 50% Period 10: 50%	Period 5: 50% Period 10: 50%	
	Technology development attributable to Center's research	Period 10: 1	Period 10: 1	
	Number of ~~events leading to~~ external articles on Center	Period 3: 100% increase Period 5: 50% increase	Period 3: 100% increase Period 4: 3 Period 5: 5	Reworded to enable a larger scope.
Center Management	Centerwide communications	1 newsletter Annual Retreat Annual NSF Review Updated Website	1 newsletter Annual Retreat Annual NSF Review Updated Website	
	Number of disputes	Annual decrease	Annual decrease	
	Annual Surveys:	3 or higher on Likert Scale		
	• Students /Postdocs		4 or higher on Likert Scale	
	• Co-PIs		4 or higher on Likert Scale	
	• External Advisory Board Survey		3 or higher on Likert Scale	
	Authorship disputes	20% decrease annually	20% decrease annually	
	Plagiarism	20% decrease annually	0	
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly	Yearly	

VIII. CENTERWIDE OUTPUT

1a. Publications

1ai. Peer Reviewed (in chronological order)

S. Chong, B. Lee, S. Mitra, R.T. Howe, and H.-S. P. Wong, “Integration of Nanoelectromechanical Relays with Silicon nMOS,” *IEEE Trans. Electron Devices*, vol. 59, No. 1, pp. 255 – 258, 2012.

A.C. Ford, S. B. Kumar, R. Kapadia, J. Guo, and A. Javey, “Observation of Degenerate One-Dimensional Sub-Bands in Cylindrical InAs Nanowires,” *Nano Letters*, vol.12, No. 3, pp. 1340–1343, 2012.

H. Kam, T.-J. King Liu, and E. Alon, “Design Requirements for Steeply Switching Logic Devices,” *IEEE Transactions on Electron Devices*, Vol. 59, No. 2, pp. 326 - 334, 2012.

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,” *Nano Letters*, Vol. 12, No. 4, pp. 2060 - 2066, 2012.

H. Fang, S. Chuang, K. Takei, H. S. Kim, E. Plis, C.-H. Liu, S. Krishna, Y.-L. Chueh, and A. Javey, "Ultrathin-Body, High-Mobility InAsSb-on-Insulator Field-Effect Transistors,” *IEEE Electron Device Letters*, Vol. 33, No. 4, pp. 504-506, 2012.

T.-J. K. Liu, D. Markovic, V. Stojanovic, and E. Alon, “The Relay Reborn,” *IEEE Spectrum*, Vol. 49, No. 4, pp. 40-43, 2012.

B. Lambson, Z. Gu, D. Carlton, S. Dhuey, A. Scholl, A. Doran, A. Young, and J. Bokor, “Cascade-Like Signal Propagation in Chains of Concave Nanomagnets,” *Applied Physical Letters*, Vol.100, p. 152406, 2012.

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,” *Physical Review B*, Vol. 85, No. 20, pp. 205308(1) - 205308 (10), 2012.

F. Lu, T. D. Tran, W. S. Ko, K. W. Ng, R. Chen, and C. Chang-Hasnain, “Nanolasers Grown on Silicon-based MOSFETs,” *Optics Express*, Vol. 20, p. 12171, 2012.

A.E. Willner, R. L. Byer, C. J. Chang-Hasnain, S. R. Forrest, H. Kressel, G. J. Tearney, and C.H. Townes, “Optics and Photonics: Key Enabling Technologies,” *Proceedings of the IEEE*, Vol. 100, pp. 1604-1643, 2012.

H. Fang, S. Chuang, T. Chang, K. Takei, T. Takahashi, and A. Javey “High Performance Single Layered WSe_2 p-FETs with Chemically Doped Contacts,” *Nano Letters*, Vol. 12, No. 7, pp. 3788-3792, 2012.

P. Matheu, B. Ho, Z. Jacobson, and T.-J. K. Liu, "Planar GeOI TFET Performance Improvement with Back Biasing," *IEEE Transactions on Electron Devices*, Vol. 59, No. 6, pp. 1629-1635, 2012.

J. Nah, H. Fang, C. Wang, K. Takei, M. H. Lee, E. Plis, S. Krishna, and A. Javey, "III–V Complementary Metal–Oxide–Semiconductor Electronics on Silicon Substrates,” *Nano Letters*, Vol. 12, No. 7, pp. 3592-3595, 2012.

S. Chuang, Q. Gao, R. Kapadia, A. C. Ford, J. Guo, A. Javey, "Ballistic InAs Nanowire Transistors", *Nano Letters*, 2012, doi: 10.1021/nl3040674, 2012.

D. Fu, K. Liu, T. Tao, K. Lo, C. Cheng, B. Liu, R. Zhang, H. A. B., and J. Wu, "Comprehensive Study of the Metal-Insulator Transition in Pulsed Laser Deposited Epitaxial VO_2 Thin Films," *J. Appl.Phys.*, Vol. 113, No. 4, pp. 043707-1 - 043707-7, 2013.

J. T. Teherani, S. Agarwal, E. Yablonovitch, J. L. Hoyt, and D. A. Antoniadis, "Impact of Quantization Energy and Gate Leakage in Bilayer Tunneling Transistors," *IEEE Electron Device Letters*, Vol. 34, No. 2, pp. 298-300, 2013.

Submitted / Accepted

D. Lee, W.S. Lee, C. Chen, F. Fallah, J. Provine, S. Chong, J. Watkins, R. T. Howe, H.-S. P. Wong, and S. Mitra, "Combinational Logic Design using Six-Terminal NEM Relays," *IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems*, accepted for publication.

H. Fang, H. A. Bechtel, E. Plis, M. C. Martin, S. Krishna, E. Yablonovitch, and A. Javey, "The Quantum of Optical Absorption in Two-Dimensional Semiconductors," submitted 2012 (*PNAS*).

K. Takei, R. Kapadia, H. Fang, E. Plis, S. Krishna, and A. Javey, "High Quality Interfaces of InAs-on-Insulator Field-Effect Transistors with ZrO2 Gate Dielectrics", submitted, 2013 (*Applied Physics Letters*).

H. Fang, M. Tosun, G. Seol, T. C. Chang, K. Takei, J. Guo and A. Javey, "Degenerate n-Doping of Few-Layer Transition Metal Dichalcogendies by Potassium", submitted, 2013 (*Nano Letters*).

E. M. Levenson-Falk, R. Vijay, N. Antler, and I. Siddiqi, "A Dispersive NanoSQUID Magnetometer for Ultra-Low Noise, High Bandwidth Flux Detection," submitted, 2013 (*Superconductor Science and Technology*).

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

K. Akarvardar, and H.-S. P. Wong, "Nanoelectromechanical Logic Gates," *Nanoelectronics and Information Technology: Advanced Electronic Materials and Novel Devices*, R. Waser Ed., 3rd ed. Weinheim, Germany: Wiley-VCH, 2011, pp. 375-388.

1b. Conference Presentations (in chronological order)

Talks:

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 -February, 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- February, 2012.

N. Antler, R. Vijay, E. Levenson-Falk, R. Naik, G. Williams, I. Siddiqi, "Dispersive Nanobridge SQUID Magnetometer," *APS March Meeting*, Boston, MA, February, 2012.
M. Trassin, "Electric-Field Induced Magnetization Reversal Using Multiferroics," *APS March Meeting 2012*, Boston, MA, March 2012.

C. Chang-Hasnain, “Nanolasers Grown on Silicon,” *Optical Fiber Communication Conference (OFC)*, Los Angeles, CA, March, 2012.

E. Yablonovitch, “New US National Center for Energy Efficient Electronics Science (E³S),” Invited Talk, *International Symposium on Development of Core Technologies for Green Nanoelectronics*, Tokyo, Japan, March, 2012.

T.-J. K. Liu, “Digital Technologies: The Next Sub-0.5V Switch?” Invited Talk, *Guardian Angel Workshop on Zero Power Technologies for Autonomous Smart Systems*, San Francisco, CA, USA, March, 2012.

E. Alon, “The Role of Low Power NEMS in Computation and Communication,” *Guardian Angel Workshop on Zero Power Technologies for Autonomous Smart Systems*, San Francisco, CA, USA, March, 2012.

E. Yablonovitch, “New US National Center for Energy Efficient Electronics Science (E³S),” Invited Talk, *Guardian Angel Workshop on Zero Power Technologies for Autonomous Smart Systems*, San Francisco, CA, USA, March, 2012.

K. Liu, D. Fu, J. Cao, J. Suh, K. X. Wang, J. Wu, “Ultra-Dense, Ultra-Thin Electron System from Gate-Controlled Surface Metal-Insulator Transition,” *2012 MRS Spring Meeting*, San Francisco, CA, USA, April, 2012.

N. Antler, R. Vijay, E. Levenson-Falk, R. Naik, G. Williams, I. Siddiqi, “Microwave Response of Aluminum Nanobridge JJ Circuits,” *ICSM 2012 Meeting*, Istanbul, Turkey, April-May, 2012.

E. Yablonovitch, “Energy Efficient Electronics Science: Searching for the Milli-Volt Switch,” Invited talk, *The Eight International Nanotechnology Conference on Communication and Cooperation*, Tsukuba, Japan, May, 2012.

T.-J. K. Liu, L. Hutin, I.-R. Chen, R. Nathanael, Y. Chen, and E. Alon, "Recent Progress and Challenges for Relay Logic Switch Technology," *2012 Symposium on VLSI Technology*, Honolulu, June 2012.

S. Agarwal, E. Yablonovitch, “Enhanced Tunneling Current in 1D-1D Edge-Overlapped TFET’s,” *70th Device Research Conference*, University Park, PA, USA, June 18-20, 2012, pp. 63-64.

R. Going, M.-K. Kim, and M. C. Wu, “Sub-fF nanophotodetector for Efficient Waveguide Integration,” *2012 IEEE 9th International Conference on Group IV Photonics (GFP),* San Diego, CA, USA, August, 2012.

M.C. Wu, “Semiconductor Nano-Emitters and Nano-Detectors,” *2012 International Nano-Optoelectronics Workshop (iNOW),* Berkeley, CA, USA, August, 2012.

E. Yablonovitch, “Energy Efficient Electronics: Searching for the Milli-Volt Switch,” *2012 International Nano-Optoelectronics Workshop (iNOW),* Berkeley, CA, August, 2012.

C. Chang-Hasnain, “High Contrast Metastructures for Silicon Photonics,” *2012 International Nano-Optoelectronics Workshop (iNOW),* Stanford, CA, USA, August, 2012.

B. Lambson, D. Carlton, S. Dhuey, R. Storz, J. Bokor, “Temperature Dependence of Heat Dissipation during Landauer Erasure of Nanomagnets” *IEEE NANO 2012*, Birmingham, England, August 2012.

A.C. Yeung, A. I. Khan, J.-Y. Cheng, S. Salahuddin and C. Hu, “Non-Hysteretic Negative Capacitance FET with Sub-30mV/dec Swing over 106X Current Range and ION of 0.3mA/μm without Strain Enhancement at 0.3V VDD,” *SISPAD*, Colorado, USA, September, 2012.

B. Lambson, S. Dhuey, R. Storz, and J. Bokor, “Nanomagnetic Logic and the Thermodynamic Limits of Computation.” *SRC TECHCON 2012*, Austin, TX, USA, September, 2012.

E. Yablonovitch, "Density-of-States Switching Mechanism for the Tunnel Field Effect Transistor," Invited Talk, *42nd European Solid-State Device Research Conference (ESSDERC 2012)*, Bordeaux, France, September, 2012.

F. Bennett, W. S. Ko, and C. Chang-Hasnain, "Dynamic Graphical Representation Of Vertical Cavity Surface Emitting Lasers," *2012 AGMUS/NSF Research Symposium*, San Juan, Puerto Rico, September, 2012.

M. Eggleston, N. Kumar, L. Zhang, E. Yablonovitch, and M. C. Wu, "Enhancement of Photon Emission Rate in Antenna-Coupled nanoLEDs," *Semiconductor Laser Conference (ISLC), 2012 23nd IEEE International*, San Diego, CA, USA, October, 2012.

N. Antler, E. Levenson-Falk, R. Naik, R. Vijay, I. Siddiqi. "High Speed Nanobridge SQUID Magnetometer," *Applied Superconductivity Conference*, Portland, OR, USA, October, 2012.

E. Yablonovitch, "Case Histories for the Introduction of New Technology through Entrepreneurship," *8th Annual Fall Symposium on Nanovation*, Berkeley, CA, USA, October, 2012.

D. Antoniadis, "What's Next In Low Power Electronics? : The E^3S Research Program," Invited Talk, *Guardian Angel Workshop on Zero Power Technologies for Autonomous Smart Systems*, Boston, MA, USA, November, 2012.

B. Lambson, Z. Gu, M. Nowakowski, S. Dhuey, A. Scholl, A. Doran, A. Young, and J. Bokor, "Advances in Nanomagnetic Logic." *Joint MMM/Intermag 2013*, Chicago, IL, USA, January. 2013.

Posters:

S. Agarwal and E. Yablonovitch, "Enhanced Tunneling Current in 1D-1D Edge Overlapped TFET's," *2012 International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, CA, USA, August, 2012.

M. Eggleston, E. Yablonovitch, and M.C. Wu "Optical Antenna Based nano-LED," *2012 International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, CA, USA, August, 2012.

R. Going and M.C. Wu, "Metal-Cavity Design for a Waveguide Coupled MSM Nanophotodiode," *2012 International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, CA, USA, August 7-10, 2012.

C. Lalau-Keraly and E. Yablonovitch, "Transistor-Based Photodetectors for Integrated Silicon Photonics," *2012 International Nano-Optoelectronics Workshop (iNOW*), Berkeley, CA, USA, August, 2012.

K. Li, F. Ren, R. Chen, T.T. D. Tran, K.W. Ng, and C. Chang-Hasnain, "Characteristics of InP nanoneedles grown on silicon by low-temperature MOCVD*," 2012 International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, CA, USA, August, 2012.

W.S. Ko, K.W. Ng, and C. Chang-Hasnain, "Size Control of Core-Shell (In)GaAs Nanopillars on a Silicon Subtrate," *2012 International Nano-Optoelectronics Workshop (iNOW)*, Berkeley, CA, USA, August, 2012.

D. Drew, A. I. Wang, F. Niroui, V. Bulovic, and J. H. Lang, "Low-Loss Voltage Actuated Switch Using Metal-Polymer Nanocomposite," Best poster award, *2012 AGMUS/NSF Research Symposium*, San Juan, Puerto Rico, September, 2012.

D. Drew, A. I. Wang, F. Niroui, V. Bulovic, and J. H. Lang, "Low-Loss Voltage Actuated Switch Using Metal-Polymer Nanocomposite," Student award, *2012 SACNAS National Conference*, Seattle, WA, USA, October, 2012.

1c. Other Dissemination Activities (in chronological order)

V. Bulovic, "Printing Nanostructures for LEDs and MEMs," Invited Lecture, *Tufts University*, February 29, 2012.

E. Yablonovitch, "New US National Center for Energy Efficient Electronics Science (E^3S)," Invited Talk, *French Young Engineers & Scientists Symposium*, Berkeley, CA, March 21, 2012.

E. Yablonovitch, "Searching for the Milli-Volt Switch," Invited Talk, *Vincent Meyer Colloquium, Technion*, Haifa, Israel, March 28, 2012.

E. Yablonovitch, "Searching for the Milli-Volt Switch," Invited Talk, *MIT Lincoln Labs*, Lexington, MA, May 17, 2012.

E. Yablonovitch, "Searching for the Milli-Volt Switch," Invited Talk, *IBM Zurich*, Ruschlikon, Switzerland, June 11, 2012.

E. Yablonovitch, "Searching for the Milli-Volt Switch," Invited Talk, *Ecole Polytechnique Federale de Lausanne (EPFL)*, Lausanne, Switzerland, June 12, 2012.

E. Yablonovitch, "Searching for the Milli-Volt Switch" & "What is the Tunneling Field Effect Transistor?", Invited Talks, *Heraeus Summer School*, Bad Honnef, Germany, June 15, 2012.

E. Yablonovitch, "Opto-electronic Devices: Spontaneous Emission Faster than Stimulated Emission", Invited Talk, *Wright-Patterson Air Force Base*, Dayton Ohio, June 27, 2012.

E. Yablonovitch, "Searching for the Milli-Volt Switch," Invited Talk, *Sandia National Laboratory*, Albuquerque, NM, July 9, 2012.

H.-S. P. Wong, "Nanoscale Electronic Devices – Examples of Transforming Scientific Discoveries into Engineering Technologies," Invited talk (Host: Prof. C.P. Wong, Dean of the Faculty of Engineering), *Chinese University of Hong Kong*, Hong Kong, August 8, 2012.

E. Yablonovitch, "What's Next Beyond the Transistor?" Invited talk, *2012 Marconi Society Symposium*, UC Irvine, September 6, 2012.

H.-S. P. Wong, "Nanoscale Electronic Devices – Examples of Transforming Scientific Discoveries into Engineering Technologies," Invited Talk (Host: Dr. An Steegen, Senior Vice President, Process Technology), *Interuniversity Microelectronics Centre (IMEC)*, Leuven, Belgium, September 19, 2012.

E. Yablonovitch, "Searching for The Milli-Volt Switch," Invited Talk, *Winton Inaugural Symposium on Energy Efficiency*, Cambridge, U.K., October 1, 2012.

H.-S. P. Wong, "Technologies for N+m Nodes, where $m \geq 4$," Invited talk (Host: Dr. Mukesh Khare, Director, Semiconductor Technology Research, IBM Research@Albany NanoTech), Albany, New York, October 3, 2012.

2. Awards & Honors

Recipient	Reason for Award	Award Name	Sponsor	Date	Award Type
Sapan Agarwal	Outstanding graduate student instructor	2011 - 2012 Outstanding Graduate Student	UC Berkeley GSI Teaching and Resource Center	May, 2012	Education

		Instructor Award			
Elad Alon (with Chintan Thakkar, Lingkai Kong, Kwangmo Jung, and Antoine Frappe)	Best paper award	IEEE Symposium on VLSI Circuits Best Student Paper Award	IEEE	June 13, 2012	Scientific
Vladimir Bulovic (and Colleagues at QD Vision)	Pioneering work in the commercialization of the colloidal quantum dot technology	SEMI Award for North America	SEMI	January, 2012	Industry Award
Vladmir Bulovic	Excellence in research and international recognition	Faculty Research Innovation Fellow	MIT EECS Department	September, 2011	Fellowship
Jesus A. del Alamo	Seminal insights into high performance and scalable III-V HEMTs	2012 Intel Outstanding Researcher in Emerging Research Devices	Intel Corporation	March, 2012	Industry
Jesus A. del Alamo	Feasibility Study of InGaAs-based QWFETs for Ultra High Speed, Low Power Logic Applications	SRC 2012 Technical Excellence Award	Semiconductor Research Corporation	September, 2012	Industry
Daniel Drew	Best Poster Award	2012 AGMUS/NSF Research Symposium	AGMUS	September 22, 2012	Scientific
Daniel Drew	Student Award for conference presentation	2012 SACNAS National Conference	SACNAS	October 13, 2012	Scientific
Taron Hakobyan	Academic performance	Osher Scholarship	UCLA	September, 2012	Education
Taron Hakobyan	Academic performance	Scholarship Recognition Award	UCLA	September, 2012	Education

Chenming Hu	Research	Honorary Ph.D.	National Chiao Tung University	April, 2012	Scientific
Chenming Hu	Education	IEEE Electron Device Society Education Award	IEEE Electron Device Society	December , 2011	Education
Chenming Hu	Research	ISDRS van derZielAward	International Semiconductor Device Research Symp	December , 2011	Scientific
Ali Javey	Young scientist who has demonstrated commitment to both excellence in scientific research and cooperation with scientist from other Asia-Pacific Economic Cooperation (APEC) member economies	APEC Science Prize for Innovation, Research and Education (ASPIRE Prize)	John Wiley & Sons, Inc. and Elsevier	September , 2011	Scientific, Education
Ali Javey	Outstanding teaching	UC Berkeley EE Outstanding Teaching Award	UC Berkeley Electrical Engineering Division	2012	Education
Asif Khan (co-recipient)	Research	Qualcomm Innovation Fellowship 2012	Qualcomm Inc.	May, 2012	Fellowship
Tsu-Jae King Liu	Outstanding contributions to nanotechnology research	2012 Intel Outstanding Researcher Award in Nanotechnology	Intel	March, 2012	Scientific & Industry
Amit Lakhani	Superior work and scholarship in the characterization, development and/or use of semiconductor, magnetic, optical or electronic materials	Ross N. Tucker Memorial Award	UC Berkeley	May 2012	Scientific, Education

Apoorva Murarka	Outstanding M. Eng Thesis Award	The Dimitri N. Chorafas Foundation Award	The Dimitri N. Chorafas Foundation		Other
Maja Oblepias	Academic performance	Berkeley Undergraduate Scholarship	UC Berkeley	August, 2012	Education
Vijay Rangari	Excellence in Scientific Research	Russell Brown Award	TU-chapter Sigma Xi	April 27, 2012	Scientific
Sayeef Salahuddin	Junior faculty who exemplify the role of teacher-scholars through outstanding research, excellent education and the integration of education and research within the context of the mission of their organizations.	NSF CAREER	NSF	January, 2012	Scientific
Sayeef Salahuddin	For contributing to the understanding of the physics of hetero-interfaces in nanostructures and investigating their use for energy efficient applications	IEEE Nanotechnology Early Career Award	IEEE	August, 2012	Industry
Timothy Swager	The Centenary Prizes are awarded to outstanding chemists, who are also exceptional communicators, fr om overseas to give lectures in the British Isles.	Centenary Prize	The Royal Society of Chemistry in the United Kingdom	November 9, 2012	Lectureship, cash award and a Medal
Jamie Teherani	Academic performance	International Winter School	NNIN	January, 2012	Award

		for Graduate Students			
Cesar Urbano	Academic performance (most prestigious scholarship awarded by UC Berkeley for entering undergraduates)	Regents' and Chancellor's Scholarship Program	UC Berkeley	August, 2012	Education
H.-S. Philip Wong	Distinguished academic and research efforts	Willard R. and Inez Kerr Bell Professor in the School of Engineering, Endowed Chair	Stanford University	October 2012	Scientific, Education
H.-S. Philip Wong	Distinguished academic and research efforts	Honorary Professor	Institute of Microelectronics, Chinese Academy of Sciences	July, 2012 – June, 2017	Scientific
Chun Wing Yeung (co-recipient)	Research	Qualcomm Innovation Fellowship 2012	Qualcomm Inc.	May, 2012	Fellowship
Eli Yablonovitch	For pioneering contributions to photonic crystals, the photonic bandgap and photonic bandgap engineering	2012 IEEE Photonics Award	IEEE	September 2012	Industry, Scientific
Eli Yablonovitch	Accomplished scientist	Member	American Academy of Arts and Sciences	October 6, 2012	Scientific
Eli Yablonovitch	For pioneering discoveries in photonics, optoelectronics, and semiconductors that impacted our lives	2012 Harvey Prize in Science and Technology	Technion | Israel Institute of Technology	January, 2013	Scientific
Tao Yu	Academic performance	IEEE EDS Master Student	IEEE Electron Device Society	June, 2012	Fellowship

		Fellowship			
Tao Yu	Academic performance	Siebel Scholarship	Siebel Foundation	August, 2012	Fellowship

3. *Graduates*

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Heerad Farkhoor	B.S.E.E., *Berkeley*	May, 2012	4	Electrical Engineering Graduate Program at Stanford

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
David Carlton	Ph.D., *Berkeley*	May, 2012	6	Postdoc at LBNL
Soogine Chong	Ph.D., *Stanford*	June, 2012	8	Samsung
Sung Hwan Kim	Ph.D., *Berkeley*	February, 2012	4.5	Suvolta
Amit Lakhani	Ph.D., *Berkeley*	May, 2012	5	Exponent
Peter Matheu	Ph.D., *Berkeley*	May, 2012	5	Starting a new company
Apoorva Murarka	M. Eng., *MIT*	June, 2012	2	EECS PhD program in the same group at MIT
Rhesa Nathanael	Ph.D., *Berkeley*	August, 2012	6	Intel Corporation
Sarah Paydavosi	Ph.D., *MIT*	June, 2012	3 years from MS	Oracle
Devang Parekh	Ph.D., *Berkeley*	December, 2011	5.5	Cosemi Technologies Inc.
Xiaoying (Evelyn) Shen	M.S., *Stanford*	June, 2012	2	Oracle
Ling Xia	Ph.D., *MIT*	October, 2011	5	MACOM

Postdocs

Name	Departure Date	Placement
Mohmmad (Tanvir) Alam	February, 2012; *Berkeley*	Intel, Portland, OR
Trisha Andrew	July, 2012; *MIT*	Assistant Professor, Univ of Wisconsin, Madison
Ximeng (Simon) Guan	August, 2012; *Stanford*	IBM SRDC, Hopewell Junction, NY
Junghyo Nah	March, 2012; *Berkeley*	Assistant Professor, Chungnam National University, South Korea
Jan Seidel	January, 2012; *Berkeley*	University of New South Wales, Australia
Morgan Trassin	December, 2012; *Berkeley*	Research Staff at ETH, Zurich

4a. *General Outputs of Knowledge Transfer Activities*

Patents: none to report.

Licenses: none to report.

Startup companies: none to report.

4b. *Other Outputs of Knowledge Transfer Activities*

None to report.

5a. *Participants*

In the current reporting period, the Center has 109 participants.

	Summer	Summer + Academic	Academic	No Salary	Total
Faculty	8	0	3	12	23

	Funded by E^3S			Other Funding Source Total	Total Participants
Category	50% or more	less than 50%	Total		
Postdocs	7	3	10	8	18
Grad Students	10	14	24	19	43
Undergrads	0	16	16	2	18
TOTAL	**17**	**33**	**50**	**29**	**79**

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
23	Faculty	12	Berkeley	16	E.E.	20	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	19	US Citizens
		7	MIT	4	Mats Sci	3	F	0	Visual Impairment	18	Not Hispanic or Latino	9	Asian	4	Permanent Resident
		1	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	4	Decline to State	0	Black or African American	0	Other non-US Citizen
		2	Tuskegee	2	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					19	None			10	White	0	Not Available
								4	Decline to State			4	Decline to State		
								0	Not Available			0	Not Available		
18	Postdocs	13	Berkeley	12	E.E.	14	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	6	US Citizens
		3	MIT	1	Mats Sci	4	F	0	Visual Impairment	18	Not Hispanic or Latino	11	Asian	0	Permanent Resident
		2	Stanford	4	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	12	Other non-US Citizen
		0	Tuskegee	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								16	None			6	White	0	Not Available
								2	Decline to State			1	Decline to State		
								0	Not Available			0	Not Available		
43	Graduate Students	26	Berkeley	31	E.E.	33	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	22	US Citizens
		10	MIT	8	Mats Sci	10	F	0	Visual Impairment	39	Not Hispanic or Latino	23	Asian	0	Permanent Resident
		5	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	3	Decline to State	2	Black or African American	20	Other non-US Citizen
		2	Tuskegee	1	ME			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
				1	Other			40	None			13	White	1	Not Available
								2	Decline to State			4	Decline to State		
								1	Not Available			1	Not Available		
18	Undergraduate Students	2	Berkeley	10	E.E.	13	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	14	US Citizens
		2	MIT	3	Mats Sci	5	F	0	Visual Impairment	15	Not Hispanic or Latino	2	Asian	2	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	2	Decline to State	5	Black or African American	0	Other non-US Citizen
		0	Tuskegee	4	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	1	Decline to State
		0	LATTC					16	None			7	White	1	Not Available
		1	CCC					1	Decline to State			3	Decline to State		
		13	Other					1	Not Available			1	Not Available		
7	Staff	5	Berkeley	0	E.E.	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	6	US Citizens
		2	MIT	0	Mats Sci	6	F	0	Visual Impairment	6	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	2	Black or African American	0	Other non-US Citizen
		0	Tuskegee	7	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								5	None			2	White	1	Not Available
								1	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		

5b. Affiliates

In the current reporting period, the Center has 155 affiliates.

	Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship
2	Faculty	1	Berkeley	1	E.E.	0	M	0	Hearing Impairment	1	Hispanic or Lantino	0	American Indian or Alaskan Native	2	US Citizens
		0	MIT	0	Mats Sci	2	F	0	Visual Impairment	1	Not Hispanic or Latino	1	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
		0	LATTC					2	None			1	White	0	Not Available
		1	CCC					0	Decline to State			0	Decline to State		
		0	Other					0	Not Available			0	Not Available		
2	Research Scientists & Visiting Faculty	0	Berkeley	0	E.E.	2	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
		1	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	Other					0	None			1	White	1	Not Available
								1	Decline to State			0	Decline to State		
								1	Not Available			1	Not Available		
9	Postdocs	8	Berkeley	3	E.E.	7	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		1	MIT	2	Mats Sci	2	F	0	Visual Impairment	4	Not Hispanic or Latino	4	Asian	1	Permanent Resident
		0	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	0	Black or African American	4	Other non-US Citizen
		0	Tuskegee	1	Chemistry			0	Other	3	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
				1	Other			5	None			2	White	3	Not Available
								1	Decline to State			0	Decline to State		
								3	Not Available			3	Not Available		
24	Graduate Students	23	Berkeley	19	E.E.	20	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	9	US Citizens
		1	MIT	3	Mats Sci	4	F	0	Visual Impairment	12	Not Hispanic or Latino	6	Asian	0	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	4	Other non-US Citizen
		0	Tuskegee	1	Other			0	Other	11	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
								13	None			5	White	11	Not Available
								0	Decline to State			1	Decline to State		
								11	Not Available			11	Not Available		
13	Undergraduate Students	3	Berkeley	6	E.E.	8	M	0	Hearing Impairment	3	Hispanic	0	American Indian or Alaskan Native	11	US Citizens
		0	MIT	1	Mats Sci	5	F	0	Visual Impairment	10	Not Hispanic or Latino	6	Asian	2	Permanent Resident
		1	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		2	Tuskegee	6	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC					13	None			1	White	0	Not Available
		1	CCC					0	Decline to State			0	Decline to State		
		6	Other					0	Not Available			3	Not Available		

Table continues on next page.

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
97	Pre-College Students	0	Berkeley	0	E.E.	60	M	0	Hearing Impairment	66	URM			0	US Citizens
		0	MIT	0	Mats Sci	37	F	0	Visual Impairment	31	Non-URM			0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment					0	Other non-US Citizen
		0	Tuskegee	0	Other			0	Other					0	Decline to State
		0	LATTC	97	N/A			0	None					97	Not Available
		0	CCC					0	Decline to State						
		97	Other					97	Not Available						
8	Staff	5	Berkeley	0	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	7	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	Tuskegee	8	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					6	None			2	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.	Applied Materials	Company	Santa Clara, CA	Klaus Schuegraf	Research, Knowledge Transfer	N
6.	Naval Research Laboratory	Federal Government	Washington, DC	Brian Bennett	Research	N
7.	ETH Zurich	University	Zurich, Switzerland	Mathieu Luisier	Research	N
8.	University of New Mexico	University	Albuquerque, NM	Sanjay Krishna	Research	N
9.	Texas Tech University	University	San Marcos, TX	Ravi Droopad	Research	N
10.	National Chiao-Tung University	University	Taiwan	Edward Chang	Research,	N
11.	Intel Corporation	Company	Santa Clara, CA	Hai-Feng Liu and Botros Youssry	Research	N
12.	Bell Labs, Alcatel Lucent	Company	Holmdel, NJ	Liming Zhang	Research	N
13.	UC Berkeley – Transfer Alliance Project	University	Berkeley, CA	Keith Schoon	Education & Diversity	N
14.	UCLA Center for Community College Partnerships	University	Los Angeles, CA	Alfred Herrera	Education & Diversity	N
15.	MIT Office of Engineering	University	Cambridge,	Shawna	Education	N

	Outreach Programs		MA	Young	& Diversity	
16.	MIT Office of the Dean for Graduate Education	University	Cambridge, MA	Monica Orta	Education & Diversity	N
17.	Berkeley Nanosciences and Nanoengineering Institute	University	Berkeley, CA	Paul Riofski	Education & Diversity	N
18.	Center of Integrated Nanomechanical Systems	University	Berkeley, CA	Meltem Erol	Education & Diversity	N
19.	Berkeley Foundations for Opportunities in Information Technology	NGO	Berkeley, CA	Orpheus Crutchfield	Education & Diversity	N
20.	Synthetic Biology Engineering Research Center	University	Berkeley, CA	Kate Spohr	Education & Diversity	N
21.	The Team for Research in Ubiquitous Secure Technology	University	Berkeley, CA	Aimee Tabor	Education & Diversity	N
22.	California MESA	NGO	Oakland, CA	Tiffany Reardon	Education & Diversity	N

7. *Summary Table for internal NSF reporting purposes*

1	the number of participating institutions (all academic institutions that participate in activities at the Center)	5
2	the number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center)	22
3	the total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC)	$215,000
4	the number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF) .	109

8. *Media Publicity of Center*

None to report.

IX. INDIRECT/OTHER IMPACTS

The Center's international activities included:

- C. Hu initiated a collaboration with Edward Chang, National Chiao-Tung University in Taiwan on material growth.
- C. Hu received an honorary Ph.D. from National Chiao-Tung University, Taiwan.
- The Center's research was presented at four conferences outside the US, 2 in Japan, 1 in France and 1 in Turkey.
- E. Yablonovtich gave talks on the Center's research at 4 institutions in Europe and Israel, while H.-S.P. Wong gave a talk on nanomechanics in Belgium.
- E. Yablonovtich gave a talk at the *French Young Engineers & Scientists Symposium* in Berkeley.
- J. Yuen provided marketing and registration support to the *San Francisco Guardian Angel Workshop on Zero Power Technologies for Autonomous Smart Systems*, a scientific workshop that was organized by the Guardian Angel Consortium, an EU research organization, in collaboration with the Consulate of Switzerland. E. Yablonovitch, E. Alon and T.J. King Liu were invited speakers at the San Francisco Workshop. A similar workshop also took place in Boston, where D. Antoniadis was an invited speaker.

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XI. APPENDICES

Appendix A: Organizational Chart

Appendix B: Annual Retreat

Appendix C: Poster Session at Annual Retreat

Appendix D: Postdoc and Graduate Students Retreat

Appendix E: Seminars and Journal Club

Appendix F: E3S Professional Development Program

Appendix G: Joint Recruitment Calendar

Appendix H: Summary of Diversity-Enhancing Activities

Appendix I: E3S Transfer-to-Excellence Recruitment Calendar

Appendix J: Newsletter

Appendix K: Website Traffic

Appendix L: Student and Postdoc Evaluation of Center's Leadership Team

Appendix M: Co-PI Collaboration, Ethics, and Leadership Survey

Appendix N: Co-PI Collaboration, Ethics, and Leadership Executive Summary