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Center for Energy Efficient Electronics Science

Final

Fifth Annual Report

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A National Science Foundation Science & Technology Center
(Award ECCS - 0939514)

Berkeley University of California | Massachusetts Institute of Technology | Stanford University | The University of Texas at El Paso | Contra Costa College | Los Angeles Trade-Tech

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I. GENERAL INFORMATION

1a. Center Information

Date submitted	December 5, 2014
Reporting period	March 1, 2014 – February 28, 2015
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	
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Phone Number	510-642-6821
Fax Number	510-666-3409
Email Address of Center Director	eliy@eecs.berkeley.edu
Center URL	https://www.e3s-center.org

Participating Institutions

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

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

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

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

Institution Name	Florida International University
Address	10555 W. Flagler Street, EC 3955 Miami, FL 33174
Phone Number	305-348-3724
Fax Number	305-348-3707
Email Address of Center Director	khizroev@fiu.edu
Role of Institution at Center	FIU is a lead research, education, and outreach partner.

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
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Email Address of Center Director	DiazM@lattc.edu
Role of Institution at Center	LATTC is an education and outreach partner to encourage greater minority participation in engineering.

1b. Biographical Information of New Faculty

Please see Appendix A for biographical information on three new faculty members. Two were added to the Center during Period 5 and one will be added in Period 6.

1c. Primary Contact Person

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

Name of the Individual	Josephine Yuen
Center Role	Executive Director
Address	552 Sutardja Dai Hall, Berkeley, CA 94720
Phone Number	510-664-4439
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2. *Context Statement*

We are experiencing the confluence of three critical trends in the information processing technology sector:

1. The increasing importance of mobile internet, wireless sensor swarms, and body-centered networks, which demand ever increasing functionality from a fixed amount of battery energy;
2. The rapid growth in the demand for information processing driven by advancements such as cloud computing, social networking, mobile internet and data analytics; and
3. The power density of today's increasingly complex IC chips is projected to be meeting its practical limits, despite continuous technological improvements to forestall the projections.

The first two trends are driving the continued growth of the worldwide volume of semiconductor-based electronics and information services continues, but the third trend could slow down or even halt the growth of information processing capability. However, at the most fundamental level, **the energy used to manipulate a single bit of information is currently ~10^5 times greater than the theoretical limit**.

Many elements factor into the energy requirements of an information processing system. The Center for E^3S concentrates on two fundamental components of digital information processing systems: the digital logic switch and the short-medium range communication of information between logic elements. We seek to approach the fundamental limits on the energy consumption required to process information, to reduce the energy per operation by many orders of magnitude.

This goal has brought forth a broad-based effort aimed at making fundamental advances in the physics, chemistry, and materials science of logic switches. Our emphasis in the Center for E^3S is on basic scientific issues, as opposed to engineering optimization or technology development. Addressing energy consumption in components for information processing is not unique to the Center, but our goal of elucidating the basic scientific issues is the Center's differentiation. Our approach is built on the understanding that the problem we are addressing requires scientific breakthroughs in physics, chemistry and materials science that governs nanotechnology. Our belief is supported by the continuing gap between the experimental results and theoretical predictions as much of the research in this area has been pursued by the engineering optimization or technology development approach.

In large measure, **we have become too dependent on the transistor**. As splendid as the transistor has been in defining the technology of our age, **it suffers from a serious drawback**. Its conduction is thermally activated, and requires a powering voltage >>kT/q=26mVolts, today ~0.8 Volt, to provide a good On/Off current ratio. On the other hand, the wires of an electronic circuit could operate with a very good signal-to-noise ratio, even at voltages below 10 milli-Volt. **A more sensitive, lower-voltage switch is needed as the successor to the conventional transistor**. The potential improvement factor in digital electronics is 10^2 in voltage, V, while power, which often goes as V^2, can improve by a factor ~10^4. Indeed the energy per bit-function in digital electronics is currently ~10^5 higher than theoretical limits.

Research in the Center for **E^3S** is organized into four distinct themes: **I. Nanoelectronics**: Solid-state milli-Volt switching; **II. Nanomechanics**: Low-leakage switching; **III. Nanophotonics**: Few-photon optical communication; and **IV. Nanomagnetics**: Magneto-electrical switching.

One of our objectives is to evaluate how closely the different technologies might be able to approach the fundamental energy efficiency limits. These evaluations are made on an ongoing basis, and a significant element of synergy among the projects comes from using the same set of metrics for all. Nonetheless, future ultra-low energy information systems may be built and integrated using elements of more than one of these approaches. The fundamental challenges and goals are common to all the Themes. Theme III addresses the challenge that is common to all digital systems, namely high bandwidth intra-chip, as well as chip-to-chip communications.

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

The Center for E^3S brings together researchers from five institutions who have the complementary skills and expertise in several basic disciplines (physics, chemistry, nanomaterials, nanodevices), and they cross the five technology areas in response to new research opportunities. The five member institutions are: University of California, Berkeley (*Berkeley*), the lead, MIT, Stanford University, The University of Texas at El Paso (*UTEP*), and Florida International University (*FIU*). FIU joined the Center in Period 5.

In this reporting Period 5,

- The effort to create a low voltage solid-state switch (Theme I) has continued to be led by **E. Yablonovitch** (*Berkeley*), with a strong device, materials and chemistry team: **D. Antoniadis**, **J. Hoyt, J. del Alamo,** and **E. Fitzgerald** (*MIT*), and **A. Javey** and **C. Hu** (*Berkeley*).
- The low-voltage nanomechanical switch approach (Theme II) recognizes that the requirements for a logic switch are very different from other nanomechanical applications. This effort has continued to be led by **T.-J. King Liu** *(Berkeley)*. Her team at three member institutions includes **J. Lang, V. Bulovic,** and chemist **T. Swager** (*MIT*), **H-S P. Wong** (*Stanford*), and materials scientist **J. Wu** *(Berkeley)*.
- By reducing the required number of photons/bit in Theme III, and using optical antenna enhanced spontaneous emission, **M. Wu** (*lead*), **C. Chang-Hasnain**, and **E. Yablonovitch** *(Berkeley),* together with **E. Fitzgerald** (*MIT)* and **D. Zubia** (UTEP) as electronic materials experts, are showing how to approach an energy/bit improvement of $\sim 10^3$ in optical communication.
- Nanomagnetics (Theme IV) research in the Center has continued to be led by **J. Bokor** *(Berkeley)***,** who collaborates with **S. Salahuddin** (*Berkeley*) and **S. Khizroev** (*FIU*), who joined the Center in this reporting Period 5.
- The research carried out under each of the Themes is kept relevant by circuit and systems analysts **E. Alon** and a new E^3S faculty, **V. Stojanovic** (*both Berkeley*).

Research: The Center's goal of a new switch is targeted to have the following specifications:

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

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

A high level summary of the research themes in Period 5 are as follows.

Theme I: The Nanoelectronics Theme continues to use a solid-state switch, but radically alters the switching principle so that it can operate at a far lower voltage than CMOS. We are changing the fundamental switching mechanism from modulating thermionic emission current over a barrier, to modulating tunneling current through a barrier, a so-called Tunnel Field Effect Transistor (TFET). The preferred TFET mechanism continues to be controversial. Theory predicts excellent results, but experimental results still failed to yield devices with the promised steepness, On/Off ratio and conductance.

The approach of the nanoelectronics Co-PI's, all from either Berkeley and MIT, has been to focus on understanding the device physics and to demonstrate the scientific principles. We have focused on the density of state switching mechanism, as opposed to simply modulating the barrier thickness. One fundamental question is the sharpness of band-edge in density of state switches. Another question that we set out to answer is whether there are novel semiconductor materials that might more readily fulfill the very demanding requirement for material perfection. In Period 5, the Center measured for the first time the actual sharpness of a band-edge (80mV/decade in an InGaAs/GaAsSb device) and detected the dominant tunnel FET leakage path, associated, not surprisingly, with interface traps, D_{it}. To address some of these material problems we explored the new chalcogenide monolayer semiconductors which have perfectly covalently bonded surfaces, and exact discretely defined quantum well thickness. The Center made the first Bilayer dual-gated tunnel FET, which was also the first chalcogenide tunnel FET of any type, and which exhibited over 5 decades of gate controlled conductivity change. Analysis of the data has also affirmed the view that we offered in the last reporting period: the need for materials of ever higher perfection.

Theme II: The nanomechanical approach uses an electrostatically actuated mechanical switch. A few nm gap is sufficient for the off-current of the switch to be essentially zero. By avoiding direct physical contact between metals, reliable operation should be achievable. Direct metallic contact is not necessary, since the 1/KΩ conductance requirement can be fulfilled in spite of limited tunneling conductance. One approach being pursued is the “Squitch” concept that uses molecular stiffness to control the switching gap. For some ultra-low-power (low activity factor) electronics applications, research into van der Waals switches is also being pursued. Over small contact areas, the small stiction forces can be successfully balanced against cantilever stiffness, with the potential of approaching the ultimate promise of <1 aJ/operation. Development of the van der Waals switches requires precision fabrication concepts compatible with the very narrow dimensions.

In Period 5, significant improvement in On/Off ratio for the "Squitch", to ~10^5, has provided a more definitive feasibility demonstration of the concept. Regardless of the approach, nanomechanical devices must have nano-size contacts to achieve millivolt switching. Thus, Theme II researchers at Berkeley, MIT and Stanford all have pursued process technology development for forming nano-gaps in this Period. These research activities will have impact beyond the Center’s research as processing techniques for sub-lithographic features have broader device applications. Materials studies are also an integral part of Squitch research. To decrease the operating voltage, researchers at MIT have been investigating molecular monolayers interspersed with long and short molecules to soften the “springs” that separate the electrodes. Novel 2D and 1D materials are candidates for controlled-stiction coatings, but little is known about their mechanical properties. In Period 5, we conducted studies to understand the elastic properties of chalcogenide monolayers.

Theme III: Communications consumes increasing more of the energy required in information processors. Indeed most of the energy in data processing goes into charging and discharging the communications wires. Both short distance and longer connections, such as the global interconnect across chip and chip-chip communications, represent a major energy burden. Silicon nanophotonics is already making inroads in intermediate distance data-communications, but short distance communication can be enabled by thresholdless light sources like antenna-enhanced light emitting diodes. A new generation of ultra-sensitive photo-detectors would be of broad importance for both short and long-distance communication.

Theme III’s achievements for Period 5 include demonstration of the first electrically injected, antenna-enhanced LED and ultra high sensitivity photo-transistors in Ge and III-V materials. A new and unplanned achievement in Period 5 is the first demonstration of an optically pumped antenna enhanced spontaneous emission from a chalcogenide monolayer, in this case WSe_2. Also new, but planned this year, is the expansion of the III-V epitaxial growth research at MIT toward the Center's Nanophotonics research to enable custom regrowth for surface passivation, in the antenna enhanced nanoLED's.

In Period 5, Theme III achieved a new milestone in collaboration. This Theme, which only involved Berkeley faculty at the Center's inception, has expanded to include Berkeley, MIT and UTEP.

Theme IV: The nanomagnetics approach in Period 5 is taking advantage of ultra-sensitive current driven switches employing the Spin-Hall effect, and ultra-high speed a-thermal magnetic phase transitions, sensed by tunnel magneto-resistance to drive wires and to provide logic fanout. Since these magnetic functions are current-driven, they are inherently low voltage. This nanomagnetics strategy, which began in the last reporting period, is completing its first full year. This change in projects also brought in new faculty. In Period 5, the researchers of this Theme have continued to focus primarily on elucidating the physics and dynamics of Spin Hall effect at a sub-10nm scale, as a follow-up to **S. Salahuddin**'s previous independent experimental discovery of the Spin Hall effect. In addition, **S. Khizroev** demonstrated a record low magnetic switching current, 0.2µA. In addition, Theme IV researchers are developing techniques to enable ultrafast switching in the picosecond range.

System Integration: The System Integration research in Period 5 has focused on providing both a path to quantifying the benefits of the emerging nanomechanical (Theme II) and nanomagnetics (Theme IV) device technologies at the circuit/system level, as well as guidance on how to overcome speed impairments (Theme 2) and On/Off ratio deficiencies (Theme 4), at the systems level. Research in this area expanded in Period 5 as **V. Stojanovic** joined the Center to team with **E. Alon** (*both Berkeley*).

Education & Diversity: The Center's mission also includes education and broadening participation. Our goals are to educate a diverse generation of scientists, engineers, and technicians to be the future leaders, researchers, educators, and workers in the new electronics science and technology. We aim to foster understanding by society of the energy challenge faced in information technology and to promote the application of the Center's research outcomes as the foundation for technological solutions in low energy consumption electronic systems.

To contribute to the US STEM workforce, the Center has established programs to educate and develop its graduate student and postdoctoral researchers, as well as programs for high school seniors, community college students and faculty, as well as upper division undergraduates. The pre-graduate level focus is also to build a pipeline for graduate school and for the STEM workforce. The programs are continuing in Period 5. The new objectives in Period 5 are follows.

Online Education: The Center looks to building its education legacy with online education and training materials that relate to the Center's research focus. This strategy was adopted in the last reporting period. This strategy is expected to impact all levels: developmental experiences for the Center' graduate students and postdocs and staff, as well as educational resources for use by a wide range of audiences. A 1.5 hour mini-course in Energy Efficient Electronics for entry level graduate students is in development for release at the end of the Period.

Program Alumni in Graduate Schools: We have continued to place a strong emphasis on recruiting students from groups that are underrepresented in the technical disciplines of the Center. In Summer 2014, the Center hosted its fourth summer Research for Undergraduates (REU) programs. Period 5 allows us to assess our strategy, as a large group of undergraduate alumni of the E^3S REU program receive their baccalaureate this year. We see an accumulative 75% placement rate of these to STEM graduate school, including at the Center's member institutions where they can join the Center's research team.

Program Enhancements for Community College Program: One key diversity effort is the Center's Transfer-to-Excellence (TTE) program, which has enabled not only higher transfer rate of California community college students to STEM baccalaureate programs, but has enabled its participants to transfer to top four-year institutions. TTE alumni have been transferring to four-year institutions since Fall 2011. The transfer rate is 94% with most transferring to Tier 1 academic institutions. Through our work with the two community college members of the Center for E^3S, Contra Costa College (CCC) and Los Angeles Trade-Technical College (LATTC), and many other California community colleges that are the home institutions of our TTE participants, we have engaged community college faculty. These individuals can further integrate E^3S science and research findings into the community college curriculum and increase community college students' awareness and knowledge about the Center's research in low-energy electronic devices. In Period 5, we have leveraged a new NSF grant to support research for teachers (RET Site grant), with the goal to provide exposure to new pedagogy methods as part of the E^3S Visiting Faculty program. This addresses the need for higher quality STEM education during the first two years of college STEM education, as stated in the 2012 the President's Council of Advisors on Science and Technology (PCAST) report [1].

Knowledge Transfer: The Center's knowledge transfer strategy is that its industry and education partnerships serve as venues for introducing new and more efficient electronics technologies. Given the Center's focus to establish new science, we recognize that researchers in academia are also knowledge transfer partners. As the Center's research results lead to changes in directions and approaches, it is critical that the Center's sharing of knowledge will lead to a community of like-minded research peers who together can accelerate the achievement of the goal of millivolt switching and few-photon communications. We believe that knowledge transfer is a two-way process and thus, the Center's knowledge transfer activities with industry and academia are built on knowledge dissemination both to and from the Center.

Recognizing that education is itself an important knowledge transfer element, the Center prepares its students and postdoctoral members to be the next generation knowledge transfer practitioners, who will have opportunities to communicate science to audiences at all levels.

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

New knowledge transfer activities in Period 5 are as follows:

We are strengthening existing partnerships with industry by collaborations on specific projects.

The device designs and the materials being investigated in the Center are very intricate and delicate, such that the process technologies to fabricate them are themselves research topics. We are beginning to see some of the Center's new process technologies attract the interest of other researchers and industry.

We are on track to release online outreach modules, reflecting that the Center's strategy for online education is successfully implemented.

Led by **E. Yablonovitch** of UC Berkeley, Center Director and Principal Investigator of the NSF Award, The Center for E^3S was started in October 2010. At the preparation of this Period 5 Annual Report, the Center has completed approximately 50 months of full operation.

Summary of the State of the Center

This section serves as an expanded summary of the Center's progress in Period 5. In depth discussions are given further into this report: Section II – Research; Section III – Education; Section IV – Knowledge Transfer; Section V – External Partnerships; Section VI- Diversity, Section VII- Management; Section VIII- Centerwide Output; Section IX- Indirect/Other Impacts; Section X- Budget

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.

Objective	Metric	Targets	Results			
			Period 2	Period 3	Period 4	Period 5
Research	Multi-PI projects	Period 2: 30% Period 5: 75%	44%	67% (14)	55% (12)	64% (14)
	Multi-Institutional projects	Period 2: 10% Period 5: 30%	4%	10% (2)	9% (2)	23% (5)
	Unplanned research projects	Period 3: 1 Period 4: 3 Period 5: 0	3	4	1	1
	New joint research funding opportunities	Period 3: 1 Period 4: 2 Period 5: 2	n/a	1	0	2
	Publications with authors from multiple institutions	Period 3: 12 Period 4: 3 Period 5: 5	0	1	1	1 1 *in review*
	Publications with authors from multiple departments	Period 4: 2 Period 5: 4	0	0	1	2 1 *in press* 2 *in review*
Education	Center graduates completed E^3S training	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50%	n/a	3 (17%)	3 (14%)	3(33%)
	Students and postdocs participating in education and diversity programs	Period 2: 5% Period 3: 60% Period 4: 70% Period 5: 75%	52%	48 (52%)	41 (69%)	36 (55%)
	Students and postdocs serving in leadership roles in the Center	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25%	11%	11 (19%)	20 (34%)	24 (36%)
Knowledge Transfer	Website hits & unique visitors	Period 2: Baseline Period 3: 20% increase Period 4: 10% Period 5: 10%	Website Hits: 11,354 Unique Visitors: 6,123	Website Hits: 140% (27,298) Unique Visitors:	Website Hits: 42% (38,800) Unique Visitors: 40% (22,809)	N/A due to server migration

				167% (16,338)		
	Contacts with industry: • General • Industry Presentations	Period 3: 36 Yearly: 2	66 4	20 2	42 6	62 3
	Research collaboration with industry	Period 4: 1 Period 5: 2	0	1	1	4
	Center publications	Per Year: 18	17	17	31	39 5 in press 13 submitted
Knowledge Transfer	External citations of publications	Period 3: 10 Period 4: 100 Period 5: 100	15	178	393	969
	Patent disclosures • Disclosure / Provisional • Patent Application Filed	Period 3: 3 Period 4: 3 Period 5: 5 Period 4: 0 Period 5: 3	1 1	0 0	1 0	1 0
	Students hired into relevant industries	Period 5: 50% Period 10: 50%	Students: 0% Postdocs: 1 (100%)	Students: 7 (64%) Postdocs: 2 (33%)	Students: 2 (16%) Postdocs: 2 (20%)	Students: 6 (16%) Postdocs: 4 (40%)
	Technology development attributable to Center's research	Period 10: 1	n/a	n/a	n/a	n/a
	External articles on Center	Period 3: 100% increase Period 4: 3 Period 5: 5	1	0	2	1
External Partnership	Research collaboration - Industry - Others	Period 4: 1 Period 5: 2	0	1	1	4
Diversity	Women in the Center's research programs	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 30%	13 (22%)	15 (25%)	13 (19%)	24 (21%)
	Underrepresented minorities in the Center's research programs	Period 2: baseline Period 3: 15% increase Period 4: 5% Period 5: 10%	2 (2%)	1 (2%)	5 (7%)	12 (11%)

Diversity	Participants from groups underrepresented in STEM in the Center's Diversity programs	Period 3: Baseline Period 4: 80% Period 5: 80%	n/a	93 (82%)	Women: 37 (44%) URM: 58 (68%) Total: 73 (86%)	Women 26 (41%) URMs 36 (56%) Total 49 (77%)
	Pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline Period 4: 70% Period 5: 70%	n/a	31 (68%)	98 (75%)	162 (82%)
	Community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80%	n/a	3 (100%)	6 (100%)	7 (88%)
	Undergraduates who pursue advanced degree in science and engineering	Period 3: 5% Period 4: 30% Period 5: 35%	n/a	0 (0%)	5 (38%)	20 (71%)
Center Management	Centerwide communications	• 1 newsletter • Annual Retreat • Annual NSF Review • Updated Website	None August 29-30, 2011 None Continuously	June 2012 August 21-22, 2012 January 9-10, 2012 Continuously	June 2013 August 26-27, 2013 January 9-10, 2014 Continuously	Jun-14 August 26-27, 2014 January 9-10, 2014 Continuously
	Annual Surveys: • Students /Postdocs	3 or higher on Likert Scale	Average: 3.9±0.2	Average: 4.0±0.3	Average: 4.2±0.2	Average: 4.5±0.2
	• Co-PIs		No survey in Period 2	Leadership 4.46 Collaboration 3.25	Leadership 4.7±0.5 Collaboration not available	Leadership 4.9±0.1 Collaboration Outside Theme: 1.3+/-0.1 Within Theme: 3+/-1
	• External Advisory Board		Strategic Plan: 4.18 Center Status: 4.01	Strategic Plan: 4.07 Accomplishments: 3.96	Strategic Plan: 4.6 Center Status: 4.6	Strategic Plan: 4.4 Center Status: 4.7
	Authorship disputes	20% decrease annually	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale	0
	Plagiarism		0	0	0	0

	Assessment of goals, objectives, and outcomes – Strategic Plan Review	Yearly	1- 5- 2012	12-19 - 2012	12-17- 2013	12-18- 2014

Research

The following summarizes research accomplishments by themes. In Period 5, the System Integration projects are theme specific and those projects are reported with the applicable themes, i.e., with Nanomechanics and Nanomagnetics.

Theme I - Nanoelectronics: Theme I comprises **E. Yablonovitch,** Theme Leader, **C. Hu**, and **A. Javey** from *Berkeley*, and **D. Antoniadis**, **E. Fitzgerald**, **J. Hoyt** and **J. del Alamo** from *MIT*. Tunnel Field Effect Transistors (FET) as the milli-volt alternative to the conventional FET has been a key focus. There are two mechanisms to obtain a steep subthreshold swing in a TFET: (i) electrostatically changing the tunneling barrier thickness and (ii) the Energy Filtering or Density-of- States overlap mechanism, whereby the current can abruptly turn on when the conduction band and valence band align. Energy Filtering, which has been advocated by the Center, requires a steep abrupt band edge for the density of states. Determining the steepness of the semiconductor band edge has been a key scientific and practical goal of Theme I. In Period 5, Theme I researchers made major strides in elucidating observed band edge sharpness in current-voltage spectroscopy.

We have been working to scientifically identify exactly those material properties that need to be improved in order to make tunnel FET's successful. During this period there have been an important series of experiments by the **Hoyt**/**Antoniadis** team working on InGaAs/GaAsSb Quantum-well TFETs; by the **del Alamo** group on InGaAs nano-wire TFET's; and by the **Fitzgerald** group on InGaAs/GaAsSb Backward diodes. Each has solved a different piece of the puzzle, and the knowledge has now been combined by **Yablonovitch** and the team, to elucidate an important leakage mechanism, that has been limiting the performance of tunnel FET's.

The data identified Tunnel Assisted Generation, enabled by interface traps as being particularly deleterious to tunnel FET's. This is one of the reasons that future tunnel FET's will demand a higher level of material perfection, than has been customary in solid-state electronics up till now.

We have been able to gate tune our 2d-2d double quantum well devices (n-InGaAs/p-GaAsSb) from the Esaki regime to the Backward diode regime. The Esaki regime revealed, for the first time, the actual sharpness of a band-edge (80mV/decade in an InGaAs/GaAsSb device), a measurement we had long sought in the Center. In the Backward diode regime, preferred for TFET operation, we identified that the transistor switching is dominated by a new thermally activated mechanism, Tunnel Assisted Generation leakage, which will need to be overcome by improving material and interface quality.

To address some of these material problems, we explored the new chalcogenide monolayer semiconductors which possess perfectly covalently bonded surfaces and exact discretely defined quantum well thickness. Guided by **Javey**, the Center made the first chalcogenide tunnel FET of any type which also happened to be the first Bilayer dual-gated tunnel FET, and additionally, which exhibited over 5 decades of gate controlled conductivity change. We plan to continue to explore novel semiconductor materials that could demonstrate ever higher levels of electronic perfection that will be required.

Theme II - Nanomechanics: In Period 5, Theme II had multi-disciplinary participation from three institutions. Led by **T.-J. King Liu** *(*EECS, *Berkeley)*, the Theme II research team includes **V. Bulovic**

and **J. Lang** (EECS, *MIT*), **T. Swager** (Chemistry, *MIT*), **H.-S. P. Wong** (EECS, *Stanford*), and **J. Wu** (MSE, *Berkeley*), and **J. Bokor** (EECS, *Berkeley*).

Promising zero off-state leakage and abrupt on/off switching behavior, mechanical relays offer the promise of a low supply voltage for ultra-low active energy consumption (projected to be <1 aJ/op). From the inception of the Center, the researchers in Theme II have recognized the need to scale the mechanical switch to nanometer-scale dimensions and address issues such as surface adhesion and wear in order to realize relay-based integrated circuits (ICs) that operate not only with good energy efficiency but also with good reliability (>10^{14} On/Off cycles). By avoiding direct physical contact between metals, reliable operation should be achievable. Direct metallic contact is not necessary, since the 1/KΩ conductance requirement can be fulfilled in spite of limited tunneling conductance.

In this period **V. Bulovic**, **J. Lang** and **T. Swager** (*MIT*) advanced the "Squitch" concept, which uses molecular stiffness to control the switching gap. The types of logic devices are expected to become useful in wireless sensor networks, "the internet of things." In this Period, the key achievement is that the On/Off ratio has been increased to ~10^5, approaching the 10^6 on/off current ratio that is part of the E^3S requirements for a millivolt switch. This achievement resulted from a focus on developing the key fabrication and characterization technologies required for the of this NEM switch. Specifically, in Period 5, we have focused on technologies that will allow us to: (1) fabricate smooth nanometer scale gaps in a controlled manner; (2) simultaneously measure gap motion and tunneling current as a function of the applied voltage for two- and three-terminal switches, for the purposes of switch understanding, model verification and molecular monolayer metrology; and (3) develop molecules with reduced stiffness to create molecular monolayers with the required mechanical properties to reduce actuation voltage. Design and synthesis of the molecules with the targeted stiffness, estimated in the previous Period 4 to be ~3mPa for 0.1 V switching, are undertaken by the **Swager** group. One approach under research is to intersperse long and short monolayer molecules so that only a fraction of the molecules reach across the gap and contribute to the modulus.

Although the Squitch avoids the issue of contact adhesive force, it does so at the cost of non-zero off-state leakage current which may be unacceptable for some ultra-low-power (low activity factor) electronics applications. Theme II researchers at Berkeley and Stanford are working on switches with van der Waals interactions between contacts (vdW switches). These switches require aggressively scaled contacts to approach the ultimate promise of <1 aJ/op. In Period 5, the **King Liu** and **Wong** groups (*Berkeley and Stanford, respectively*) have been working complementarily on van der Waals switches. The Berkeley group has mainly focused on switch design while the Stanford group has pursued the development of a novel CMOS-compatible technique to fabricate vdW switches with ultra-small gap (down to atomic scale). Specifically, the **King Liu** group has modelled a switch design that is normally on to have the promise of achieving 1 aJ/op.

The process technology development required for forming controlled nano-gaps is also useful for broader device applications. In conjunction with material scientist **J. Wu** (*Berkeley*), the **King Liu** group has pursued the approach to induce fracture to form a sub-1 nm contact gap; by carefully designing the shape (pattern) of a thin metallic electrode layer, and optimizing the thin-film deposition conditions to achieve significant tensile strain, crack formation can be well controlled. Relay structures to experimentally verify this approach have been fabricated, enabled by a recently invented technique to controllably form sub-lithographic contact gaps. A provisional patent application is being prepared for filing to occur before the end of Period 5.

The **Wong** group (*Stanford*) has designed a novel CMOS-compatible technique that uses few-layer graphene sheets to fabricate atomic-sized ultra-small gaps for van der Waal switches. Process flows have been designed and a six-terminal carbon nanotube (CNT) NEM switch has been fabricated. While the initial results fall short of the goal of millivolt switching, the accomplishment here is the demonstration of the successful transfer and growth of different types of thin film materials.

At the system level, one of the most dominant sources of lost performance and hence increased energy consumption in today's computing systems is the relatively high energy and latency cost of accessing/utilizing external dense memory (DRAM). The group of **E. Alon** (*Berkeley*) has been studying nano-electro-mechanical memory (NEMory) as it has several attractive characteristics that may address these issues. In particular, it can be integrated on top of CMOS electronics and offer extremely low latency/energy access while achieving non-volatility. During this period analytical models for NEMory devices have been developed to predict the devices' operating characteristics (e.g., pull-in/pull-out vs. device dimensions). The models have been applied to predict the operating voltage versus cell density tradeoffs for various potential material systems. In particular, because of its high strain limit and low Young's modulus, TiNi appears to be a particularly attractive candidate for implementing dense yet low-voltage cells.

To establish if the energy-efficiency and design-style of the Nanomechanics technology extend all the way to the system level, **V. Stojanovic** (*Berkeley*) has been studying the design of the largest computational block (the floating-point unit - FPU) with NEM relays. This study showed how new relay circuit design techniques combined with those we already demonstrated on smaller relay blocks enable optimization of the design of the most complex arithmetic unit, i.e. the FPU. The energy, performance, and area trade-offs of FPU designs with NEM relays have been examined and compared with those of state-of-the-art CMOS designs in an equivalent scaled process.

Theme III – Nanophotonics*:* At the inception of the Center, Theme III only had faculty participation from Berkeley. **M.C. Wu, C. Chang-Hasnain** and **E. Yablonovitch** were the nano-device researchers and **E. Alon** provided system analysis of optical interconnects. Last Period 4, **D. Zubia** (*UTEP*) joined the Center and the Theme to collaborate on selective area growth for phototransistors. Now, new to Theme III in Period 5 is **E. Fitzgerald** *(MIT)*, who will provide regrowth for surface passivation of the devices. The focus of this Theme has continued to be the fundamental physical and technological investigation of the nanophotonic transceiver components. During Period 5, there has been progress made on emitter and receiver projects.

The research on Spontaneous Hyper Emission (SHE) has reached some important landmarks, as a result of a new and unplanned achievement in Period 5, the first demonstration of optically pumped antenna enhanced spontaneous emission from a chalcogenide monolayer, in this case WSe_2. The monolayers are covalently bonded, which would eliminate surface recombination, while allowing the antenna arms to converge closely adjacent to the covalently bonded flat faces of the monolayer. This has provided the highest spontaneous emission enhancement that we have observed, 200×, close to the threshold at which LED's could be regarded as faster than semiconductor lasers. The **Javey** group (*Berkeley*) has been collaborating on the materials aspects of this demonstration, as the group has been research chalcogenides for nanoelectronics applications (*Theme I*). It is expected that the research of these materials will led to further understanding of the materials properties that will, in turn, provide new insights for better TFET designs. The continuous progress in chalcogenide nanoLED will depend on a larger supply of high quality materials. In response, **D. Zubia** (*UTEP*) has established a capability for CVD synthesis of chalcogenides. His research will also focus on enhancing the quality of the materials.

Theme III researchers achieved another first with the demonstration of an electrically pumped nanoLED that is assisted by an optical antenna, showing at least a 10× speedup in LED direct modulation. With custom epitaxial structures available from the **Fitzgerald** group before the end of Period 5, the nano-device researchers will begin to have a new way to address surface recombination effects and accelerate their progress towards higher performing electrically pumped nanoLED.

This light emitter research needs to be complemented by ultra-high sensitivity phototransistors to ensure a low energy communications channel. In Period 5, phototransistor projects in Germanium (**M. Wu** and **Yablonovitch** groups) and III-V materials (**Chang-Hasnain** group) have achieve working photo-bipolar devices. The research in Period 4 concluded with bipolar phototransistors the approach. A Ge n-p-n photo-BJT has a high responsivity (>14 A/W) and gain (~18) and also shown moderately high speed operation, resulting in a gain-bandwidth product measured at over 15 GHz. An InP photo-BJT shows very linear photo response with responsivity approaching 4 A/W at very low bias voltage of 0.5V, indicating that the device with regrown junctions for low dark current facilitating very low voltage operation.

Theme IV - Nanomagnetics: There has been a change of faculty researchers of personnel as the Nanomagetics Theme heads toward a concrete form of low energy logic, in which a current switches a magnet, which changes a magneto-resistance that in turn drives a current providing gain and fan-out. Theme Leader, **J. Bokor** (*Berkeley*) is now joined by **S. Salahuddin** *(Berkeley)* and **S. Khizroev** *(Florida)*. As a result of the new breakthroughs in the Spin-Hall effect, Theme IV is now pursuing current control of magnetic switching versus voltage control, the approach that had been in place since the start of the Center. For nanomagnetic devices to have practical applications, the issue of the very low magneto-resistance ratio in nanomagnetic materials must be addressed. **V. Stojanovic** (*Berkeley*) has been studying the circuit topologies and block-level mechanisms to mitigate the low Ion/Ioff ratio of nanomagnetic switches (which leads to large standby power), by exploiting their non-volatility, while leveraging the low supply voltage operation of these devices for very low active power.

In Period 5, the researchers of this Theme have continued to primarily focus on elucidating the physics and dynamics of Spin Hall effect, ultrafast magnetic switching, and magnetic switching in sub-10nm scale magnetic tunneling junctions.

In Period 5, the **Salahuddin** group reported for the first time that it is possible to move a magnetic domain wall orthogonal to the current flow using spin orbit torque. Switching a magnetic nanodot with an in-plane current by spin-Hall effect without needing an external magnetic field for symmetry breaking was also demonstrated.

The **J. Bokor** group has completed the initial study of the dynamics of the magnetization, measuring the change of polarization on reflection of a short probe pulse from different magnetic material samples with a Magneto-Optical Kerr Effect (MOKE) magnetometer. Not only was the demagnetization time of less than 100 fsec confirmed, but even more significantly, the magnetization recovery time can be as fast as ~1 psec.

S. Khizroev and **J. Bokor** (*Berkeley*) have been collaborating in the study of the STT effect in MTJ nano-structures made of Ta/CoFeB/MgO/CoFeB/Ta, building on the prior work of the Khizroev group [2]. At Berkeley, testing of wafer level test structures trimmed by focused ion beam to sizes that ranged from several hundred nanometers to sub-10 nm confirms the findings of the prior work on a junction built on the tip of a nanoprobe. The switching current is linearly scaling down from mA range to sub μA range in sub-10nm structures. Some samples revealed signals that indicate multi-junction structures showing characteristics favorable for multiple bit per cell applications.

The **Stojanovic** group has completed a nanomagnetic logic power-gating model that extends the work on pulsed magnetic logic. The model was used to study the energy advantages of non-gated magnetic logic devices over CMOS gated logic blocks. Even though in this circuit architecture, the study showed a significant improvement, this still brings the effective Ion/Ioff ratio to only ~100, as compared to 1,000-10,000 in CMOS. The group is now analyzing circuit blocks that can more strongly from power gating, such as cache memories, as well as blocks that have high activity factor, such as communications links, in which standby power dissipation is less important.

Education and Diversity

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

The goal of the diversity programs of the Center for E^{3}S is to increase the number of students from historically underrepresented groups in engineering who attend university and graduate programs in technical disciplines that will contribute to low energy electronics. While the Center seeks to ensure that the composition of center participants reflects the diversity of the US, with a particular focus on underrepresented racial/ethnic backgrounds, women, and people with disabilities, there is increasing recognition that the more tangible goal is to attain a diversity profile that is better than a comparable benchmark. 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.

During Period 5, the Center graduated 28 students and postdocs (17 undergraduates, 9 graduates, and 2 postdocs). To date, E^{3}S has had 79 graduates (25 undergraduates, 35 graduates, and 19 postdocs). Our graduates students and postdoctoral researchers have gone on to pursue careers in industry, academia, and national research laboratories around the globe.

At the beginning of this reporting period, Period 5, the Center had 161 students and postdoctoral researchers that have been trained in our Center under the supervision of E^{3}S faculty. Twice since the inception of the Center, **E. Yablonovitch**, Center Director, developed and taught EE 290: Advanced Topics in Solid State Devices covering the topics of the Center for E^{3}S members. The Center members from all institutions can attend the course via remote access and course materials are provided online. Thus, one-third of our graduate students and postdoctoral researchers who have graduated from the Center have completed this course. However, as we look ahead to new students and postdoctoral researchers joining the Center, we recognize that early introduction to the Center's research and novel approaches to designing low-energy electronic devices by this biennial course is very important. In Period 5, a team of E^{3}S graduate students and postdoctoral researchers from across the Center (**S. Agarwal, C. Keraly, M. Eggleston, J. Hong, G. Zheng, M. Nowakowski, D. Bhowmik, Y. Yang, F. Niroui)** are creating an online mini-course, *Energy Efficient Electronics*. This course includes five 1.5-hour lectures of research approaches and real-world examples on Tunneling Field Effect Transistors, Nanomechanical Switches, Nanophotonics, Nanomagnetics, and Systems Approach to Solid State Devices. The mini-course is still underdevelopment with three of the lessons complete. We expect that this online course will be made available to all Center members by the end of Period 5. To broaden the participation of individuals who are trained in low-energy electronics science, the course will be available on the Center's website for an external audience.

The Center integrates research and education strategies in building a library of online courses of energy efficient electronics science that will reach a broader audience, including other researchers, scientists, and engineers, undergraduate and graduate students at other colleges and universities, and pre-college students and teachers. A Period 5 goal is to make great strides in developing the online materials. In addition to the short course modules mentioned above, the Center also has used a similar approach to design online education curriculum for undergraduates, creating a 5-hour mini-course introducing the basics of electronics, including an overview of semiconductors and devices, discrete & integrated circuits, and circuit theory & network analysis. The target audience for this course is students who have little to no prior knowledge about electronics and electrical engineering. The Center has partnered with two community colleges to use these lectures in engineering courses. In addition to using these course modules in the classroom, this mini-course is easily accessible on the Center's website for students and educators interested in mastering the basics of electronics.

Moreover, for a k-12 audience and general public, the Center has leveraged the resources of the MIT's Office of Digital Learning Science Out Loud program to design a free, easily accessible video. E^{3}S graduate student, **J. Teherani**, developed and served as the speaker in the video, *How Computers Compute* (http://www.youtube.com/watch?v=8cVsgFN3hSM&feature=youtu.be), to show a side of science different from what is typically found in a textbook. This is one of a series of three videos that the Center is creating to show the benefits of smaller, faster, and more energy efficient solid-state transistors. The other two videos, *Semiconductors as Switches* and *Scaling of Switches Using Cleanrooms*, are expected to be complete in early 2015.

Many established education efforts for training and professional development of the Center's students and postdoctoral researchers have continued to be embedded in Center activities. As in previous years, the Center organizes a series of seminars where the graduate students, post-doctoral researchers and occasionally E^{3}S faculty present their research results. Once again, the 2014 annual survey of students and postdocs revealed that a large majority of the respondent (85%) find these seminars to be very useful in "sharpening their understanding of low energy consumption device science and technology." The Center has continued to use its Annual Retreat, External Advisory Board Meeting and NSF Site Visit for the student and postdoctoral researchers to communicate their research, mainly in the form of poster presentations, to an external audience. The same survey found that 69% of the respondents find that opportunities to present their own research have sharpened their technical skills. Opportunities to communicate one's research have not been limited to graduate students and postdoctoral researchers. Previously in Period 4, the Center formalized support to its undergraduate members with funding of travel and registration for conference presentation of their research. In Period 5, two undergraduates (one a former college intern of the TTE program and one an ETERN at Berkeley) have papers accepted in peer-review conferences. The former presented the 2014 Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Conference, while a paper authored by the ETERN and his international internship hosts has been accepted for oral presentation at 2015 IEEE EuroSOI-ULIS conference.

The Center also promotes learning from outside the Center. New in this Period is an Invited Speaker Series. In Summer 2014 series featured four speakers, 3 from industry and 1 from another NSF STC, Center for Integrated Quantum Materials, a science domain of applicable to our Center's research. The graduate students and postdoctoral researchers utilized this year's Graduate Student and Postdoc Summer Retreat to survey the research that is competitive to that of the Center. In this Period, E^{3}S students and postdoctoral researchers at Berkeley had the opportunity to learn about the research at CEA-Leti, Grenoble, France during a visit by 15 graduate students of the French government laboratory. It was a two-way knowledge transfer event as the agenda also included seminars of the Center's research for the visitors.

Approximately 50% of the Center's students and postdoctoral researchers are participants in the Center's education, leadership, diversity, and outreach programs, serving as mentors, course instructors, outreach leaders, or lab tour guides. The Center's students, both graduate and undergraduate, have continued to support Cal Day and Bay Area Science Festival, major community outreach events that reach over 600 adults and children. The Center's demonstrations have been found to be especially popular students in the early grades.

For our diversity programs, 74% (275) of the 363 students hosted by E^{3}S are from underrepresented groups, including women, ethnic minorities, and veterans. In Period 5, 12 undergraduates have enrolled in a graduate program in science or engineering and 7 (88%) community college students have transferred to a 4-year institution. The cumulative total for the Center to date is 18 undergraduates enrolled in a graduate program in science or engineering and 17 (94%) community college students transferred to a 4-year institution. Among these participants, 7 (39%) of our undergraduates who are now enrolled in a graduate program are women and 3 (17%) are from an underrepresented minority group. For the community college students who have transferred to a 4-year institution, 4 (22%) are women, 5 (28%) are from an underrepresented minority group, and 9 (50%) are first-generation college students.

In the previous Period 4, the Center focused on streamlining our diversity programs to better align with the Center's vision and goals for enhancing diversity in the field of low-energy electronic devices and cultivating a diverse pool of applicants for our programs. In the current Period 5, the Center has refined and expanded these successful programs and strengthened and formalized relationships with Historically Black Colleges and Universities.

Highlights of programmatic activities in Period 5 include:

- The ETERN program, research experiences for undergraduates in the Center's member institutions during the academic year had 8 participants, the largest cohort to date. E^3S faculty at Berkeley, MIT and UTEP advised the ETERNs and were mentored by E^3S graduate students in their research. In Period 5, the Center continued to offer an international internship for one ETERN who spent 9 weeks doing research at CEA Leti in Grenoble France, mentored by an E^3S postdoctoral alumnus. The Center's vertical integration mentoring scheme reached beyond the boundaries of the Center.
- E^3S Research Experiences for Undergraduates program (E^3S REU), the Center's 9-week research program, received approximately 200 applications. Eleven of these students were matched with Center faculty at Berkeley, two were matched with faculty at MIT, and one was matched at Stanford. This is the first year the E^3S REU has placed a student at the Stanford campus. At Berkeley, they were hosted by E^3S faculty, **J. Bokor, C. Chang-Hasnain, A. Javey, S. Salahuddin, M.C. Wu,** and **E. Yablonovitch**. At MIT and Stanford, they were hosted by E^3S faculty, **E. Fitzgerald,** and **J. del Alamo** and **P. Wong**, respectively. In addition, the students attended weekly enrichment activities that included field trips and preparation for the GRE. This summer, Sandia National Labs provided the students an overview of Sandia's research technology and a tour. Each student also received weekly one-on-one mentorship meetings with **S. Artis**, Education and Outreach Director.
- During summer 2014 (Period 5), the Center at Berkeley hosted 5 of the 14 community college students in the TTE REU program. These students completed nine weeks of research in the laboratories of E^3S faculty**, T.-J. King Liu, E. Yablonovitch, M. Wu,** and **J. Wu,** and the Marvell Nanofabrication Laboratory, where most of the E^3S experimental research is conducted, became an Education Affiliate, as one of its staff, **J. Clarkson,** advised and mentored an intern from the community college REU program.
- E^3S Visiting Faculty Program (formerly the Teacher Fellows program; named changed as suggested by the External Advisory Board's Education Working Group) hosted two community college faculty members. **A. Navarro**, a faculty member in the Department of Engineering at Los Angeles Trade Technical College, one of the Center's education partners, was hosted by Prof. **J. Bokor** and co-mentored by graduate students, **K. Messler** and **J. Clarkson**. **N. Wang**, a faculty member of Electronics Technology program of Sacramento City College conducted nine weeks of research in the laboratory of **V. Stojanovic** in Berkeley, mentored by **Chen Sun**, Ph.D. candidate at MIT who is resident at Berkeley.
- The Center's pre-college programs are targeting rising high school seniors. The Center has leveraged the existing partnership and infrastructure at the member institutions. MIT's Online Science, Technology, and Engineering Community (MOSTEC) promotes student's early interest in science and engineering careers, particularly among female and students from underrepresented groups. The Center for E^3S is one of the founding sponsors of MOSTEC, an online enrichment program for high school seniors that includes an electronics workshop. MOSTEC, now in its third year, also provides

a weeklong conference at MIT and assists the participant during the college application process. The Center hosted 39 of students in MOSTEC.

- New in Period 5 was the Center's participation in the EECS Rising Stars Workshop at UC Berkeley for women interested in careers in academia, for two days of scientific interactions and career-oriented discussions. In an effort to recruit more women, E^3S hosted a tour of the Marvell Nanofabrication Laboratory and a session with Center's faculty and leadership (**E. Yablonovitch, J. Bokor,** and **P. Wong**) to share E^3S research and provide participants advice for advancing their careers.

Knowledge Transfer

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. The Center thinks of Knowledge Transfer as cross-fertilization that goes in both directions, up and down the food chain from fundamental research to technology development and ultimately commercialization.

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

Center's researchers have continued to support information dissemination and knowledge exchanges with communities of peers through publications in peer-reviewed journal, presentations both in peer-reviewed conferences and other fora, and private meetings with companies. Since the last annual report, the Center achieved a high watermark with 23 new papers on the Center's research being published in peer-reviewed journals, 2 additional are in press, and 16 papers are under review. Moreover, the papers from 16 talks, presented at peer reviewed conferences, have newly been published as conference proceedings. The Center's publication record in Period 5 also includes a paper on learnings from the Center's engagement with community college students being accepted for publication, complementing the two published papers as part of proceedings of a conference on engineering education. Among the talks at peer-reviewed conferences are two technical papers that included two E^3S undergraduate researchers as authors. An E^3S community college intern presented the results from his internship at the 2014 Conference of the Society for Advancement of Hispanics/Chicanos and Native Americans in Science (SACNAS), while one of the Center's ETERNs who did research at CEA-LETI has been offered the opportunity by his French advisor to present a paper that was accepted for oral presentation at the 2015 IEEE EuroSOI-ULIS conference.

New and particularly noteworthy in Period 5 for the Center's Knowledge Transfer mission are the emerging opportunities for the Center's research outcomes to find application beyond the pursuit of the Center's goal of energy efficient devices. Since the Center's inception, the Center's researchers have been developing underlying new technologies, establishing new fundamental understandings, and designing new device structures. Reflecting their entrepreneurial spirit, the Center's faculty identified five opportunities to apply research beyond the technical scope of the Center. Of the five, two were device designs, two processing technologies, and one a material system. The emergence of these opportunities constitutes another new milestone for the Center, complementing the opportunities of knowledge transfer among the Center's research Themes that is enabled by the Center mode. In Period 5, there have been two cases of re-use of new technologies within the Center.

Another aspect in knowledge transfer is knowledge dissemination for broadening access to low-energy electronics science and research through informal learning. In Period 5, the education and diversity efforts of the Center have included transfers of knowledge via curriculum development and outreach. New during Period 5 has been the development of short online vignettes for undergraduates and graduate students (see Education Section) to transfer knowledge and enable informal learning to a larger and more diverse audience. A TFET entry was established in Wikipedia. These online resources complement the in-person outreach events that Center's students, postdocs, and staff have conducted during this Period. In past 12 months, the Center engaged over 600 students, educators, and parents in hands-on electronics activities that are related to the Center's mission of low-energy electronics science and research.

External Partnerships

The Center for E^3S has utilized partners to advance the research portfolio and achieve programmatic goals. Industry partnerships were formed prior to the Center's inception and continue to serve as the cornerstone in the execution of E^3S' two-way knowledge transfer strategy. The Center's researchers have created both formal and informal partnerships as they pursue their scientific investigations. The education and diversity programs leverage the experience, expertise and resources of campus partners at home and subaward institutions to deliver highly successful programs. In period 5, the Center has continued to execute and enhance its partnership strategy to enable successful achievement of all its goals.

In Period 5, the Center strengthened the level of engagement with its industry members. Four out of five member companies have project specific engagements. One E^3S student from the **M. Wu** group was an intern for six months with Intel's Si Photonics group. Applied Materials and Lam Research are providing either direct funding or in kind funding. Two IBM locations, Zurich and Yorktown Heights, have provided custom wafers and characterization capability.

New Research partners were also developed. **J. Bokor's** collaboration with **M. Klaui** in Mainz, Germany involves student exchange, while the squitch team at MIT is beginning to utilize MIT Lincoln Labs' unique nanofabrication capabilities to achieve nano-gaps with smooth surfaces. This partnership will allow the E^3S researcher to work with the MIT Lincoln Labs researchers as each party exploit the squitch technology for different applications.

The Center's education and diversity programs have continued to leverage the expertise and resources of campus partners. At MIT, partnerships have allowed E^3S to deliver electronics training for a high school online community (MOSTEC) and to support REU interns at the laboratories of E^3S MIT faculty. At UC Berkeley, campus collaborations have provided the participants with more substantive experiences for summer internship programs, enhanced diversity recruitment, and supported the transfer of community college students who are alumnae of the Center's programs. We have worked with these partners for many years, some since the start of the Center. Since we have named them and described our relationship with them in past annual reports, we will not do so again in this report. Instead, we will identify the following as new partners: 1) CEA-Leti, Grenoble France that has partially funded an ETERN for 9 weeks of research and is looking for the Center to send another undergrad for summer 2015; 2) **R. Freishtat**, senior consultant, the Berkeley Center for Teaching and Learning, who organized a workshop on Context-Based teaching that also includes online teaching for the benefit of community college teachers; 3) MIT Office of Digital Learning for being a partner on the development of the three outreach online modules for the general public; and 4) the National Nanotechnology Infrastructure Network (NNIN) served as the local host for an E^3S REU at Stanford.

Center Management

The E^3S Executive Committee continues to provide management oversight as well as planning and making decisions for the Center. Annually, the Center measures the effectiveness in its leaders primarily through two perception surveys of the faculty, postdocs and graduate students. Period 5 is the fourth year for the survey of graduate students and postdocs of the Center's leadership and environment, as well as the effectiveness of its operations. Similarly, there has been a survey of E^3S faculty for three years on leadership and collaboration. The participation in the Students and Postdoc survey has been strong from the very beginning and has grown steadily over the past 4 years to 26 participants in Period 5. The participation by faculty was weaker in the first two years of the survey, but in the current Period 5, the participation grew to 100%; all 21 co-PI's participated in the Period 5 faculty survey.

The Period 5 survey results indicate that the Center's students and postdocs' agree that the Center leadership is promoting team work, supports an inclusive environment, and is open with its communications by giving an aggregate score of 4.7±0.6. This score is similar the result of previous three reporting periods: Period 4 = 4.2±0.6; Period 3 = 4.2±0.5; Period 2 = 4.0±0.7. Similarly, in Period 5, the E^3S co-PI's indicated agreement that the Center's leadership is living up to its espoused values; Likert score = 4.8±0.2. This can be compared with the results from Periods 3 & 4, when the similar scores were: Period 4 = 4.7±0.5 and Period 3 = 4.5. The Center's students and postdoc's agree that their colleagues act in an ethical manner with 96.2% (25) of respondents indicating that was the case. One respondent indicated that they were unable to respond. None of the respondents indicated they witnessed unethical behavior

The Graduate Students & Postdoc and the Faculty Surveys attempt to assess the state of collaboration differently. For this and the two preceding Periods, graduate students and postdocs have been asked questions about the help they have received. The Faculty Survey has attempted to assess the degree of collaboration in each of the three surveys the Center has conducted.

The Faculty Survey of Period 5 shows that the co-PI's within a Theme mainly "coordinate" as defined by formalized collaboration on an E^3S project within one institution. Survey results revealed that the level of interactions among faculty working in different Themes is between "networking" to "cooperation", as defined by "interactions during centerwide meetings" to "adhoc sharing of research ideas, recipes and/or equipment." The survey data aligns with an analysis of joint publications among the faculty of the Center, which shows that to date, there are 4 cross institutional journal publications, each between MIT faculty and the Center Director, 3 Theme I publications and 1 Theme II publication.

The Students and Postdoc Survey shows a stronger collaborative environment. The student and postdoc respondents indicated that their E^3S research was helped through discussions, inputs, and general collaborations, see Figure VII-I. For the students, the center clearly hosts a high level of informal collaboration, however, this has not translated into formal outputs in terms of papers or conference proceedings.

The primary sources of external advice and guidance for the Center for E^3S are two groups: the External Advisory Board and the Industrial Research Board, both of which met with the Center in Period 5. As in previous Periods, the Industrial Research Board, which is made up of representatives from Applied Materials, IBM, Intel HP, and Lam Research met with the E^3S Executive Board as part of the E^3S Annual Retreat where they, as Center members, are updated on the progress of the Center.

In Period 5, however, the External Advisory Board (EAB) had a number of changes aimed at strengthening the Board's ability to handle its Education and Diversity responsibilities: (i) An Education Working Subgroup, chaired by **D. Rover** (*Utah State*) was established to dedicate more energy to Education and Diversity; and (ii) the addition of **E.W. Chang** (*Mercer County Community College, Trenton, NJ*) to provide community college expertise. The Education Working Group only advises, and the assessment is the responsibility of the full board. **D. Radack** (*Institute for Defense Analysis*), continuing the second year of his two year term as the Board's Chair, suggested to lengthen the annual meeting of the full board to 1.5 days so as to allow more time for deliberations and feedback to the Center. Thus, the Board met on November 5-6 with all but two in attendance at Berkeley, with two participating remotely.

Center for Energy Efficient Electronics Science

Center Output

Publications		
	Peer Reviewed Journal Publications	23
	In press	3
	Submitted for Review	15
	Peer Reviewed Conference Proceedings*	22
	Books and Books Chapters (In Press)	5
	Non-Peer Reviewed Publications	2
Conference Presentations		23
Other Dissemination Activities		40
Awards and Honors		10
Ph.D. and M.S. Graduates		10
Postdoc Alumni		2
Patents Disclosures		1**

* excludes published proceedings from venues organized by the Center
** in preparation, to be filed before end of Period 5

PLANS FOR PERIOD 6

In Period 6, the last six months of this award, the research in the Center will continue to build on the progress achieved in Period 5. The direction of each research Theme is as follows.

Theme I: There is a two prong approach in Period 6. We will continue to identify the scientific obstacles that face tunnel FET's as they try to achieve steepness, On/Off ratio, and good conductance. For discovering the scientific facts we will continue to learn from devices made in III-V semiconductors.

For overcoming the issues that have been identified, we will continue to develop potential candidate materials, like the chalcogenide monolayers. At the same time, we will initiate new research that targets materials perfection. A new chemist Co-PI, **F. Fischer** (*Berkeley*) will join with chemist **T. Swager** (MIT) in Theme I to investigate synthetic chemical approaches to achieve perfection at the atomic level in anticipation that a molecular approach may ultimately be needed.

Theme II: Demonstration of devices operating near 0.1V is a key milestone for the nanomechanics researchers at Berkeley, MIT and Stanford.

Theme III: The Berkeley researchers are expected to accelerate their progress in electrically pumped III-V nanoLED enabled by in-house custom epitaxial materials from the materials growers at MIT. We are on the verge of announcing spontaneous emission faster than stimulated emission, as observed in chalcogenide monolayers. New insights in this novel material system will be obtained from Theme I. The goal for the phototransistor research is to achieve device performance that will verify the Center's claims that creating a phototransistor and shrinking the capacitances will reduce the necessary photons/bit needed for communications.

Theme IV: The progress made in Period 5 is allowing the nanomagnetics researchers to begin development of device structures to be understand the limits of energy dissipation during switching. High speed magnetic switching induced by electrical pulses is expected to be observed soon. Research on circuit architecture approaches to address the challenge of low on/off ratio in magnetics will continue.

Period 6's duration of six months allows the Center's summer Education programs to have one more session before the end of the current award. Thus, much of Period 6 will be spent in continuing the established education programs.

As the Center will have newly released online modules on electronics, we will use Period 6 for assessment and promotion. The Center will evaluate the efficacy of the online teaching modules, particularly the collection of mini-course modules on Energy Efficient Electronics for new Center members. We expect to implement an assessment instrument to determine the impact on learning. We will also promote the Introduction to Electronics modules with faculty in community college, conduct follow up to understand how the modules are used, and find opportunities to receive information on efficacy and impact on learning.

In Period 6, the Center will continue to recruit diverse candidates to its Education programs. New for the REU program is the plan to attract students from HBCU's through the activities of the newly established UC-HBCU program of which Theme Leader, **T.-J. King Liu**, is the PI. The UC-HBCU program has been unable to accept many qualified applicants because the program is small. E^3S already has scheduled a webinar for the unsuccessful HBCU applicants to provide guidance on applying to the E^3S REU program.

Analysis of the data on REU alumni attending graduate school and joining the Center as graduate students calls for a program change. We have concluded that there should be greater emphasis in selecting electrical and electronics engineering undergraduates to ensure that when they successfully join one of the Center's member institutions, the program participants will be in a department where there is a choice of E^3S faculty to serve as their advisors. While E^3S takes a multi-disciplinary approach in undertaking its research program, the majority of the Center's co-PI's are electrical engineering faculty. Advisor's participation in E^3S is prerequisite to a graduate student being in the Center.

The Center expects that in Period 6, the E^3S administrative and programmatic team will continued to be challenged by workload, even though there is sufficient expertise for the Center to execute its programs. Recruitment for a full-time hire for the Education and Outreach position will begin in the beginning of 2015. Recruitment for this position will have the first priority, subject to the renewal of the Center.

II. RESEARCH

1a. Goals and Objectives

The foundations of the thermodynamics of computation were established by Landauer and Bennett; a good review of this work was published by Bennett in 1982 [3]. An oft-quoted result is that a computer operating at temperature T must dissipate at least kTln{2} (about 18meV at room temperature) per logical operation. This is frequently referred to as the “Landauer limit” [4]. However, for reversible, or adiabatic operations, in fact the minimum dissipation can even be made much less than kT [5]. For reference, leading edge CMOS today dissipates a minimum of ~400,000kT per digital function, when the energy required to charge the wires is included. The ITRS Roadmap [6] projects a goal for this value to be reduced to ~40000kT/digital function in 2022.

In principle, digital logic systems can approach the Landauer limit. This requires a switch that is more sensitive than the transistor, and which can therefore operate at a lower powering voltage. Switch sensitivity in Figure 1 is parameterized by sub-threshold swing, S, where the 60mV/decade is equivalent to the Boltzmann factor, and represents today's thermally activated devices such as the transistors.

At the end of the CMOS roadmap, the operating voltage is projected to be ~0.7V. Since conventional transistors are thermally activated, they rely on this voltage >>kT/q to maintain the desired On/Off ratio ~10^6. Logic transistors are often at rest waiting for a signal, necessitating low leakage current in the off-state. An important requirement for a new switch is to maintain the On/Off ratio ~10^6, but at a lower operating voltage.

Since electrical noise in circuits is ~1mV, good Signal-to-Noise ratio can be maintained even while lowering the powering voltage below 10mV. This results in ~10^4 energy reduction relative to today's logic circuits. In this respect, it is important to distinguish between the energy requirement in eV units versus the voltage requirement in V units. A bit of information on a wire is represented by many electrons, easily satisfying the Landauer requirement >>kT, even when the voltage is <kT/q.

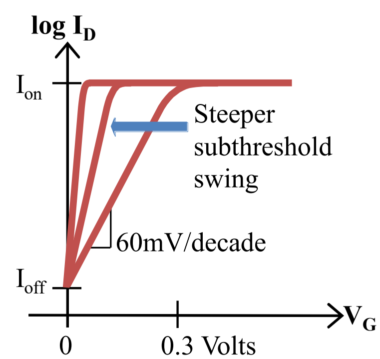


Figure 1: Current (logarithmic scale) vs. voltage V_G (linear scale) characteristics of a logic switch. The subthreshold swing (S) is conventionally limited by the Boltzmann factor to be no steeper than $ln\{10\}$kT/q=60mV/decade at room temperature

In addition to sensitivity and On/Off ratio, there is a 3rd requirement. For integration, a small switch must deliver sufficient current to charge the wires in less than a clock period, the usual requirement being 1mA per 1µm of transistor size in a 1Volt circuit. Given that we are seeking to lower the voltage well below 1Volt, the corresponding switch conductance requirement becomes 1milli-S/µm rather than 1mA/µm.

Thus there are three basic requirements, sub-threshold swing, On/Off ratio, and conductance. The Center is concentrating on four promising device principles that can fulfill these requirements.

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Integrative Research	Multi-PI Projects	Yearly	Period 2: 30% Period 5: 75%
	Multi-Institutional Projects	Yearly	Period 2: 10% Period 5: 30%

	Unplanned research projects	Yearly after Period 2	Period 3: 1 Period 4: 3 Period 5: 0
	New joint research funding opportunities	Beginning in Period 3	Period 3: 1 Period 4: 2 Period 5: 2
	Publications with authors from multiple institutions	Yearly beginning in Period 2	Period 3: 12 Period 4: 2 Period 5: 4

1c. Problems Encountered

Theme I: Device fabrication has continued to be challenging for Theme I researchers because the device designs are complex and the materials employed are difficult to handle. This issue has gated Theme I's progress towards achieving experimental device results that can verify the analytical studies.

- While the InGaAs/GaAsSb QWTFET was successfully fabricated, undetermined process variation issues were experienced. Alternative metallization for the GaAsSb contact is under test.
- The three gate design makes the fabrication of the 3Gate bilayer TFET quite challenging. Initial attempts at wafer bonding a patterned wafer failed. A new mask with dummy fill pattern has been developed to yield better CMP effectiveness.
- Indium-containing compounds are notoriously difficult to dry etch. For the nanowire TFET fabrication, we have been able to successfully solve this problem by carefully optimizing the etching conditions, including substrate temperature, substrate bias power, chamber pressure and gas flows.
- Gate isolation technique in vertical nanowire devices via planarization and etch back process through spin-on glass (SOG) is another challenge. Wet etch back was not a viable option as HF-based solution produces pin-holes in SOG films. In order to achieve uniform SOG layer for isolation purpose, a dry etch back process was used. To protect the semiconductor nanowire from dry etch damage, ALD Al_2O_3 is deposited as a protection layer. We need to control the thickness of the final SOG accurately (10 nm resolution for a total thickness of 500 nm). The etcher used here is not very reproducible. To overcome this problem, long time chamber pre-condition is used. In order to control the thickness accurately, etch/SEM cycles of very short etch time are repeated until the desired thickness is reached.
- Learning to handle chalcolgenides during electronic device fabrication is itself a research topic. Currently all heterojunctions are formed by mechanical transfer which not only leaves unwanted organic residues between van der Waal layers, but also limits upward scalability of heterojunction TFET devices when implemented towards CMOS or more complicated logic implementations. Developing other controllable junction formation via chemical such as growth or direct chalcogen exchange will potentially solve this problem.

Theme II: In Period 5, Theme II's efforts to overcome the fundamental energy-efficiency limit of a mechanical switch have included research into the formation of sub-lithographic contact gaps for both squitches and van der Waals switches. Challenges to forming nanometer-scale gaps using conventional approaches, such as the removal of a thin sacrificial material (Stanford) and filling in an oversized gap (MIT), have been encountered.

- At Stanford, the removal of an ultra-thin sacrificial graphene layer has been difficult to achieve. This may be due to a combination of the small gap size and the materials employed. We are now using other materials (such as ALD deposited Al_2O_3) to determine which of the above two factors is the main factor.

- At MIT, the two biggest challenges have been the fabrication of nanometer-scale gaps with smooth surfaces, and the simultaneous measurement of gap motion and current as a function of the applied voltage. The former is essential because it is central to the reproducible fabrication of squitches. The latter is critical to understand the operation of the squitch and to verify its analytical model. To address the former challenge we have pursued a new approach, namely to fabricate vertical gaps by transferring a graphene conductive electrode onto the squitch molecular monolayer. This is an additive process in which the monolayer sets the nanometer-scale gap thickness. Simultaneously, we have partnered with the MIT Lincoln Laboratory to use their fabrication facilities to better fabricate our original horizontal gaps. Those nanometer-scale gaps are created by filling in an originally oversized gap. To address the latter challenge, we are pursuing the development of a plasmonic ruler.

Theme III:

- Chalcogenide NanoLED: The main bottleneck is the supply of Chalcogenide materials. The results reported in this Period have been from materials that were exfoliated from bulk crystals which is a very low yield and time intensive process. The solution will lie in the development of CVD of monolayers of such materials; a task that has been initiated by **D. Zubia** (*UTEP*); see section on Research in Period 6.
- InP Phototransitors: The measured 3 dB bandwidth for the BJT device reported in this Period is 2.5 GHz. Upon analysis, the constraining factors for this speed involve both parasitic capacitances and transit times, which is made up of emitter-depletion layer charging time and base transit time. A few approaches to boosting the gain-bandwidth product would include shrinking the base width (to reduce transit time), shrinking the device height (to reduce capacitances) and operating at higher DC biases. The use of heterojunctions and doping gradients to set up electric fields for fast transit times is also very promising for high f_T device designs [7]. Further analysis of the responsivity of the device versus collector bias current indicates saturation at 4 A/W at 0.5 V collector bias in forward active mode. As collector bias continues to increase, responsivity dips. This dip in responsivity is likely caused by the large amount of Early effect observed in the device since Early effect is known to reduce gain in conventional BJT devices. We also observe base punch-through at around 0.8 V collector bias, which is a little low. The large amount of Early effect and rather low punch-through voltage indicate that base width, or base doping concentration, is not quite high enough. We believe through more thorough device simulation and design, we will be able to better optimize the design to reach even higher device performance.

Theme IV: The problems encountered were typical of research projects that did not affect progress substantively, except in the Ultrafast Magnet Switching project of the group of **J. Bokor** *(Berkeley)*, where there were difficulties obtaining a supply of LT-GaAs samples. Wafers from the well-established commercial epi-suppliers, like IQE, BATOP, POWERWAY, are relatively expensive and the delivery times are uncertain. Since a number of samples with variation of the material design are needed in order to optimize the device for the project's purposes, the full study would not only be costly, but more importantly, the time needed for each iteration would be uncertain. An alternative solution is to use a commercial supplier for an external LT-GaAs based pulse emitter that can be contacted to our magnetic sample similar to a conventional probe tip.

2a. Research Thrusts in Period 5

The most challenging aspect of energy efficiency in electronic devices is internal communication in processors. Indeed the main function of the electronic switch is to drive signal currents and voltages along the internal wire in an integrated circuit; these wires are often referred to as interconnects. Through four distinct themes, the Center is researching different approaches to electronic switching and communication at the chip level. The same four research themes that have been part the Center since inception have continued in the current Period 5.

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

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

The Center has also continued to recognize that its research in novel electronics components must be guided by circuit/system perspectives. The detailed technical goals/specifications for the novel electronic components in the context of a circuit is itself a research endeavor. This research activity of the Center is known as System Integration. The principal goal of this project is to explore the implications of actual communication and computation circuits/systems on the design, optimization, and requirements of the emerging device technologies being explored in the rest of the center.

While the research themes have stayed the same, the research approaches have evolved as the Center's researchers make advancements in the understanding of the technical challenges, and faculty and institutional participation in the Center have changed accordingly.

Theme I: The nanoelectronics Theme continues to use a solid-state switch, but to radically alter the switching principle so that it can operate at a drastically lower voltage than CMOS. We are changing the fundamental switching mechanism from modulating thermionic emission current over a barrier, to modulating tunneling current through a barrier, the so-called Tunnel Field Effect Transistor. However the preferred TFET mechanism has continued to be unclear. Theory predicts excellent results, but experimental results still failed to yield device performance with sufficient steepness and current simultaneously.

The approach of the nanoelectronics researchers, all from either Berkeley or MIT, has been to focus on understanding the device physics versus device fabrication to demonstrate performance. We have focused on exploring the device physics of density of state switches, as an alternative to tunneling based on modulating the barrier. One fundamental question is the sharpness of bandedge in density of state switches. Another question that we set out to answer is whether there are materials systems, alternative to III-V materials, with Type III band alignment. Both questions are concerned with the role that inhomogeneities play. In Period 5, the experimental device data obtained by the Theme I researchers offer answers to both questions. Analysis of the data has also affirmed the view that we offered in the last reporting period; i.e. the need of materials of higher perfection.

Theme II: The nanomechanical approach uses an electrostatically actuated mechanical switch. The gap between electrodes needs only be increased to a few nm for the off-current of the switch to be essentially zero. By avoiding direct physical contact between metals, reliable operation should be achievable. One approach being pursued is the "Squitch" concept that using molecules to control the switching gap. Direct metallic contact is not necessary, since the 1/KΩ conductance requirement can be fulfilled in spite of a tunneling gap. Although the Squitch avoids the issue of contact adhesive force, there is the potential cost of non-zero off-state leakage current which may be unacceptable for some ultra-low-power (low activity factor) electronics applications. Thus, research into van der Waals switches is also being pursued, as aggressively scaled contacts have the potential of approaching the ultimate promise of <1 aJ/op. Development of van der Waals switches involves materials studies for anti-stiction coatings for the contact surfaces, as well as investigations into novel device design concepts.

In Period 5, significant improvement in On/Off ratio for a Squitch has provided a more definitive feasibility demonstration of the switching concept. Regardless of the approach, naomechanical devices must have nano-size contacts to achieve millivolt switching. Thus, Theme II researchers at Berkeley, MIT and Stanford all have pursued process technology development for forming nano-gaps in this Period.

These research activities will have impact beyond the Center's research as processing techniques for sub-lithographic features have broader device applications. Materials studies are also an integral part of Squtich research. To decrease the operating voltage, researchers at MIT investigating have been studying monolayers interspersed with long and short monolayer molecules to reduce the modulus of the "springs" that are connect contact layers. Low adhesion 2D and 1D materials are candidates for ant-stiction coatings, but little is known about their mechanical properties. In Period 5, we conducted studies to understand the elastic properties of chalcogenides.

Theme III: Communications is increasingly an important part of the energy required in information processors. Indeed most of the energy in data processing goes into charging and discharging the communications wires. Nearest-neighbor interconnections are reasonably efficient, but it is the longer connections, such as the global interconnect across chip and the chip-chip communications, that represent the major energy burden. Silicon nanophotonics is already making inroads in data-comm, but it can be made much more efficient, by using thresholdless light sources like antenna-enhanced light emitting diodes, by a new generation of ultra-sensitive photo-detectors.

Theme III's goals for Period 5 include demonstration of an electrical injection nanoLED and working bipolar photo-transistors of Ge and III-V materials. A new and unplanned goal in Period 5 is the first demonstration of an optically pumped We_2S nanoLED. Also, new, but planned, is the expansion of the III-V epitaxial growth research at MIT into the Center's Nanophotonics research to enable custom wafers that will address issues, like the need for surface passivation, as a means to accelerate the electrical injection pumped nanoLED project.

In Period 5, Theme III achieved a new milestone in collaboration. This Theme, which only involved Berkeley faculty at the Center's inception, has expanded to have research efforts at Berkeley, MIT and UTEP. MIT III-V materials growers, who have been working on elucidating materials effects in tunneling devices in Theme I, are now also working towards custom epitaxial structures for the nanoLED device designers at Berkeley. The co-PI at UTEP, who joined Theme II in the prior Period 4, has refocused the research program on synthesis and materials studies of 2D Chalcogenides, in support of the need for a large supply of higher quality materials.

Theme IV: The nanomagnetics approach in Period 5 takes advantage of ultra-sensitive current driven switches employing the Spin-Hall effect, or ultra-high speed a-thermal magnetic phase transitions, sensed by tunnel magneto-resistance to drive wires and to provide logic fanout. Since these magnetic functions are current-driven, they are inherently low voltage. This nanomagnetics strategy, which started in the last reporting period, is completing its first full year. This change also brought in new projects and new faculty. In Period 5, the researchers of this Theme have continued to primarily focus on elucidating the physics and dynamics of Spin Hall effect and Spin Torque Transfer (STT) in magnetic tunnel junctions (MTJ) that are sub-10nm in size, as very low energy switching has previously been demonstrated in both cases. In addition, Theme IV researchers are also trying to develop techniques to enable ultrafast switching in the picosecond range.

System Integration: The System Integration research in Period 5 has focused on providing both a path to quantifying the benefits of the emerging nanomechanical (Theme II) and nanomagnetics (Theme IV) device technologies at the circuit/system level, as well as guidance to the device designers on which device design parameters are critical to improve at the system level. Research in this area expanded in Period 5 as **V. Stojanovic** joined the Center to team with **E. Alon** (*both Berkeley*). Because the research in this area is Theme specific, details of these efforts are reported below as part of the Themes.

The Researchers: In Period 5, the Center's research is led by 21 faculty researchers in five academic institutions. Florida International University (FIU) joins the other four institutions that have been with the Center in Period 4 and earlier: UC Berkeley, MIT, Stanford and The University of Texas at El Paso (UTEP). The E^3S co-PI's are:

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

The following table identifies faculty participation in the five research areas during Period 5. It 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*		
	Bokor	*x*		*x*		*x*
	Chang-Hasnain				*x*	
	Hu		*x*			
	Javey		*x*			
	King Liu	*x*		*x*		
	Salahuddin					*x*
	Stojanovic	*x*		*x*		*x*
	J. Wu			*x*		
	M.C. Wu				*x*	
	Yablonovitch		*x*		*x*	
MIT	Antoniadis		*x*			
	Bulović			*x*		
	del Alamo		*x*			
	Fitzgerald		*x*		*x*	
	Hoyt		*x*			
	Lang					
	Swager			*x*		
Stanford	Wong			*x*		
UTEP	Zubia				*x*	
FIU	Khizroev					*x*

Center Synergy: 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 its Themes are evolving into a community/communities. Informal collaborations also abound.

As discussed in the upcoming section on Center Management, Section VII, this synergy is reflected the Center's annual surveys. For the last four years since the Center's graduate students and postdocs were first surveyed, 90+% of the respondents agreed that their research is helped by someone in their Theme. For the first time, the 2014 survey indicated that >50% of the respondent received help from someone in the Center who is with another member institution.

Behind numbers are examples of progress made as a result of operating in the Center mode:

- The Theme I TFET research is a joint activity between the experimentalists at MIT (Antoniadis, del Alamo and Hoyt) and the Berkeley theorist (Yablonovitch). In this report, the experimental results of each experimental group are delineated, but the report show an analysis that explains the observed results.

- The Theme II Nanomechanics research is coordinated around two approaches, the Squitch pursued at MIT (Bulovic, Lang & Swager) that involves tunneling; and the normally-on van der Waals switch that will likely have no leakage. The research on van der Waals is further coordinated in that Berkeley (King Liu) focuses on switch design and Stanford (Wong) on the processing technologies. At the same time, the researchers at MIT would deposit on molecular monolayers on mechanical switches made at Berkeley for experimentation.
- Theme I's characterization of chalcogenides (Javey) led Theme III researchers (M. Wu) to initiate a nanoLED made from chalcogenides. A highly successful demonstration of a WeS_2 nanoLED by the Wu group was made possible with the material know-how of the Theme I researchers (Javey group), Theme I researchers believe that the research of chalcogenides as an optical material will provide further insights that will be beneficial to design TFETs.
- Theme IV sub-10 nm STT device joint project between FIU and Berkeley.

The main approach of the Nanoelectronics researchers (*Berkeley and MIT*), has been to focus on understanding the device physics versus device fabrication to demonstrate performance. We have focused on exploring the device physics of density of state switches, as an alternative to tunneling based on modulating the barrier. There are two questions the team has set out to answer.

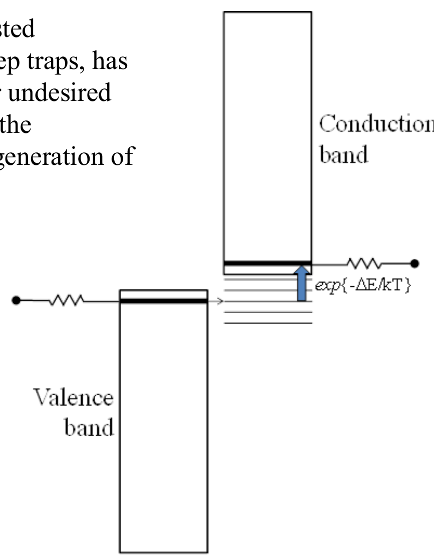
- How sharp is the band-edge density of states?
- Are there materials systems, other than III-V materials, that may provide a better platform for making sharp tunnel switches?

The density of states switch relies upon sharp band-edges or sharp energy levels. From the beginning of the Center, we have confronted the fact that Science does not know much about the inherent sharpness of band-edges. Indeed, the mechansim of the optical band-edge, called the Urbach tail, remains controversial to the present day.

In Period 5, experimental device data obtained by Theme I researchers is offering answers to both questions. Analysis of the data has also affirmed the view that we mentioned in the last reporting period; i.e. the need for materials of higher perfection for the tunnel FET to fulfil its promise.

Band-Edge Sharpness: In Period 5, Theme I researchers continued their design, fabrication and characterization efforts to increase the fundamental understanding of the semiconductor band-edge. Some of the problems are extrinsic: There are deep traps responsible for tunnel assisted generation, shallow traps often caused by heavy doping, and energy level shifts created by dimensional variability. In addition there are intrinsic effects, predominated by thermal broadening of band-edges, phonon side-bands, and Coulomb blockade effects.

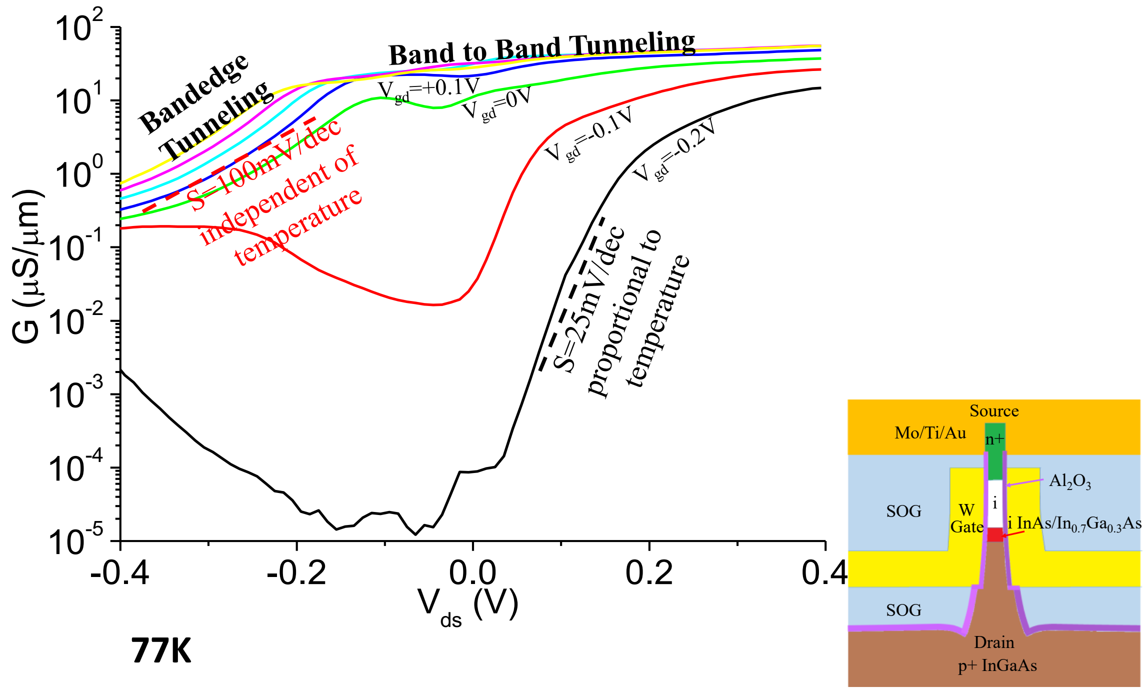
Figure I-1: Tunneling Assisted Generation Current from deep traps, has emerged as one of the major undesired mechanisms that is limiting the performance of the present generation of tunnel FET's



During this period there have been an important series of experiments at MIT by the **Hoyt/Antoniadis** team working on InGaAs/GaAsSb Quantum-well TFETs, by the **del Alamo** group on InGaAs nano-wire TFET's, and by the **Fitzgerald** group on InGaAs/GaAsSb Backward diodes. Each has solved a different piece of the puzzle, which has now been combined to elucidated an important leakage mechanism, that has been limiting the performance of tunnel FET's. That leakage mechanism is represented by Figure I-1.

The nano-pillar device, fabricated and tested by **del Alamo** *(MIT)*, was particularly informative, since it could be tuned to be either an Esaki diode or a Backward diode, which is the preferred TFET regime. The conductance steps in Figure I-2 represent the overlap of conduction and valence bands. In the Esaki step region, at 100mV/decade, the switching action is independent of temperature, and represents the true overlap of bands, a band-edge sharpness smeared by heavy doping, among a series of other inhomogeneities represented in Figure I-3. On the right side of Figure I-2 is a 25mV/decade step, which represents the Backward diode regime, which should have a cleaner band-edge overlap. Surprisingly, this edge is thermally activated, when it should be independent of temperature.

Figure I-2: The tunnel switch can be tuned to either the Esaki regime or the Backward diode regime. In the Esaki regime the slope is limited to 100mV/decade independent of temperature, a direct indication of band-edge sharpness. In the preferred Backward diode regime, the slope is steeper, 25mV/decade, but thermally activated at 77K, by the Tunnel Assisted Generation mechanism indicated in Figure I-1.



The steep band edge present on the right side of Figure I-2, is obscured by the thermally activated leakage at77K, with a slope of 25mV/decade defined by the newly recognized Tunnel Assisted Generation mechanism of Figure I-1. On the other hand the temperature independent slope 100mV/decade is smeared by spatial inhomogeneity as illustrated in Figure I-3. This is further affirmed the data on ungated Zener diodes of the **Fitzgerald** group (*MIT*), given in Figure I-4, which also have temperature independent slope.

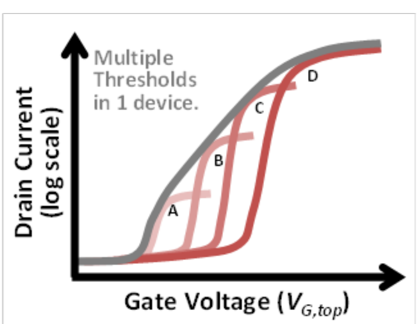


Figure I-3: Spatial inhomogeneity, smearing the overlap of band-edges.

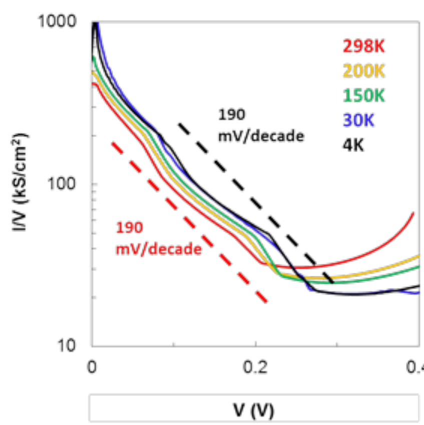


Figure I-4: Temperature independent InGaAs/GaAsSb Esaki band-edge.

Nonetheless, the 100mV/decade steepness, independent of temperature, and measured by direct two-terminal band overlap, represents an important scientific result, and fulfills one of the intermediate goals of the Center. We expect that this will be the first of many such measurements in the future. It's still not a fully intrinsic measurement, since the device is gated. Inefficiency in the gate action, even when the gate is grounded, influences the observation. With an effective gate efficiency of ~50%, the steepness could actually be as sharp as 50mV/decade, slightly better than the thermal benchmark.

An unexpected achievement, on the right side of Figure I-2, is the identification of interface traps, D_{it}, the bane of all transistors, as providing a serious tunnel FET leakage mechanism, Tunneling Assisted Generation, as illustrated in Figure I-1. This is responsible for the thermally activated 25mV/decade edge in Figure I-2. Typically Dit $>10^{11}$ defect states/eV even at good III-V/insulator interfaces, while an ideal 2d quantum well or inversion layer would have slightly more, 10^{12} defect states/eV. This would suggest the importance of further materials development to reduce the density of surface defects states, among a long series of material structural perfection requirements for the tunnel FET to meet its promise. The **Yablonovitch** group (*Berkeley*) worked very closely with MIT device fabrication groups in interpreting this new device physics.

Another important outcome of our research represented in Figure I-2 is that it is the first demonstration of a device that can tuned all the way from an Esaki diode to a Backward diode by gate control. This is emerging as very important to scientifically dis-entangling all the inhomogeneities and leakage mechanisms in this device class.

Owing to the importance of material perfection, the Center in its first year of full operation, 2011, identified that the chalcogenide monolayer semiconductors could provide some advantages. The surfaces are covalently bonded, promising low interface state density, and the thickness of quantum wells could be discretely defined, assuring reproducible quantum well energies levels, and limiting smearing of the band-edges. We have now made our first tunnel FET's in the chalcogenide monolayers.

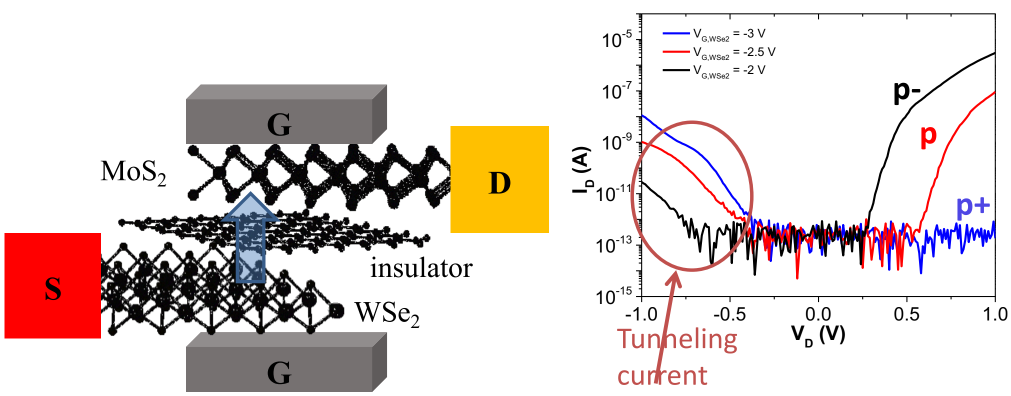


Figure I-5: First Chalcogenide TFET--Reverse tunneling in the MoS_2/WSe_2 heterojunction system, is modulated by the gates in a bilayer double-gated structure.

Our Center's most advanced achievement in chalcogenide devices is illustrated in Figure I-5. The device shown on the left side of Figure I-5, is simultaneously a double-gated bilayer tunnel FET, a monolayer diode, and a heterojunction tunnel FET. Exquisite control in this 4-terminal device arises from the double gating of the thin active layers, and the separate Ohmic contacts to each layer. With no gate bias, this is simply a p-n junction from p-WSe_2 to n-MoS_2. Both forward thermionic flow and backward tunneling can be seen. Gate action completely shifts the classical pn-junction I-V curve to the left and right. The gates are already providing almost 4 decades of tunnel current modulation.

The device made in Figure I-5 was produced by mechanically stacking the layer, (so-called scotch-tape method). That such well-controlled results were achieved in such an uncontrolled environment is suggestive of further rapid progress to be expected. The development of such a new materials system in a short time is representative of a large effort that included both Center Co-PI's, and many researchers outside the Center. We regard this major outside interest as a form of leveraging of the NSF investment in such an ambitious goal. The paper reporting our multi-faceted materials and device work on the chalcogenides appeared in PNAS with 19 co-authors.

In the chalcogenide part of Theme 1, the Center made the first Bilayer dual-gated tunnel FET, which was also the first chalcogenide tunnel FET of any type, and which exhibited over 5 decades of gate controlled conductivity change. In the III-V part of Theme 1, the Center measured for the first time the actual sharpness of a band-edge, (100mV/decade), and the Center detected the dominant tunnel FET leakage path, not surprisingly, associated with interface traps, D_{it}.

The Center has identified a series of material requirements that successful future tunnel FET's will be obligated to fulfill, from a D_{it} specification, to a dimensional specification that should be fabricated reproducibly, or to shallow traps that merely shift energy levels. We have placed attention squarely on novel materials systems beyond the traditional semiconductors capable of producing the most perfect molecular scale device structures that will likely be a pre-requisite for future progress. Theme 1 is prepared to go in the direction of material perfection to achieve our goal of introducing a lower voltage transistor.

This conclusion has implications on the on-going Theme I research. For example, at Berkeley, there also has been a continuing research effort of **C. Hu,** in collaboration with **A. Javey** *(both Berkeley)*, to improve on the device performance of InAs/AlSb/GaSb TFET. The preliminary device data reported in the last Reporting Period 4 already showed temperature dependent switching characteristics. With the additional detailed device data from the MIT groups (**del Alamo, Antoniadis & Hoyt**) in this Period 5, the research effort of the **Hu** group is being phased out.

Below are further details of the research efforts that led to the above conclusions. Some details are presented to further substantiate the conclusions, while the following sections also include complementary work that the groups have pursued.

1) InGaAs/GaAsSb Quantum-well TFETs: The **Antoniadis** & **Hoyt** groups designed a process flow and created a 12-level mask-set for creating strained-Si/strained-Ge 3Gate bilayer TFETs. The many levels are required because of 3 separate gates and separate source and drain implants. The device fabricated in is a 2d-2d TFET structure. Low temperature measurements were performed to investigate the potential of the QWTFETs for steep-subthreshold application. The achieved minimum subthreshold swing (SS) at 77K was measured 24 mV/dec (shown in Figure I-6, left), and the SS vs. 1/T is shown Figure I-6, right. The study indicates a dominant current component arises from thermal process.

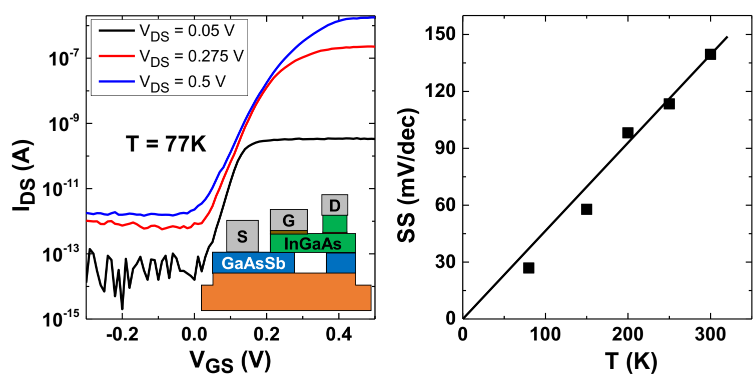


Figure I-6: Left - Threshold swing at 77K of the InGaAs/GaAsSb QWTFET fabricated at MIT; Right – Temperature dependence of the subthreshold slope.

2) InAs/InGaAs Nanowires TFETs: The InGaAs/InAs heterojunction vertical nanowire (NW) TFETs of the **del Alamo** group (*MIT*) was fabricated via a top down approach for the first time; details of the heterostructure are given in Figure I-7. These high aspect ratio devices have been enabled by the development of a top down etching processing that the group initiated and reported on in the last Reporting Period 4 (Figure I-8a). The novel reactive-ion-etching technique that is capable of defining sub-20 nm InGaAs nanowires with a vertical, smooth sidewall and an aspect ratio over 10. This technique paves the way to realize devices with single or a few quantum channels that minimize the impact of inhomogeneities. We have also developed a new technique to reduce the gate-source leakage in vertical nanowire devices by introducing a spin-on glass layer between the gate electrode and the source contact. With this technique, we are able to scale the gate oxide thickness while maintaining acceptable gate leakage current. Figure I-8b shows the impacts of the digital etch on device performance. New in Period 5 is a key process improvement, the reduction of gate-to source leakage due to gate source isolation (Figure I-5).

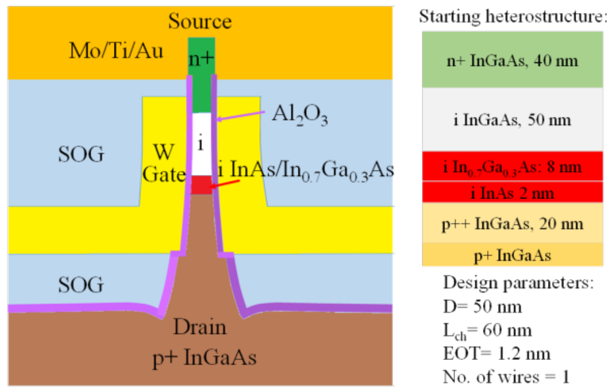


Figure I-7: Graphic of the vertical nanowire TFET

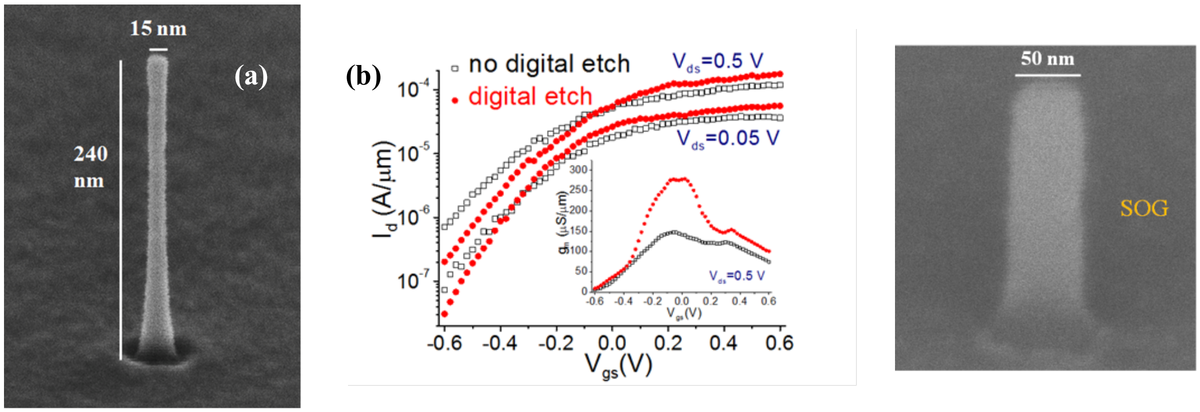
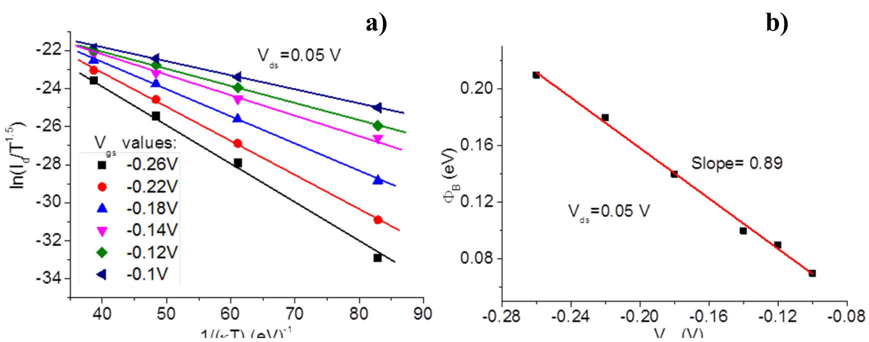


Figure I-8: (a) 15 nm diameter InGaAs nanowire with an aspect ratio greater than 15; (b) Impact of digital etch on subthreshold and transconductance (inset) characteristics of D= 30 nm gate-all-around InGaAs NW-MOSFETs. 30 nm is the final device diameter in both cases; (c) Reduction of source -to-gate leakage at scaled gate dielectric thickness

Compared to other NW TFETs with III-V materials, these devices exhibit an excellent combination of steep slope and high ON current [8-12]. Figure I-9 shows that at V_{ds} of 0.3V, the average sub-threshold slope is 75 mV/dec (79 mV/dec accounting for hysteresis) for a single NW TFET with a diameter of 50nm with a channel length of 60nm. Characterization over a range of temperature shows the switching characteristics have strong temperature dependence (Figure I-10).

Figure I-10: a) Arrhenius plot of the subthreshold current at various V_{gs} versus inverse thermal energy. b) The slope of the linear relationship is the thermal barrier height.



The subthreshold current exhibits strong thermally activated behavior and the activation energy drops linearly as V_{gs} increase (Figure I-10a). The barrier height is extracted to be 0.89ev. (Figure I-10b).The strong temperature dependence that is observed in the subthreshold behavior is consistent with a trap-assisted tunneling process.

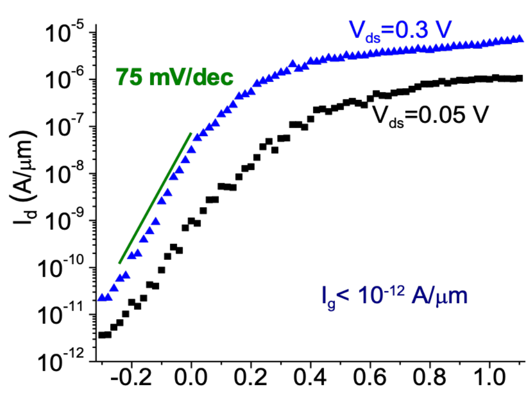


Figure I-9: Subthreshold characteristics of a D=50nm single NW-TFET

3) Study of Material Quality with InGaAs/GaAsSb Diodes: As reported earlier in this report, the **Fitzgerald** group (*MIT*) obtained conductance data that showed no temperature dependence from room temperature down to 4K for binary type-III InAs/GaSb heterojunctions for both InAs-grown on GaSb diodes with high defect densities, and GaSb grown on InAs diodes with no observable defects in cross-section TEM. This result contrasts strongly with three-terminal results, which primarily show a linear temperature dependence of subthreshold slope that others Theme I researchers have reported.

In contrast, we have identified that the main temperature dependence of two-terminal devices is on the peak current of the diode, and that, contrary to devices with a barrier, the current increases with temperature down to very low temperatures, before beginning to decrease (Figure I-11). We attribute this increase to the change in the Fermi-distribution allowing more carriers to be within the band-overlap region allowing them to tunnel, and the decrease at very low is likely due to the loss of carrier confinement near the interface at lower temperature as a result of the Fermi levels increasing with temperature. Interestingly, devices with defects show a much-less pronounced dependence of peak current on temperature. This is proposed to be due to increase nonuniformity in the band-edges which overpower the temperature dependence of the Fermi function. As we have reported in the previous reporting period, this nonuniformity is what leads to less-steep conductance slopes for interfaces with more defects.

Beyond binary compounds for type-III band alignment, we have also utilized ternary alloys to tune the band alignment anywhere from type-III to type-II. As can be seen in Figure I-12, the switching portion of the curve can be shifted to the left into reverse bias with increasing alloying. Furthermore, by adding a graded buffer to grade the strain and lower the threading dislocation density, a marked improvement in conductance slope steepness is obtained. We have also developed the ability to grow thin InAlAs tunnel barriers, lattice matched to the InGaAs and GaAsSb.

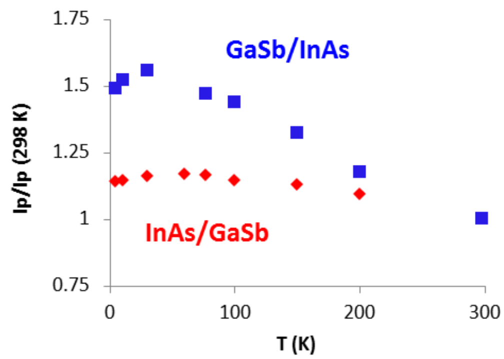


Figure I-11: Peak current temperature dependence

Chalcogenide TFET: To progress towards the Center's goal of low energy switching using a material system that is alternative to the traditional Si and III-V, the **Javey** Group (*Berkeley*) has been researching into the manipulation of 2D layered materials for the application of high performance tunneling FETs, tackling all ranges of issues from contact resistance reduction to individual layer gating to improved band alignments. In fabricating reliable and high performing layered TFETs, we first address the issue of contact resistance by ascertaining a stable doping method. Then we will investigate dual gating of bilayer homojunctions towards creating successful Type III band offset for TFET operation. This step can also be aided by stable doping results demonstrated by our first step. Simultaneously, using the transfer processed developed earlier in Period 5, we will investigate dual gating of bilayer heterojunctions also towards successful implementation of Type III band offset.

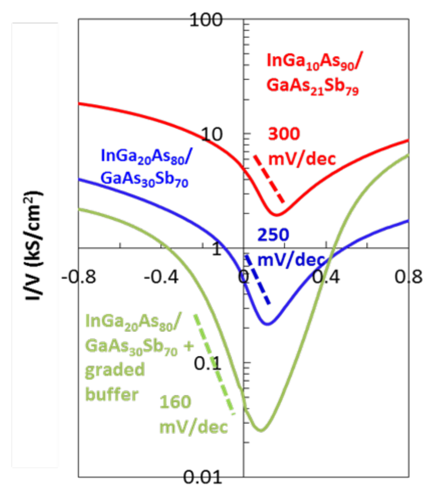


Figure I-12: Steepness improves with a graded buffer to grade the strain.

Building on the initial demonstration of layered material doping via NO_2 and K (which unfortunately were not air stable) that was reported in Period 4, we have now overcome the hurdle of stability via three different paradigms of layered material modifications. Specifically, surface charge transfer and covalent functionalization methods are shown in Figure I-13. Using these two complimentary techniques (for n+ and p+ doping air stable doping respectively), we were able to drastic reduce contact resistance up to 5 orders of magnitude. Notably, this work directly provides a solution to the contact resistance problem. The metal to chalcogenide contact is usually Schottky contact and has large contact resistance. This work paves a steady path towards high performance TFET design by addressing simultaneously the contact resistance problem and mitigating the rigor required for Type III band alignment between both homo- and heterojunctions.

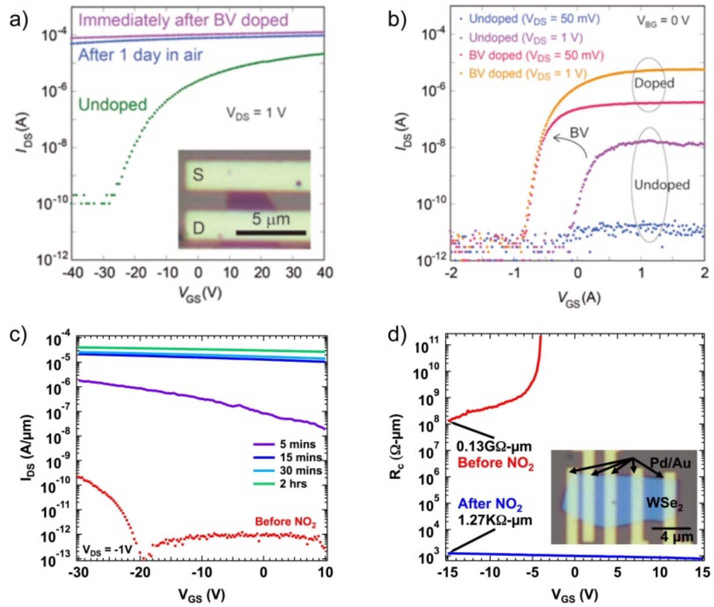


Figure I-13: a). Transfer characteristic curves of the device before (green), right after BV doping (purple) and after the doped device is kept in air for one day (blue) at V_{DS} = 1 V. Inset shows the optical microscope image of the device, consisting of a trilayer MoS_2. b). Transfer characteristic curves of the top-gate device before (blue and purple) and after (pink and orange) BV treatment at V_{DS} = 50 mV and 1 V. Substrate was grounded during the measurements. c). Representative IDS_VGS for WSe2 device exposed to NO2 at different functionalization time. d). 5 orders of magnitude decrease in contact resistance realized via NO_2 functionalization. Inset: Optical microscopy of fabricated back-gated device used for TLM.

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

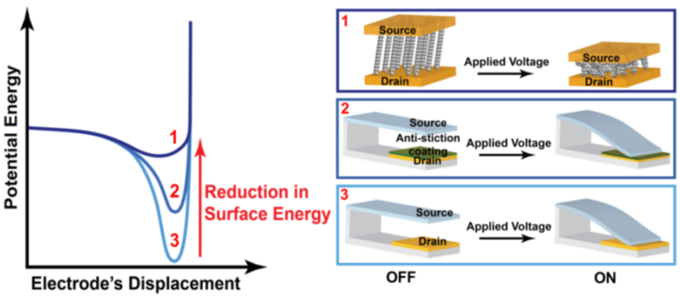


Figure II-1: Illustration of methods to reduce surface energy in a mechanically contacting switch

As discussed in the report of last year, surface adhesion, alternatively known as stiction, can be mitigated by decreasing the surface energy (Figure II-1). In Period 5, the Theme II researchers have continued to address this issue via two main approaches:

- Squitch: Actuation of a mechanical structure brings the source and drain electrodes into contact with each other resulting in solid-solid surface adhesion. The multidisciplinary collaboration of **V. Bulovic**, **J. Lang** and **T. Swager** *(all, MIT)* has continued to focus on the use of a compressible organic thin film between the source and drain electrodes that provides localized spring restoring force to alleviate stiction (Case 1, Figure II-1). This approach, referred to as the "Squitch," was initiated towards the end of Period 2 and has continued in this Reporting Period 5. The monolayer: (1) defines the switch gaps; (2) provides a scaffolding to support the movable source and a spring to restore its position upon removal of the gate-source voltage; and (3) prevents direct metal-metal source-drain contact thereby alleviating contact surface adhesion problems that limit the energy efficiency of contacting NEM switches. In addition, since this is a non-contacting switch that only modulates tunneling current, surface wear is also avoided. The experience over the last several periods made it apparent that key technologies required for the fabrication and characterization of this NEM switch were lacking. Consequently, in Period 5, building on the focus of the previous reporting period, the Squitch research primarily addressed the development of supporting technologies and directed away from specific switch development. Specifically, in this Reporting Period 5, we have focused on technologies that will allow us to: (1) fabricate smooth nanometer scale gaps in a controlled manner; (2) simultaneously measure gap motion and tunneling current as a function of the applied voltage for two- and three-terminal switches, for the purposes of switch understanding, model verification and molecular monolayer metrology; and (3) create molecular monolayers with the required mechanical properties. As this work proceeds, it is always accompanied by the testing of related two- and three-terminal switches, but this testing has often been secondary to technology development. Nevertheless, a key project milestone achieved in this period is the demonstration of current modulation in a vertical device of up 5 orders of magnitude, approaching the 10^6 on/off current ratio that is part of the E^{3}S requirements for a millivolt switch.

- van der Waals (vdW) Switch with Nanogaps: Although the Squitch avoids the issue of contact adhesive force, it does so at the cost of non-zero off-state leakage current which may be unacceptable for some ultra-low-power (low activity factor) electronics applications. Therefore, the research groups **H.-S.P. Wong** (*Stanford*) and **J. Wu** *(Berkeley)* have been investigating anti-stiction coatings to mitigate contact adhesive force (Case 2, Figure II-1). The research goal is to elucidate the materials science necessary for enabling sub-0.1V mechanical switch operation. The focus has been on low dimensional materials that have weak van der Waal interactions, and thus, low Hamaker's constants. In Period 5, the Stanford group has been focusing on understanding impact of these coatings of these electronic properties of contacts, while the Berkeley group's focus has been on the mechanical properties of these coatings by completing a characterization study of the Young's modulus and interlayer sliding properties in atomically thin transition metal dichalcogenides (TMDs) and graphene.

  We refer to switches with van der Waals interactions between contacts as vdW switches. These switches require aggressively scaled contacts to approach the ultimate promise of <1 aJ/op. In Period 5, the **King Liu** and **Wong** groups (*Berkeley and Stanford, respectively*) have been working complementarily on van der Waals switches. The Berkeley group has focused on switch design while the Stanford group has pursued the development of a novel CMOS-compatible technique to fabricate ultra-small gap (down to atomic scale) vdW switches.

The device focus of the Nanomechanics Theme is complemented by research to quantify the benefits of the emerging device technologies at the circuit/system level. The Theme II device designers collaborate with the System Integration research for guidance on which device design parameters are critical to improve at the system level. Specifically in Period 5, the Theme II specific System Integration research that is jointly led by **E. Alon** and **V. Stojonovic** *(both Berkeley)* aims to:

- Explore the circuit and system-level opportunities offered by dense electro-mechanical memory (NEMory) devices integrated on top of CMOS by developing optimized interface circuitry and array organizations and utilize these designs to predict the energy/area/performance capabilities of the technology; and
- Adapt the infrastructure that has been established on circuit/system demonstrations of NEM relay-based VLSI systems with the properties of the new sub 0.1V relay circuits.

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

- *Squitch*

Improved On/Off Current Ratio: A significant accomplishment is the development of a vertical-gap switch with a graphene top layer transferred onto a molecular monolayer assembled onto underlying gold electrodes with on/off current ratios that approach 6 orders of magnitude to meet this E^3S metric for a milli-volt switch. A graphic of the vertical two-terminal switch is shown on the left in Figure II-2. The right of the Figure II-2 is a graph that presents measured conductance data *vs.* applied voltage. The three right curves (red, green and cyan) for three new vertical graphene devices show up to 5 orders of magnitude on/off current ratio, even with the current clipped (set by the compliance limit of the measurement instrumentation); thus, these devices probably have even higher on/off current ratios than observed and may easily approach the required 6 orders of magnitude. For comparison, the blue curve corresponds to data for the horizontal device that was reported last Reporting Period 4, as a device proof of concept, which shows only 1 order of magnitude variation over the same range of applied voltage. All of the new switches show conductance behavior consistent with a tunneling current modulated by the compression of a gap containing a molecular monolayer.

Besides exhibiting significantly better current modulation data, this vertically actuated switch fabrication approach using a bridging graphene electrode has the following advantages: (1) the molecular monolayer is directly assembled onto the lower electrodes and is not subjected to potentially damaging fabrication steps; (2) a narrow switching gap is easily created by selecting the thickness of the monolayer; and (3) the top graphene electrode surface is naturally smooth.

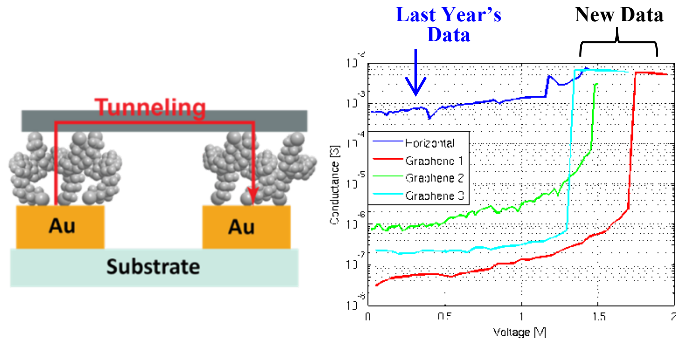


Figure II-2: Graphic of a NEM switch with a graphene top layer transferred onto a molecular-monolayer scaffolding (left); Measured conductance-voltage relations for four two-terminal NEM switches

Monolayer Engineering for Lower Actuation Voltage: To reduce the actuation voltage of a squitch it is necessary to reduce the mechanical modulus of its monolayer. One way to reduce the modulus is to intersperse long and short monolayer molecules so that only a fraction of the molecules reach across the gap and contribute to the modulus. We have, for example, developed and characterized PDMS-based and cavitand molecules. This also has the advantage of introducing void space into which the long molecules can bend and fold as they are compressed. Figure II-3 comprises atomic force microscopy (AFM) surface scans of three monolayers: fluorous decanethiol alone; a 1:4 composite of fluorous decanethiol and octadecanethiol; and a 1:1 composite of fluorous decanethiol and octadecanethiol. The differing topologies indicate that we can engineer the morphology of molecular monolayers using composites, and thereby engineer the mechanical modulus.

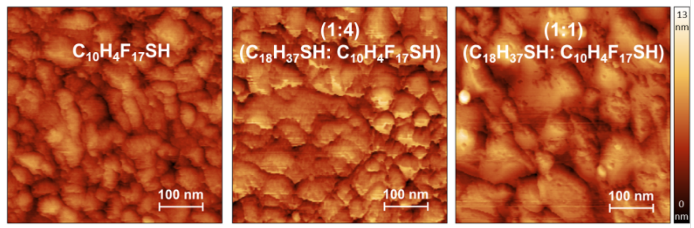


Figure II-3: AFM surface scan of three molecular monolayers; the two to the right are composites.

We have further modified many molecules to assemble on aluminum and other metals for the King Liu group (*Berkeley*) and research efforts to deposit monolayer on a relay with sub-lithographic gaps (Figure II-7), fabricated at Berkeley, are underway.

Metrology Tool for Mechanical Properties of Monolayers: Simultaneously measuring gap motion and current in a squitch is critical to understanding its operation and verifying our analytical models. Consequently, efforts to develop a plasmonic ruler to support the requisite measurements are in progress. The plan is to use this ruler more generally as a device to measure the mechanical properties of molecular monolayers. A graphic of the ruler is shown in Figure II-4. It has been shown previously that the plasmon resonance peak of nano-scale gaps between two metallic surfaces shifts as a function of the gap thickness [13]. This phenomenon can be used to measure changes in gap separation as a function of monolayer compression. To enable this characterization, monolayer gaps are fabricated with gold nanocubes serving as top electrodes; nanocubes we have fabricated are shown to the right. The gold nanocubes possess flat single-crystalline facets which promote the formation of well-defined nanometer gaps while allowing plasmonic coupling to the opposing electrode surface. The shift in the plasmon resonance peak wavelength is then monitored through use of reflectance and scattering spectroscopy while compressing the molecular layer. The compression can be induced mechanically or electrically with the simultaneous measurement of gap voltage and current. Beyond the characterization

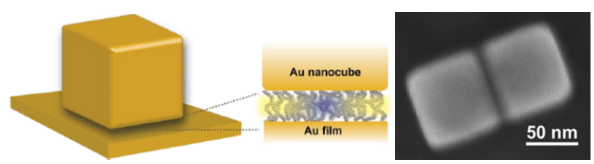


Figure II-4: Graphic of a plasmonic ruler (left); SEM micrograph of two gold nanocubes (right).

of the electrically tunable tunneling gaps, we expect the device to offer a new approach to characterizing the mechanical properties of molecular monolayers in general. We will work towards having both a first demonstration of the plasmonic ruler and corroborating experiments involving two- and three-terminal vertical-gap switches fabricated with a transferred graphene layer by March 2015.

- *vdW Switches:*

Switch Design: It is generally believed that contact adhesion sets a lower limit for the switching energy of a mechanical switch [14, 15]. The goal of this project is to find a way to overcome this perceived energy-efficiency limit, while maintaining a compact (< 1 μm^2) footprint and low-voltage (< 0.1 V) operation of a nanomechanical switch. Three types of force affect a nano-electro-mechanical (NEM) switch: an applied force electrostatic force (F_{elec}) that actuates the suspended structure, surface adhesive force (F_{adh}) at the physical contact(s), and the spring restoring force (F_{spring}) of the suspended structure.

Figure II-5: Conventional NEM switch design. (a) Isometric views in OFF and ON states, showing key dimensions and relevant forces exerted on the movable structure. (b) Calculated force vs. displacement curves. (c) Calculated potential energy profiles in the OFF state (zero applied voltage) and in the ON state (20 mV applied voltage), showing a minimum at ~0 beam displacement in the OFF state, and ~5 Å beam displacement (in contact) for the ON state. This switch requires 4.1 aJ to turn ON, which is greater than the surface adhesion energy 2.2 aJ.

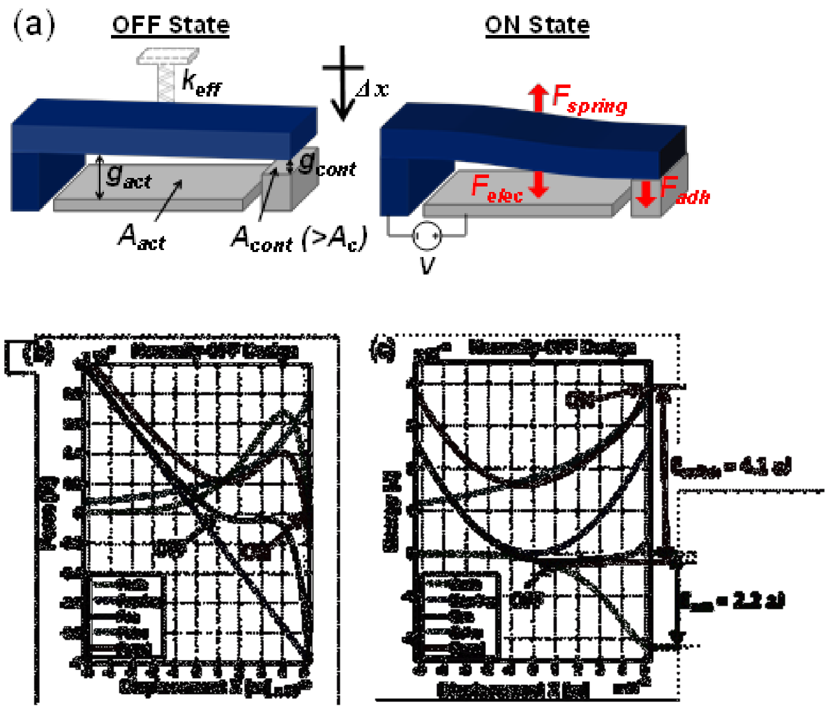
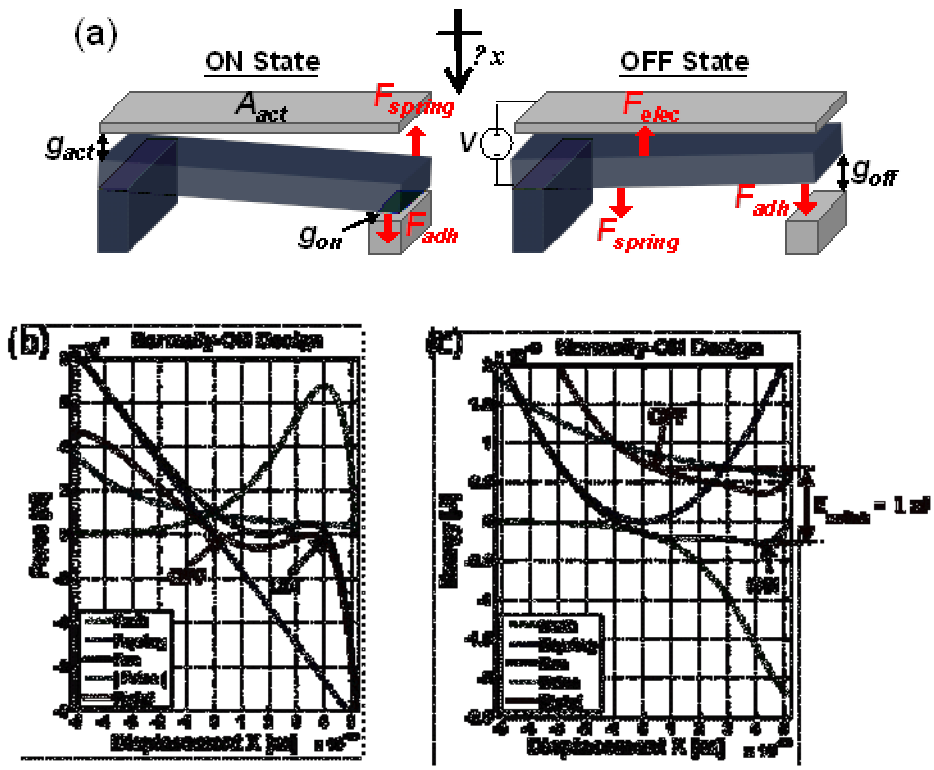


Figure II-5 (a) illustrates the operation of a conventional three-terminal NEM switch design, showing the relevant forces and geometrical design parameters. In the OFF state, a contact air gap separates the movable suspended electrode (which has an effective spring constant, k_{eff}) from the fixed contacting electrode. When a sufficiently large voltage is applied between the suspended electrode and the actuator electrode ($V > 0$), $F_{elec} > F_{spring}$ such that the suspended electrode comes into contact with the contacting electrode so that the switch is turned ON. To turn OFF the switch, the applied voltage is removed ($V = 0$) and $F_{spring} > F_{adh}$ is required to break the contact. This means that F_{elec} must be greater than F_{adh}, and therefore contact adhesion sets a lower limit for the switching energy. Note that, as fabricated ($V = 0$), the actuation gap and area are larger than the contact gap and area, respectively (*i.e.* $g_{act} > g_{cont}$ and $A_{act} > A_{cont}$), for reliable low-voltage operation [16]. Due to surface roughness, the real contact area (A_c) usually is a small fraction of the apparent contact area (A_{cont}).

Figure II-6 (b) shows how each of the various forces acting on the suspended electrode depend on Δx, while Figure II-7 (c) shows the corresponding potential energy (E) curves, for an aggressively scaled switch design with $A_{act} = 1\ \mu m^2$, $g_{act,0} = 10$ Å, $A_c = 1\ nm^2$, $g_{cont,0} = 5.2$ Å and $k_{eff} = 20$ N/m. When a sufficiently large actuation voltage is applied (ON state), the total force, $F_{total} > 0$ for all $\Delta x < g_{cont,}$ so that the suspended electrode moves into contact with the contacting electrode. When no voltage is applied (OFF state), F_{spring} restores the suspended actuator back to $\Delta x \sim 1$ Å, corresponding to the stable operating point where $F_{adh} + F_{spring} = F_{sa} = 0$ and $dF_{sa}/d(\Delta x) < 0$. The energy required to turn ON the switch is highlighted in Figure II-8 (c) and can be seen to be much greater than the contact adhesion energy, which is 2.2 aJ for aluminum contacting electrodes with surface energy density $\gamma = 1.1\ J/m^2$ and characteristic

Figure II-6: Normally-ON relay design to overcome the surface adhesion energy limit. (a) Isometric views in OFF and ON states. (b) Calculated force *vs*. displacement curves. (c) Calculated potential energy profiles in the ON state (zero applied voltage) and in the OFF state (15mV applied voltage), showing a minimum at >4 Å beam displacement in the ON state, and ~0 Å beam displacement for the OFF state. This switch requires 1 aJ to turn OFF, which is less than the surface adhesion energy 2.2 aJ.



decay length (related to the Thomas-Fermi screening length) $\lambda_M = 1.2$ Å [17].

Figure II-6 (b) and (c) show the force and potential energy plots for the tunneling switch design, respectively. For the purpose of comparison, the actuation and contact design parameters of this tunneling switch are taken to be identical to those of the conventional switch design described above. Stable operating points are found near contact ($\Delta x \sim g_{cont0} - 1$Å) with zero applied voltage, and near $\Delta x = 0$ with a small applied voltage (~15 mV). Lower switching energy is achieved with this design because the spring restoring force effectively reduces the depth of the potential well due to adhesive force (depicted by the green dashed line in Figure II-6 (c)) and prevents the suspended electrode from coming into contact with the contacting electrode (*i.e.* $\Delta x < g_{cont0}$). The tunneling current across an air gap is given by the equation $I_{tunnel} = CAVe^{-a g_{cont}\sqrt{B}}$, where $C \cong 3.16\times10^{13}$ A/m^2/V, A is the tunneling area, V is the contact voltage, $a = 10.25$ nm^{-1}, and B is the average barrier height for an electron at the Fermi energy [18]. To achieve an on/off current ratio of 10^4, ~4 Å displacement is required.

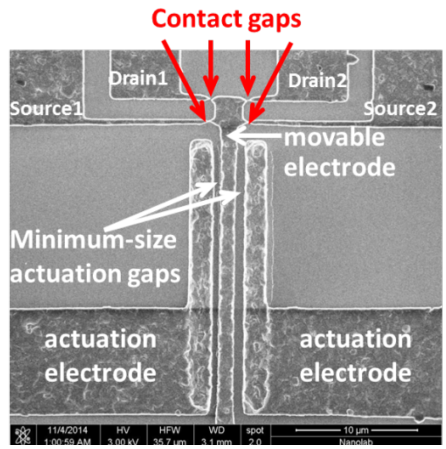


Figure II-7: Plan-view scanning electron micrograph of a fabricated aluminum micro-relay with sub-lithographic contact gaps. (This is a laterally actuated, single-pole/double-throw switch.)

Processes for Forming Nanoscale Gaps: In order to realize a normally-ON switch, the as-fabricated contact gap (gcont0) must be extremely small so that the adhesive force is sufficient to actuate the switch into the ON state. One approach being pursued in collaboration with J. Wu group (*Berkeley*) is to induce fracture to form a sub-1 nm contact gap; by carefully designing the shape (pattern) of a thin metallic electrode layer, and optimizing the thin-film deposition conditions to achieve significant tensile strain, crack formation can be well controlled. The **King Liu** group (*Berkeley*) has fabricated relay structures (Figure II-7) for this collaboration, enabled by a novel approach to controllably form sub-lithographic contact gaps has been invented [provisional patent application in preparation], and the implementation of the single-pole/double-throw relay design in the back-end-of-line (BEOL) process of a CMOS technology to achieve very small (<0.1 μm^2) device footprint, which is advantageous for implementation of compact hybrid NEM/CMOS circuits. By the end of 2014, we will be able to conclude whether the controlled facturing method would work as a strategy for creation of nanometer gap. The goal is that functional single-pole/double-throw switches which operate with ultra-low voltage (<< 1 V) will be realized before the end of this Reporting Period.

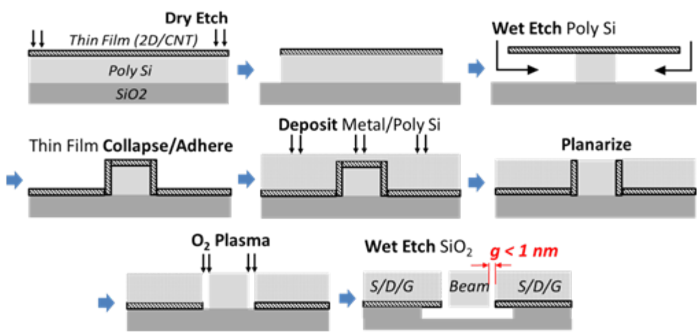


Figure II-8: Process flow of atomic gap NEM switch using few layer graphene sheets.

Complementing the switch design effort at Berkeley, the group of **H.-S.P. Wong** (*Stanford*) designed a novel CMOS-compatible technique that uses few-layer graphene sheets to fabricate atomic-sized ultra-small gaps for van der Waal switches. The process flow, illustrated in Figure II-8, uses single- or few- layer graphene sheet as a sacrificial layer to create an ultra-small gap. The key step in this process is to obtain conformal coverage of the ultra-thin graphene layer over a beam, since any air gap between the graphene and the sidewall of the beam will result in dimensional variation of the gap between the beam and the drain, thus resulting in variations switching voltage. We carried out a series of experiments to achieve conformal graphene coverage. Preliminary results (Figure II-9) show that on a hydrophilic Si substrate, the transferred few-layer and single-layer graphene sheets each can conformally cover a 650 nm-high SiO_2 beam without any air gap. The thickness of the multi-layer graphene in our experiment is less than 2.94 nm, which would define the thickness of the air gap in the NEM switch. This thickness can be further reduced in the future by using graphene with fewer layers – down to a single layer with 0.3 nm thickness. We believe that the conformal coverage can be attributed to the flexible nature of the thin graphene sheet and strong surface adhesion forces (such as capillary force) during liquid evaporation after the transfer.

A second technique we are investigating for ultra-small-gap formation is atomic layer deposition (ALD), which is known to be highly conformal. Figure II-10 shows an example of a 10nm-thick Al_2O_3 ALD thin film conformally covering a 500 nm-thick Poly-Si/TiN beam. The thickness of the thin-film material can be well-controlled by ALD growth cycle number, down to less than 1 nm.

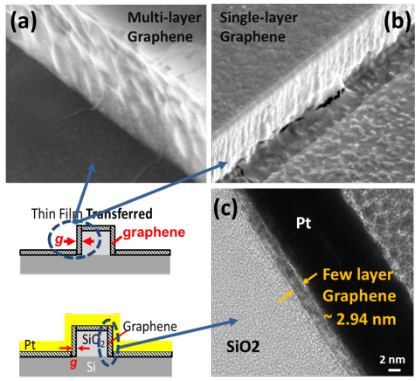


Figure II- 9: SEM images of the conformal coverage of (a) multi-layer graphene and (b) single-layer graphene on 650 nm high SiO_2 step. (c) TEM image of the conformally covered sidewall in (a).

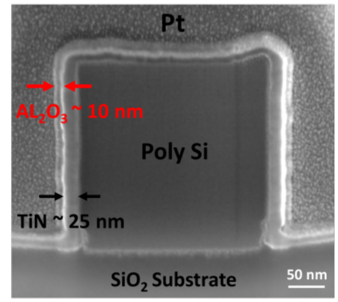
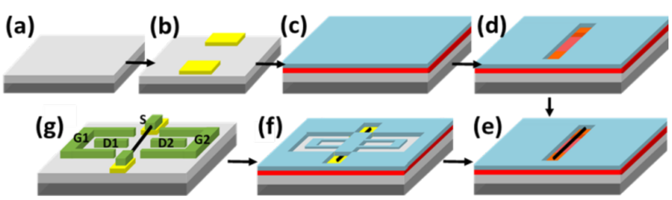


Figure II-10: SEM image of the cross-section of a TiN coated Poly Si beam showing the conformal coverage of 10 nm Al_2O_3 grown by ALD method.

The experimental setup and process flow for a six-terminal carbon nanotube (CNT) NEM switch (Figure II-12(a)) have been developed and verified. The fabrication process is based on a high-precision assembly technique, and is depicted in Figure II-11. For simplicity, the schematic illustration in this figure shows the process flow of half of the six-terminal CNT NEM switch structure. First, 140 nm photoresist (LOR)/50 nm e-beam resist (PMMA) layers were coated on a SiO_2/Si substrate with pre-patterned guiding electrode pairs. A 50 nm-wide trench then was defined by e-beam lithography (EBL), between each guiding electrode pair (Figure II-11(d)).

Then 20µl CNT solution was cast onto the sample surface and ac-dielectrophoresis was applied between the guiding electrodes. By electric-field forces, metallic CNTs were attracted and trapped into the trenches (Figure II-11(e)). Subsequently a second PMMA layer was spun on. The drain and gate electrodes and the CNT clamps on top of the source electrode were defined by EBL and deposited by metal evaporation (Figure II-11(f)). Finally the CNT switches were released by stripping the resist materials and dried in a CO_2 critical point drier to avoid surface tension. Meanwhile, misaligned CNTs and impurities were lifted off (Figure II-11(g)).

Six-terminal CNT switches have been successfully fabricated in the Stanford Nanofabrication Facility, as shown in Figure II-12(b). The 2 µm long CNT is precisely assembled and suspended between two sets of drains and gates. The as-fabricated distance between the CNT and drain is ~100 nm. A preliminary *I-V* characteristic of the six-terminal CNT NEM switch is shown in Figure II-12(c). The pull-in voltage is around 16 V, which can be further decreased by shrinking the CNT-to-drain/gate distance.



9: scheme used to fabricate precisely-aligned and clamped-clamped six-terminal CNT NEM switches.

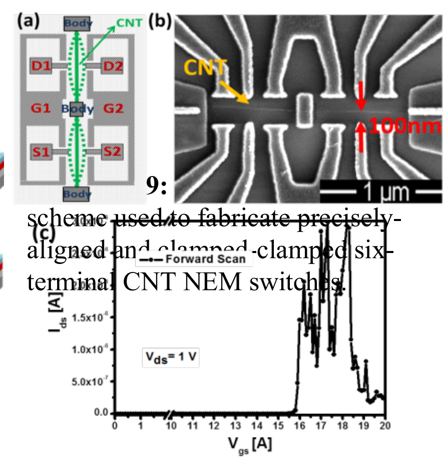


Figure II-10: (a) Schematic and (b) SEM pictures of the six-terminal CNT NEM switch fabricated at Stanford. (c) I-V characteristic of the six-terminal CNT NEM switch showing a pull in voltage at ~ 16 V**.**

While these initial results fall short of the goal of millivolt switching, the accomplishment here is the demonstration of the successful transfer and growth of different types of thin film materials.

The next step will be the integration of two-dimensional (2-D) materials into NEM switches. With the two key components (synthesis/transfer and micromechanical structures) developed, we anticipate that the integration process will be straightforward because graphene and MoS_2 should not be affected by the fabrication process, in principle. We expect this work to be completed by the end of this Reporting Period.

Characterization of Low-Adhesion Contact Materials: The **J. Wu** group *(Berkeley)* has been characterizing the Young's modulus and interlayer sliding in atomically thin transition metal dichalcogenides (TMDs). Elastic properties of materials are an important factor in their integration in applications related to the Theme II. Chemical vapor deposited (CVD) monolayer semiconductors are proposed as key components in industrial-scale flexible devices and building blocks of 2-D van der Waals heterostructures, and specifically for the Theme II, as tunneling layers, sacrificial layers or conducting membranes. However, their mechanical and elastic properties have not been fully characterized. In this work we demonstrated high elastic moduli of CVD-grown monolayer MoS_2 and WS_2 (~170 N/m), which is almost half the value of the strongest material, graphene. The 2-D moduli (see Figure II-13) of their bilayer heterostructures are lower than the sum of 2-D modulus of each layer but comparable to the corresponding bilayer homostructure, implying similarly strong interactions between the hetero monolayers as between homo monolayers. These results not only shed light on understanding interlayer interactions in 2-D van der Waals structures, but also potentially allow engineering of their elastic properties as desired.

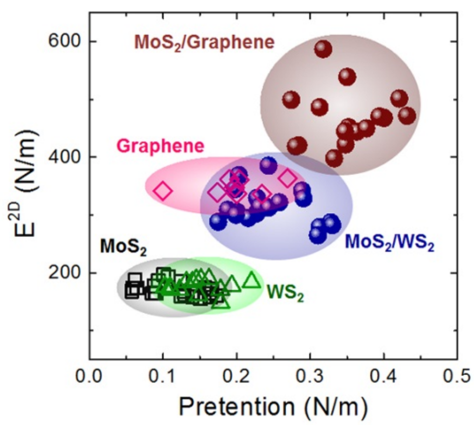
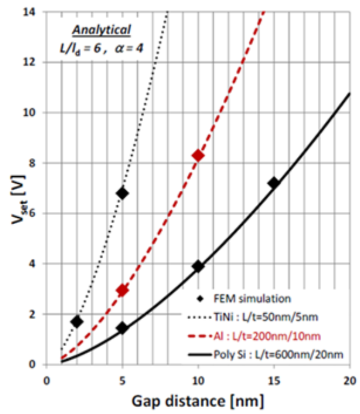


Figure II-11: Elastic properties of selected TMD's, as individual layers, bilayers of each other and bilayers with graphene.

Electro-Mechanical Memory (Nemory) Devices Integrated on Top of CMOS: One of the most dominant sources of lost performance and hence increased energy consumption in today's computing systems is the relatively high energy and latency cost of accessing/utilizing external dense memory (DRAM). The group of **E. Alon** (*Berkeley*) has been studying nano-electro-mechanical memory (NEMory) as it has several attractive characteristics that may address these issues. In particular, it can be integrated on top of CMOS electronics and offer extremely low latency/energy access while achieving non-volatility. During this period we have developed analytical models for NEMory devices that predict their operating characteristics (e.g., pull-in/pull-out vs. device dimensions), and we have applied these models to predict the operating voltage versus cell density tradeoffs for various potential material systems. In particular and as shown in Figure II-14, because of its high strain limit and low Young's modulus, TiNi appears to be a particularly attractive candidate for implementing dense yet low-voltage cells.

To ensure the accuracy of these analytical models, we have performed finite-element based simulations and confirmed that they match with the predictions of the model. With this verified model in hand, we felt that it was next critical to evaluate the potential of NEMory with actual layouts compatible with a state-of-the-art CMOS process. We therefore utilized the model to find an optimized NEMory structure that would be compatible with IBM's 14nm CMOS process in terms of metal/contact pitch. The resulting optimized individual cell design was then compared against an SRAM in the same process technology. Although the reads are substantially slower than the CMOS cell (due to the limited current available through the NEMory device), the comparison appeared otherwise favorable for NEMory in terms of write delay, read and write energy, and density.



Beam material	Poly-Si	Al	TiNi
Young's modulus E	169 GPa	77 GPa	14 GPa
Total length ($L=2l+l_d$)	600 nm	200 nm	50 nm
Thickness (t)	20 nm	10 nm	5 nm
Strain limit	0.93%	0.18%	8%
Minimum beam length L for t=5nm and g=2nm	105 nm	**235 nm**	35 nm

Figure II-14: Operating voltage vs. cell density tradeoffs for various potential material systems as predicted by model.

Even with these preliminarily promising results, further work is required to evaluate NEMory within a complete array. To facilitate this, a verilogA model of the NEMory devices was developed; this model could then be utilized in co-simulations with CMOS transistors to evaluate performance and energy at the complete array level. Similarly, driver circuitry compatible with a NEMory array was designed in the IBM 14nm process. This effort exposed more substantial challenges with NEMory arrays – in particular, the high series resistance associated with each cell and the potentially limited forward vs. reverse current ratios of the diodes embedded within the NEMory. Both of these issues lead to the requirement for large CMOS drivers, making integration of these drivers fully underneath the NEMory array substantially more challenging. Nonetheless, preliminary floorplans/layouts for these drivers have been completed, and we expect to have a holistic analysis of the potential of NEMory-based arrays available by the end of this period.

NEM Relay Based VLSI Systems with Properties of the New Sub 0.1V Relay Circuits: In Period 5, the group of **V. Stojanovic** (*Berkeley*) studied the design of the largest computational block (the floating-point unit - FPU) with NEM relays, in order to establish if the energy-efficiency and design-style of this technology extend all the way to the system level. This study showed how new relay circuit design techniques combined with those we already demonstrated on smaller relay blocks enable optimization of the design of the most complex arithmetic unit, i.e. the FPU. The energy, performance, and area trade-offs of FPU designs with NEM relays have been examined and compared with those of state-of-the-art CMOS designs in an equivalent scaled process.

Circuits that are critical path bottlenecks for the FPU specifically, most notably the leading zero detector (LZD) and leading zero anticipator (LZA), have been optimized with new relay-tailored circuit techniques; see Figure II-15. These optimizations reduce the NEM relay FPU latency from 71 mechanical delays in an optimal-CMOS-style implementation to 16 mechanical delays in a generalized custom NEM relay implementation.

In a 90nm process node, the FPU designed with NEM relays is projected to achieve 15x lower energy per operation compared to the FPU designed with CMOS; see Figure II-16.

Confirming that the energy benefits of NEM relays over CMOS extend all the way to the large functional blocks is the only way to prove the true value of this technology to further the scaling of computation. Limiting the new technology evaluation to any other smaller scale will be potentially misleading due to simple consequences of Amdahl's law where other costs in the system very soon begin to dominate after one component has been optimized.

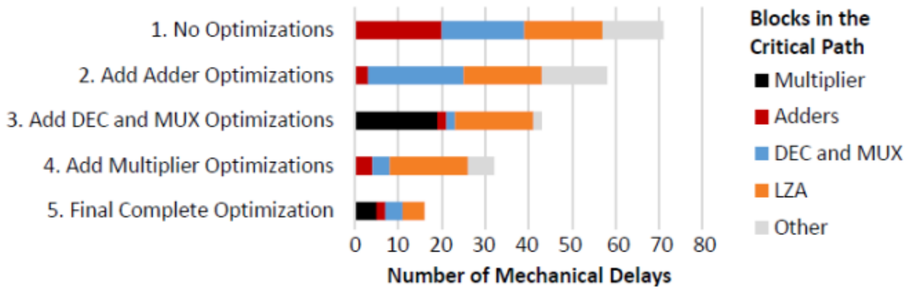


Figure II-15: Number of mechanical delays for the FPU FMA operation. (1) the design is translated directly from optimal CMOS to NEM relays, (2) the design in (1) also has adders optimized for NEM relays, (3) the design in (2) also has decoders and multiplexers optimized for NEM relays, (4) the design in (3) also has the multiplier optimized for NEM relays, and (5) the FMA design has all optimizations for NEM relays reported in this work.

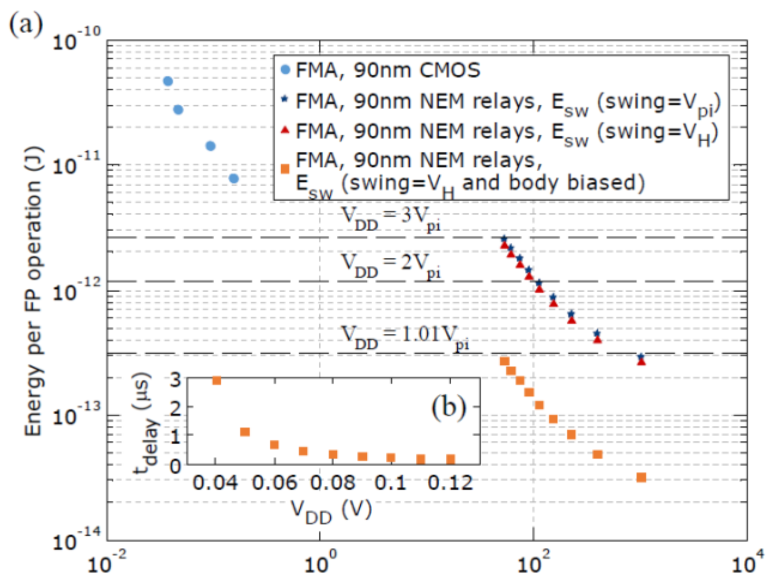


Figure II-16: (a) Energy per operation and compute density comparison with CMOS in 90nm process node. (b) Mechanical delay vs. supply voltage in the 90nm scaled NEM relay model.

Center for Energy Efficient Electronics Science

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

The researchers in the Nanophotonics Theme are continuing to work towards the ultimate goal in optical communications: approaching quantum-limited sensitivity (20 photons/bit) with an energy efficiency of 20 aJ/bit. Given today's state of the art optical communication in fiber interconnect at board- and box-level has a sensitivity of ~10^5 photons/bit and consumes an energy of ~1 pJ/bit, Theme III's goal is to reduce the amount of energy used by 20,000 times. The researchers' approach is to improve *both* energy efficiency and sensitivity of the emitters and detectors of optical links for on-chip application. Beginning in Period 3, the strategy has included two elements:

- coupling of optical antennas to nanoscale devices to make spontaneous emission faster than stimulated emission at the nanoscale, as a means to achieve highly efficient optical sources, ideally with no DC bias, and with high bandwidth (100Gbps); and
- direct integration of detector and the first transistor to minimize load capacitance (< 100 aF) in a form of photo-transistor as a means to achieve ultra-sensitive photo-receivers.

The research also includes the integration of the novel components on photonic waveguides to understand the performance and energy consumption in optical links.

In Reporting Period 5, three Theme III projects continued, building on the progress made in prior periods.

- Spontaneous Hyper Emission (SHE) III-V nanoLEDs, pursued by the **M. Wu** and **E. Yablonovitch** groups (*Berkeley*) and **G. Fitzgerald** (*MIT*);
- Germanium nano-phototransistors, pursued by the **M. Wu** and **E. Yablonovitch** groups (*Berkeley*); and
- III-V on silicon nano-phototransistors, pursued by the **C. Chang-Hasnain** group (*Berkeley*).

Up to the current Reporting Period, all research performed on NanoLED in the Center has been done with traditional III-V optical material, mainly InGaAsP and InP. Because of the high surface-to-volume ratios in the nanoscale emitter, the quantum efficiency is limited by surface recombination. In this Period, we have explored alternative material systems based on monolayer chalcogenides, which have much lower surface recombination on top and bottom surface. During Period 5, a new project on monolayer chalcogenide nanoLEDs was initiated in the **M. Wu** group, in collaboration with the **A. Javey** group (*Berkeley*) where research in Chalcogenide nanoelectronics (Theme I) has been actively pursued since Period 2.

Also new in Period 5 is the planned participation of the **E. Fitzgerald** group (*MIT*) in the nanoLED project. The participation of a materials grower as an integral part of nanoLED project offers advantages over material obtained from commercial epitaxy companies, including faster turn-around time, decreased cost, and an increased level of intellectual collaboration. In addition to fabricating starting epitaxial structures, the **Fitzgerald** Group is working on regrowing semiconductor and oxide films on patterned devices, which will act as high-quality passivation.

Also planned for Period 5 is the research to understand selective-area growth of InP on Si(111), to enhance the yield of nanopillar growth technology that is used for material growth of III-V on silicon nano-phototransistors. The research to understand selective-area growth was carried out by **D. Zubia** (*UTEP*). During Period 5, however, this research effort was refocused to a more limited scope that only involves the theoretical aspects to understand nanoscale growth selectivity. Instead, the Zubia group refocused to research on synthesis of chalcogenides; see Section on Problems Encountered.

Research highlights for the three device projects are as follows:

- First demonstration of an electrical injection III-V nano-LED: Electrical injection is a key milestone indicating that the approach being pursued by Theme III researchers has the potential for use in practical optical links. Results from prior periods were from optically-pumped nano-LEDs.

- First demonstration of Chalcogenide nanoLEDs with 100x enhancement: This is an experimental demonstration of a nanoLED in a novel material system that theory predicts would give an enhancement of 850x enhancement; i.e. the potential for quantum efficiency > 50% and lifetimes <10ps.
- Successful demonstrations of photo-BTJ in Ge and III-V materials: A Ge n-p-n photo-BJT has a high responsivity (>14 A/W) and gain (~18) and also shown moderately high speed operation, resulting in a gain-bandwidth product measured at over 15 GHz. An InP photo-BJT shows very linear photo response with responsivity approaching 4 A/W at very low bias voltage of 0.5V, indicating that the device with regrown junctions for low dark current facilitating very low voltage operation.

Details of these projects are given below.

- *Spontaneous Hyper Emission (SHE) III-V nanoLEDs:*

Nano-LEDs show great promise as high-speed and low-power optical emitters for efficient on-chip optical interconnects. In previous research periods we demonstrated large spontaneous emission enhancement of 35X by coupling an III-V material to an optical antenna at the nanoscale. We later showed that light emitted from such devices can be coupled to an on-chip waveguide with good coupling efficiency (~70%) thus demonstrating the feasibility of this approach for intra-chip communication. In this period, there were two major goals: (i) Demonstrate fast and efficient electrically injected nanoLED, which is a challenge due to the nanoscale size of the active region (high contact resistance, high surface-to-volume ratio, etc.); and (ii) Determine the fundamental limit of spontaneous emission rate enhancement in III-V materials, by exploring InP emitters small enough to couple to an optical dipole with extremely small antenna gap spacing (< 15nm).

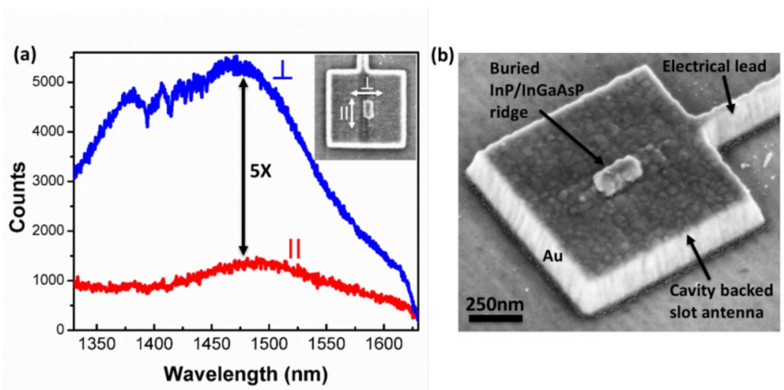


Figure III-1: (a) Spectral measurements of electro-luminescence showing 5X higher intensity of light with polarization transverse to long axis of slot (parallel with antenna mode). (b) SEM image of nanoLED with gold cavity backed slot antenna.

Electrical Injection NanoLED: The successful fabrication and measurement luminescence from an electrical injection InP/InGaAsP double heterostructure ridge nanoLED that was coupled to a newly developed optical slot antenna. Previous nanoLED designs relied on the optical arch-dipole antenna, which has a narrow antenna width (~50nm) that makes direct electrical contact difficult. The slot antenna, the complimentary structure to the dipole antenna, consists of a metal plane with a slot cut out. By inserting an optically active material in the slot (i.e. InGaAsP), this material experiences large spontaneous emission enhancement. Unlike the dipole antenna, this structure does not suffer from large gap capacitances shorting out enhancement and therefore wider ridges can be used (~200nm). This structure not only makes electrical contact easier, but also enhances emission from a larger portion of the active material in the slot compared to an arch-dipole of similar dimension. For example, an InGaAsP ridge 100nm tall, 40nm wide, and 200nm long experiences 4x greater enhancement when coupled to a slot antenna than to an arch-dipole antenna.

Figure III-1 shows the intensity of light emitted from the device polarized parallel to the antenna mode was 5X higher than the intensity of emitted light with polarization perpendicular to the antenna mode

(This is an improvement from 2X that was reported in the first half of Period 5). Considering the field distribution within the slot as predicted by simulation, the *peak* enhancement factor is estimated at ~10X.

With this first demonstration of an electrically pumped nanoLED, the next milestone is to to demonstrate ~15X overall enhancement through device downscaling by the end of this Reporting Period. In addition, recognizing III-V materials suffer from large surface recombination rates, the **Fitzgerald** group (*MIT*) is exploring the growth of InGaAsP structures with InP regrowth as a means of passivating the InGaAsP surface. It is expected that the first photoluminescence results of passivating InGaAsP surface with InP regrowth will be obtained by the **M. Wu** group by the end of this Reporting Period.

Fundamental Limit of Emission Enhancement: Experimental determination of the fundamental limit of spontaneous emission rate enhancement in III-V materials will allow researchers to understand the potential of this material system in enabling the goal of a non-biased emitter; i.e. one that is performance competitive with a laser, a biased emitter. In this Reporting Period, the **Yablonovitch** group fabricated and measured arch dipole antenna coupled to a highly scaled (12nm) wide InP emitter was successfully undertaken. Figure III-2 shows optical excitation of InP ridges led to a 120x increase in light output from InP coupled to the antenna over bare InP ridges. Measurement of light emission polarized perpendicular to the antenna was used to quantify a pump enhancement of 8.5x. Therefore, an increase in radiative rate of at least 14x was observed.

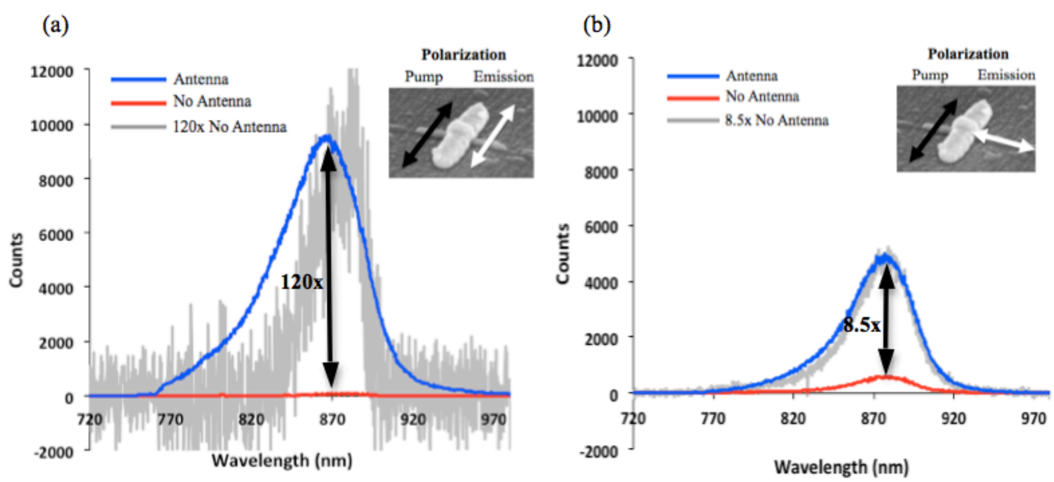
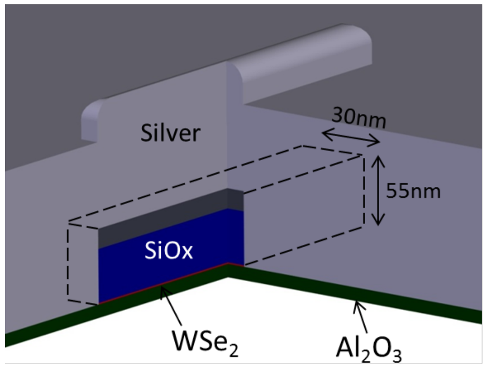


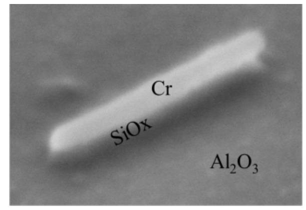
Figure III-2: (a) Photoluminescence (PL) signals with both pump and emission polarizers directed along the axis of the antenna. (b) PL signals with the pump polarizer directed along the axis of the antenna and the emission polarizer directed perpendicular to the axis of the antenna.

As reference, a spontaneous emission rate enhancement of 200x will enable the nanoLED to be faster than semiconductor lasers.

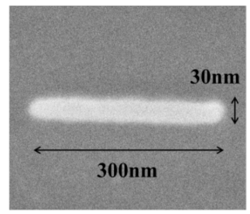
Chalcogenide NanoLED: All research performed on NanoLED in the Center up until Period 5 was done with traditional III-V optical material. While we have made progress and have achieved significant results with NanoLED with the III-V materials, mainly InGaAsP and InP, these traditional optical materials suffer from large surface recombination rates, which limit their quantum efficiencies.

Recently, 2D chalcogenide materials [19] have shown great promise as active materials in nano-scale optical devices due to their near ideal surface. Monolayers of WSe_2 exhibit a direct bandgap with internal quantum yield as high as 10%. We plan to fabricate a nanoLED with a 2D chalcogenide material (WSe_2) as the active layer. With proper antenna design, the inherent monolayer thickness of this material will allow for intimate electromagnetic coupling that will enable us to probe the limits of spontaneous hyper emission. Such small dimensions are impossible with traditional III/V materials. At the same time, the material's ideal surfaces can allow for aggressive scaling of antenna dimensions without sacrificing quantum yield.





Perspective view of SiOx/Cr ridge before Ag deposition.



Top view of SiOx/Cr ridge before Ag deposition.

Figure III-3i: (a) Cut-away schematic of fabricated slot-antenna device. The SiO_x layer acts as the slot in the silver plane with E-field concentrated in the WSe_2 active layer. (b) Perspective and top view of SiO_x slot before metal deposition.

In order to study 2D monolayers of WSe_2 as emitters, a new antenna design and fabrication processes must be developed. Previous antenna designs all relied on the thickness of the material to form the feed-gap of the optical antenna. The very thin nature of these materials, however, makes it impossible to use this same strategy. By adopting the optical slot antenna and using an evaporated SiO_x spacer as the slot, antennas with very small gaps can be patterned on the WSe_2 without difficult wet-etching. Because of the very inert surfaces and delicate nature of this material, significant time was put into developing a process to make <30nm features without damaging the flake.

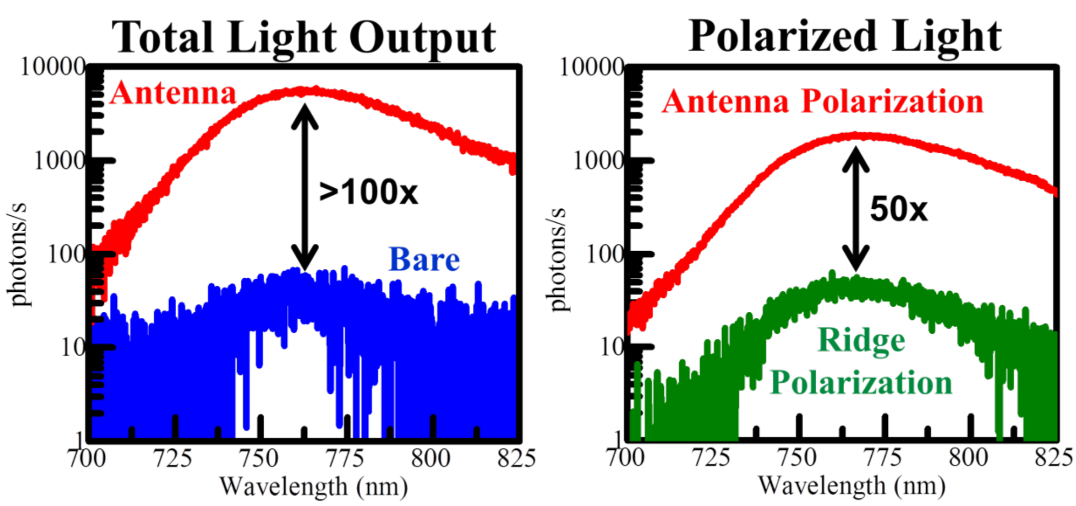


Figure III-3ii: (Left) Comparison of total light output between a bare and an antenna-coupled strip of WSe2 (300nm x 30nm). Plot takes into account the different pumping and collection efficiencies of the two cases. (Right) Polarization ratio between the antenna direction and the perpendicular direction for an antenna coupled device. 50x is the highest polarization ratio measured to date.

As shown in Figure III-3i, a slot antenna was fabricated using Silver as the antenna with a 30nm gap. CW PL measurements show >100x enhancement in light output. This could possibly correspond to a spontaneous emission rate speedup of 400x, the largest we have ever measured. Light is also highly polarized, showing a polarization ratio along the antenna vs. perpendicular of 50x. This is four times larger than any ratio previously measured.

In collaboration with the **X. Zhang** group (*Mechanical Engineering, Berkeley*), time resolved measurements have been performed both on unprocessed WSe_2 flakes and on antenna-coupled devices using ultrafast streak camera with a time resolution of 1 ps. This is the first time we have been able to directly measure lifetimes and may be due in part to the high quality surfaces of this material and its visible wavelength of emission. These results (showing in Figure III-3ii), coupled with CW results, will allow a better understanding the operation of our Chalcogenide devices.

Germanium based Nanophototransistors: During this Period 5, the **M. Wu** group pursued a Ge bipolar homojunction phototransistor integrated on silicon photonics using the rapid melt growth technology that was developed in the previous period. The unique nature of the rapid melt growth has allowed a novel device design to be created where the detector wrapped around the silicon waveguide. This process was first demonstrated with a germanium PIN photodiode, which had a unique high responsivity geometry where the germanium wrapped around the silicon waveguide as seen in the cross-sectional SEM in **Figure III-4**. The photodiode included activated n and p-implants and crystalline germanium on a silicon photonics optical routing layer. The high quality of the germanium crystal can be seen from **Figure III-5** which shows extremely low dark current (6 nA at -1 V) from a 16 µm long diode and high Responsivity (1 A/W at 1550 nm). RF measurements show frequency response over 10 GHz, and for diodes with narrower transit regions, operating frequencies over 26 GHz at the expense of reduced responsivity.

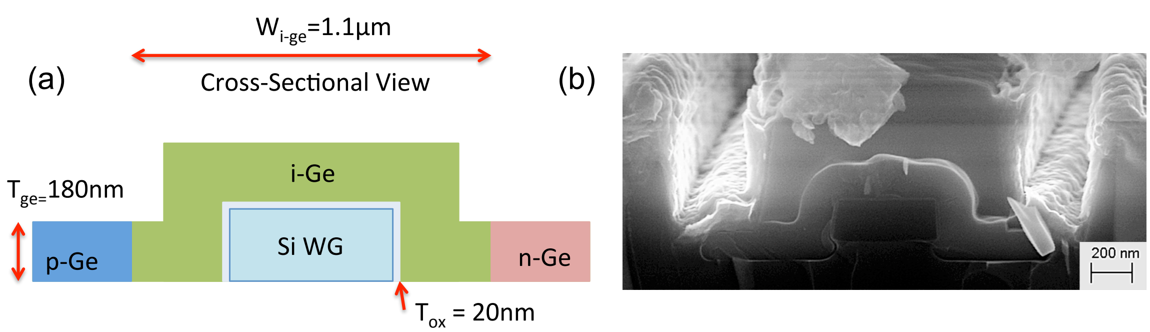
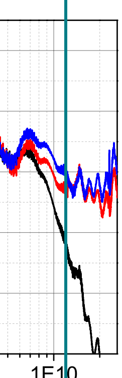


Figure III-4: (a) Schematic cross-section of wrap-around PIN photodiode and (b) actual SEM cross-section



current at -1V,
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In Period 5, we also used the same device architecture and process flow to produce floating base photoBJTs, where instead of p and n-doped contacts, the device simply had two n-doped contacts with a very low-doped p-region in the center. High Responsivity (>14 A/W) and gain (~18) was seen from an 8 µm long NPN phototransistor in Figure III-6. It also demonstrated moderately high speed operation, resulting in a gain-bandwidth product measured at over 15 GHz.

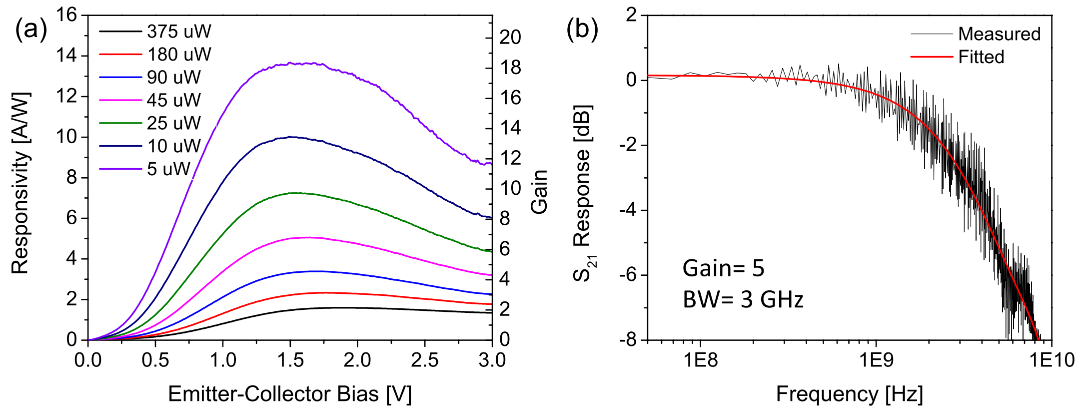

Figure III-6: (a) 8 µm long NPN showing high Responsivity and gain and (b) showing high speed operation with moderate gain.

Finally we have modified the existing process slightly to allow for more sophisticated base/emitter implants and separate electrical base contacts, which should allow for more control over the gain and operating speed of the phototransistor. The **Yablonovitch** group has simulated in Sentaurus with conservative designs showing gain bandwidth product, f_T, of 25 GHz, seen in Figure III-7. More aggressive simulations with shallower emitter junctions have shown f_T in excess of 50 GHz, which is primarily limited by the emitter width (250 nm) set by the lithography resolution available in the Berkeley Nanolab. Narrower emitters combined with thinner junctions, likely enabled by epitaxially grown germanium doped in-situ will allow for much faster f_T for high gain at high speed.

Center for Energy Efficient Electronics Science

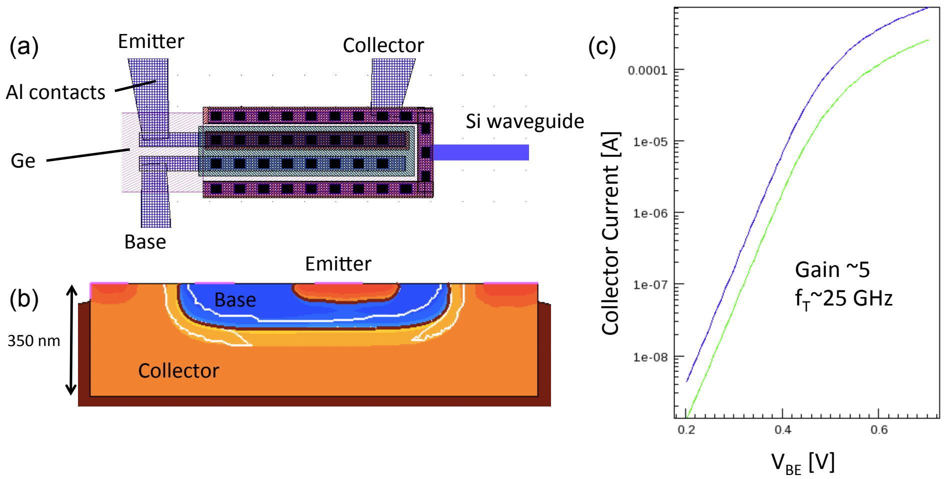

Figure III-7: (a) Layout of new phototransistor design with (b) simulated cross-section and (c) simulated gummel plot.

High Sensitivity III-V Phototransistor on CMOS: The broader perspective of this project has always been the integration of the flexibility and transformative capability of III-V absorber materials with the scale and manufacturability of the Si-CMOS framework – towards compact, low-energy devices. But, as the **Chang-Hasnain** group (*Berkeley*) has gained better understanding, the material absorber of choice has undergone refinement. In particular, Indium Phosphide has emerged as the preferred material system for nanopillar-based optoelectronics for the following key reasons.

- InP, among III-V materials, has a low surface recombination velocity – making it well-suited for the high surface to volume ratio of nanostructures. This allows InP to have much lower dark current associated with surface and defect-based recombination – leading to better device performance.
- InP is very well suited for integration with $In_xGa_{1-x}As$ for the design of heterojunction-based devices that can absorb at Silicon transparent wavelengths (1.3 - 1.5 µm in particular). This heterostructure design flexibility is further aided by the lifting of lattice matching requirements that the nanopillar geometry enables. With $In_xGa_{1-x}As$ absorbers clad with InP passivating layers, we hope to leverage the unique benefits of heterojunction bipolar transistors that allow state of the art gain-bandwidth products as high as 700 GHz.

In this Reporting Period 5, we used InP nanopillars as a template to build working bipolar junction phototransistor (photo-BJT) devices. The design of our photo-BJT has a regrown p-n-p junction. This is done because if we just grow the collector, base and emitter layers in a continuous core-shell growth, as shown in Figure III-8, the p-doped emitter shell will be directly connected to the p-doped substrate. This means there will be a current flowing from the emitter to the collector contact at the substrate, shunting the desired current path through the device layers.

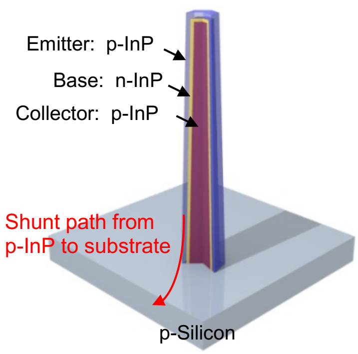

Figure III-8: Schematic showing the problem of shunt current path when the layers of a bipolar junction photo-transistor is grown in one continuous growth.

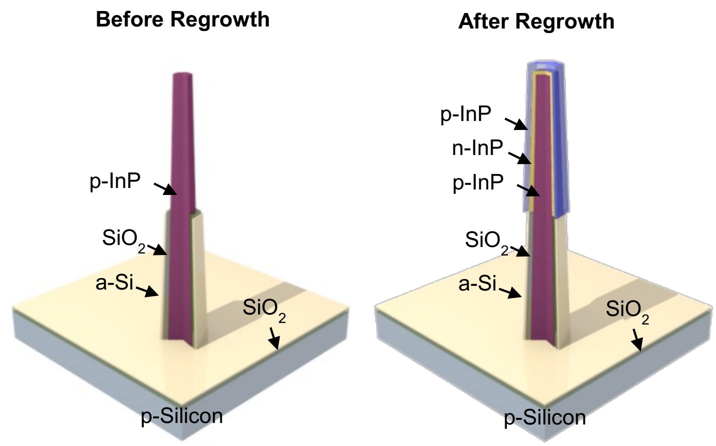

Figure III-9: Schematics of a nanopillar before and after regrowth to address the shunt current path problem.

To get rid of this shunt current path, we developed a regrowth technique to isolate the p-doped emitter and n-doped base from the substrate. Instead of growing all the layers in one single growth, we grew only the light p-doped collector first. After selective etching outside the MOCVD chamber, a sample is returned for a regrowth to complete the n-doped base and p-doped emitter shell, as seen in Figure III-9. With regrowth, the size and location of the p-n-p junction can be controlled precisely along the length of the nanopillar. This added control allows us to lift the emitter and base layers away from the substrate, cutting off the current leakage path entirely. Figure III-10a shows the before and after regrowth scanning electron micrographs, showing the smooth sidewalls of a regrown nanopillar as a sign of excellent regrowth material quality.
Indeed, when examined under transmission electron microscope (Figure III-10b) the regrown junction exhibits high crystal quality with little to no stacking dislocation.

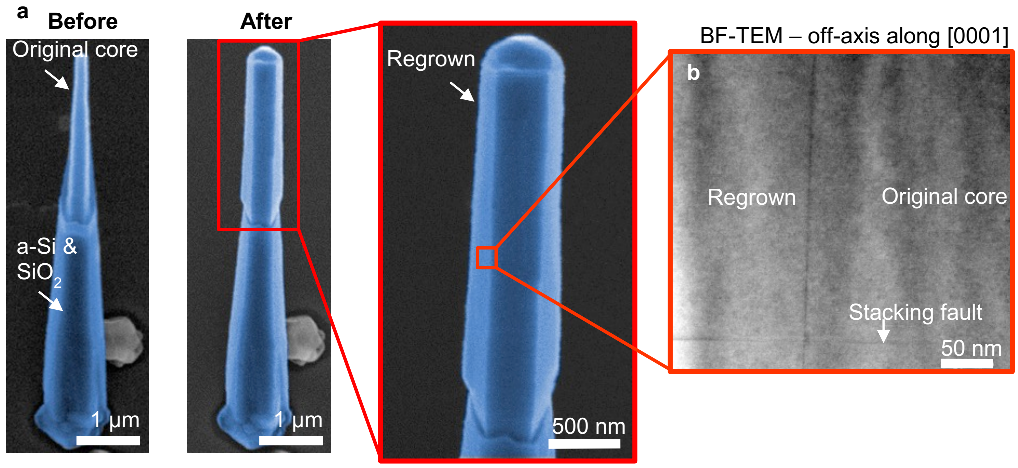

Figure III-10: a - Scanning electron micrographs of a nanopillar before and after the regrowth. Regrowth only occurs on the top portion of the nanopillar because the bottom half of the nano-pillar is masked. B - Bright field tunneling electron micrograph of a nanopillar showing the junction between the regrown layers and the original nanopillar core showing very few stacking dislocations.

The photo-BJT was tested with 785 nm laser illumination from the side at a 30° angle through a multi-mode fiber with numerical aperture of 0.27. When not illuminated, the device shows minor collector current for much of the collector-emitter bias since the p-n junctions inside are reverse biased. But when the device is illuminated, the photocurrent generated inside the device biases the base in a similar way as applying a base bias current in a conventional BJT. As a result of this base bias current, the potential barrier at the emitter-base junction lowers, allowing a finite amount of carriers to flow freely from the emitter to the collector to form a constant collector current. In a way, this photo-BJT behaves just like a conventional BJT, except that the base is biased solely through photons. As such, a characteristic BJT current-voltage (I-V) behavior can be clearly seen in Figure III-11a. When biased in forward active mode, the photo-BJT shows linear photo response with responsivity approaching 4 A/W, or a gain of 6.3. Figure III-11b shows such linear photo response from the photo-BJT when it is biased with 0.5 V collector bias. Such a linear and sensitive photo-BJT is a promising device in bringing low energy optical interconnects to silicon electronics.

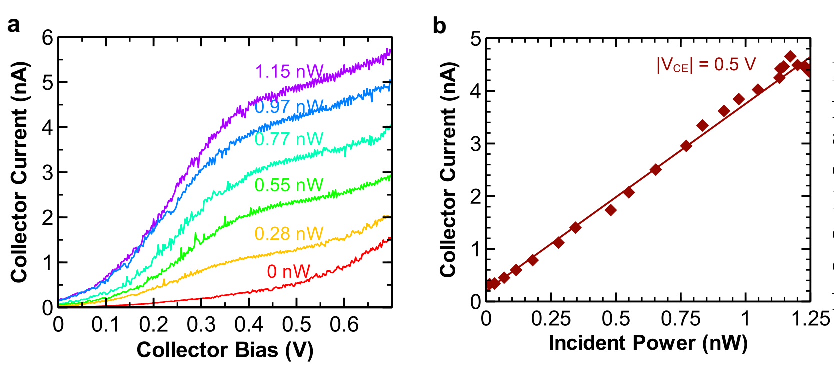

Figure III-11: InP nanopillar phototransistor device characteristics. a, Photo-BJT collector current versus collector voltage at different 785 nm laser excitation. b, Photo-BJT collector current versus 785 nm laser excitation power curve showing linear photo response from photo-BJT.

Establishing Internal Capability for Novel Materials

1) Epitaxial III-V material: In Period 5, the **E. Fitzgerald** Group (*MIT*) expanded their research to Theme III. This shift is intended to provide highly-customized epitaxial structures for the fabrication of optoelectronic devices. For example, the flexibility of the Fitzgerald Group's MOCVD reactor allows for the regrowth of semiconductor material over patterned samples.

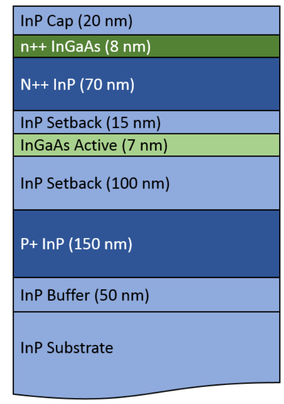

Figure III-12: Schematic of the nanoLED structure growth within the Center for use by the Theme II device research

The first structure being grown for the fabrication of nano-LEDs is shown in Figure III-12. Layer compositions have been calibrated using high-resolution x-ray diffraction. Cross-sectional TEM has been used to measure growth rates and verify interface quality. Doping was verified using Hall Effect measurements. This information can now be used in a final device growth, which is expected to be completed for use by the Theme III nanoLED researchers before the end of Period 5.

2) Synthesis and Characterization of 2D Layered Materials: In mid Period 5, the research direction at the **D. Zubia** group (*UTEP*) changed to research on 2D layered materials, so as to better align with the needs of Theme III to have a supply of materials optimized for the nanoLED device fabrication and the laboratory infrastructure at UTEP. With this change, the first goal is to establish the physical and human resources needed to perform research on 2D layered materials. Thus, this project has been setting up the physical infrastructure to synthesize and characterize 2D layered materials via CVD.

To date, a tube furnace was installed and thin films were deposited using MoO_3 and S as source materials. A schematic of the deposition system and picture of the furnace are shown in Figure III-13. Thin films have been deposited and characterization by SEM has begun. Further experimentation is being performed to determine the crystallography of platelets and deposition conditions that yield continuous 2D domains.

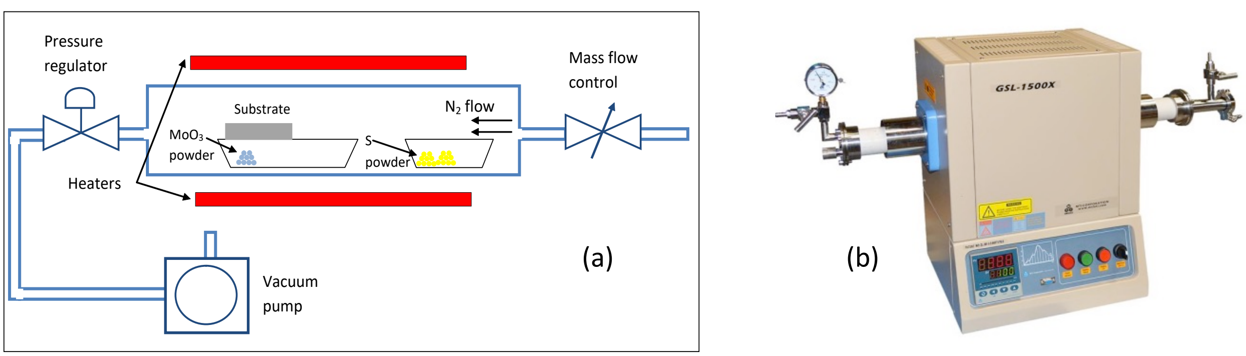

Figure III-13: (a) A schematic of the deposition system used to deposit MoS_2 films and (b) picture of the furnace.

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

Reporting Period 5 saw the completion of transition to a new nanomagnetics research portfolio that is comprised of research projects based on the concept of current controlled switching of nano-magnets followed by magneto-resistively controlled currents, with net current gain and fan-out. This Theme has continued to primarily focus on elucidating the physics and dynamics to lay the foundation for device demonstrations in future years.

- The fundamental physics of spin Hall effect (SHE) switching in a nanomagnetic heterostructure, a phenomenon that is about 100× more sensitive than Ampere's Law for switching a magnet, has been studied in the context of power dissipation in magnetic switching specifically by looking into new materials, size scaling and dynamics. **S. Salahuddin**, in collaboration with **J. Bokor** (*both Berkeley*), has been working towards the goal of establishing a coherent understanding of the spin current generated by spin orbit interaction and its interaction with other magnetic entities. In this Period, reported in literature for the first time was the demonstration that it is possible to move a magnetic domain wall orthogonal to the current flow using spin orbit torque. Switching a magnetic nanodot with an in-plane current by spin-Hall effect without needing an external magnetic field for symmetry breaking was also demonstrated

- The **J. Bokor** group (*Berkeley*) has continued to study the concept of ultrafast magnetic switching via a highly non-equilibrium process that is created by selectively 'heating' only the electrons with an ultrafast source. Conventional magnetic switching is governed by precessional dynamics that sets a minimum switching time of ~100ps, but to have practical application in logic, a switching speed in the range of a few psec would be far more attractive. In the ultrafast magnetic switching concept, the 'heating' is with a 60 fsec laser pulse that selectively heats ONLY the electrons. In a few psec, the excited electrons exchange energy and thermalize with the crystal lattice. Prior to thermalization with the lattice, the optically excited electrons are heated to a temperature of 1000-2000K. It is during the transient high electronic temperature phase that the Curie temperature of the ferromagnet is exceeded, and a rapid demagnetization on a sub-psec time scale results [20]. But since electrons are much lighter than the ions, after the electrons share energy with the lattice, the net temperature rise is only a few K. Building on other prior work, [21] [22], the Bokor group has completed the initial study of the dynamics of the magnetization, measuring the change of polarization on reflection of a short probe pulse from different magnetic material samples with a Magneto-Optical Kerr Effect (MOKE) magnetometer. Not only was the demagnetization time of less than 100 fsec confirmed, but even more significantly, the magnetization recovery time can be as fast as ~1 psec.

- **S. Khizroev** *(FIU)* and **J. Bokor** (*Berkeley*) have been collaborating in the study of the STT effect in MTJ nano-structures made of Ta/CoFeB/MgO/CoFeB/Ta, building on the prior work of the Khizroev group [2]. At Berkeley, testing of wafer level test structures trimmed by focused ion beam to sizes that ranged from several hundred nanometers to sub-10 nm confirms the findings of the prior work on a junction built on the tip of a nanoprobe. The switching current is linearly scaling down from mA range to sub μA range in sub-10nm structures. Some samples revealed signals that indicate multi-junction structures which show characteristics favorable for multiple bit per cell applications.
- For nanomagnetic devices to have practical applications, the issue of the very low magneto-resistance ratio in nanomagnetic materials must be addressed. The group of **V. Stojanovic** (*Berkeley*) has been studying the circuit topologies and block-level mechanisms to mitigate the low Ion/Ioff ratio of nanomagnetic switches (which leads to large standby power), by exploiting their non-volatility, while leveraging the low supply voltage operation of these devices for very low active power. In Reporting Period 5, a nanomagnetic logic power-gating model has been constructed that extends the work on pulsed magnetic logic. The model was used to study the energy advantages of non-gated magnetic logic devices over CMOS gated logic blocks. Even though in this circuit architecture, the study showed a significant improvement, this still brings the effective Ion/Ioff ratio to only ~100, as compared to 1,000-10,000 in CMOS. The group is now analyzing circuit blocks that can more

strongly from power gating, such as cache memories, as well as blocks that have high activity factor, such as communications links, in which standby power dissipation is less important.

Details of these research projects are given below.

Physics of Spin Hall Effect: According to the conventional spin transfer torque model, when spin polarized electrons coming from a magnetized region impinge on the spins in a domain wall, they exert a torque that tries to orient the domain wall spins in the direction of the incoming spins [23] [24, 25] [26]. The strength of the torque is proportional to the relative angle between the incoming spins and domain wall spins. If a domain wall is formed in the short direction of a magnetic wire (transverse domain wall) as shown in Figure IV-1a, then a current flowing in the long direction can exert such a torque and move the domain wall. This has been the canonical configuration for studying current induced domain wall motion [23]. If, on the other hand, a domain wall is formed in the long direction (Figures 1b & d), then, by symmetry, no torque is exerted on this longitudinal wall by a current that flows in the long direction. This is because the magnetization is uniform everywhere in the path of the current flow. Therefore, a motion of the domain wall in the orthogonal direction of the current flow is not expected within the conventional spin transfer torque model, henceforth to be referred to as the bulk spin torque model [24-26]. The situation is different in a magnetic heterostructure where an underlying non-magnetic metal can provide a spin orbit torque [27]. Here the torque originates from spin accumulation at the interface whose direction of polarization is different from the magnet and is determined by the direction of current flow and the sign of the spin-orbit coefficient. For example, in our heterostructure of CoFeB/Ta, a current flowing in the longitudinal +x direction (electrons in -x direction) would accumulate –y polarized spins in the CoFeB/Ta interface (Figure IV-1c). In comparison, the magnet CoFeB is polarized in the ±z direction. Due to the presence of a relative angle between magnetic polarization and accumulated spins, a torque is

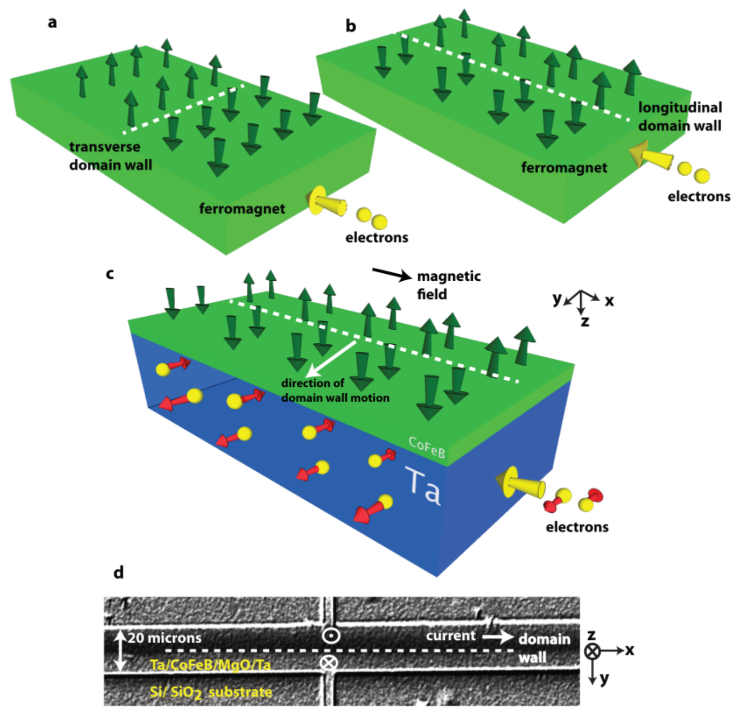

Figure IV-1: Spin Hall effect controlled domain wall motion. a, Current flows along a magnetic wire having a domain wall in its short direction, called the transverse domain wall. Green arrows represent the magnetic moments. b, Current flows along a magnetic wire having a domain wall in its long direction, called the longitudinal domain wall. c, When current flows through the Ta in x direction (electrons in –x direction) electrons with spin polarization in -y direction accumulate at the interface of the Ta and CoFeB. This results in the transfer of spin orbit torque to the domain wall in CoFeB. d, The MOKE image of the 20 microns wide magnetic bar shows the formation of a longitudinal wall along it when current flows in the +x direction. The longitudinal domain wall at y=0 separates an "out of the plane" (+z) polarized domain for y<0 and an "into the plane" (-z) polarized domain for y>0. Anomalous Hall voltage is measured across the orthogonal bar.

exerted on the magnet independent of the specific topology of the magnetic domain wall. Indeed, here we show that a longitudinal current can deterministically move a longitudinal domain wall orthogonal to the current flow in the presence of an in-plane magnetic field. Reversing the direction of the current flow or the direction of the field reverses the direction of the domain wall motion. Therefore, spin orbit torque provides a new way to control domain walls in magnetic wires that was not possible by conventional bulk spin torque. In addition, the fact that, due to geometrical symmetry, the bulk spin torque cannot contribute to such motion of domain walls, also makes it possible to investigate and analyze the efficiency of spin orbit torque directly, without needing elaborate methods to subtract the effects of bulk spin torque[28] .

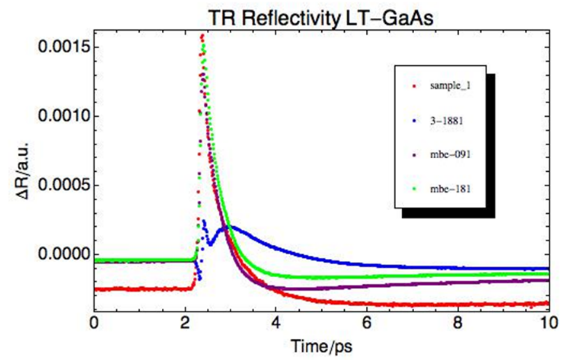

Figure IV-3: Time-resolved reflectivity data for 4 separate LT-GaAs samples.

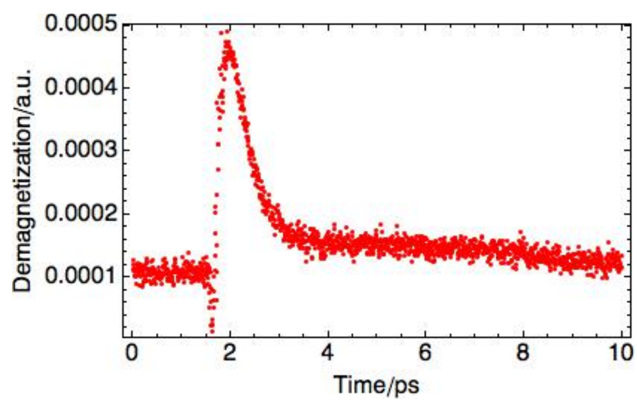

Figure IV-2: Time-resolved MOKE measurement of ultrafast demagnetization in Ni using 100 fs excitation pulse of ~5 mJ/cm^2 fluence, 800 nm wavelength. The t=0 point on x-axis is arbitrary in this preliminary data.

Dynamics of Ultrafast Magnet Switching: The **Bokor** group (*Berkeley*) has succeeded in building the ultrafast MOKE magnetometer and have used it to measure ultrafast demagnetization effect in a number of different magnetic material samples. An example of our data for a Ni thin film is shown in Figure IV-2. The demagnetization time is less than 100 fsec, but even more significantly, the magnetization recovery time is only about 1 psec. This is extremely encouraging for our interests in using this effect for fast magnetic devices.
To make the application of ultrafast demagnetization practical, we are investigating the use of picosecond electrical pulses. In this Reporting Period 5, we are also making progress towards the second milestone of fabricating fast photoconductive switches for generating picosecond electrical pulses. We obtained some suitable samples of appropriate “low-temperature GaAs (LT-GaAs)”, which is the material of choice for this type of optoelectronic pulse generator. Ultrafast transient reflectivity measurements were used to characterize the samples that we obtained, in order to confirm picosecond carrier lifetime. This screening step turned out to be crucial, since some of the samples show the desired carrier lifetime, but other samples do not. Some representative carrier lifetime data for different LT-GaAs samples is shown in Figure IV-3.

Furthermore, we have designed and fabricated several coplanar waveguide based photoconductive switches on various LT GaAs substrates. Initial photocurrent measurement indicates relative high peak current (~0.4A) with fairly low bias voltage (5V) and optical power (3mW). This is desired to achieve high current injection to drive magnetic device to non-equilibrium states.
The last months of Reporting Period 5 will be used to conduct ultrafast demagnetization / remagnetization studies of Ta/CoFeB/MgO spin-Hall effect (SHE) samples, using simple optically-triggered demagnetization. These studies will give insight into the fast dynamics underlying the SHE, which is important to the studies on the use of SHE for devices. The magnetic surface second harmonic generation

(MSHG) will be used to detect the spin accumulation at the surface of normal metals (Pt, W, Ta) resulting from spin-Hall effect. The sub-nsec response of the spin accumulation to fast current pulse input will be characterized. In addition, a supplier has been identified for commercial, fully fabricated photoconductive switches on an external LT-GaAs based pulse emitter. These are designed to operate like an active microwave probe tip and can be contacted to the device under test on a separate chip. These probes have now been ordered and will be evaluated during the last months of the reporting period for use in delivering ultrafast current pulses into magnetic device structures. Magnetization dynamics induced by these current pulses will be probed using our time-resolved MOKE apparatus.

Spin Switching in Sub-10nm STT Magnetic Tunneling (MTJ) Devices: In previous work [2], prior to joining the E3S Center, the **Khizroev** group (*FIU*) showed that a current density of 0.1 MA/cm^2 was sufficient to switch a magnetic state in a STT-MTJ nanodevice with a characteristic cross-sectional diameter of 6 nm, as shown in Figure IV-4. In that experiment, the entire junction was deposited on the tip of a silicon nano-probe that was brought down into contact with a metal substrate. The figure shows a full resistance-versus-current hysteresis loop for a standard tri-layer MTJ configuration, i.e., made of two 1-nm thick ferromagnetic CoFeB layers separated by a 1-nm layer of MgO. This observed switching current density was almost 30 times smaller than the smallest value reported for STT

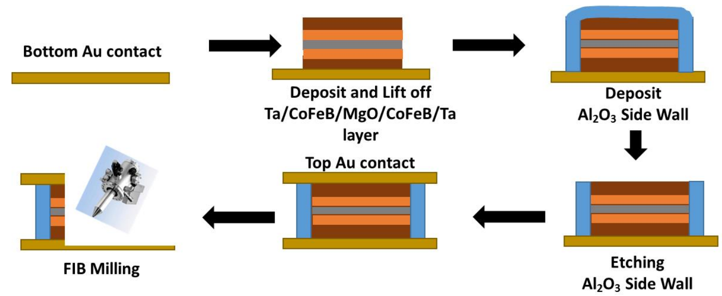

Figure IV-5: FIB-modified wafer-level STT-MTJ.

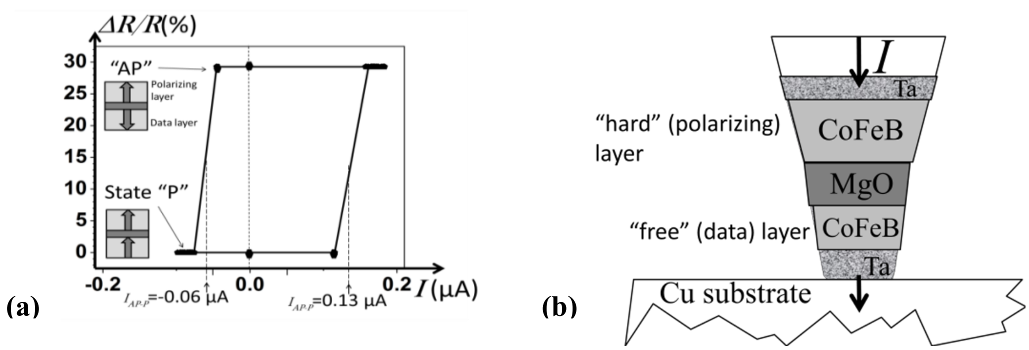

Figure IV-4: (a) R (I) curve for a point contact MTJ with an average resistance of 185 kOhm. (b) Schematic illustration of an MTJ coated on an STM probe tip, contacted to a Cu substrate.

MTJs of larger dimensions, e.g. a square bit with a side of 20 nm. According to the group's theoretical hypothesis, the significant reduction of the switching energy can be explained by a significant reduction of the orbit-spin (L-S) coupling and resulting spin damping reduction due to the increase surface contribution in this size range. This study is in line with the goals of Theme IV.

The special test structure shown in Fig IV-4b is impractical for device applications. However, the **Khizroev** group *(FIU)* joined the E3S Center during the current Reporting Period 5 with the goal to demonstrate this effect in a practical monolithic device structure. In collaboration with the **Bokor** group (*Berkeley*), a fabrication process utilizing precise focused ion-beam (FIB) etching was implemented which could create sub-10 nm MTJ structures. The process is shown schematically in Fig. IV-5. The significant reduction of the switching energy in the sub-10-nm range was confirmed during Reporting Period 5 using devices fabricated by this process. Typical I-V and magnetoresistance curves for a junction with a resistance of ~ 2 MOhm for a structure of size on the order of 5 nm that was fabricated at

FIU are shown in Figures IV-6a and b, respectively. The switching current on the order of 100 nA and the magnetoresistance on the order of 100% could be observed.

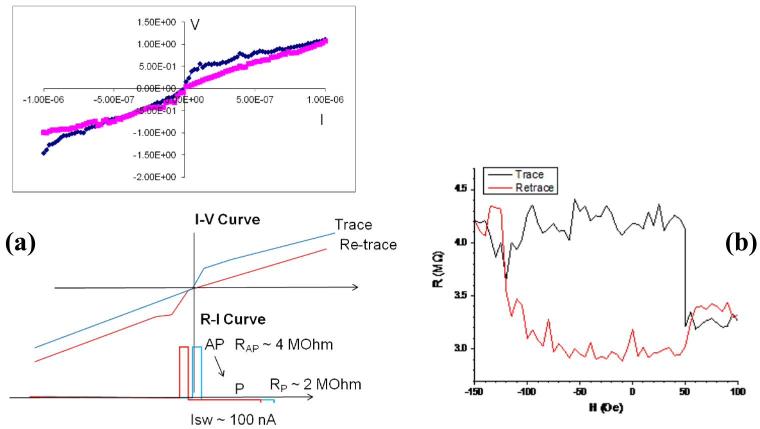

Figure IV-6: (a) I-V curve of a 2-MOhm STT-MTJ nanodevice (~5nm). The bottom illustration helps understand the dependence. (b) Magnetoresistance curve of a 2-MOhm STT-MTJ nanodevice.

Also, the following comment can be made regarding the I-V curve. This I-V curve is somewhat different from the conventional STT-MTJ dependences. The origin of the difference is application-related and is due to the fact that no magnetic layer was "fixed" in this test structure. Both layers were made more or less equivalent. In practical memory devices, one of the layers is "fixed" via a high coercivity or exchange biasing.

The switching current for another MTJ of ~10nm in size was observed to be 1.1μA (Figure IV-7). The group also observed a "negative resistance" regime in relatively low-resistance (~10 KOhm) sub-10-nm STT-MTJ nano-devices, as shown in Figure IV-8. The origin of the negative resistance might be due to an enhanced spin alignment by the spin-polarized current, which results in significant energy gain (of ~mH, where m is the magnetic moment of the effective region and H is the magnetic field). The unusually high room-temperature magnetoresistance of 500 % is also worth mentioning.

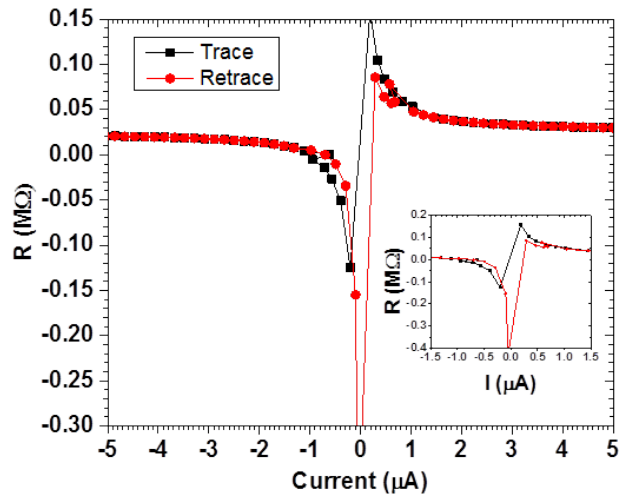

Figure IV-7: Switching characteristic for 10 nm MTJ device structure fabricated using process shown in Fig. IV-5.

It is anticipated that by the end of the Reporting Period 5, experiments necessary for drawing a phase diagram that could separate the conventional (linear scaling) size range and the novel sub-10-nm non-linear scaling range dominated by quantum mechanical effects will be completed. Also, measurements that allow an estimation of the thermal stability of these nano-scale MTJ devices will be conducted.

Circuit Architectures with Nanomagetic Switches: The V. Stojanovic group (*Berkeley*) has been modeling the circuit topologies and block-level mechanisms to mitigate the low Ion/Ioff ratio of nanomagnetic switches, yet leverage the low supply voltage operation of these devices. They have constructed a nanomagnetic logic power-gating model that extends the work on pulsed magnetic logic by incorporating the energy losses in supply pulse generation (through pulsed CMOS power-gates). These models are used to find the optimal CMOS power-gate sizing for given duty-cycle, logic depth and technology node, and calculate the savings over non-power gated and ideally power-gated solutions. The initial results are given in Figure IV-9.

Figure IV-9a illustrates that CMOS power-gates have significant energy overhead – between 2x and 4x depending on the logic depth, compared to ideally gated magnetic logic. This result shows the importance of proper modeling and system-use conditions for any emerging technology. “Forgetting” to model some critical part of the system often means that the overhead migrates there and limits the overall performance.

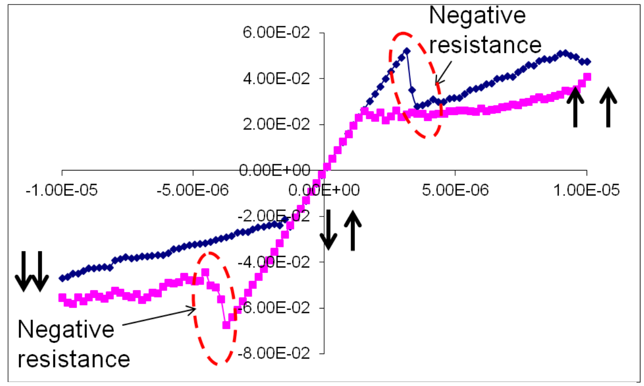

Figure IV-8: I-V curve of a 10-KOhm sub-10-nm STT-MTJ that shows “negative resistance” regions (circled in red).

Figure IV-9b illustrates the energy advantages of CMOS gated over non-gated magnetic logic, illustrating that on practical logic blocks (like FPU for example) which have a logic depth up to 100, savings of 30x can be obtained. Even though this is a significant improvement, this still brings the effective Ion/Ioff ratio to ~ 100, compared to 1,000-10,000 in CMOS. Considering 30x lower supply voltage in magnetic logic than CMOS, this brings the effective mLogic energy to 30x higher than leakage-dominated CMOS designs, with a potential energy-savings coming from further activity reduction in magnetic logic through coarser granularity power-gating (block by block).

We expect that by the end of this Reporting Period 5, the first pass of modeling and energy-performance evaluation of power-gated nanomagnetic-based cache design will be completed.

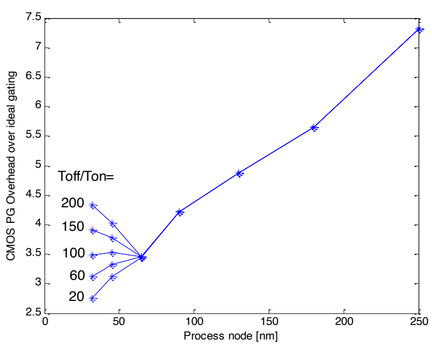

Figure IV-9a: Energy overhead of CMOS power-gates vs. CMOS technology node compared to ideally power-gated mLogic, parameterized for various logic depths (Toff/Ton)

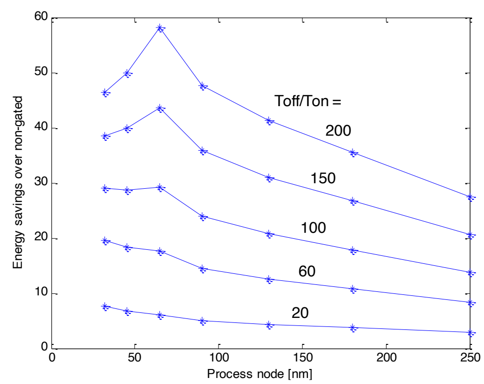

Figure IV-9b: Energy savings of CMOS power gated mLogic vs. non-gated mLogic vs. CMOS technology node, for various logic depths (Toff/Ton).

2b. Performance Against Metrics

Objective: Research					
Metric	**Targets**	**Results**			
		Period 2	**Period 3**	**Period 4**	**Period 5**
Multi-PI projects	Period 2: 30% Period 5: 75%	44%	67% (14)	55% (12)	64% (14)
Multi-Institutional projects	Period 2: 10% Period 5: 30%	4%	10% (2)	9% (2)	23% (5)
Unplanned research projects	Period 3: 1 Period 4: 3 Period 5: 0	3	4	1	1
New joint research funding opportunities	Period 3: 1 Period 4: 2 Period 5: 2	n/a	1	0	2
Publications with authors from multiple institutions	Period 3: 12 Period 4: 3 Period 5: 5	0	1	1	1 1 *in press*
Publications with authors from multiple departments	Period 4: 2 Period 5: 4	0	0	1	1 1 *in press* 2 *in review*

2c. Research in Period 6

In Period 6, the last six months of this award, the research in the Center will continue to build on the progress achieved in Period 5.

Theme I: There is a two prong approach in Period 6. We will continue to identify the scientific obstacles that face tunnel FET's as they try to achieve steepness, On/Off ratio, and good conductance. For discovering the scientific facts we will continue to learn from devices made in III-V semiconductors.

For overcoming the issues that have been identified we will continue to develp potential candidate materials, like the chalcogenide monolayers. At the same time, we will initiate new research that target materials perfection. A new chemist Co-PI, Felix Fischer (Berkeley) will join with chemist Tim Swager (MIT) in Theme I to investigate synthetic chemical approaches to achieve perfection at the atomic level in anticipation that a molecular approach may ultimately be needed.

Theme II: Demonstration of devices operating near 0.1V is a key milestone for the nanomechanics researchers at Berkeley, MIT and Stanford.

Theme III: The Berkeley researchers are expected to accelerate their progress in electrically pumped III-V nanoLED enabled by in-house custom epitaxial materials from the materials growers at MIT. We are on the verge of announcing Spontaneous emission faster than stimulated emission, as observed in chalcogenide monolayers. New insights in this novel material system will be obtained from Theme I. The goal for the phototransistor research is to achieve device performance that will verify the Center's claims that creating a phototransistor and shrinking the capacitances will reduce the necessary photons/bit needed for communications.

Theme IV: The progress made in Period 5 is allowing the nanomagnetics researchers to begin development of device structures to be understand the limits of energy dissipation during switching. High speed magnetic switching induced by electrical pulses is expected to be observed soon.

In Period 6, given the emerging change of research direction, the composition of the Theme I research team will change. **C. Hu** (*Berkeley*) will not continue with Center, while chemist, **F. Fischer** (*Berkeley*) will join the Center to enhance Theme I research for electronic material perfection at the atomic level. He and another synthetic chemist, **T. Swager** (*MIT*) will also begin to pursue chemical synthetic and purification method for bottoms up molecular electronics. The biographical information for Prof. Fischer is given in Appendix A.

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

Antoniadis & **Hoyt** will continue to investigate the mechanisms that limit TFET's, especially 2D-to-2D III-V device structures: It is hoped that they can reveal(1) the parasitic thermal components in the device operation; (2) eliminate heavy doping inhomogeneity by Work Function control or external Electrostatically doping by gates surrounding theelectron/hole 2D-to-2D ("bilayer") tunneling device structure. It will be interesting to find out how effectively this would eliminate band tails showing a steeper Esaki edge; **del Alamo**: By further narrowing the nano-wire, the limit of a single conducting channel is expected to be reached. A single channel is expected to eliminate the inhomogeneous threshold variation that has been plaguing all tunnel FET's, until now. To support that goal, we will complete the development of the technologies necessary to fabricate nanowire superlattice transistors with diameter smaller than 20 nm with high aspect ratio (>10). Also new characterization techniques, like on an STM with bias and low temperature capabilities, will be developed.

Javey & Yablonovitch: The research will shift toward monolayer chalcogenide materials, to demonstrate that they can fulfil the degree of material perfection that they seem capable of. This will include heterojunction formation and type III band alignment. The active channel materials will continue to be 2D monolayer materials with the necessary band alignments tuned either by double gating electrostatic control, or by the introduction of some of the previously unexplored members of this family.

Fischer & **Swager**: **Felix Fischer** has developed a bottom-up synthesis method for quantum dot device architectures based on semiconducting graphene nanoribbons. **Fischer** will use traditional cross-coupling chemistry in solution, chemically purified for reproducible yield, to form the double dot nanoribbon that can be used to study a 0-d to 0-d tunneling transitions that should reveal have a sharp threshold voltage distribution commensurate with the energy level linewidth caused by electrical contact broadening. If that is the only broadening, then that would become a cause for great optimism.

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

The direction of the nanomechanical switch research will continue toward the goal of demonstrating sub-0.1 Volt switching.

- Squitch: This work will have three foci. The first focus will be fabrication. The Theme II research at MIT will focus on the continued fabrication process development and testing of vertically actuated switches based on a transferred upper graphene (or equivalent) electrode. The MIT Lincoln Laboratory, a partner new to this research effort in Period 5, will focus on extending the work on horizontal switches using their SEM-guided ALD system to smoothly close the horizontal switch gaps to approximately 4 nm. The second focus will be the engineering of molecular monolayers exhibiting a much lower mechanical modulus. Here we will pursue both the use of new monolayer materials and the use of composite monolayers. The target will be a modulus of 4-6 MPa. The third focus will be on the completion of the development of the plasmonic ruler, as previously described.

This ruler is critical for measuring monolayer properties and for confirming squitch models.

- vdW Switch: A process for fabricating a six-terminal single-pole/double-throw switch (which has an insulating material to electrically insulate the input electrode from the output electrodes) with ultra-small contact gaps will be developed to enable the demonstration of zero-leakage and zero-crowbar-current circuits operating at very low voltage. There will be parallel efforts at Berkeley and Stanford to develop fabrication methods for sub-lithographic gaps.

  At Berkeley, the King Liu and J. Wu groups will continue their collaboration to test a few different approaches that would lead to the creation of nanometer-gap along a suspended bridge. This includes in-situ metal deposition, using 2-D materials as sacrificial layer, etc. After nanogap creation, we will test the reliability of the gap during the NEM switch operation, to elucidate any issues such as contact oxidation and charge trapping resulting in unstable contact resistance and switching voltage, respectively.

  At Stanford, the Wong group will continue to develop the novel CMOS-compatible technique to fabricate ultra-small gap (down to atomic scale) vdW switches. Based on the accomplishments given in Part I (the successful transfer and growth of different types of thin-film materials), we will create controllable ultra-small lateral gaps. The gap size will be determined by the thickness of the thin-film material, which can be well-controlled by the transfer and growth techniques. Atomic-gap vdW switches will be fabricated and characterized in detail. We will also continue to improve the integration of low-dimensional materials (MoS2 and CNT) and study the electrical properties of these low-vdW NEM switches.

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

In Period 6, Theme III researchers will be making progress towards few-photon optical communications using the same strategy as previously articulated: antenna enhanced LED emitters, ultra-sensitive phototransistors and their integration into waveguides. Collaboration with System Integration researchers in the Center will enable circuit considerations guide the device research.

Research in NanoLEDs made with traditional III-V materials and the more novel Chalcogenide materials will continue. The expected availability of exploratory III-V epitaxial materials, through the collaboration between Berkeley and MIT, will allow the device researchers to aggressively attack surface parasitic effects so that progress on improving the performance of electrical injection III-V nanoLEDs can rapidly be made. To make rapid advancement in nanoLEDs made from Chalcogenides, the issue of supply of Chalcogenides materials will be addressed. UTEP will contribute to addressing this need with supply as well as research into the quality of the Chalcogenide films made by CVD.

Bipolar phototransistor both in Ge and InP will be explored with the emphasis of maximizing gain bandwidth product, f_T. To demonstrate the effect of integrating photodiode and amplifying transistor in a single device, work on characterizing the system level sensitivity of the fabricated phototransistors will be undertaken. This should help verify the claims of the Center that creating a phototransistor and shrinking the capacitances will reduce the necessary photons/bit needed for communications.

Specifically, the key Period 6 goals by research areas are as follows.

- III-V NanoLEDs: (i) Increase nanoLED output power to microwatts; and (ii) Reach spontaneous emission enhancement factor of at least 100X.
- Chalcogenides NanoLEDs: Make substantial advances in process development as well as device design and simulation as part of the work towards electrical injection of Chalcogenide devices.

- Germanium Nanophototransistors: (i) Achieve 50 GHz f_T in a Germanium phototransistor; and (ii) complete an initial working circuit model for a more advanced photoreceiver for chip level communication.
- InP Nanophototransistors: Achieve a gain of 10 and cutoff frequency of 10 GHz.
- III-V Optical Materials: (i) Grow low-defect-density $In_xGa_{1-x}P$ and $GaAs_yP_{1-y}$ films grown via MOCVD monolithically on a Si substrate; (ii) Correlate electrical properties of active layers with processing conditions and defect concentration; and (iii) Grow optimized epitaxial heterostructures for the fabrication of nano-LEDs.

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

The four areas of nanomagnetics research will continue with emphasis of developing components / mechanisms for magnetic devices, identifying limits of energy dissipation.

- *Physics of Spin Hall Switching*: Research to understand the fundamental nature of spin orbit torque will continue, specifically with the goal of demonstrating spin Hall switching to μA regime.

- *Dynamics of Ultrafast Magnet Switching:* We expect that by early Period 6, the magnetic device will be integrated with the picosecond electrical pulse generator. We will then undertake a systematic study of the magnetic response of various magnetic multilayer structures to fast current pulses, starting with very simple single-layer magnetic structures and probe the magnetic response using magneto-optic Kerr effect (MOKE) and magnetic surface second harmonic generation (MSHG). We wish to characterize the degree of demagnetization as a function of both the peak current amplitude as well as the current pulse duration and directly compare the case of current pulse excitation to direct optical excitation of the same magnetic structures. Atomistic modeling techniques will be used to understand any differences in the response.

- *Spin Switching in Sub-10nm STT Magnetic Tunneling (MTJ) Devices:* A focus of the next Reporting Period 6 will be the study of the stability in sub-10 nm spin-torque devices. Investigation of a new approach of depositing magnetic junctions on the tip of a nanoprobe to study the physics of STT-MTJ nanodevices with critical sizes substantially below 5 nm via “point-contact” methods will also be conducted. Exploratory studies on new spin nanodevice architectures will be initiated, including simulations to propose and study specific designs of energy-efficient logic nanodevices and circuits based on the new STT-MTJ physics in the sub-10-nm size range.

- *Circuit Architectures with Nanomagetic Switches:* We will finalize the modeling infrastructure for the energy and performance evaluation of the nanomagnetic logic, including the models of the updated devices from Theme IV. These models will be applied to the nanomagnetic cache memory design as an important part of modern processors. Cell, decoder, level-shifter and power-gating circuits will be designed to help establish the realistic energy-performance modeling.

III. EDUCATION

1a. Goal and Objectives

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

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

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

1b. Performance Metrics

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

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

1c. Problems Encountered

During Period 5, the Center's greatest challenge has been the ability to publish the online materials in a timely fashion. The Center initiated a strategy to multiple courses and mini-courses to diverse audiences in Period 4. We have learned that the creation of one 1-2 hour online course or lecture typically involves 35-40 person-hours to record, edit, and assess content with a team of lectures, editors, and evaluators. The

Center is developing a more streamlined process for video production and now has more accurate estimates of production time.

The online education strategy of the Center included the use of the iLab of MIT as remote laboratory platform. In Period 5, the scope of engagement had to be streamlined as the decrease in users of the platform resulted in access costs beyond what the Center could afford. Nevertheless, an online module for remote access to experiments was developed and implemented for the high school participants of the MIT Online Science Technology Engineering Community (MOSTEC). Instead, the E^3S faculty who established iLab, **J. del Alamo** and **S. Artis**, E^3S Education Director, submitted a proposal to NSF to enable community colleges to have access to iLab. Unfortunately, the proposal was not awarded.

2. Educational Activities

During Period 5, the Center graduated 28 students and postdocs, (17 undergraduates, 9 graduates, and 2 postdocs). To date, E^3S has had 79 graduates (25 undergraduates, 35 graduates, and 19 postdocs). These students and postdocs have gone on to pursue careers in industry, academic, and national research laboratories around the globe (see Graduates Chart).

Progress towards these goals in Period 5 was marked by the creation of a new portfolio of online courses to augment the Center's formal courses integrating low-energy electronics science and research. The Center has developed 7 short course modules for graduate students and postdocs, undergraduates and one video for k-12 and the general public. For current graduate students and postdocs in the Center, E^3S offers a biennial semester-long seminar on Solid States Devices to introduce the Center's research and novel approaches to designing low-energy electronic devices. This course is taught by E^3S Director, **E.Yablonovitch**. To augment this course with new research findings and a scaled-down version of the course that can be completed over an 8-hour period, a cadre of E^3S graduate students and postdocs from across the Center (**S. Agarwal, C. Keraly, M. Eggleston, J. Hong, G. Zheng, M. Nowakowski, D. Bhowmik, Y. Yang, F. Niroui)** created an online version, called the Energy Efficient Electronics Mini-Course. This course includes five 1.5-hour lectures of research approaches and real-world examples on Tunneling Field Effect Transistors, Nanomechanical Switches, Nanophotonics, Nanomagnetics, and Systems Approach to Solid State Devices. While the mini-course is still underdevelopment with three of the lessons complete, this course will be made available to all Center members by the end of Period 5. To broaden the participation of individuals who are trained in low-energy electronics science, the course will also be available on the Center's website for an external audience.

The Center has also used a similar approach to design online education curriculum for undergraduates, creating a 5-hour mini-course introducing the basics of electronics, including an overview of semiconductors and devices, discrete and integrated circuits and circuit theory and network analysis. The target audience for this course is students who have little to no prior knowledge about electronics and electrical engineering. The Center has partnered with two community colleges to use these lectures in engineering courses. In addition to using these course modules in the classroom, this mini-course is easily accessible on the Center's website for students and educators interested mastering the basics of electronics.

For a k-12 audience and general public, the Center has partnered with the MIT's Office of Digital Learning Science Out Loud program to design a free, easily accessible video on How Computers Compute (http://www.youtube.com/watch?v=8cVsgFN3hSM&feature=youtu.be) to show a side of science different from what is typically found in a textbook. This is one of a series of three videos that the Center is creating to show the benefits of smaller, faster, and more energy efficient solid-state transistors. The other two videos, Semiconductors as Switches and Scaling of Switches Using Cleanrooms, are expected to be complete in early 2015. The pre-release quality process consists of evaluating the effectiveness of the online learning approaches, including the content and usability of the education modules. The evaluations will assess five critical course components: learning objectives, instructional materials, course activities and learner interaction, and the course technology.

2a. Internal Educational Activities

The internal education activities that were initiated in previous reporting periods continued in Period 5. Seminars, external speaker series, poster sessions, and the Center's Annual Retreat are all informal education venues for graduate students and postdocs. The research internship program, ETERN, for early engagement of undergraduates involved 8 interns conducting research during the academic terms at 3 institutions.

Activity Name	Recorded Lectures - Energy Efficient Electronics Mini-Course
Led by	**S. Agarwal** (Berkeley)**, C. Keraly** (Berkeley)**, M. Eggleston** (Berkeley)**, J. Hong** (Berkeley)**, G. Zheng** (Berkeley)**, M. Nowakowski** (Berkeley), **D. Bhowmik** (Berkeley), and **Y. Yang** (Berkeley) and **F. Niroui** (MIT)
Intended Audience	For use by E^3S members in their courses and made available online for use by non-E^3S members
Approx Number of Attendees (if appl.)	n/a

Graduate students and postdocs from across the Center created a mini-course, including five 1.5-hour lessons on Tunneling Field Effect Transistors, Nanomechanical Switches, Nanophotonics, Nanomagnetics, and Systems Approach to Solid State Devices. These lectures will be used as modules to introduce energy-efficient electronic science research to upper-division undergraduate, graduate students, and postdocs.

Designed to augment an existing classroom course with new research findings and a scaled-down version of the course that can be completed over an 8-hour period, a cadre of E^3S graduate students and postdocs from acrsoss the Center (**S. Agarwal, C. Keraly, M. Eggleston, J. Hong, G. Zheng, M. Nowakowski, D. Bhowmik, Y. Yang, F. Niroui)** created an online version, called the Energy Efficient Electronics Mini-Course. This course includes five 1.5-hour vignettes of research approaches and real-world examples

The following lectures are complete: Systems Overview, Theme I – Tunneling Field Effect Transistors, and Theme III – Nanophotonics. The two remaining lessons, Theme II – Nanomechanical Switches and Theme IV – Nanomagnetics, will be completed by the end of Period 5.

Activity Name	E^3S Research Seminars
Led by	**Y. Yang** (Berkeley), **J. Carter** (Berkeley), **T. Yu** (MIT), **P. Zhao** (Berkeley) and **R. Iutzi** (MIT)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 258 Undergraduate Students: 10 Berkeley Graduate Students: 107 Berkeley, 25 MIT, 1 UTEP, 1 Stanford, 9 FIU Postdocs: 32 Berkeley, 3 Stanford, 4 UTEP, 1 FIU

The E^3S seminars serve as a vehicle to share the research being undertaken at the Center across research themes and member institutions, as well as an educational forum. The speakers are mainly graduate students and postdocs, who share the progress of their research. Occasionally, E^3S faculty present new projects, and industry partners have presented the research efforts in their company. Period 5 is expected to conclude with 11 seminars; a list of scheduled seminars can be found at this website: http://www.e3s-center.org/research/rsh-seminars.htm. For attendance at the seminars, please see Appendix D.

Activity Name	External Speaker Seminar Series
Led by	**Y. Yang** (Berkeley), **J. Carter** (Berkeley), and **R. Iutzi** (MIT)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 187 Undergraduate Students: 59 Berkeley Graduate Students: 32 Berkeley, 2 UTEP, 1 FIU, 15 Stanford, 2 MIT Postdocs: 13 Berkeley, 3 Stanford

In lieu of the summer Journal Club, the Center organized an external speaker series for the summer of 2014. The topics included silicon photonics in avalanche photodetectors, a roadmap of semiconductors, process variations and scaling considerations for TFET, and an introduction to the new NSF funded STC, CIQM. Speakers included U. Avci, Intel; Y. Kang, Intel, P. Gargini, ITRS; and R. Westervelt, Harvard & PI of CIQM (another STC). While attendees at these seminars were the Center members from the five academic institutions of the Center, the seminars also attracted attendees who are not Center members. A list of meeting topics can be found at this website: http://www.e3s-center.org/research/rsh-seminars.htm. For attendance at the seminars, please see Appendix D.

Activity Name	Fifth Annual Retreat & Poster Session
Led by	**E. Yablonovitch** (Berkeley)
Intended Audience	Faculty, Staff, Students, Postdocs, Industry Partners & Programmatic Partners
Approx Number of Attendees (if appl.)	Total – 79 Graduate Students: 19 Berkeley, 6 MIT, 2 FIU Postdocs: 7 Berkeley, 2 MIT, 1 Stanford, 1 UTEP

The Annual Retreat has continued to be a multi-purpose venue. One purpose is to educate graduate students and postdocs through two days of presentations and discussions. Part of the education is the opportunity to present one's research at a poster session attended by representatives of member companies. There were 16 posters at the 2014 Annual Retreat presented by 17 graduate students (7 Berkeley, 4 MIT, 2 FIU) and 4 postdocs (2 Berkeley, 1 UTEP, 1 Stanford). For a list of posters, please see Appendix H.

Activity Name	Poster Presentation at the External Advisory Board Meeting
Led by	**L. Marlor** (Berkeley) and **J. Yuen** (Berkeley)
Intended Audience	External Advisory Board
Approx Number of Attendees (if appl.)	Total – 9 Graduate Students: 5 Berkeley, 2 MIT Postdocs: 1 Berkeley, 1 Stanford

This year, nine students and postdocs from 3 member institutions were given the opportunity to present their research to the external advisory board.

Activity Name	Fourth Annual Student and Postdoc Retreat
Led by	**L. Marlor** (Berkeley)
Intended Audience	Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 16 Graduate Students: 7 Berkeley, 4 MIT, 2 FIU Postdocs: 2 Berkeley, 1 UTEP

In August, the Center hosted its 4th Annual Student and Postdoc Retreat for graduate students and postdocs. Graduate students and postdocs spent the day in breakout sessions by research theme. This year the students focused on creating presentations to give at the E^{3}S Annual Retreat that would serve as feedback to the faculty on where the research of the Center should be headed. The students also participated in a group session doing a team building low ropes course.

Activity Name	E^{3}S Internship (ETERN)
Led by	**L. Marlor** (Berkeley) and **S. Artis** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx Number of Attendees (if appl.)	Total – 8 Undergraduate Students: 4 Berkeley, 1 MIT, 3 UTEP

The ETERN program is an academic-year program for undergraduates at all of the Center's institutions. The primary goal is to attract students to energy efficient electronics science by providing research experiences to lower-division undergraduate students of member institutions, with the goal of enhancing the pipeline of students interested in graduate studies in the science and engineering disciplines of relevance to the Center. In Period 5, we had 8 participants. These students were advised by E^{3}S faculty and mentored by E^{3}S graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs such as research seminars. In Period 5, the Center continued its international internship for one ETERN who spent 8 weeks doing research at CEA Leti in France; see Section IV – External Partnership.

2b. Professional Development Activities

The students and postdocs of the Center for E^{3}S can avail themselves of many professional development opportunities. In previous periods, we implemented training in ethics, diversity, entrepreneurship, project management, and mentoring. The Center has also developed the E^{3}S Leadership Certificate that students receive after completing enough areas in the Professional Development Program (E^{3}S PDP) with the goal of guiding the students and postdocs to acquire a diverse and balanced set of experiences.

Activity Name	E^{3}S Professional Development Program (E^{3}S PDP)
Led by	**S. Artis** (Berkeley) and **L. Marlor** (Berkeley)
Intended Audience	All Graduate Students and Postdocs
Approx Number of Attendees (if appl.)	Total – 36 Graduate Students: 16 Berkeley, 6 MIT, 2 FIU, 3 UTEP Postdocs: 7 Berkeley, 1 MIT, 1 Stanford

Students and postdocs can develop professionally when they participate in the many programmatic activities of the Center. These programs offer different areas of development: leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship. The Center's Professional Development Program is a framework to ensure a student or postdoc receives well-rounded professional experiences (Appendix E). For a certificate of completion, students and postdocs must complete: 1) at least one activity in the area of leadership, outreach, or mentoring; and 2) at least one education activity in three other training areas (teaching, proposal writing, science communication, and entrepreneurship). In Period 5, six students earned a certificate of completion, and 23 (35%) students and postdocs completed training in at least one of the training areas.

Activity Name	Annual Retreat Review Panel
Led by	**W. Chern** (MIT), **J. Cao** (Stanford), **J. Hong** (Berkeley), **R. Going** (Berkeley)
Intended Audience	All E^3S Center
Approx Number of Attendees (if appl.)	Total – 79 Graduate Students: 19 Berkeley, 6 MIT, 2 FIU Postdocs: 7 Berkeley, 2 MIT, 1 Stanford, 1 UTEP

At the 2014 Annual Retreat, the Center hosted a student panel consisting of graduate students and post-docs from each research theme. The students spoke at the retreat about the strengths and weaknesses of each research topic and discussed where they believed the research should be heading. Faculty had the opportunity to ask questions of the panel after their individual presentations.

Activity Name	Project Management and Mentor Training
Led by	**L. Marlor** (Berkeley) and **S. Artis** (Berkeley)
Intended Audience	Graduate Student and Postdoc mentors
Approx Number of Attendees (if appl.)	Total – 15 Graduate Students: 11 Berkeley Postdocs: 4 Berkeley

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

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

As part of the Center's objective to provide leadership experiences, graduate students and postdocs who served as mentors in the Center's summer undergraduate and precollege programs participated in an hour diversity training on creating an inclusive learning environment. The training, conducted by **S. Artis** and **L. Marlor**, discussed communication strategies to make learning environments more active and inclusive, particularly when engaging with issues of human diversity.

Activity Name	REU Selection Committee
Led by	**S. Artis** (Berkeley) and **L. Marlor** (Berkeley)
Intended Audience	Postdocs as primary target
Approx Number of Attendees (if appl.)	Total – 20

	Graduate Students: 7 Berkeley, 4 MIT Postdocs: 6 Berkeley, 1 MIT, 1 Stanford, 1 UTEP

Special emphasis is given to secure postdocs to serve on the selection committee for the E^{3}S Research Experience for Undergraduates. Given the substantial increase in the number of applications received, graduate students were also invited to participate in 2014. Each member of the selection committee reviews the application, personal statement, transcript, and letters of recommendations of ~5 applicants. Based on the review, the postdocs and graduate students provided a list of applicants that should be considered for placement in a summer research project.

Activity Name	REU Poster Review
Led by	**S. Artis** (Berkeley) and **L. Marlor** (Berkeley)
Intended Audience	Undergraduate students at Center's institutions
Approx Number of Attendees (if appl.)	Total – 3 Postdocs: 3 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 5, three E^{3}S postdocs evaluated the posters based on the following criteria: presentation skills, poster layout, and content (problem, methods, results & understanding). One member 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.

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

W. Chern, a Ph.D. student at MIT, and **J. Cao**, a postdoc at Stanford, served as student representatives at the STC Director's Meeting. This was a great opportunity for them to network with students from other STCs and to further cultivate their leadership skills within the Center's students.

2c. External Educational Activities

Activity Name	E^{3}S Teacher Fellows Program (formerly Research Experiences for Teachers - E^{3}S RET)
Led by	**J. Yuen** (Berkeley) and **S. Artis** (Berkeley)
Intended Audience	Community college professors
Approx Number of Attendees (if appl.)	Total: 2 URM: 1

With the Center's focus on creating a pipeline of community college students who pursue a baccalaureate degree in science and engineering, it is imperative for the Center to engage community college faculty. These individuals can further integrate E^{3}S science and research findings into the community college curriculum and increase community college students' awareness and knowledge about low-energy electronic devices. In Period 5, the Center hosted two community college faculty members in our E^{3}S Visiting Faculty Program which allows a community college faculty to spend six to nine weeks in a research laboratory associated with the Center or develop curricula mentored by Center members. The name of this program was changed in Period 5 from being a "Teachers" program to one for "Visiting Faculty" in response to input from the Education Subcommittee of the Center's External Advisory Board. In addition to the name change, the new programmatic elements were introduced. Leveraging a new community faculty program that NSF awarded to the Center's PI, **E. Yablonovitch**, E^{3}S Visiting Faculty participated in a pedagogy workshop that taught community college faculty participants about Context-Based and online teaching. The two E^{3}S visiting community college faculty are described below.

A. Navarro, a faculty member in the Department of Engineering at Los Angeles Trade Technical College, one of the Center's education partners, was hosted by Prof. **J. Bokor** and co-mentored by graduate students, **K. Messler** and **J. Clarkson**. **A. Navarro** created new curriculum for his Materials of Engineering Course (ENG GEN 151) that introduced nanoscale particles. He also created a new context-based lab activity to improve students' understanding of material behavior at the nanoscale level. As part of his fellowship experience, he visited Nanosys, a Bay Area startup that applies quantum dots to enhance the color of displays. This emphasis on experiential learning about the "context" of research is a new program element in the Visiting Faculty Program in Period 5.

N. Wang, a faculty member of Electronics Technology program of Sacramento City College conducted nine weeks of research in the laboratory of Prof. **V. Stojanovic** in Berkeley, mentored by **Chen Sun**, Ph.D. candidate from MIT. After his research on Ultrasound Effects on Optical Ring Resonators, **Dr. Wang** planned to introduce optoelectronics into his teaching.

Activity Name	Online Laboratory: iLab
Led by	**J. del Alamo** (MIT)
Intended Audience	High school
Approx Number of Attendees (if appl.)	n/a

J. del Alamo developed an experiment to study the energy balance of a logic inverter using the iLab platform, an online laboratory that his group has built. This online laboratory allows pre-college students to remotely control the signal parameters and read off the currents and voltages through the circuit as it switches between its two logic states. Energy dissipation is visualized through an infrared camera, and waveforms can be collected and delivered to the student for computation of transients and energy balance. During Period 5, the study was used as a controlled educational experiment for a three-week online project for MIT Online Science Technology Engineering Community (MOSTEC), one of the Center's pre-college diversity program.

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

A. Ragsdale, the graduate student instructor for the Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU) bootcamp, a diversity program for undergraduate students, recorded lectures from the programs on circuit theory, network analysis, semiconductors and devices, and discrete and integrated circuits. This series of lectures covering a total five hours of material will be used as modules to introduce high-school and lower-division undergraduate students, including community college students, to low-energy electronics. With both online modules, E^{3}S plans to augment the course content with supplemental readings and assignments to provide a comprehensive learning experience. The target audience for this course is students who have little to no prior knowledge about electronics and electrical engineering. The Center has partnered with two community colleges to use these lectures in engineering courses. In addition to using these course modules in the classroom, this mini-course is easily accessible on the Center's website for students and educators interested mastering the basics of electronics.

Activity Name	Introduction to Electronics Mini-course
Led by	**J. Teherani** (MIT)
Intended Audience	High school seniors with admission offers from Berkeley and their families
Approx Number of Attendees (if appl.)	Total- 7 Undergraduate Students: 6 Berkeley Graduate Students- 1 Berkeley

For a k-12 audience and general public, the Center has partnered with the MIT's Office of Digital Learning Science Out Loud program to design a free, easily accessible video on How Computers Compute (http://www.youtube.com/watch?v=8cVsgFN3hSM&feature=youtu.be) to show a side of science different from what is typically found in a textbook. Two additional videos titled "Semiconductors as Switches" and "Scaling of Switches Using Cleanrooms," are expected to be complete in early 2015.

Activity Name	Cal Day
Led by	**L. Marlor** (Berkeley)
Intended Audience	High school seniors with admission offers from Berkeley and their families
Approx Number of Attendees (if appl.)	Total- 7 Undergraduate Students: 6 Berkeley Graduate Students- 1 Berkeley

Each April, UC Berkeley hosts a campus wide open house to attract high school seniors who have received admission offers. This yearly event also attracts the local community, school counselors and teachers visiting the campus with their students, and community college students aspiring to transfer. During Period 5, **L. Marlor** worked with 5 ETERNs, and 1 graduate student to develop 3 demonstrations for Cal Day. The demonstrations were on graphene and 2D conducting material; lithography; and piezoelectricity. Two other people, a former community college REU participant and past ETERN participant, joined to support the demonstrations on the day of the event; the E^{3}S demonstrations were attended by ~150 people.

Activity Name	Bay Area Science Festival
Led by	**L. Marlor** (Berkeley)
Intended Audience	The Bay Area Community
Approx Number of Attendees (if appl.)	Total- 5 Undergraduate Students: 4 Berkeley Graduate Students: 1

Each fall, a science festival is held at AT&T Park in San Francisco that showcases fun and exciting science to the general population. This year was the second year that E^{3}S participated in the event. **L. Marlor** led one ETERN student, one graduate student, two community college REU participants, and one former ETERN student in demonstrating how 2D materials (graphene) conduct electricity. If the participant was old enough, the ETERNs would explain how the center is using 2D materials to tackle the energy efficiency problems faced in our current electronics. Approximately 28,000 people attended the fair, and of those, approximately 450 people participated in the E^{3}S demonstration.

2d. Integration of Education and Research

Research is the driving force behind all of our education programs. As with previous years, the Center continues to integrate its research in its education programs. This level of integration is interwoven into the Center's curriculum, videos, hands-on demonstrations, research seminars, and presentations topics. We also use a vertical model, where faculty are mentoring postdocs and graduate students, postdocs and graduate students are mentoring undergraduates, and undergraduates are mentoring pre-college and k-12 students through the Center's outreach programs.

2e. Performance Against Metrics

During this reporting period, the Center has compared the education programs against the Period 5 target. The table below displays this data and future metrics to measure education success.

Objective: Education					
Metric	**Targets**	**Results**			
		Period 2	**Period 3**	**Period 4**	**Period 5**
Center graduates completed E^{3}S training	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50%	n/a	3 (17%)	3 (14%)	3(33%)
Students and postdocs participating in education and diversity programs	Period 2: 5% Period 3: 60% Period 4: 70% Period 5: 75%	52%	48 (52%)	41 (69%)	36 (55%)
Students and postdocs serving in leadership roles in the Center	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25%	11%	11 (19%)	20 (34%)	24 (36%)

2f. Education Activities in Period 6

Period 6's duration of six months allows the Center's summer Education programs to have one more session before the end of the current award. Thus, much of Period 6 will be spent in continuing the established education programs.

As we will have newly released online modules on electronics, we will use Period 6 for assessment and promotion. We will to assess the efficacy of the online teaching modules, particularly the collection of mini-course modules on Energy Efficient Electronics for new Center members. We expect to implement an assessment instrument to determine the impact on learning. We will also promote the Introduction to

Electronics modules with faculty in community college and conduct follow up to understand how the modules are used and find opportunities to receive information on efficacy and impact on learning.

IV. KNOWLEDGE TRANSFER

1a. Goals and Objectives

The key knowledge transfer goal of the Center for E^3S is to establish and utilize partnerships to accelerate the Center's research and programmatic endeavors, create venues that increase visibility of new and more efficient electronics technologies, and engage workers at all levels on the new opportunities resulting from E3S research. We think of knowledge transfer as the cross-fertilization of ideas within the Center, as well as throughout the ecosystem of innovation in which the Center participates. For Research, the reach of knowledge transfer will include materials and device researchers, circuit designers, CAD software writers, all the way to manufacturers. For Education and Diversity, knowledge transfer partners will include other educators and potential employers of the Center's students, thereby creating opportunities for students at all levels, from community college students up to Ph.D. graduates from research universities.

We place great emphasis on building strong liaisons with industry to make certain that the academic, technical and programmatic directions will be practical, and result in success. Moreover, we recognize the importance of researchers in academia – in our center and at other locations – as knowledge transfer partners. As the Center's research leads to new fundamental understanding that points to novel research directions to be pursued, it is critical that other researchers in the same technology domain participate in developing approaches that are built on similar learnings, so that a community of likeminded researchers can leverage one another to accelerate progress towards ultra-low energy devices. In the area of Education and Diversity, other educators and diversity professionals enable the sharing of best practices, tools and channels of engagement. Finally, educating students and the general public and grooming students and program participants to be knowledge transfer agents are all part of the Center's knowledge transfer mission.

Knowledge transfer is envisioned to be through the following channels:

- Publications, talks at professional meetings, and workshops where results and knowledge gained through Center's research, education and programmatic activities are shared;
- Collaborations where knowledge exchanges will accelerate outcomes;
- 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;
- Knowledgeable graduates who have been trained to have research and entrepreneurial skills;
- Online availability of results from research and curricula activities either through the E3S or third party websites.
- Advice to policy makers at all levels of government on the implications for various device and education systems; and
- Outreach to general public to stimulate support for STEM education and research related to the Center's scope.

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 external articles on the Center	Yearly beginning in Period 3	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase

1c. Problems Encountered

No significant problems to report

2a. Knowledge Transfer Activities

Center's researchers have continued to support information dissemination and knowledge exchanges with communities of peers through publications in peer-reviewed journal, presentations both in peer-reviewed conferences and other forum, and private meetings many with companies. Since the last annual report, the Center achieved a high watermark with 23 new papers on the Center's research having been published in peer-reviewed journals, 3 additional are in press, and 15 papers are under review. Moreover, the papers from 22 talks, presented at peer reviewed conferences, have newly been published as conference proceedings. The Center's publication record in Period 5 also includes a paper on learnings from the Center's engagement with community college students having been accepted for publication, complementing the two published papers as part of proceedings of a conference on engineering education. Among the talks at peer-reviewed conferences are two technical papers that included two E^3S undergraduate researchers as authors. An E^3S community college intern presented the results from his internship at the 2014 Conference of the Society for Advancement of Hispanics/Chicanos and Native Americans in Science (SACNAS) , while one of the Center's ETERN who did research at CEA-LETI has been offered by his French advisor to present their paper that was accepted for oral presentation by the 2015 IEEE EuroSOI-ULIS conference.

New and particularly noteworthy in Period 5 for the Center's Knowledge Transfer mission are the emerging opportunities for the Center's research outcomes to find application beyond the pursuit of the Center's goal of energy efficient devices. Since the Center's inception, the Center's researchers have been developing underlying new technologies, establishing new fundamental understandings, and designing new device structures. Reflecting their entrepreneurial spirit, the Center's faculty are perceiving opportunities to extend the two device designs, two processing technologies and one material system that have been researched in the Center to applications beyond the technical scope of the Center. The emergence of these opportunities constitutes another new milestone for the Center, complementing the opportunities of knowledge transfer among the Center's research Themes that is enabled by the Center mode. In Period 5, there have been two cases of re-use of new technologies within the Center.

Another aspect in knowledge transfer is knowledge dissemination for broadening access to low-energy electronics science and research through informal learning. In Period 5, the education and diversity efforts of the Center have included transfers knowledge via curriculum development and outreach. New during Period 5 has been the development of short online vignettes for undergraduates and graduate students (see Education Section) to transfer knowledge and enable informal learning to a larger and more diverse audience. A TFET entry was established in Wikipedia. These online resources complement the in-person outreach events that Center's students, postdocs, and staff have conducted during this Period. In past 12 months, the Center engaged over 600 students, educators, and parents in hands-on electronics activities that are related to the Center's mission of low-energy electronics science and research.

Details of the Center's Knowledge Transfer Activities are as follows.

- With their research making substantive progress, the Center's researchers are beginning to see the broader impact of their research outcomes; i.e. the knowledge acquired can be transferred for broader applications. A few of these broader impact examples are within the Center, demonstrating the synergy that is expected, but several are for applications outside the scope of the Center.

InGaAs/GaAsSb QWTFET for RF Applications		
Led by	**J. Hoyt & D. Antoniadis**	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	Notre Dame University	Cambridge, MA

RF measurement of the InGaAs/GaAsSb QWTFET fabricated in 2013 was carried out in collaboration with P. Fay at Notre Dame. The QWTFETs exhibit remarkable sensitivity as a tunable microwave detector. The measured voltage sensitivity βV,max of ~400,000 V/W under high drain bias conditions, dropping to ~89,500 V/W under low drain bias conditions. This result compares favorably with the highest reported diode-based detectors.

Squitch Switches as Analog Valves		
Led by	**J. Lang, V. Bulovic and T. Swager**	
Organizations Involved		
	Name	*Address*
1.	MIT EECS	Cambridge, MA
2.	MIT Lincoln Labs	Cambridge, MA

The Squitch project, being researched as part of the Nanomechanics Theme, will likely have applications beyond that of a digital switch. Between the two digital input-output regimes is a high-gain regime that can support amplification. Essentially, the E^3S goals can be viewed as developing analog valves that are optimized for a digital application. However, there are many applications for low-power high-gain low-noise temperature-insensitive analog valves. MIT Lincoln Labs has shown interest in exploring the use of the Squitch approach as analog valves by funding process development on their unique nanofabrication capabilities to enable such device design. The processes being developed at Lincoln Labs will also support the fabrication of horizontal switches being in development in the Center.

Multifunctional Thermal Switch via Nanostructured Phase Transition in VO_2		
Led by	**J. Wu**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Samsung Electronics	San Jose, CA

From Periods 3 through 4, the Center funded an exploratory study of the use the electromechanics of metal-insulator phase transition of VO_2 for a NEM switch (Theme II). Although this concept has proven to unable to achieve the E^3S goal of ultra-low energy electric switching, the new fundamental understanding of the materials inspired Samsung to fund a project on the use of the phase transition of VO_2 for a multifunctional thermal switch.

RIE process with Digital Etch Technology for III-V Features of High Aspect Ratios		
Led by	**J. del Alamo**	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	Multiple Parties	Various Addresses

Developed for III-V nanowires, as part of Theme I's TFET research, the REI digital dry etch technology has found great use in other research programs in the del Alamo group. They have proven to be transformational. Excellent devices results have demonstrated the potential of III-V MOSFETs for future CMOS. During Period 5, J. del Alamo a contract with Defense Threat Reduction Agency (DTRA) to investigate the radiation hardness of InGaAs MOSFETs. Prof. del Alamo has talked extensively about this novel processing technologies with industry, including TSMC, Samsung, STMicroelectronics, IBM, Lam Research, and Applied Materials.

RIE Process Digital Etch for Optical Device Applications		
Led by	**J. del Alamo** *(MIT)*	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, MA
2.	UC Berkeley	Berkeley, CA

The del Alamo group initiated a project with the M. Wu group to extend the dry etch technology for use in the NanoLED project, to replace the wet etch technique that is currently in use.

Process for Developing Sub-lithographic Features		
Led by	**T.J. King Liu** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	Applied Materials	Santa Clara, CA

Process development for formation of nanogaps is being pursued as part of the Nanomechanics. Applied Materials, one of the member companies of the Center, has recognized that the invention of an approach to controllably form sub-lithographic contact gaps by the King Liu group can potentially overcome technical barriers to sustain Moore's Law; i.e., it can enable continued improvements in transistor density at lower cost per device. This has led to Applied Materials' funding to T.J. King Liu's research efforts.

Chalcogenide Materials for NanoLED	
Led by	**A. Javey & M.C.Wu**

Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA

Thematic structure of the Center has allowed for interesting exchanges of ideas and exploration of familiar material systems towards new avenues previously not thought of. An example is the extensively that the A. Javey group has been exploring 2D materials for TFET applications (Theme I) since Period 2. Beginning in Period 5, M.C. Wu's group has followed with applying the know-how of the same material system for nanoLED applications (Theme III), which in term is yielding valuable optical properties of these materials that the Javey group can leverage towards better TFET design.

- The main Knowledge Transfer venue has continued to be dissemination of research results by E^{3}S researchers through journal and talks at public conferences.

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

In 2014, the Center's faculty, students and collaborators have published 23 papers, all in peer-reviewed journals. Two papers from Berkeley and 1 from MIT are in press and 15 papers have been submitted for review, including a joint paper between Berkeley and MIT. One metric in the Strategic Plan is the number of citations of the Center's publications, which is 719 total from the Center's inception to date.

Dissemination of the Center's Research via Published Proceedings of Peer-Reviewed Conferences		
Led by	E^{3}S Faculty	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford University	Stanford, CA
4.	The University of Texas at El Paso	El Paso, TX

Talks by researchers from Berkeley, MIT and Stanford were published in conference proceedings in Period 5. Twenty-two were in proceedings of major conferences, like IEEE International Electron Devices Meeting, Device Research Conference and IEEE Int'l MEMS conference. Among the IEEE published proceedings is the Proceedings of the 3rd Berkeley Symposium on Energy Efficient Electronic Systems that the Center organized in Period 4.

See:http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6697908. As the Center is an organizer, we have not counted the printed abstracts of these talks as part of publication record.

- In Period 5, E^3S researchers made verbal and poster presentations on their research results through private meetings and forums with 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.	The University of Texas at El Paso	El Paso, TX
5.	Florida International University	Miami, FL
6.	Applied Materials	Santa Clara, CA
7.	Hewlett Packard	San Jose, CA
8.	IBM	Yorktown Heights, NY
9.	Intel Corp.	Hillsboro, OR
9.	Lam Research	Fremont, CA

The Center also used its Annual Retreat to share the Center's direction and progress in research with its industry members. The attendees from industry were: B. Wood, Applied Materials; N. Draeger, Lam Research; P. Solomon, IBM; S. Williams, HP; and I. Young, Intel. The industry members also attended a poster session that featured 16 posters by students and postdocs. See Appendix H for a list of the presented posters.

E^3S Research Presentation at Applied Materials		
Led by	**T.-J. King Liu** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	Applied Materials	Santa Clara, CA

T.-J. King Liu, Leader of Theme II, provided an update on the research program of the Center to E. Yieh, Vice President; J. Dukovic, External Research Programs; and A. Brand, Transistor Technology group, all of Advanced Product Technology Development, Silicon Systems Group, Applied Materials in May 2014. Ms. Yieh is Applied Materials' corporate executive representative to the Center for E^3S. This meeting led to the funding from Applied Materials for research to develop a process for forming sub-lithographic features.

Nanoelectronics Presentation at IBM		
Led by	**E. Yablonovitch** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	IBM Watson Laboratory	Yorktown Heights, CA

E. Yablonovitch presented "Replacing the Transistor with a Lower Voltage Switch: What are the Prospects?" at IBM Watson Research Center. Hosted by G. Shahidi, IBM Fellow and Director, Silicon Technology, who IBM's corporate executive representative to the Center for E^3S, included meeting with 5 other researchers.

Research Presentation at Intel		
Led by	**E. Yablonovitch** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	Intel Corp.	Hillsboro, OR

E. Yablonovitch gave a seminar on "Replacing the Transistor with a Lower Voltage Switch: What are the Prospects?" at a visit to Intel. His visit was hosted by I. Young, Intel Senior Fellow, Technology and Manufacturing Group and Director, Advanced Circuits and Technology Integration Industry Research Partnerships, who is Intel's corporate executive to the Center for E^3S. The meeting included M. Bayberry, Intel's corporate vice president of the Technology and Manufacturing Group.

MTL Annual Research Conference		
Led by	**J. del Alamo** *(MIT)*	
Organizations Involved		
	Name	*Address*
1.	MIT	Cambridge, CA
2.	Various MTL Industry Members	Multiple

Many of the E^3S co-PIs at MIT are part of the Microsystems Technology Laboratories (MTL) at MIT which support their research with shared laboratory facilities. Each year, the MTL organizes a conference to showcase the research of its members. E^3S graduate students presented 4 posters on E^3S research at the January 2014 MTL Research Conference, which was attended by ~ 220 people with 25 members from industry.

- The Center's two-way knowledge transfer strategy seeks to share the Center's research with industry, as well as learn from other researchers in related research and technology domains, particularly from the researchers in industry.

Seminars by Invited Speakers		
Led by	**J. Yuen** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	Intel	Hillsboro OR Santa Clara, CA
2.	International Technology Roadmap for Semiconductors	http://www.itrs.net/home.html
3.	Harvard University	Cambridge, CA
4.	U of California, Berkeley	Berkeley, CA
5.	MIT	Cambridge, CA
6.	Stanford University	Palo Alto, CA

7.	The U of Texas at El Paso	El Paso, CA
8.	Florida International University	Miami, FL

The Center organized a series of four seminars by external speakers: U. Avci, Intel; Y. Kang, Intel, P. Gargini, ITRS; and R. Westervelt, Harvard & PI of Center for Integrated Quantum Materials (another STC); see http://www.e3s-center.org/research/rsh-seminars.htm. While attendees at these seminars were the Center members from the five academic institutions of the Center, the seminars also attracted attendees who are not Center members.

Meeting of the Industrial Research Board		
Led by	**E^3S Executive Committee**	
Organizations Involved		
	Name	*Address*
1.	Hewlett Packard	San Jose, CA
2.	IBM	Yorktown Heights, NY
3.	Intel Corp.	Hillsboro, OR
4.	Lam Research	Fremont, CA

As in prior Periods, the annual meeting of the Industrial Research Board met with the E^3S Executive Committee during the Center's Annual Retreat. The discussion included an analysis of the state of the Center's research in the context of allied research activities outside the Center and industry's outlook.

CEA-Leti Young Researchers Visit to UC Berkeley – Research Exchange Forum		
Led by	**C. Keraly Lalau** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	CEA-LETI	Grenoble, France

E^3S graduate student at Berkeley, C. Keraly Lalau, organized a visit by 15 Ph.D. students from Grenoble, France, who are conducting their Ph.D. thesis research at CEA-Leti, a French government laboratory. The French visitors spent 1 day with E^3S graduate students and postdocs, who presented talks on the Center's nanoelectronics, nanophotonics and nanomagnetic research of the Center. The French visitors presented their research on resistive nonvolatile memory, III-V power transistors, optics, photonics, and III-V materials growth.

Competitive Analysis Workshop – Summer Students & Postdocs Retreat		
Led by	**L. Marlor** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, CA
3.	The U of Texas at El Paso	El Paso, CA
4.	Florida International University	Miami, FL

The graduate students and postdocs took advantage of their summer retreat to work together on identifying the competition of each Theme. The workshop is as much an educational event as it is a knowledge transfer event. The workshop participants worked with others in their theme to exchange and research information about others in their domain of research. The findings were presented by a representative from each Theme at the 2014 Centerwide Annual Retreat.

- The Center's knowledge transfer through its education and diversity efforts are in three ways: written and oral dissemination of best practices, curriculum development and dissemination, and in-person outreach.

Dissemination through publications and conferences		
Led by	**S. Artis** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

One paper on community college students has been accepted for publication. The Education and Outreach Director and Program Manager, S. Artis and L. Marlor co-presented with program directors from the National Institute of Health to share best practice for REU application, selection, and placement at the SACNAS Conference. During this period, the Center disseminated best practices in one journal article (Community College Journal of Research and Practice) and two proceedings (American Society for Engineering Education Conference).

Development of Online Educational Vignettes		
Led by	**S. Artis** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA

To transfer knowledge to a larger and more diverse audience, the Center has been developing short online vignettes for undergraduates and graduate students; details are given in the Education Section. This includes a new Wikipedia entry on Tunneling FET that was initiated by E^3S graduate student at MIT, J. Teherani; see: http://en.wikipedia.org/wiki/Tunnel_field-effect_transistor.

Outreach Events		
Led by	**L. Marlor** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA

The Center's students, postdocs, and staff also participated in four K-12 outreach events, Science at Cal, Bay Area Science Festival, STEM Day at West Oakland Middle School, and Leadership Day; see Diversity Section. Together, the Center engaged over 600 students, educators, and parents in hands-on activities integrating low-energy electronics science and research.

Undergraduate dissemination through publications and conferences	
Led by	**S. Artis** *(Berkeley)* and **L. Marlor** *(Berkeley)*

Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	Diablo Valley College	Pleasant Hill, CA
3.	CEA-Leti	Grenoble, France

Through Transfer to Excellence, the Center program for community college student researchers that is funded by the E3S STC grant and a NSF REU Site, five students shared their research at poster sessions at the Society for Advancement of Hispanics/Chicanos and Native Americans in Science (SACNAS) Conference and the Council for Undergraduate Research REU Symposium. One of these students, from Diablo Valley College, was funded directly through the Center. A second undergraduate, funded through the Center's ETERN program was able to conduct research in Grenoble, France for the summer. With this research, the student was among the authors of a paper accepted for oral presentation at the 2015 IEEE EuroSOI-ULIS conference. The undergraduate's advisor at CEA-Leti is offering the student the opportunity to present at the conference.

2b. Outcomes

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

2c. Performance Against Metrics

Objective: Knowledge Transfer						
Metric	**Targets**	**Results**				
		Period 2	**Period 3**	**Period 4**	**Period 5**
Website hits & unique visitors	Period 2: Baseline Period 3: 20% increase Period 4: 10% Period 5: 10%	Website Hits: 11,354 Unique Visitors: 6,123	Website Hits: 140% (27,298) Unique Visitors: 167% (16,338)	Website Hits: 42% (38,800) Unique Visitors: 40% (22,809)	N/A due to server migration
Contacts with industry: • **General** • **Industry Presentations**	Period 3: 36 Yearly: 2	66 4	20 2	42 6	62 3
Research collaboration with industry	Period 4: 1 Period 5: 2	0	1	1	4
Center publications	Per Year: 18	17	17	31	39 5 *accepted* 13 *submitted*

External citations of publications *(cum)*	Period 3: 10 Period 4: 100 Period 5: 100	15	178	393	969
Patent disclosures • **Disclosure/Provisional** • **Patent Application Filed**	Period 3: 3 Period 4: 3 Period 5: 5 Period 4: 0 Period 5: 3	1 1	0 0	1 0	1 0
Students hired into relevant industries	Period 5: 50% Period 10: 50%	Students: 0% Postdocs: 1 (100%)	Students: 7 (64%) Postdocs: 2 (33%)	Students: 2 (16%) Postdocs: 2 (20%)	Students: 6 (16%) Postdocs: 4 (40%)
Technology development attributable to Center's research	Period 10: 1	n/a	n/a	n/a	n/a
External articles on Center	Period 3: 100% increase Period 4: 3 Period 5: 5	1	0	2	1

2d. Transfer Activities in Period 6

In Period 5, the Center achieved important results, especially for Theme I and III and in Period 6, the Center plans to continue its efforts in disseminating these results as it is critical that the results be shared and openly discussed.

E^{3}S organizes a biennial symposium on energy efficient electronic systems which should happen again in Fall 2015. The symposium will be structured to allow an open discussion of the results. Organizing activities for the symposium will begin towards the end of Period 5 and we will seek IEEE Electron Devices Society sponsorship again. See: http://www.e3s-center.org/symposium/.

There must also be a concerted effort to publish the results in influential journals, venues that will ensure knowledge diffusion.

On the educational side of knowledge transfer, dissemination of educational videos that are made by E^{3}S members will be occurring during Period 6. Two undergraduate researchers from summer 2014 will also be presenting their research at peer reviewed conferences in March and April 2015.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

The Center for E^3S has utilized partners to advance the research portfolio and achieve programmatic goals. Industry partnerships were formed prior to the Center's inception and continue to serve as the cornerstone in the execution of E^3S' two-way knowledge transfer strategy. The Center's researchers have created both formal and informal partnerships as they pursue their scientific investigations. The education and diversity programs leverage the experience, expertise and resources of campus partners at home and subaward institutions to deliver highly successful programs. In period 5, the Center has continued to execute and enhance its partnership strategy to enable successful achievement of all its goals.

1b. Performance Metrics

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

1c. Problems Encountered

In Period 5, plans to recruit mid-size companies as member companies have once again been pushed out. The Center's leadership concluded that the best strategy for the short term is to enhance the level of engagement with existing industry partners. When the Center is ready to recruit additional corporate partners, we can leverage the existing industry relationships that the faculty has with industry to accelerate new member recruitment.

2a. Activities in Period 3

The Center for E^3S has continued to strengthen its partnership with industry through the five member companies, Applied Materials, Hewlett-Packard, IBM, Intel and Lam Research. Four of the five companies are partnered on research projects with E^3S faculty and students or are providing resources for the Center's research.

- Applied Materials has provided funding to **T.-J. King Liu** to accelerate the development of an implantation-enhanced lithography for creating sub-lithographic features.
- The faculty of two E^3S research projects at MIT have been working with two groups at IBM. IBM Zurich has provided IIV-V on insulator wafers for bilayer TFETs being fabricated by the Antoniadis/Hoyt groups. The squitch team of **Bulovic**, **Lang** and **Swager** has looked to the researchers at IBM Yorktown Heights for direct measurement of the displacement between the two electrodes of the switch.
- Intel's silicon photonics program has collaborated with **M. Wu** due to a shared interest in photodetector research. This year, the E^3S graduate student in the Wu group, **R. Going**, who had been the student interface with Intel engineers was an intern with Intel in Santa Clara for six months.
- Lam Research has pledged free equipment maintenance for the Marvell Nanofabrication Laboratory, estimated to be worth $75K annually, in support of the Center's bid for a second NSF award. Much of the Center's research take place at the Nanolab and thus, Lam's contribution will support E3S researchers.

This level of engagement with industry in Period 5 serves as a new milestone for the Center.

E^3S faculty have primarily been engaged in ad hoc research collaborations with other researchers, some tend to have very limited in scope. In Period 5, however, two new Research collaborations are emerging to be more extensive.

- **J. Bokor** is collaborating with **M. Klaui**, Johannes Gutenberg University, Mainz, Germany on magnetics research that includes exchange of graduate students. One German student spent 1 month with the Bokor lab in Fall 2014.
- Another formal partnership is between MIT Lincoln and the E^3S Squitch team. MIT Lincoln Labs is providing funding for the E^3S Squitch team to use their unique nanofabrication capabilities (e-beam lithography, specialized resist and etch processes, atomic layer deposition (ALD) and focused ion beam milling) to fabricate horizontal switches. The two groups are working on developing the Squitch technology for different applications.

Also new in Period 5 are education collaborations to benefit student, faculty and the general public.

- CEA Leti, a French government laboratory, in Grenoble, France, is interested in developing young researchers. As mentioned in the Education section, CEA Leti, hosted ETERN, **R. Oeflein**, as a summer research intern last summer, paying an internship stipend to cover living costs in France, while E3S covered the travel. The French laboratory invited E^3S to send another student under the same arrangements in summer of 2015. Because there is mutual interest for a sustained internship engagement that will cover more students, **T.-J. King Liu,** has submitted a proposal to NSF for an International Research grant for undergraduate and graduate students.
- The Berkeley Center for Teaching and Learning is also a new education partner. **R. Freishtat**, senior consultant, organized a pedagogy workshop on Context-Based teaching that also includes online teaching for community college teachers. This workshop also involved C. Halverson of the Lawrence Hall of Science. While this workshop was developed to serve as a programmatic activity in the RET program, the workshop also benefited the visiting community colleges faculty this past summer.
- MIT Office of Digital Learning has been a partner on the development of the three outreach online modules for the general public.
- The National Nanotechnology Infrastructure Network (NNIN) served as the local host for an E^3S REU at Stanford

These partnerships and collaborations are called out because they are new. Nevertheless, the Center's education and diversity programs have continued to leverage the expertise and resources of campus partners. At MIT, partnerships have allowed E^3S to deliver electronics training for a high school online community (MOSTEC) and to support REU interns at the laboratories of E^3S MIT faculty. At UC Berkeley, campus collaborations have provided the participants with more substantive experiences for summer internship programs, enhanced diversity recruitment, and supported the transfer of community college students who are alumnae of the Center's programs. We have worked with these partners for many years, some since the start of the Center. Since we have named them and described our relationship with them in past annual reports, we will not do so again in this report.

A list of the Center's partners in Period 5 is given in VIII Centerwide Output.

2b. Outcomes and Impact

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

2c. Performance Against Metrics

Objective: External Partnership						
Metric	**Targets**	**Results**				
		Period 2	**Period 3**	**Period 4**	**Period 5**
Research collaboration **- Industry** **- Others**	Period 4: 1 Period 5: 2	0	1	1	4

2d. Partnerships Plans for Period 6

Most of the new partnerships of Period 5 will continue, as will many of the existing campus partnerships we formed in prior years. However, some of these partners will not continue with us. For example, the Transfer to Excellence REU Site grant concluded and the two partnering NSF funded Centers will not be a partner in Period 6, even though E^{3}S will continue to have a community college REU program. For the REU program for upper division undergraduates, we plan to develop partnerships with HBCU faculty through activities of the UC-HBCU program; see VI Diversity.

VI. DIVERSITY

1a. Goals and Objectives

The goal of the diversity programs of the Center for E^3S is to:

- increase the number of students from historically underrepresented groups in engineering who attend university and graduate programs in technical disciplines that will contribute to low energy electronics

While the Center seeks to ensure that the composition of our participants reflects the diversity of the US, with a particular focus on underrepresented racial/ethnic backgrounds, women, and people with disabilities, there is increasing recognition that the more tangible goal is to attain a diversity profile that is equal to or better than a comparable benchmark. In Period 3, we introduced benchmark data as part of goal setting and we are constantly tracking and assessing our progress.

The Center promotes diversity by implementing pathway programs to sustain interest and excellence in STEM among students from underrepresented groups. Accordingly, many of the Center's educational programs also have a strong diversity focus. The diversity activities involve and/or impact students many levels: postdocs, graduate students, undergraduate students, and high school students. In Period 4, the Center concentrated on streamlining our programs to align with the Center's vision and goals for enhancing diversity in the field of low-energy electronic devices and cultivating a diverse pool of participants in our pipeline. Now, in Period 5, the Center has continued to implement its diversity programs, but also track past participants and provide advising, support, and preparation for applying for transfer admissions a four-year institution or for graduate school.

In Period 5, 12 undergraduates have enrolled in a graduate program in science or engineering and 7 (88%) community college students have transferred to a 4-year institution to major in a STEM field. The cumulative total for the Center to date is, 18 undergraduates have enrolled in a graduate program in science or engineering and 17 (94%) community college students have transferred to a 4-year institution majoring in STEM. Among these participants, 7 (39%) of our undergraduates who are now enrolled in a graduate program are women and 3 (17%) are from an underrepresented minority group. For the community college students who have transferred to a 4-year institution, 4 (22%) are women, 5 (28%) are from an underrepresented minority group, and 9 (50%) are first-generation college students. For our pre-college programs, 162 (82%) of past participants have self-reported that they are currently enrolled in baccalaureate degree program.

New Online Laboratory for High School Students: This period, the Center had its first class complete the three-week online project integrating **J. del Alamo's**, E^3S faculty at MIT, well established online laboratory platform, iLab. Specifically, MIT Online Science Technology Engineering Community (MOSTEC) students interacted with the iLab platform online to experiment with energy flow, storage and dissipation in a digital inverter during switching. For the MOSTEC course, students conducted EECS-themed lab assignments and projects using Arduino, Beagle-Bone, or Raspberry Pi environments and associated lab equipment.

Sustained Diversity Recruitment Initiatives: The Center has remained committed to the recruitment of graduate and undergraduate students from underrepresented groups into our activities. During this period, the Center has formalized and strengthened its partnership with Historically Black College and Universities (HBCUs). **T. King Liu** and **S. Artis** expanded the E^3S REU program to offer undergraduate students from Historically Black College and Universities (HBCU) a second summer experience through the Center. This expansion is funded by the University of California Office of the President (UCOP). This award provided three years of summer funding. To launch this new initiative, **T. King Liu** and **S. Artis** traveled to four HBCUs (Hampton University, Howard University, Jackson State University, and Norfolk State University) to conduct a research seminar to introduce the Center's research and new opportunity for students at HBCUs. It is expected that early and continuous engagement with students from HBCUs will enhance the students' experience and preparation for graduate school at UC Berkeley. In addition to student engagement, the awards funds faculty development workshops, where Berkeley and HBCU faculty come together to cultivate research collaborations by meeting to discuss research interests, identify research synergies, and share projects your undergraduate researcher can work on at UC Berkeley and your institution.

In Period 5, the Center also participated in the EECS Rising Stars Workshop to increase recruitment efforts for women. This workshop, which was chaired by **T. King Liu**, brought together women who are near the completion of their graduate degree or currently pursuing a postdoc that are interested in careers in academia, for two days of scientific interactions and career-oriented discussions. The workshop included research talks/posters as well as presentations on aspects of life in academia – from finding a faculty position to parameters of success as a junior faculty member. Participants had the opportunity to present their ongoing research, to interact informally with our faculty members at UC Berkeley and from MIT, Stanford University, University of Washington, UC San Diego and Harvey Mudd College. During the workshop, the Center hosted a tour of the Marvell Nanofabrication Laboratory and a session with Center's faculty and leadership (**E. Yablonovitch, J. Bokor,** and **P. Wong**) to share E^3S research and provide participants advice for advancing their careers. **T. King Liu** and **P.Wong** also gave presentations on the tenure process and faculty recruitment.

Additional details of the Center's efforts in diversity are discussed in this section. The details include:

- Program status (if it has not been reported previously in the Education section);
- The diversity profiles of all programs;
- Outcomes of program alumni; and
- The Center's recruiting efforts.

1b. Performance Metrics

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

Objective	Metrics	Frequency	Targets
Diversity	Number of women participating in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 30%
	Number of underrepresented minorities participating in the Center's research programs	Annually	Period 2: Baseline Period 3: 15% increase Period 4: 5% Period 5: 10%
	Number of diversity program participants from groups underrepresented in STEM	Annually	Period 3: Baseline Period 4: 80% Period 5: 80%
	Number of pre-college students who pursue a bachelor's degree in science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 70% Period 5: 70%
	Number of community college students who transfer from 2-year institutions to 4-year universities	Annually	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80%

	to pursue a bachelor's degree science and engineering		
	Number of undergraduates who pursue advanced degree in science and engineering	Annually	Period 2: Baseline Period 3: 5% Period 4: 30% Period 5: 35%

1c. Problems Encountered

In Period 5, the Center is most challenged by the low number of women and underrepresented minorities at the graduate- and postdoc-level. The Center's diligent work to increase the number of women and underrepresented minorities in the Center has shown steady progress, however significant increase has been slow. One reason for the slow progression is the difficulty to transition undergraduate students from the Center's research programs (i.e., REU and E^3S Internship). While many past summer interns continue on to graduate school, often continuing their graduate degree at a member institution, they are not continuing their tenure on an E^3S project. Instead they are pursuing graduate research in another STEM area. The second reason is contributed to the low retention rate among current Center graduate researchers.

2a. Development of US Human Resources

In Period 5, the Center has ensured that its diversity programs include a strong integration of the Center's research. 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 enter and diversify the workforce. The Center has further developed a clear understanding of which activities are effective for advancing underrepresented groups in high schools, community colleges, 4-year institutions, and graduate schools. The Center continues to conduct strategic planning meetings with representatives from diversity programs at Berkeley and MIT, and program partners at Los Angeles Trade-Technical College, Mathematics Engineering Science Achievement (MESA), and Berkeley's Transfer Alliance Project (TAP) to discuss partnership opportunities.

- *Pre-college Programs*

  In Period 5, the Center continued to partner with MIT's Office of Engineering Outreach Programs (OEOP) on programs for high school seniors. These existing MIT programs promote early interest in science and engineering careers to students from underrepresented groups, and the Center's role is to promote the career path of electrical engineering and related technical fields. We do this by supporting the offering of electronics training in the MOSTEC program. Previously in the Goals and Objectives section, we shared the history of our involvement with OEOP and these remaining partnership programs that have continued to Period 5.

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**S. Young** (MIT) and **S. Artis** (Berkeley)
Intended Audience	Rising 12^{th} grade high school students
Approx Number of Attendees (if appl.)	Total: 39 Females: 17 (44%), URMs: 30 (77%)

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

In Period 5, the Center supported 39 students, 19 who participated in the new three-week online electronics course project and 30 who participated in the electronics workshop at the MOSTEC Conference. Of the students, 44% were females and 77% were from underrepresented racial groups. MOSTEC held its second online three-week electronics project course in Period 5. This online project was implemented using **del Alamo's** remote laboratory, iLab. The students interacted with the iLab online platform to experiment with energy flow, storage and dissipation in a digital inverter during switching. For the MOSTEC course, students conducted EECS-themed lab assignments and projects using Arduino, Beagle-Bone, or Raspberry Pi environments and associated lab equipment. During the weeklong conference, the Center sponsored an electronics workshop and tour of MIT's Microsystems Technology Laboratories.

- *Undergraduate Programs*

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

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

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

Activity Name	Transfer-to-Excellence Research Experiences for Undergraduates (TTE REU)
Led by	**S. Artis** (Berkeley) and **T.-J. King Liu** (Berkeley)
Intended Audience	Community college students
Approx Number of Attendees (if appl.)	Total: 5 Females: 2 (40%), URMs: 2 (40%)

During summer 2014 (Period 5), the Center at Berkeley hosted 5 of the 14 community college students in the TTE REU program (TTE REU Recruitment Flyer: http://www.e3s-center.org/education/2015-TTEREU_Flyer.pdf). These students completed nine weeks of research in the laboratories of E^3S faculty, **T.-J. King Liu, E. Yablonovitch, M. Wu,** and **J. Wu,** and E^3S Education Affiliate**, J. Clarkson**. Education Affiliates are not part of the Center's research team, but their research disciplines are similar to those of the Center. **J. Clarkson** joins the Center as an affiliate in Period 5.

In Period 5, the TTE REU experience starts with a one-week bootcamp on the fundamentals of electronics, laboratory procedures, safety training, ethics training, and software training before embarking on independent research. During the 8 weeks of hands-on independent research, the TTE REU students also attend a variety of enrichment activities and participated in weekly one-on-one mentorship meetings with **L. Marlor.** For details on enrichment activities, see http://www.e3s-center.org/education/2014-TTEREU-Program_Calendar.pdf. TTE participants were trained on scientific ethics, technical presentations, and science communication, received individualized academic and transfer advising, and participated in group enrichment activities provided by TAP. At the end of the program, the students write a brief research paper, and present their research at a poster session and a research symposium.

To date, all of the Center's TTE REU alumni (2011-2013 cohorts) who were eligible to apply for transfer admission to a 4-year institution are currently enrolled in a baccalaureate program. One student is pursuing a degree in a non-STEM field, but the remaining 14 (3 females, 4 URMs) are pursuing B.S. degrees in STEM fields at UC Berkeley (11), UCLA (2), and UC San Diego (1). Among this group, six of these students transferred to a 4-year institution in Period 5, six in Period 4 and two transferred in Period 3.

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

One student from Berkeley City College participated in TTE X-Enroll, successfully completing a 4-credit lower division mathematics course in summer 2014. The student also received individualized academic and transfer advising and had access to group enrichment activities from Berkeley's TAP, the Center's partner. As with all TTE students, TAP continues to provide transfer support as the X-Enroll student seeks to transfer to a 4-year institution.

In Periods 2-4 we had a total of three participants in the TTE X-Enroll program. All participants are currently STEM undergraduates at UC Berkeley. In Period 5, one of these students transferred to a 4-year institution. The others transferred in Period 3 and Period 4.

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

Activity Name	E^3S Research Experiences for Undergraduates at Berkeley, Stanford, & MIT (E^3S REU)
Led by	**S. Artis** (Berkeley) and **E. Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx Number of Attendees (if appl.)	Total: 14 Female: 4 (29%), URMs: 5 (36%)

The Center's 9-week research program received approximately 200 applications (E^3S Recruitment Flyer: http://www.e3s-center.org/education/2015-E3SREU_Flyer.pdf). Eleven of these students were matched with Center faculty at Berkeley, two were matched with faculty at MIT, and one was matched at Stanford. This is the first year the E^{3}S REU has placed a student at the Stanford campus. At Berkeley, they were hosted by E^{3}S faculty, **J. Bokor, C. Chang-Hasnain, A. Javey, S. Salahuddin, M.C. Wu,** and **E. Yablonovitch**. At MIT and Stanford, they were hosted by E^{3}S faculty, **E. Fitzgerald,** and **J. del Alamo** and **P. Wong**, respectively. In addition, the students attended weekly enrichment activities that included field trips and preparation for GRE. This summer, Sandia National Labs, provided the students an overview of Sandia's research technology and a tour. Each student also received weekly one-on-one mentorship meetings with **S. Artis**, Education and Outreach Director. For calendar of events and activities, see: http://www.e3s-center.org/education/2014_E3S_REU-Program_Calendar.pdf.

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

- *Recruitment and Public Outreach*

In addition to these diversity programs, Center members attend diversity conferences and give seminars to local pre-college, undergraduate and graduate audiences to share the exciting work of the Center and student involvement opportunities. Often, these seminars target underrepresented groups, including individuals from underrepresented racial/ethnic backgrounds, women, and students from low socioeconomic backgrounds. In Period 5, the Center targeted students at institutions that may not offer, or have limited offerings in, courses and research on energy efficient electronics science, to introduce them to our field.

This fall, E^{3}S collaborated with the Berkeley College of Engineering to recruit for the Center's diversity programs targeting students at 4-year institutions. Together, 5 universities were visited and 6 diversity conferences were attended (see Appendix F: Joint Recruitment Calendar). The Center also continued its virtual recruitment sessions by offering three webinars to introduce the Center's research and diversity programs and how to successful apply for the Center's research internship programs (see http://cc.readytalk.com/play?id=3oq7go). During these webinars **S. Artis** and **L. Marlor** provided students information on successful application tips, the importance of research for graduate school applications and transfer applications, and tips on how to get good letters of recommendation, and also allowed time for students to ask questions.

For the 4-year university visits, **T. King Liu, S. Artis,** and **L. Marlor** visited five 4-year universities: Norfolk State University, Morgan State University, Howard University, Hampton University, and University of California Riverside. During these visits, the Center conducted graduate school 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. The Center also sponsored booths at three diversity and graduate fair conferences: Society for Advancement of Chicanos and Native Americans in Science (SACNAS), Society of Hispanic Professional Engineers (SHPE), and Society of Women Engineers (SWE).

For the community college programs, **S. Artis,** and **L. Marlor** visited 7 2-year colleges: Chabot College, Diablo Valley College, Santa Monica College, Sacramento City College, Los Angeles Trade-Technical College, East Los Angeles College, and El Camino College. **S. Artis** was an invited speaker at the Mathematics, Engineering, and Science Achievement (MESA) Student Leadership

Conference. While there, she led an interactive workshop engaging students on topics related to strategies for being competitive applicants for transferring to a baccalaureate program in science and engineering. For a complete list of recruitment for the community college program, please see Appendix G. The Center also supported five students from its summer research program to present their research in a poster session format at the information sessions at the Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Conference and the Council for Undergraduate Research's Research Experiences for Undergraduates Symposium.

New in Period 5 was the Center's participation in the EECS Rising Stars Workshop at UC Berkeley for women interested in careers in academia, for two days of scientific interactions and career-oriented discussions. In an effort to recruit more women, E^3S hosted a tour of the Marvell Nanofabrication Laboratory and a session with Center's faculty and leadership (**E. Yablonovitch, J. Bokor,** and **P. Wong**) to share E^3S research and provide participants advice for advancing their careers.

2b. Impact on the Center's Diversity

In Period 5, 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 more students from underrepresented groups pursue research in the Center or closely related science and engineering fields.

The Center has been able to successfully develop a talent pool of students at the pre-college and undergraduate level that have been exposed to energy efficient electronics science through research or lecture. To date, approximately, 59% (47) 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 82% (162) are pursuing a bachelor's degree in science and engineering.

For our undergraduate programs targeting community college students, we've seen a significant impact on diversity. Seventeen (94%) of the Center's alumni from the Transfer-to-Excellence (TTE) programs have transferred to a 4-year institution. Fourteen (78%) of these students are current undergraduate students at UC Berkeley. For our upper-division undergraduate programs for juniors and seniors, 24 (44%) of our students have graduated with a Bachelor's degree. Seventeen REU alumni are pursuing PhD degrees in science and engineering. One participant is employed by a government research laboratory and another at an engineering company. Of the 17 PhD students, 9 are currently Ph.D. students at UC Berkeley, including 4 that are part of the Center as graduate students.

As shown in this section of the report, the Center has continued to make diversity a high priority in Period 5. The Center leveraged existing partnerships with 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

Objective: Diversity						
Metric	**Targets**	**Results**				
		Period 2	**Period 3**	**Period 4**	**Period 5**	
Women in the Center's research programs	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 30%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	
Underrepresented minorities in the Center's research programs	Period 2: baseline Period 3: 15% increase Period 4: 5% Period 5: 10%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	
Participants from groups underrepresented in STEM in the Center's Diversity programs	Period 3: Baseline Period 4: 80% Period 5: 80%	n/a	93 (82%)	Women: 37 (44%) URM: 58 (68%) Total: 73 (86%)	Women 26 (41%) URMs 36 (56%) Total 49 (77%)	
Pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline Period 4: 70% Period 5: 70%	n/a	31 (68%)	98 (75%)	162 (82%)	
Community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80%	n/a	3 (100%)	6 (100%)	7 (88%)	
Undergraduates who pursue advanced degree in science and engineering	Period 3: 5% Period 4: 30% Period 5: 35%	n/a	0 (0%)	5 (38%)	20 (71%)	

2d. Plans in Period 6

In Period 6, the Center will continue to attract diverse candidates to its Education programs. For the REU program, we plan to attract students from HBCU's through the activities of the newly established UC-HBCU program of which Theme Leader T.-J. King Liu is the PI. The UC-HBCU program has been unable to accept many qualified applicants because the program is small. E^3S already has scheduled a webinar for the unsuccessful HBCU applicants to provide guidance on applying to the E^3S REU program.

Analysis of the data on REU alumni attending graduate school and joining the Center as graduate students, we see that a program change is necessary. We have concluded that there should be greater emphasis in selecting electrical and electronics engineering undergraduates to ensure that when they successfully join one of the Center's member institutions, the program participants will be in a department where there is a choice of E^3S faculty to serve as their advisors. While E^3S takes a multi-disciplinary approach in undertaking its research program, the majority of the Center's co-PI's are electrical engineering faculty.

VII. MANAGEMENT

1a. *Organizational Structure and Underlying Rationale*

In Period 5, the Center is similarly organized as in previous reporting periods; Appendix B gives the current organizational chart. Explanation of the organizational structure and its underlying rationale can be found in past Annual Reports [Period 1: http://www.e3s-center.org/pubs/52/Center_for_E3S_-_1st_Annual_Report_2010_Final%20-%20PUBLIC.pdf, Period 2: http://www.e3s-center.org/pubs/167/E3S_2nd_Annual_Report_PUBLIC2.pdf, Period 3: http://www.e3s-center.org/pubs/168/E3S_3rd_Annual_Report_Final_Public.pdf, Period 4: http://www.e3s-center.org/pubs/233/E3S_4th_Annual_Report_Final_Public.pdf]. Below we highlight changes in this Period 5 and upcoming Period 6.

- *Member Institutions & Faculty*: The Center's lead institution has continued to be University of California, Berkeley, home institution of the PI of the STC award, E. Yablonovitch. MIT, Stanford and The University of Texas at El Paso (UTEP) continued to be the subaward institutions through Period 4. In Period 5, with the approval of NSF, the Center added Florida International University (FIU), because of the synergy of the research of a FIU faculty, **S. Khizroev**, with the Nanomagnetics research in Theme IV. FIU joins four other institutions, University of California, Berkeley, MIT, Stanford and The University of Texas at El Paso (UTEP).

- In Period 5, the Center also experienced a change of faculty at Berkeley. **S. Siddiqi** and **R. Ramesh** left the Center, but we continued to partially fund two Ph.D. students in the Spring semester 2014, one in each of the research groups, to smooth the transition for these individuals. As encouraged by past Site Visit Teams to increase its efforts in System Integration research, the Center added **V. Stojanovic** (*Berkeley*) to expand the System Integration efforts to include Theme IV, Nanaomagnetics.
- In next Period 6, the Center will have the same number of faculty by institution as it has been having in this Period5. However, **C. Hu** (Berkeley) has informed the Center of his resignation, effective the end of this Period. Instead, **F. Fischer** (*Berkeley*) will join the Center, as the Theme I research is directed towards studies for materials with increased perfection for nanoelectonics switching.
- The biographical information of the faculty, new in Periods 5 and 6, are given in Appendix A.

- *Leadership Team*: The E^3S Executive Committee continues to provide leadership to the Center. Membership on this committee, which has not changed since the inception of the Center, has been discussed in previous annual reports and identified in the organization chart in Appendix B. The leadership is governed by a set of by-laws that were adopted in Period 2 and continues, as adopted, to be in effect; see Period 2 annual report for the bylaws - [http://www.e3s-center.org/pubs/167/E3S_2nd_Annual_Report_PUBLIC2.pdf]. Period 5 transactions of the E^3S Executive Committee are given below; see Management & Communications.
- Administrative and Programmatic Team: The Center's team of full-time staff who are responsible for the Center's operations and programmatic activities has experienced major changes in the later part of Period 5. Two full time staff, **S. Artis**, Education and Outreach Director, and **J. Peng**, Administrative Manager, resigned to accept promotions at other organizations. **A. Tabor** (*Berkeley*) is serving the role of interim Education and Outreach Director at 50% time, beginning in mid November 2014. Recruitment for a full-time hire for this Education and Outreach position will begin in the beginning of 2015. Recruitment for this position will have the first priority, subject to the renewal of the Center.
- Graduate Students and Postdoc Council: The Center's organizational structure provides for a Graduate Students and Postdoc Council (GSPC) with the goal of promoting community and leadership building among the students and postdocs. The format of a council has not been fully utilized by the Center's students and postdocs. Instead, students and postdocs activities are organized through ad hoc participation. In its fourth year, the Center is experiencing a change in its graduate

student population, as many of the graduate students, who have been associated with the Center since its inception, have graduated or about to graduate during Period 5. New graduate students are joining the Center, but thus, the Center's study body is once again going through another teaming cycle, and as such, Period 5 experienced less interest in student-led activities.

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly	Yearly
Center Management	Centerwide Communications	Yearly	• 1 newsletter • Annual Retreat • Annual NSF Review • Updated website
	Number of disputes	Yearly	Period 2: Baseline Annual decrease
	Annual Surveys:	Yearly	3 or higher on Likert Scale
	• Students/Postdocs		
	• Co-PIs		
	• External Advisory Board		
	Authorship disputes	Yearly	Period 2: Baseline 20% decrease annually
	Plagiarism	Yearly	

1c. Performance Against Metrics

Objective: Center Management					
Metric	**Targets**	**Results**			
		Period 2	**Period 3**	**Period 4**	**Period 5**
Centerwide communications	• 1 newsletter • Annual Retreat • Annual NSF Review • Updated Website	None August 29-30, 2011 None Continuously	June 2012 August 21-22, 2012 January 9-10, 2012 Continuously	June 2013 August 26-27, 2013 January 9-10, 2014 Continuously	Jun-14 August 26-27, 2014 January 9-10, 2014 Continuously
Annual Surveys: • **Students /Postdocs**	3 or higher on Likert Scale	Average: 3.9±0.2	Average: 4.0±0.3	Average: 4.2±0.2	Average: 4.5±0.2

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• **Co-PIs**		No survey in Period 2	Leadership: 4.46 Collaboration 3.25	Leadership: 4.7±0.5 Collaboration not available	Leadership: 4.9±0.1 Collaboration Outside Theme: 1.3+/-0.1 Within Theme: 3+/-1
• **External Advisory Board**		Strategic Plan: 4.18 Center Status: 4.01	Strategic Plan: 4.07 Accomplishments: 3.96	Strategic Plan: 4.6 Center Status: 4.6	Strategic Plan: 4.4 Center Status: 4.7
Authorship disputes	20% decrease annually	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale	0
Plagiarism		0	0	0	0
Assessment of goals, objectives, and outcomes – Strategic Plan Review	Yearly	January 5, 2012	December 19, 2012	December 17, 2013	December 18, 2014

1d. Problems Encountered

The loss of two key individuals has created a large workload for the remaining staff. However, there continues to be adequate expertise in the Center to meet its goals. The Center's Education and Diversity programs are well-established, and the newly appointed part-time Interim Education Director, **A. Tabor**, can augment the Center's full-time staff in the execution of the Center's Education and Diversity programs.

The internal survey of graduate students and postdocs has continued to indicate that the E^{3}S website to be highly effective, despite Google Analytics have recorded yearly rise in the website traffic up to the last period, Period 4. We have not been able to verify that the E^{3}S website traffic has continued to grow during Period 5. The problem was caused when the server migration, to upgrade to the platform on which the website resides, resulted in the loss of such tracking. The problem was not detected for more than 3-5 months and thus, the data available in Google Analytics for Period 5 has been compromised.

Some input has indicated that the website's navigation scheme is difficult and thus, there is an on-going effort to change the navigation system; i.e. implement a "face-lift" for the website. In addition, we will use the opportunity to add online education resources during the website's "face-lift". In the longer term, as its full-time staffing team is rebuilt, the Center will recruit an individual who can spend substantially more time to improve the website content.

2. Management and Communications Systems

Executive Committee: The E^3S Executive Committee is the Center's leadership and provides management oversight as well as planning and decisions for the Center. The committee's work has mainly been done through regular meetings, which are pre-announced with agendas. These processes were shared previously in the Period 2 annual report.

The following is a list of eight Executive Committee meetings that were scheduled in Period 5. All meetings are held via videoconferencing, except for the August 27 meeting which an in-person meeting that was held at the close of the Center's 2014 Annual Retreat.

Executive Committee – Period 5 Meetings	
Meeting Dates	**Agenda Topics**
Feb 4	Debrief of 2014 Site Visit Report; Review of Renewal Proposal Process
Mar 25	Period 5 Budget Review; Membership in the External Advisory Board: 4 appointments to a second term and 1 new appointments; renewal proposal preparation schedule
May 6	Review of Renewal Proposal Draft
June 4	Review of Renewal Proposal Draft
July 15	Review of Draft of 2015-2020 Strategic Plan; Plan for Annual Retreat
August 27	Debrief of Annual Meeting; Debrief of the Industrial Research Board Meeting; Preparation for External Advisory Board Meeting and NSF Site Visit
October 7	Review of Research; Preparation for the External AdvisoryBoard Meeting; Review of Comments by NSF Reviewers of the Renewal Proposal
December 17	Review of Strategic Plan Results, Review External Advisory Board Assessment Report, Preparation for Renewal Site Visit

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

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

Period 5 is the fourth year that the Center has conducted an annual survey of its graduate students and postdocs on their view of the Center's leadership and environment, as well as the effectiveness of its operations. Similarly, there has been a survey of E^3S faculty for three years on leadership and collaboration. The participation in the Students and Postdoc survey has been strong from the very beginning and has grown steadily over the past 4 years to 26 participants in Period 5. The participation by faculty was weaker in the first two years of the survey, but in the current Period 5, the participation grew to 100%; all 21 co-PI's participated in the Period 5 faculty survey.

In Period 5, the Center's external evaluator redesigned the both surveys so that the questions to assess the Center's leadership to be the same. We believe that the change have resulted in both instruments being clearer for the respondents and also, allows the evaluator, if necessary, to assess whether there are differences in perception in the two populations.

The Period 5 survey results indicate that the Center's students and postdocs' agree (Likert score = 4.5 ± 0.2) that the Center leadership is living up to its espoused values, as given above. The Period 5 aggregate result is similar the result of previous three reporting periods: Period 4 = 4.2±0.2; Period 3 = 4.0±0.3; Period 2 = 3.9±0.2. Similarly, in Period 5, the E^{3}S co-PI's indicated agreement that the Center's leadership is living up to its espoused values; Likert score = 4.8±0.2. This can be compared with the results from Periods 3 & 4, when the similar scores were: Period 4 = 4.7±0.5 and Period 3 = 4.5.

The respondents' Period 5 view of the climate of the Center relative to each espoused value is as follows.

	Students & Postdocs	Faculty
Inclusiveness	4.6	5.0
Teamwork	4.6	5.0
Open and timely communications	4.7	4.9
Agility/Decision Making	4.5	4.8
Focus on Performance	4.5	4.7

Collaboration: The Graduate Students & Postdoc and the Faculty Surveys attempt to assess the state of collaboration differently. For this and the two preceding Periods, graduate students and postdocs have been asked questions about the help they have received. The Faculty Survey has attempted to assess the degree of collaboration in each of the three surveys the Center has conducted. The second method has proven to be a challenge in that the survey is hard to understand, and we believe has discouraged participation. In Period 4, we did not receive participants to allow the results to be published without compromising anonymity. In this Period 5, the descriptions of the different levels of collaboration were simplified.

The Faculty Survey of Period 5 shows that the co-PI's within a Theme mainly "coordinate" as defined by formalized collaboration on an E^{3}S project within one institution. Survey results revealed that the level of interactions among faculty working in different Themes is between "networking" to "cooperation", as defined by "interactions during centerwide meetings" to "adhoc sharing of research ideas, recipes and/or equipment". The survey data aligns with an analysis of joint publications among the faculty of the Center, which shows that to date, there are 4 cross institutional journal publications.

The Students and Postdoc Survey shows a stronger collaborative environment. The student and postdoc respondents indicated that their E^{3}S research was helped through discussions, inputs, and general collaborations; see Figure 2. For the students, the center clearly hosts a high level of informal collaboration; however, this has not translated into formal outputs in terms of papers or conference proceedings.

Nearly 100% of the students and postdocs said that others working in his/her Theme has been of help to the progress of their research, while in the last three years, the percent helped by someone in the Center from another institution has grown from over 1/3 to1/2. We like to interpret the student and postdoc data are most relevant as informal teamwork and collaboration reflect the climate of the Center.

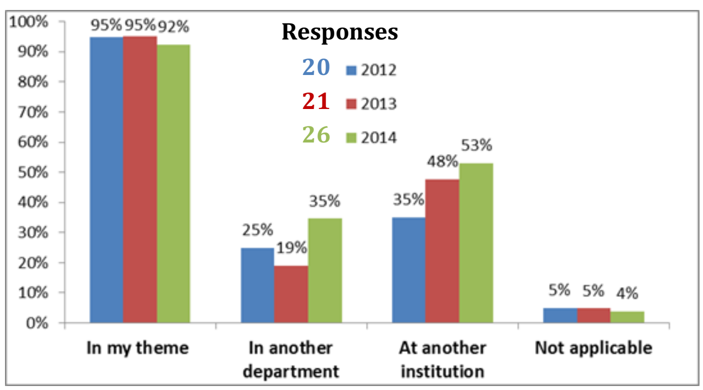

Figure 2: % of Graduate Students and Postdocs who indicated that their E^{3}S research was helped by the Center's environment and other Center's members.

Ethical Conduct:

The Center's leadership team is responsible for the Center to operate in an ethical manner. The two annual surveys have included questions addressing whether there are incidences of unethical behaviors. After changes of the survey instrument in the past two years, the Period 5 surveys both have the same question on whether "E^{3}S colleagues act in an ethical manner." If the answer is no, the external evaluator would follow up. In both surveys, students, postdocs and faculty all answered yes.

Communications:

The Center recognizes the importance of communication in enabling synergy in the Center. Both the Students and Postdoc Survey as well as the Faculty Survey indicated that the Center has been communicating effectively; Period 5 Likert scores of 4.6 and 4.9, respectively. The Center has continued to assess the effectiveness of its communication venues through the Students and Postdoc Survey. Figure 3 shows the effectiveness of different communications vehicles the Center has and is using to share information. This chart also gives a comparison with the respondents' perception in the previous two periods when the same survey was also conducted.

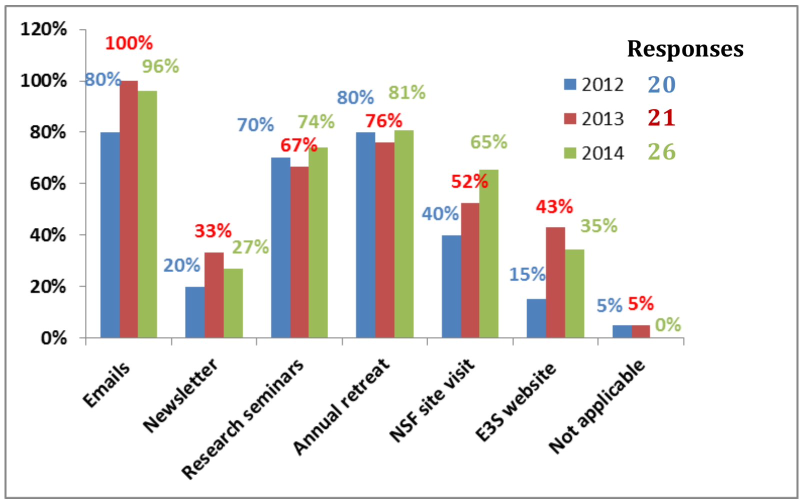

Figure 3: The responses of graduate students and postdocs on the effectiveness of the Center's communication venues.

Noteworthy are two communication venues:

- *Center's Annual Retreat*: The 5th Annual Center-wide Retreat was held on August 26-27 at UC Berkeley with the theme of "Next Five Years – Building on Accomplishments"; the agenda can be found here: http://www.e3s-center.org/events/14/annual-retreat.htm. The two-day meeting was attended by the Center's faculty, postdocs, graduate students, staff, education and diversity partners, and industry members. The first day was devoted to research presentations and discussions, while the second day was devoted to Education and Diversity, which included a community college panels addressing some topics brought up at the Education Working Group of the External Advisory Board; see Section 3 below. There were discussions on sustainability of research internship programs and how the faculty at community colleges are trying to create pathways for students from technician training to bachelor's degrees. From this discussion it was learned that community college faculty would like to have curriculum that is still under development, as they do not want to wait for a final product because the need is great and their faculty and students would benefit from early access. New in this Period's Annual Retreat was the opportunity for the Center's graduate students and postdocs of each Theme to present the "competition" and analyze the Theme's research program in such context. The students and postdocs of each theme worked together on developing the analysis.
  The meeting also offered the opportunity for the industry members who make up the Center's Industrial Research Board to provide input to the Center; see below - *Internal and External Advisory Bodies*. The Retreat included a recognition ceremony when the Center's faculty, postdocs, students and industry members were thanked for their support of the Center's programmatic activities.
- *Seminars*: The E^{3}S seminars are both communication as well as education venues. As education vehicles, they have been discussed in Section *III. Education*. There were 15 seminars in Period 5, four of which featured external invited speakers.

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 5 activities for each group.

- *External Advisory Board (EAB)*: In Period 5, 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. **D. Redack** (*Institute for Defense Analysis*) continues the second year of his two year term as the Board's Chair. In Period 5, the Center made changes to strengthen the Board's ability to handle its Education and Diversity responsibilities: (i) the establishment of the Education Working Subgroup, chaired by **D. Rover** (*Utah State*) to provide more time to address Education and Diversity; and (ii) the addition of **E.W. Chang** (*Mercer County Community College, Trenton, NJ*) to provide community college expertise.

  Membership: The table below provides the list of the current members and their interests.

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

  The five individuals marked to have interest in Education and Diversity in the above table are members of the Education Working Group.

  Education Working Group: This group has the responsibility to advise and guide, but it does not assess. The assessment of the Center's Education and Diversity efforts is done as part of the annual evaluation by the entire External Advisory Board. A virtual meeting of the Education Working Group was held on May 1; all members of the Working Group participated. Representing the Center were **S. Artis**, **J. Bokor**, **J. Yuen** and **D. Zubia** *(UTEP)*. The Center's program delivery partner for its highschool program, MOSTEC, was also present, represented by **S. Decker** *(MIT)* and the Center's external evaluator, Catherine Amelink. The meeting was chaired by **D. Rover**. The main purpose of the meeting was to present details of the program including how recruitment has been conducted. Discussions included how to demonstrate the impact, sustain research internships for community college students, as well as a suggestion of involving the California Community Colleges Chancellor's Office in the Center's community college programs.

Annual Meeting: The Period 5 annual meeting of the External Advisory Board took place at Berkeley on November 5-6 chaired by **D. Radack.** This year's meeting had a longer (1.5 days) format to allow sufficient time for the Center to present its status and for the Board to deliberate. 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 is made available at the January 2015 NSF Site Visit. The Executive Committee is scheduled to review the assessment at its meeting on December 17, after which the assessments will be shared with all funded faculty members in the Center and with the Vice Chancellor of Research of Berkeley and the Dean of Engineering of MIT. Berkeley and MIT serve as home for 90% of the E^3S faculty in Period 4.

- *Industrial Research Board (IRB)*: The Center for E^3S continues to have receive strong support from four leaders in the semiconductor industry even before its inception. The IRB monitors, advises and participates in the Center's research. The Period 5 board's membership is as follows.

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

At the Center's 2014 Annual Retreat in August, the Industrial Research Board met with the Center's Executive Committee. Representatives of all five member companies participated in the 2014 Industrial Research Board meeting:

- Nerissa Draeger, Lam Research
- Ian Young, Intel
- Stan Williams, Hewlett Packard
- Paul Solomon, IBM

The industry representatives provided input on the Center's presentations. One representative raised the concern that since we are still from the goal, the goal may be unreachable. Nevertheless, another member recognized that there may be spinoff applications. One representative advised that the Center should learn about the energy losses at the systems level and assess whether improvements at the component will be relevant at the system level. Nevertheless, the same representative agreed that components will have impact in wireless devices.

4. Changes in the Strategic Plan

No changes in Strategic Plan are planned at this time.

VIII. CENTERWIDE OUTPUT

1a. *Publications*

1ai. *Peer Reviewed*

Journal Articles *(Chronological)*

1. J. Yaung, L. Hutin, J. Jeon, and T. J. K. Liu, "Adhesive Force Characterization for MEM Logic Relays With Sub-Micron Contacting Regions," *Journal of Microelectromechanical Systems,* vol. 23, pp. 198-203, Feb 2014.
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3. J.Lin, X.Zhao, D. A. Antoniadis, and J. A. del Alamo, "A Novel Digital Etch Technique for Deeply Scaled III-V MOSFETs," IEEE Electron Device Letters, vol. 35, pp. 440-442, April 2014.
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9. H. Sun, F. Ren, K. W. Ng, T-T. D. Tran, K. Li, and C. J. Chang-Hasnain, "Nanopillar Lasers Directly Grown on Silicon with Heterostructure Surface Passivation," *ACS Nano*, vol. 8, no. 7, pp. 6833–6839, 2014. doi 10.1021/nn501481u.
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11. R. M. Iutzi and E. A. Fitzgerald, "Microstructure and Conductance-Slope of InAs/GaSb Tunnel Diodes," *Journal of Applied Physics*, vol. 115, pp. 234503 (10 pp.), Jun 2014.
12. R. Chen, K. W. Ng, W. S. Ko, D. Parekh, F. Lu, T.-T. D. Tran, K. Li, and C. Chang-Hasnain, "Nanophotonic Integrated Circuits from Nanoresonators Grown on Silicon," *Nat Commun*, vol. 5, Jul 2014.
13. A. I. Khan, P. Yu, M. Trassin, M. J. Lee, L. You, and S. Salahuddin, "The Effects of Strain Relaxation on the Dielectric Properties of Epitaxial Ferroelectric Pb(Zr0.2Ti0.8)TiO_3 Thin Films," *Applied Physics Letters,* vol. 105, p. 4, Jul 2014.
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23. W. W. Gao, A. Khan, X. Marti, C. Nelson, C. Serrao, J. Ravichandran, R. Ramesh, and S. Salahuddin, "Room-Temperature Negative Capacitance in a Ferroelectric Dielectric Super Lattice Heterostructure," *Nano Letters,* vol. 14, pp. 5814-5819, Oct 2014.
24. J. Teherani, W. Chern, D. Antoniadis, and J. Hoyt, "Ultra-Thin, High Quality HfO_2 on Strained-Ge MOS Capacitors with Low Leakage Current," *ECS Transactions*, vol. 64, no. 6, pp. 267–271, Oct. 2014. doi:10.1149/06406.0267ecst.
25. S. Agarwal and E. Yablonovitch, "Fundamental Conductance Divided by Voltage Limit in Low Voltage Tunnel Switches," *IEEE Electron Device Letters,* vol. 35, pp. 1061-1062, Oct 2014.
26. J. Lin, X. Zhao, D. A. Antoniadis, and J. A. del Alamo, "Off-State Leakage Induced by Band-to-Band Tunneling and Floating-Body Bipolar Effect in InGaAs Quantum-Well MOSFETs," *IEEE Electron Device Letters*, vol. 35, no. 12, pp 1203-1205, Dec 2014. doi: 10.1109/LED.2014.2361528
27. A. I. Khan, K. Chatterjee, B. Wang, S. Drapcho, L. You, C. Serrao, S. R. Bakaul, R. Ramesh, and S. Salahuddin, "Negative Capacitance in a Ferroelectric Capacitor," *Nature Materials*, Dec 2014. doi: 10.1038/nmat4148.

<u>Accepted</u> *(alphabetical by 1st author)*

1. S. Artis, C. Amelink, and T.-J. King Liu, "Examining the Self-Efficacy of Community College STEM Majors: Factors Related to Four Year Degree Attainment," *Community College Journal of Research and Practice* (in press).
2. M. Eggleston, K. Messer, L. Zhang, E. Yablonovitch, and M.C. Wu, "Optical Antenna Enhanced Spontaneous Emission," *Proceedings of the National Academy of Sciences* (accepted).
3. A. Vardi, W. Lu, X. Zhao, and J. A. del Alamo, "Nano-Scale Mo Ohmic Contacts to III-V Fins," *IEEE Electron Device Letters* (accepted).

4. Y. Lee, Z. Q. Liu, J. T. Heron, J. D. Clarkson, J. Hong, C. Ko, M. D. Biegalski, U. Aschauer, S. L. Hsu, M. E. Nowakowski, J. Wu, H. M. Christen, S. Salahuddin, J. Bokor, N. A. Spaldin, D. G. Schlom, and R. Ramesh, "Large Resistivity Modulation in Mixed-Phase Metallic Systems," *Nature Communications* (accepted).
5. G. Zheng, M. E. Nowakowski, D. B. Carlton, R. Storz, J. Hong, W. Chao, B. Lambson, P. Bennett, M. T. Alam, M. A. Marcus, A. Doran, A. Young, A. Scholl, and J. Bokor, "Sub-Nanosecond Signal Propagation in Anisotropy Engineered Nanomagnetic Logic Chains," *Nature Communications* (accepted).

Under Review/Submitted *(alphabetical by 1st author)*

1. S. Agarwal and E. Yablonovitch, "A Nanoscale Piezoelectric Transformer for Low Voltage Transistors," submitted to *ACS Nano Letters*.
2. S. Agarwal and E. Yablonovitch, "Pronounced Effect of pn-Junction Dimensionality on Tunnel Switch Threshold Shape," submitted to *Proceedings of the National Academy of Sciences*.
3. S. Almeida, E. Ochoa, J. Chavez, X. Zhou, and D. Zubia, "Calculation of Surface Diffusivity and Residence Time by Molecular Dynamics with Application to Nanoscale Selective-Area Growth," submitted to *Journal of Crystal Growth.*
4. D. Bhowmik, M. Nowakowski, L. You, O. Lee, D. Keating, M. Wong, J. Bokor, and S. Salahuddin, "Deterministic Control of a Longitudinal Ferromagnetic Domain Wall by Spin Orbit Torque," submitted to *Physical Review Letters*.
5. I-R. Chen, C. Qian, E. Yablonovitch, and T.-J. K. Liu, "Nanomechanical Switch Design to Overcome the Surface Adhesion Energy Limit," submitted to *IEEE Electron Device Letters*.
6. Y. Chen, I-R. Chen, J. Yaung, and T.-J. K. Liu, "Study of Contact Detachment Delay in Micro-Relays for Digital Logic Applications," submitted to *IEEE Transaction on Electron Device*.
7. J. Hong, B. Lambson, S. Dhuey, and J. Bokor, "Experimental Investigation of the Landauer Erasure of Nanomagnetic Memory Bits: Confirmation of the Second Law of Information Thermodynamics in Nanoscale," submitted to *Nature*.
8. R. M. Iutzi, E. A. Fitzgerald, "Defect and Temperature Dependence of Tunneling in InAs/GaSb Heterojunctions," submitted to *Applied Physics Letters.*
9. J.H. Kim, D. Fu, S. Kwon, K. Liu, J. Wu, and J.Y. Park, "Crossing the Thermal Lubricity and Electronic Effects in Friction: Vanadium Dioxide under Metal-Insulator Transition," submitted to *Scientific Rep*ort.
10. J. Lin, D. A. Antoniadis and J. A. del Alamo, "Physics and Mitigation of Excess Off-state Current in InGaAs Quantum-Well MOSFETs," submitted to *IEEE Transactions Electron Devices*.
11. H. Sohn, M. E. Nowakowski, C. Y. Liang, J. L. Hockel, K. Wetzlar, S. Keller, B. M. McLellan, M. A. Marcus, A. Doran, A. Young, M. Kläui, G. P. Carman, J. Bokor, R. N. Candler, "Reversible Electrically-Driven Magnetic Domain Wall Rotation in Multiferroic Heterostructures to Manipulate Suspended On-Chip Magnetic Particles," submitted to *ACS Nano*.
12. L. You, O. Lee, D. Bhowmik, D. Labanowski, J. Hong, J. Bokor, and S. Salahuddin, "Switching of Perpendicularly Polarized Nanomagnets with Spin Orbit Torque Without an External Magnetic Field by Engineering a Tilted Anisotropy," submitted to *Proceedings of the National Academy of Sciences*.
13. Y. Zeng, C. Kuo, C. Hsu, M. Najmzadeh, A. Sachid, R. Kapadia, C. Yeung, E. Chang, A. Javey, C. Hu, "Quantum Well InAs/AlSb/GaSb Tunneling Field-Effect Transistor with HSQ Mechanical Support," submitted to *IEEE Transaction on Nanotechnology*.

Conference Proceedings

1. S. Agarwal and E. Yablonovitch, “Why Tunneling FETs Don’t Work, and How to Fix It,” in *Third Berkeley Symposium on Energy Efficient Electronic Systems*, ed: IEEE, 2013.
2. S. Agarwal, E. Yablonovitch, "The Piezoelectric Transformer Field Effect Transformer,” in *72nd Device Research Conference*, ed: IEEE, 2014, pp. 21-22.
3. S. Artis, C. Amelink, and T.-J. King Liu, “Transfer-to-Excellence: Research Experiences for Undergraduates at California Community Colleges,” in *Proceedings of the 2014 American Society for Engineering Education Annual Conference & Exposition*, Indianapolis, IN, June 2014.
4. S. Artis, and C. Amelink, “The Influence of Summer Research Experiences on Community College Students’ Efficacy and Pursuit of a Bachelor’s Degree in Science and Engineering,” in *Proceedings of the 2014 American Society for Engineering Education Annual Conference & Exposition,* Indianapolis, IN, June 2014.
5. J. A. del Alamo, D. Antoniadis, A. Guo, D. H. Kim, T. W. Kim, J. Lin*,* W. Lu, A. Vardi; and X. Zhao, "InGaAs MOSFETs for CMOS: Recent Advances in Process Technology," in *2013 IEEE International Electron Devices Meeting*, ed: IEEE, 2013, pp. 2.1 (4 pp.).
6. S. Dutta and V. Stojanovic, "Floating-Point Unit Design with Nano-Electro-Mechanical (NEM) Relays," in *2014 IEEE/ACM International Symposium on Nanoscale Architectures*, ed: IEEE, 2014, pp. 145-150.
7. M. Eggleston, K. Messer, S.A. Fortuna, E. Yablonovitch, and M.C. Wu, “Waveguide-Integrated Optical Antenna Nanoleds for On-Chip Communication,” in *Third Berkeley Symposium on Energy Efficient Electronic Systems*, ed: IEEE, 2013.
8. R. Going, J. Loo, T.-J. King-Liu, and M.C. Wu, “2.5 GB/s Germanium Gate Photomosfet Integrated to Silicon Photonics,” in *Third Berkeley Symposium on Energy Efficient Electronic Systems*, ed: IEEE, 2013.
9. A. Javey, “Quantum Membranes: A New Materials Platform for Future Electronics,” in *Third Berkeley Symposium on Energy Efficient Electronic Systems*, ed: IEEE, 2013.
10. *CLEO: 2014, OSA Technical Digest (online)* L. Jianqiang, Z. Xin, Y. Tao, D. A. Antoniadis, and J. A. del Alamo, "A New Self-Aligned Quantum-Well MOSFET Architecture Fabricated by a Scalable Tight-Pitch Process," in *2013 IEEE International Electron Devices Meeting*, ed: IEEE, 2013, pp. 16.2 (4 pp.).
11. C. Lalau-Keraly, S. Bhargava, V. Ganapati, and E. Yablonovitch, "Shape Optimization of Nanophotonic Devices Using the Adjoint Method," in *CLEO: 2014, OSA Technical Digest* (online) (Optical Society of America, 2014), paper STu2M.6.
12. W. Li, T. Yu, J. Hoyt, and P. Fay, "InGaAs/GaAsSb Interband Tunneling FETs as Tunable RF Detectors," in *72nd Device Research Conference*, ed: IEEE, 2014, pp. 21-22.
13. K. Messer, M. Eggleston, M. Wu, and E. Yablonovitch, "Enhanced Spontaneous Emission Rate of InP using an Optical Antenna," in (Optical Society of America, 2014), paper STu1M.3.
14. A. Murarka, A. I. Wang, J. Jean, J. H. Lang, and V. Bulovic, “Printed MEMS Membrane Electrostatic Microspeakers,” *Proceedings: Solid-State Sensors, Actuators and Microsystems Workshop*, Hilton Head Island, SC, June 8-12, 2014, 311-314.
15. F. Niroui, E. M. Sletten, P. B. Deotare, A. I. Wang, T. M. Swager, J. H. Lang, V. Bulovic. “Controlled Fabrication of Nanoscale Gaps Using Stiction,” *Proceedings: IEEE MEMS Workshop*, Estoril, Portugal, January 18-22, 2014.
16. F. Niroui, P. B. Deotare, E. M. Sletten, A. I. Wang, E. Yablonovitch, T. M. Swager*,* J. H. Lang, and V. Bulovic, "Nanoelectromechanical Tunneling Switches Based on Self-Assembled Molecular

Layers," in *2014 IEEE 27th International Conference on Micro Electro Mechanical Systems*, ed: IEEE, 2014, pp. 1103-1106.
17. L. Seunghyun, A. Tang, J. P. McVittie, and H. S. P. Wong, "NEM Relays Using 2-Dimensional Nanomaterials for Low Energy Contacts," in Third Berkeley Symposium on Energy Efficient Electronic Systems, ed: IEEE, 2013.
18. J.T. Teherani, T. Yu ; D.A. Antoniadis, and J.L. Hoyt, "Electrostatic Design of Vertical Tunneling Field-Effect Transistors," in *Third Berkeley Symposium on Energy Efficient Electronic Systems*, ed: IEEE, 2013.
19. J. T. Teherani, W. Chern, D. A. Antoniadis, and J. L. Hoyt, "Simulation of Enhanced Hole Ballistic Velocity in Asymmetrically Strained Germanium Nanowire Trigate p-MOSFETs," in *2013 IEEE International Electron Devices Meeting*, ed: IEEE, 2013, pp. 32.4 (4 pp.).
20. J. Teherani, W. Chern, D. Antoniadis, and J. Hoyt, "Ultra-Thin, High Quality HfO_2 on Strained-Ge MOS Capacitors with Low Leakage Current," *ECS Transactions*, vol. 64, no. 6, pp. 267–271, Oct. 2014.
21. A. Vardi, Z. Xin, and J. A. del Alamo, "InGaAs Double-Gate Fin-Sidewall MOSFET," in *72nd Device Research Conference*, ed: IEEE, 2014, pp. 219-220.
22. A. Wang, W. Chang, A. Murarka, J. H. Lang, and V. Bulovic, "Transfer-Printed Composite Membranes for Electrically-Tunable Organic Optical Microcavities," in *2014 IEEE 27th International Conference on Micro Electro Mechanical Systems*, ed: IEEE, 2014, pp. 1217-1220.
23. Z. Xin, L. Jianqiang, C. Heidelberger, E. A. Fitzgerald, and J. A. del Alamo, "Vertical Nanowire InGaAs MOSFETs Fabricated by a Top-Down Approach," in *2013 IEEE International Electron Devices Meeting*, ed: IEEE, 2013, pp. 28.4.1 - 28.4 .4.
24. C.W. Yeung , A.I. Khan, A.I. , S. Salahuddin, and C. Hu "Device Design Considerations for Ultra-Thin Body Non-Hysteretic Negative Capacitance FETs," in *Third Berkeley Symposium on Energy Efficient Electronic Systems*, ed: IEEE, 2013.

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

To Be Published

1. S. Agarwal and E. Yablonovitch, "Designing a Low Voltage, High Current Tunneling Transistor," in T.-J. K. Liu and K. Kuhn (Ed.), *Beyond CMOS: Logic Switches for Terascale Integrated Circuits*, Cambridge University Press, March 2015, ISBN: 978-1-107-04318-3.
2. E. Alon, "Energy-Efficiency Limits of Digital Circuits based on CMOS Transistors," in T.-J. K. Liu and K. Kuhn (Ed.), *Beyond CMOS: Logic Switches for Terascale Integrated Circuits*, Cambridge University Press, March 2015, ISBN: 978-1-107-04318-3.
3. A.I. Khan, S. Salahuddin, "Extending CMOS with Negative Capacitance," in T.-J. K. Liu and K. Kuhn (Ed.), *Beyond CMOS: Logic Switches for Terascale Integrated Circuits*, Cambridge University Press, March 2015, ISBN: 978-1-107-04318-3.
4. T.-J. K. Liu and K. Kuhn (Ed.), *Beyond CMOS: Logic Switches for Terascale Integrated Circuits*, Cambridge University Press, March 2015, ISBN: 978-1-107-04318-3.
5. R. Nathanael and T.-J. King Liu, "Mechanical Switches," in T.-J. K. Liu and K. Kuhn (Ed.), *Beyond CMOS: Logic Switches for Terascale Integrated Circuits*, Cambridge University Press, March 2015, ISBN: 978-1-107-04318-3.

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

1. L. Hutin and T.-J. King Liu, "NEMS Switch Technology," to appear in *Emerging Nanoelectronic Devices*, An Chen, Jim Hutchby, Victor Zhirnov, and George Bourianoff (Ed.), John Wiley & Sons, Ltd, January 2015, ISBN: 978-1-118-44774-1.
2. E. Ochoa, S. Almeida, J. Chavez, D. Zubia, "Calculating Diffusion Coefficient of CdTe on CdS and SiO_2 by Molecular Dynamics Simulations," Conference Proceedings, 4th Southwest Energy Science and Engineering Symposium, El Paso, Texas, March 22, 2014.

1b. Conference Presentations (in alphabetical order)

Talks: *(does not include 2014 talks that have published proceedings by 12/31/2014;* *see p114.)*

1. E. Alon, Y. Lu, and M. Wu, "Power Analysis and Limits of Photonic Links," *IEEE Optical Interconnects Conference*, May 2014.
2. J. A. del Alamo, "III-V MOSFETs for CMOS: Recent Advances in Process Technology," invited talk at *Semicon Korea 2014*, Seoul, Korea, February 12-14, 2014.
3. J. A. del Alamo, "InGaAs MOSFET Electronics," invited plenary talk at 17th International Symposium on the Physics of Semiconductors and Applications (ISPSA-2014), Jeju Island, Korea, December 7-11, 2014.
4. D. Bhowmik, L. You, M. Nowakowski, D. Keating, M. Wong, J. Bokor, and S. Salahuddin, "Size Dependence of Spin Hall Effect Spin Torque Switching of Perpendicularly Polarized Magnets-Meta-Stable State Formation," *Magnetism and Magnetic Materials Conference*, Honolulu, HI, Nov 3-7, 2014.
5. C. J. Chang-Hasnain, "III-V Nanopilar Photonic Devices on Silicon," *IEEE Photonics Society Summer Topical Meeting on Nanowire Materials and Integrated Photonics*, Montréal, Québec, Canada, July 14-16, 2014
6. K. Crabbe and J. Clarkson. "Investigation of Spin-on Dielectrics as an Interlayer Dielectric for the Marvell Nanofabrication Laboratory CMOS210 Baseline Project." *2014 Society for Advancement of Hispanics/Chicanos and Native Americans in Science Conference*, October 26-27, 2014.
7. M. Eggleston, K. Messer, E. Yablonovitch, M. C. Wu, "Circuit Theory of Optical Antenna Shedding Light on Fundamental Limit of Rate Enhancement," *CLEO: Science and Innovations*, San Jose, CA, June 2014.
8. M. Eggleston, K. Messer, E. Yablonovitch, M. C. Wu, "Circuit Theory of Optical Antenna Shedding Light on Fundamental Limit of Rate Enhancement," *CLEO: Science and Innovations*, San Jose, CA, June 2014.
9. S. A. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch, M.C. Wu, "Electrically Injected NanoLED with Enhanced Spontaneous Emission from a Cavity Backed Optical Slot Antenna," *IEEE Photonics Society Conference*, San Diego, CA, October 2014.
10. R. Going, T. J. Seok, M. C. Wu, "Rapid Melt Grown Germanium p-i-n Photodiode Wrapped around a Silicon Waveguide," *CLEO: Science and Innovations*, San Jose, CA, June 2014.
11. Z. Gu, R. Storz, M. Marcus, A. Doran, A. Young, A. Scholl, W. Chao, D. Carlton, B. Lambson, M. Nowakowski, and J. Bokor, "Time-Resolved Photo-Emission Electron Microscopy of Nanomagnetic Logic Chains," *Ultrafast Magnetism Conference 2013*, Strasbourg, France.
12. C. Hu, "From FinFET to a Bold Future," *NSF Conference on Electronic Materials, Devices and Systems for Sustainable Future*, King Abdullah University of Science and Technology, Saudi Arabia, Feb. 10, 2014.
13. T.-J. K. Liu, "Mechanical Computing Redux: Limitations at the Nanoscale," *American Physical Society March Meeting 2014*, Denver, CO, March 3-7, 2014.

14. T.-J. K. Liu, N. Xu, I-R. Cheng, C. Qian, and J. Fujiki, "NEM Relay Design for Compact, Ultra-Low-Power Digital Logic Circuits," *2014 IEEE International Electron Devices Meeting*, San Francisco, CA, December 15-17, 2014.
15. W. S. Ko, I. Bhattacharya, T. Tran, K. Ng, and C. J. Chang-Hasnain, "InP Nanowire Avalanche Photodiode and Bipolar Junction Phototransistor Integrated on Silicon Substrate," *The 26th International Conference on Indium Phosphide and Related Materials Conference (IPRM 2014)*, Montpellier, France, May 11-15, 2014.
16. W. S. Ko, T. Tran, I. Bhattacharya, K. W. Ng, H. Sun, C. J. Chang-Hasnain, "Omnidirectional, High Efficiency Single InP Nanowire Solar Cell", *The 41st International Symposium on Compound Semiconductor (ISCS 2014)*, Montpellier, France, May 11-15, 2014.
17. F. Niroui, A. Wang, E. Sletten, P. Deotare, A. Murarka, T. Swager, J. Lang, and V. Bulović, "Tunneling Nanoelectromechanical Switches using Molecular Thin Films," *Materials Research Society*, Fall 2013 Meeting, Boston, MA, December 2013.
18. E. Ochoa, S. Almeida, J. Chavez, D. Zubia, "Calculating Diffusion Coefficient of CdTe on CdS and SiO_2 by Molecular Dynamics Simulations," Oral Presentation, *4th Southwest Energy Science and Engineering Symposium*, El Paso, Texas, March 22, 2014.
19. S. Salahuddin, "Negative Capacitance Transistors," MRS Spring Meeting, San Francisco, 2014..
20. J. Teherani, W. Chern, D. Antoniadis, and J. Hoyt, "Ultra-Thin, High Quality HfO_2 on Strained-Ge MOS Capacitors with Low Leakage Current," *ECS SiGe, Ge, and Related Compounds Symposium*, Oct. 2014.
21. H.-S. P Wong, "Innovating Our Way Through the End of Moore's Law," invited keynote paper, *IC China*, Shanghai, China, November 12 – 14, 2013.
22. J. Wu, "Potential Applications of 2D Materials in Microelectronics and Optoelectronics," *China Semiconductor Technology International Conference (CSTIC) 2014, Symposium IV: Thin Film Technology*, Shanghai, China, March 16, 2014,
23. N. Xu, J. Sun, I-R. Chen, L. Hutin, Y. Chen, J. Fujiki, C. Qian, and T.-J. K. Liu, "Hybrid CMOS/BEOL-NEMS Technology for Ultra-Low-Power IC Applications," at the *2014 IEEE International Electron Devices Meeting*, San Francisco, CA, December 15-17, 2014
24. X. Zhao, A. Vardi and J. A. del Alamo, "InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs Fabricated by a Top-down Approach," at *IEEE International Electron Devices Meeting*, San Francisco, CA, December 15-17, 2014.

<u>Conference Talks – Accepted</u>

1. R. P. Oeflein, L. Hutin, J. Borrel, A. Villalon, C. Le Royer, S. Martinie, C. Tabone, and M. Vinet, "Investigation of Ambipolar Signature in SiGeOI Homojunction Tunnel FETs," to be presented at EUROSOI-ULIS 2015, Bologna, Italy, January 26-28, 2015,

<u>Posters</u>

1. S. A. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch, M.C. Wu, "Electrically Injected NanoLED with Enhanced Spontaneous Emission from a Cavity Backed Optical Slot Antenna," iNOW 2014, St. Petersburg, Russia, August 2014.
2. J. Teherani T. Yu, D. Antoniadis, and J. Hoyt, "Tunneling Transistors for Low Power Electronics," Tenth International Nanotechnology Conference (INC10), NIST, May 2014.
3. J. Teherani, "NSF Center for Energy Efficient Electronics Science (E3S)," Tenth International Nanotechnology Conference (INC10), NIST, May 2014.
4. J. Teherani, W. Chern, D. Antoniadis, and J. Hoyt, "Enhanced Hole Ballistic Velocity in Germanium Nanowire p-FETs through Asymmetric Strain," MTL Annual Research Conference, January 2014.

5. A. Vardi, X. Zhao, and J. A. del Alamo, “Double-Gate Fin-Sidewall InGaAs MOSFETs,” (oral and poster presentation) MTL Annual Research Conference, Bretton Woods, NH, January 29-30, 2014.
6. T. Yu, J. Teherani, D. Antoniadis, and J. Hoyt, “InGaAs/GaAsSb Quantum-well Tunnel-FETs,” MTL Annual Research Conference, January 2014.
7. Y. Zeng and C. Hu, “Fabrication of III-V TFETs”, invited talk, the 4th international conference on Nanotek and Expo, Dec 1-3, San Francisco, 2014.
8. X. Zhao and J. A. del Alamo, “Vertical Nanowire InGaAs MOSFETs Fabricated by a Top-Down Approach,” MTL Annual Research Conference, Bretton Woods, NH, January 29-30, 2014.

1c. Other Dissemination Activities (in chronological order)

1. S. Artis and L. Marlor, Presenters at Workshop on “Successfully Finding, Applying, and Obtaining a Summer Research Internship and Postbac Position,” (E. Hernández-Ramón and S. Artis, co-chairs), Society for Advancement of Hispanics/Chicanos and Native Americans in Science Conference, National Harbor, MD, Oct 16 - 18, 2014.
2. S. Artis, Presenter at Workshop on “The In's and Out's of Landing a Summer Research Internship”, 2014 MESA Student Leadership Conference, San Diego, Oct 31 - Nov 1, 2014.
3. Bulovic, invited faculty lecture, MIT Alumni Club of Boston, November 2013.
4. V. Bulovic, invited faculty lecture, MIT Alumni Club of Zurich, Switzerland, January 2014.
5. V. Bulovic, invited talk, "Extremely Thin Devices Deployable on Any Surface (Through Printing)," Xerox Distinguished Lecture, Xerox Research Center of Canada, November 2013.
6. V. Bulovic, invited talk, “Large Area Nanomanufacturing of 21st Century Technologies”, World Economic Forum, IdeasLab, Davos, Switzerland, January 2014.
7. V. Bulovic, invited talk, “Printing Nano-structures for LEDs, PVs and MEMS,” Rutgers University, March 2014.
8. V. Bulovic, keynote address, "Extremely Thin Devices Deployable on Any Surface (Through Printing)," Quebec Center for Functional Materials (CQMF), November 2013.
9. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” Lam Research, Online Seminar, November 1, 2013.
10. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology. Part II-Research at MIT”, Lam Research, San Jose, CA, January 14, 2014.
11. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” IBM Research Physical Sciences Seminar, T. J. Watson Research Center, January 17, 2014;
12. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology”, Samsung Electronics, Seoul, South Korea, February 13, 2014
13. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” IBM Zurich Research Center, Zurich, Switzerland, March 25, 2014
14. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” STMicroelectronics, Catania, Italy, March 26, 2014;
15. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” STMicroelectronics, Castelletto, Italy, March 27, 2014;
16. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” STMicroelectronics, Crolles, France, March 31, 2014;
17. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” Skyworks, Woburn, MA, April 30, 2014;
18. J. A. del Alamo, “III-V MOSFETs for CMOS: Recent Advances in Process Technology,” TSMC, Leuven, Belgium, July 3, 2014.
19. J. A. del Alamo, “InGaAs MOSFET Electronics,” Lund University, Lund, Sweden, September 2014.
20. J. A. del Alamo, “Nanometer-Scale III-V Electronics.” The Age of Si Symposium, MIT Campus, July 25, 2014.

21. C. J. Chang-Hasnain, “Nano- Optoelectronics on Silicon”, OSA Siegman International School on Lasers, Stanford, August 4-8, 2014.
22. C. J. Chang-Hasnain, “Nano- Photonics on Silicon”, International Nano-Optoelectronics Workshop (iNOW), St. Petersburg, Russia, August 10-22, 2014.
23. D. Fu, Demonstration for K-12 students on “How Nanotechnology and Materials Science Work”, Cal Day, Lawrence Hall of Science, April 12, 2014.
24. C. Hu, "University Innovation Changes Semiconductor Technology", Synopsys Inc, Nov. 4, 2014.
25. C. Hu, "University Innovation Changes Semiconductor Technology", Fudan University, Nov. 7, 2014.
26. T.-J. King Liu, “Mechanical Computing Redux: Nanomechanical Devices for Ultra-Low-Power Memory and Computation,” seminar given to Department of Electrical and Computer Engineering, University of California, Davis (Davis, California, USA), October 3, 2014.
27. T.-J. King Liu, “Nanomechanical Switches,” presentation at the International Technology Roadmap for Semiconductors Emerging Research Device (ERD) Assessment Workshop (Albuquerque, New Mexico, USA), August 28, 2014.
28. J. Lang, invited talk, “MEMS/NEMS Relays”, MIT Laureates & Leaders Program, October 2014.
29. J. Teherani, “Tunnel Field-Effect Transistor; “ created on Wikipedia, http://en.wikipedia.org/wiki/Tunnel_field-effect_transistor, January, 2014.
30. H.-S. P Wong, “Devices and Technologies Beyond the 7 nm Node,” invited plenary talk, Samsung Future Technology Forum, November 5, 2013. Host: Samsung Electronics, Dr. E.S. Jung, Executive Vice-President and General Manager.
31. H.-S. P Wong, “Innovating Our Way Through the Long Tail of Moore’s Law,” invited plenary talk, IBM Semiconductor Technology Symposium, Yorktown Heights, New York, December 5, 2013. Host: Dr. Anda C. Mocuta, Manager, 300mm Custom Logic Test & Integration, Client interface, IBM SRDC.
32. M. Wu, “Optical Antenna-Coupled Nano-LED for Energy-Efficient On-Chip Interconnect,” IEEE Photonics Conference, San Diego, CA, October 2014.
33. E. Yablonovitch, “Spontaneous Emission Faster than Stimulated Emission,” Materials Research Society Fall Meeting, Boston, MA, Dec. 5, 2013.
34. E. Yablonovitch, “Spontaneous Emission Faster than Stimulated Emission,” Meeting on Fundamental Problems on Quantum Physics, Weizmann Institute, Rehovoth, Israel, Mar. 24, 2014.
35. E. Yablonovitch, “Replacing the Transistor with a Lower Voltage Switch: What are the Prospects?” Intel, Hillsboro, OR, April 14, 2014.
36. E. Yablonovitch, “Replacing the Transistor with a Lower Voltage Switch: What are the Prospects?” IBM, Yorktown Heights, NY, April 18, 2014.
37. E. Yablonovitch, “Enhanced Spontaneous Emission by Means of Optical Antennas,” 11th International Symposium on Photonic and Electromagnetic Crystal Structures, Shanghai, China, May 15, 2014.
38. E. Yablonovitch, “The Challenge of Using Optical Antennas to Accelerate Spontaneous Emission,” 5th International Conference on Metamaterials, Photonic Crystals and Plasmonics, Singapore, May 21, 2014.
39. E. Yablonovitch, “Optical-Antenna-Enhanced Spontaneous Emission,” Nano-Quantum Optics Science and Technology, Seoul, Korea, July 24, 2014.
40. E. Yablonovitch, “Optical-Antenna-Enhanced Spontaneous Emission,”13th International Conference on Near Field Optics, Snowbird, UT, Sept. 1, 2014.
41. E. Yablonovitch, “Optical-Antenna-Enhanced Spontaneous Emission,” UCSD ECE Dept. Seminar, La Jolla, CA, Sept. 10, 2014.
42. E. Yablonovitch, "The Search for Really Low Threshold Voltage," 2014 IEEE S3S Conference, Millbrae, CA, Oct. 9, 2014.

2. Awards & Honors

Recipient	Reason for Award	Award Name	Sponsor	Date	Award Type
D. Antoniadis	Teaching and research contributions	2014 SRC Aristotle Award	Semiconductor Research Corporation (SRC)	Sep 2014	Scientific, Education, Industry
C. Chang-Hasnain	For pioneering contributions to vertical cavity surface emitting lasers (VCSELs)	Quantum Device Award	International Symposium on Compound Semiconductor	May 2014	Scientific, International recognition
Yida Duan, Elad Alon		Best Student Paper Award	2013 IEEE Custom Integrated Circuits Conference	Presented at CICC 2014	Scientific
Jodi Loo	Demonstration of a keen sense of creativity and inventiveness	James H. Eaton Memorial Scholarship	International Engineering Consortium through EECS Dept	May 2, 2014	Fellowship
Michael Eggleston	Contribution to the advancement of opto-electronic materials	Ross N. Tucker Memorial Award	Metallurgical Society Northern CA Electronics Materials Symposium and EECS Dept	May 2, 2014	
Seth A. Fortuna	Demonstration of electrically injected nanoLED	Best student paper finalist	IEEE Photonics Society	Oct 13, 2014	Scientific
Ali Javey		Nano Letters Young Investigator Lectureship	ACS	Aug 2014	
Tsu-Jae King Liu	Record of professional contributions has been influential in setting directions for integrated circuit technology	2014 Semiconductor Industry Association (SIA) University Researcher Award	Semiconductor Industry Association (SIA)	Mar 2014	Industry

Junqiao Wu	Cutting edge research	Presidential Early Career Award for Scientists and Engineers (PECASE)	The White House (nominated by NSF)	Dec 23 2013	Scientific
Eli Yablonovitch	Significant contribution to optoelectronics – pioneering work on strained-layer laser structures	2014 Rank Prize in Optoelectro nics	Rank Foundation, United Kingdom	Feb 10, 2014	Scientific

3. Graduates

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Arunima Balan	B.S. Chemistry/ Physics, *MIT*	Spring, 2014	4	Graduate student at Berkeley
Franiece Bennett	B.S. EE, *Norfolk State*	Spring, 2014	4	Graduate student at Berkeley
Rene Brito	B.S. EE, *UTEP*	Spring, 2014	4	Graduate student at UTEP
John Bryant	B.S., *Florida International University*	May, 2014	4	Post-Bac at FIU
Anna Colleen Crouch	B.S. Polymer/Fiber Engineering, *Georgia Tech*	Spring, 2014	4	Graduate student at Michigan
Wei Dai	B.S. EE, *UC Riverside*	Spring, 2014	4	Industry
Chen Dan Dong	B.S. Applied Math/ EE, *MIT*	Spring, 2014	4	Industry
Christopher Gaytan	B.S. EE, *UTEP*	December, 2014	4	N/A
Jordan Goldstein	B.S. Physics/ EE, *MIT*	Spring, 2014	4	Graduate student at MIT
Matthew Hartley	B.S. EE, *UL Lafayette*	Spring, 2014	4	Graduate student at Michigan
Janice Lin	B.S., *UM College Park*	Spring, 2014	4	Graduate student at UCLA
Jodi Loo	B.S., *Berkeley*	May, 2014	4	Graduate student at Berkeley
Nathan Martin	B.S., *U. Connecticut*	Spring, 2014	4	Graduate student at Penn State

Chelsea McConnell	B.S. Chem E., *Oregon State*	Spring, 2014	4	Graduate student at CU Boulder
Benjamin Osoba	B.S. EE, *Norfolk State*	Spring, 2014	4	Graduate student at Berkeley
Erick Romo-Mendoza	B.S. EE, *UTEP*	December, 2014	4	N/A
Victoria Xu	B.S. Physics, *UCSB*	Spring, 2014	4	Graduate student at Berkeley

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree*	Placement
Zheng Gu	Ph.D., *Berkeley*	December, 2014	5	Applied Materials
Sergio Almeida	Ph.D., *UTEP*	December, 2014	4	Post doc at UTEP
Natania Antler	Ph.D., *Berkeley*	May, 2014	5	KLA Tencor
Steven Chuang	Ph.D., *Berkeley*	May, 2014	5	Lam Research
Hui Fang	Ph.D., *Berkeley*	May, 2014	5	Postdoctoral Fellow, UIUC
Wilson Ko	Ph.D., *Berkeley*	July 2014	6	Infinera corporation, test and characterization engineer
Yue Lu	Ph.D., *Berkeley*	December, 2014	6	Apple Inc.
Kar Wei (Billy) Ng	Ph.D., *Berkeley*	December, 2013	5.5	Post-doc at Hong Kong University of Science and Technology
Matthew Spencer	Ph.D., *Berkeley*	December, 2014	6	Visiting Professsor, Harvey Mudd College
Jack Yaung	Ph.D., *Berkeley*	May, 2014	6	Intel Corporation
Chun Wing Yeung	Ph.D., *Berkeley*	December, 2013	5	IBM

Postdocs

Name	Departure Date	Placement (where did they go?)
Deyi Fu	June, 2014	Postdoc, National University of Singapore
Rehan Kapadia	May, 2014	Assistant Professor, Electrical Engineering, U. Southern California
Sapan Agarwal	November, 2014	Postdoc, Sandia National Laboratories, Albuquerque, NM

4a. General Outputs of Knowledge Transfer Activities

Patents: 1 provisional patent application submitted to the UC Berkeley's Office of Intellectual Property and Industry Research Alliances.

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 110 participants. Funding of faculty, postdoctoral, graduate student and undergraduate student participants are summarized as follows.

Period 5	**Summer**	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	6	0	0	17	23

	Funded by E³S				
Category	50% or more	less than 50%	**Total**	**Other Funding Source Total**	**Total Participants**
Postdocs	9	1	10	4	14
Grad Students	13	13	26	19	45
Undergrads		21	21	0	21
TOTAL	**22**	**35**	**57**	**23**	**80**

The demographics of all participants are given the following page.

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
23	Faculty	11	Berkeley	19	E.E.	20	M	0	Hearing Impairment	2	Hispanic or Lantino	0	American Indian or Alaskan Native	19	US Citizens
		7	MIT	1	Mats Sci	3	F	0	Visual Impairment	18	Not Hispanic or Latino	7	Asian	4	Permanent Resident
		1	Stanford	1	Chemistry			0	Mobility/Orthopedic Impairment	3	Decline to State	0	Black or African American	0	Other non-US Citizen
		1	UTEP	2	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					21	None			14	White	0	Not Available
		1	FIU					2	Decline to State			2	Decline to State		
		1	Other					0	Not Available			0	Not Available		
14	Postdocs	8	Berkeley	12	E.E.	10	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	4	US Citizens
		3	MIT	1	Mats Sci	4	F	0	Visual Impairment	14	Not Hispanic or Latino	11	Asian	2	Permanent Resident
		2	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	8	Other non-US Citizen
		0	UTEP	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	FIU					14	None			3	White	0	Not Available
								0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
45	Graduate Students	30	Berkeley	35	E.E.	40	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	26	US Citizens
		11	MIT	5	Mats Sci	5	F	0	Visual Impairment	42	Not Hispanic or Latino	21	Asian	1	Permanent Resident
		1	Stanford	2	Physics			0	Mobility/Orthopedic Impairment	1	Decline to State	2	Black or African American	17	Other non-US Citizen
		2	UTEP	1	ME			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	1	Decline to State
		1	FIU	2	Chemistry			44	None			19	White	0	Not Available
				1	Other			1	Decline to State			3	Decline to State		
								0	Not Available			0	Not Available		
21	Undergraduate Students	3	Berkeley	12	E.E.	15	M	0	Hearing Impairment	5	Hispanic	1	American Indian or Alaskan Native	18	US Citizens
		1	MIT	1	Mats Sci	6	F	0	Visual Impairment	16	Not Hispanic or Latino	4	Asian	2	Permanent Resident
		0	Stanford	3	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	1	Black or African American	1	Other non-US Citizen
		2	UTEP	1	ME			0	Other	0	Not Available	1	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	3	ChemE			21	None			17	White	0	Not Available
		0	CCC	1	Engr Phys			0	Decline to State			0	Decline to State		
		0	FIU					0	Not Available			0	Not Available		
		15	Other												
7	Staff	5	Berkeley	0	E.E.	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	6	US Citizens
		2	MIT	0	Mats Sci	6	F	0	Visual Impairment	5	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	2	Black or African American	0	Other non-US Citizen
		0	UTEP	5	E3S			0	Other	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
			FIU	2	Other			4	None			2	White	1	Not Available
								1	Decline to State			0	Decline to State		
								2	Not Available			1	Not Available		
110	**TOTAL PARTICIPANTS**														

5b. Affiliates

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

Category		Institutional		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
40	Pre-College Students	0	Berkeley	0	E.E.	23	M	0	Hearing Impairment	30	URM			0	US Citizens
		0	MIT	0	Mats Sci	17	F	0	Visual Impairment	10	Non-URM			0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment					0	Other non-US Citizen
		0	UTEP	0	Other			0	Other					0	Decline to State
		0	LATTC	40	N/A			0	None					40	Not Available
		0	CCC					0	Decline to State						
		40	Other					40	Not Available						
10	Staff	6	Berkeley	1	E3S	4	M	0	Hearing Impairment	2	Hispanic	0	American Indian or Alaskan Native	9	US Citizens
		3	MIT	3	OEOP	6	F	0	Visual Impairment	7	Not Hispanic or Latino	1	Asian	0	Permanent Resident
		0	Stanford	5	TAP			0	Mobility/Orthopedic Impairment	0	Decline to State	3	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Other			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		1	LATTC					8	None			4	White	1	Not Available
								1	Decline to State			1	Decline to State		
								1	Not Available			1	Not Available		
78	**TOTAL AFFILIATES**														

6. *Center Partners*

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

10.	Lawrence Berkeley National Laboratory	National Laboratory	Berkeley, CA	Hans A. Bechtel & Michael C. Martin	Research	N
11.	Aerospace Corporation	Company	El Segundo, CA	Joel Schulman	Research	N
12.	Western Digital Corporation	Company	Fremont, CA	Rabee Ikkawi	Research	
13.	MIT Lincoln Laboratory	FRDC	Lexington, MA	Kenneth Diest	Research	N
14.	Johannes Gutenberg University	University	Mainz, Germany	Mathias Klaui	Research	Yes
15.	UT Dallas	University	Dallas, TX	Bob Wallace	Research	N
16.	University of Florida	University	Gainesville, FL	Jing Guo	Research	N
17.	National Chiao-Tung University	University	Taiwan	Edward Y. Chang	Research,	N
18.	University of California, Berkeley, ME Dept.	University	Berkeley, CA	Xiang Zhang	Research	N
19.	CEA-LETI	French National Laboratory	Grenoble, France	Louis Hutin & Susana Bonnetier	Education	N
20.	Nanosys	Company	Milpitas, CA	Veeral Hardev	Education	N
21.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Shawna Young	Education & Diversity	N
22.	MIT Office of the Dean of Graduate Education	University	Cambridge, MA	Eboney Hearn & Monica Orta	Education & Diversity	N
23.	MIT Office of Digital Learning	University	Washington DC	Elizabeth COE	Education & Diversity	N
24.	National Nanotechnology Infrastructure Network (NNIN)	University	Stanford, CA	Mike Deal	Education & Diversity	N
25.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Keith Schoon	Education & Diversity	N
26.	UC Berkeley Summer Sessions	University	Berkeley, CA	Richard Russo	Education	N
27.	Center of Integrated Nanomechanical Systems	University	Berkeley, CA	Meltem Erol	Education & Diversity	N

28.	Synthetic Biology Engineering Research Center	University	Berkeley, CA	Kate Spohr	Education & Diversity	N
29.	The Team for Research in Ubiquitous Secure Technology	University	Berkeley, CA	Aimee Tabor	Education & Diversity	N
30.	UC Berkeley, Center for Teaching & Learning	University	Berkeley, CA	Richard Freishtat	Education	N
31.	Lawrence Hall of Science	Museum	Berkeley, CA	Catherine Halversen	Education	N
32.	UC Berkeley, School of Public Health	University	Berkeley, CA	Deborah Barnett	Education	N
33.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon	Education & Diversity	N
34.	UC Berkeley, Berkeley Edge Conference	University	Berkeley, CA	Ira Young	Education & Diversity	N
35.	UC Berkeley, Science@Cal	University	Berkeley, CA	Rachel Winheld	Education & Diversity	N
36.	Berkeley Foundations for Opportunities in Information Technology	Non-Profit	Berkeley, CA	Orpheus Crutchfield	Education & Diversity	N
37.	Mathematics Engineering Science Achievement	Non-Profit	Oakland, CA	Julian Martinez	Education & Diversity	N
38.	SEM Link Inc.	Non-Profit	Oakland, CA	Tokiwa Smith	Education & Diversity	N
39.	Center for Integrated Quantum Materials	University	Washington D.C.	Tina L. Brower-Thomas	Education & Diversity	N
40.	University of California Office of the President	University	Oakland, CA		Diversity	N
41.	Engineering Outreach @ Berkeley	Non-Profit	Berkeley, CA	Matthew Spencer	Education & Diversity	N
42.	Berkeley Engineering and Mentors	Non-Profit	Berkeley, CA	Siddarth Krishna	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)	7
2	the number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center)	42
3	the total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC)	$269,061
4	the number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF) .	106*

* The number will be finalized before the version of the report is submitted. This number will likely increase as all demographics forms are submitted.

8. Media Publicity of Center

None.

IX. INDIRECT/OTHER IMPACTS

International Activities:

- R. Oeflein, an undergraduate researcher at the Center, spent 9 weeks at CEA-Leti, Grenoble France doing research in SiGeOI TFET. He and other scientist in the hosting laboratory have co-authored a paper that was accepted for oral presentation at IEEE EuroSOI-ULIS 2015 in Bologna, Italy.
- The Center for E^3S hosted 15 French Ph.D. students who are doing their thesis research in Grenoble, France in October. The visit was a technical exchange in that E3S students present their own research while the French studies presented theirs. The French visitors also brought shared information about research in Grenoble. The Center also sponsored a networking event that allowed informal interactions.
- E. Yablonovitch received the 2014 Rank Prize in Optoelectronics for "Significant contribution to optoelectronics – pioneering work on strained-layer laser structures", awarded by the Rank Foundation, UK
- E. Yablonovitch gave talks related to Spontaneous Emission and the use of Optical Antennas at various locations outside the US: Shanghai, Soeul, Rehovoth, Israel. This topic relates to Theme III research of the Center.
- C. Chang-Hasnain and a number of E^3S graduate students attended International Nano-Optoelectronics Workshop (iNOW), St. Petersburg, Russia, August 10-22.
- J del Alamo gave talks on III-V MOSFETs for CMOS: Recent Advances in Process Technology, which includes the RIE with digital etch for high aspect ratio III-V features at various locations outside the US: Sweden, Belgium, France, Italy, Switzerland, South Korea. The development of the REI process was funded by E3S as part of Theme I research.

Center Funded Research that likely have impact beyond the goals of the Center:

- In the knowledge transfer section of this report, we identified 2 device structures, 2 processing technologies and 1 material system that the Center has funded and in the past year have solicited third party interest; see p84 of this report. examples of

Education and Diversity:

- Impacted >30% of the campuses in the California Community College System: In 2012, the Center was awarded a NSF Research Experiences for Undergraduates (REU) Site to extend the E^{3}S Transfer-to-Excellence REU program to community college students outside of disciplines affiliated with the Center from five to fifteen summer students annually. During the summer 2014 (period 5), the Center hosted 10 community college students from science and engineering majors in 9 different labs on Berkeley's campus, including labs at Lawrence Berkeley National Laboratory (LBNL). These students research focused on nanotechnology, synthetic biology, and bioengineering. Over the Center's lifespan, E^{3}S has hosted 44 community college students from 33 institutions from every region in the state of California. This total consists of 44 projects advised by 28 faculty mentors and supervised by 41 graduate student and postdoc mentors. Among this group, over 90% have transferred to a 4-year institution.
- Coummunity College Faculty: Similar to the expansion for the summer research program for community college students, the Center expanded its E^{3}S Teacher Fellows Program from two to six community college faculty with a NSF Research Experience for Teachers (RET) Site award. New in Period 5 because of this new NSF award was the implementation of curriculum development workshops on context-based learning, a pedagogical approach, which has been shown through assessments to enhance the students' interest in STEM. Closely aligned with project-based learning and inquiry-based science education, a context-based approach was selected to provide community college faculty a pedagogical method that can enhance learning, engage students, and improve the relevance of the science being taught in Period 5, four community college faculty from electrical engineering, biology, phyics, and computer science departments at Bay Area community colleges conducted a nine-week research experience in green and sustainable manufacturing in Berkeley's Department of Mechanical Engineering. In addition to coordinating the logistics (i.e., application, selection, placement, and implementation) for the summer RET program, the Center hosted five curriculum development workshops, three on context-based learning pedagogy and two on digital/online education with Berkeley's Center for Teaching and Learning, Berkeley Resource Center for Online Education, and School of Public Health; and Lawrence Hall of Science. At the conclusion of the summer, these faulty members each developed a course module or lab assignment, which will be taught at their respective community college during the 2014-2015 academic year.

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XI. APPENDICES

Appendix A: Biographical Information of New Faculty

New Faculty in Period 5

- **Sakhrat Khizroev** is an inventor with an expertise in nanomagnetic/spintronic devices. Since 2011, he is a tenured Professor at the Colleges of Engineering and Medicine of Florida International University, Miami, FL. From 2006 to 2010, Khizroev was a tenured Professor at the Department of Electrical Engineering, University of California, Riverside (UCR). Prior to his academic career, Prof. Khizroev spent almost four years as a Research Staff Member with Seagate Research (1999-2003) and one year as a Doctoral Intern with IBM Almaden Research Center (1997-1998). Perpendicular magnetic recording (PMR), three-dimensional (3-D) magnetic memory and near-field magneto-optical transducers for 5-nm recording are among the pioneering and patented technologies which emerged under Khizroev's leadership. PMR is currently the main technology in the multi-billion-dollar data storage industry. He holds over 30 granted US patents, has authored over 120 refereed papers, 1 book and many book chapters. He is a Fellow of National Academy of Inventors (NAI). Khizroev received a BS in Physics from Moscow Institute of Physics and Technology, a MS in Physics from the University of Miami, and a PhD in Electrical and Computer Engineering from Carnegie Mellon University in 1992, 1994, and 1999, respectively.

- **Vladimir Stojanovic** is an Associate Professor of Electrical Engineering and Computer Science at University of California, Berkeley. His research interests include design, modeling and optimization of integrated systems, from CMOS-based VLSI blocks and interfaces to system design with emerging devices like NEM relays and silicon-photonics. He is also interested in design and implementation of energy-efficient electrical and optical networks, and digital communication techniques in high-speed interfaces and high-speed mixed-signal IC design. Vladimir received his Ph.D. in Electrical Engineering from Stanford University in 2005, and the Dipl. Ing. degree from the University of Belgrade, Serbia in 1998. He was also with Rambus, Inc., Los Altos, CA, from 2001 through 2004 and with MIT as Associate Professor from 2005-2013. He received the 2006 IBM Faculty Partnership Award, and the 2009 NSF CAREER Award as well as the 2008 ICCAD William J. McCalla, 2008 IEEE Transactions on Advanced Packaging, and 2010 ISSCC Jack Raper best paper awards. He is an IEEE Solid-State Circuits Society Distinguished Lecturer for the 2012-2013 term.

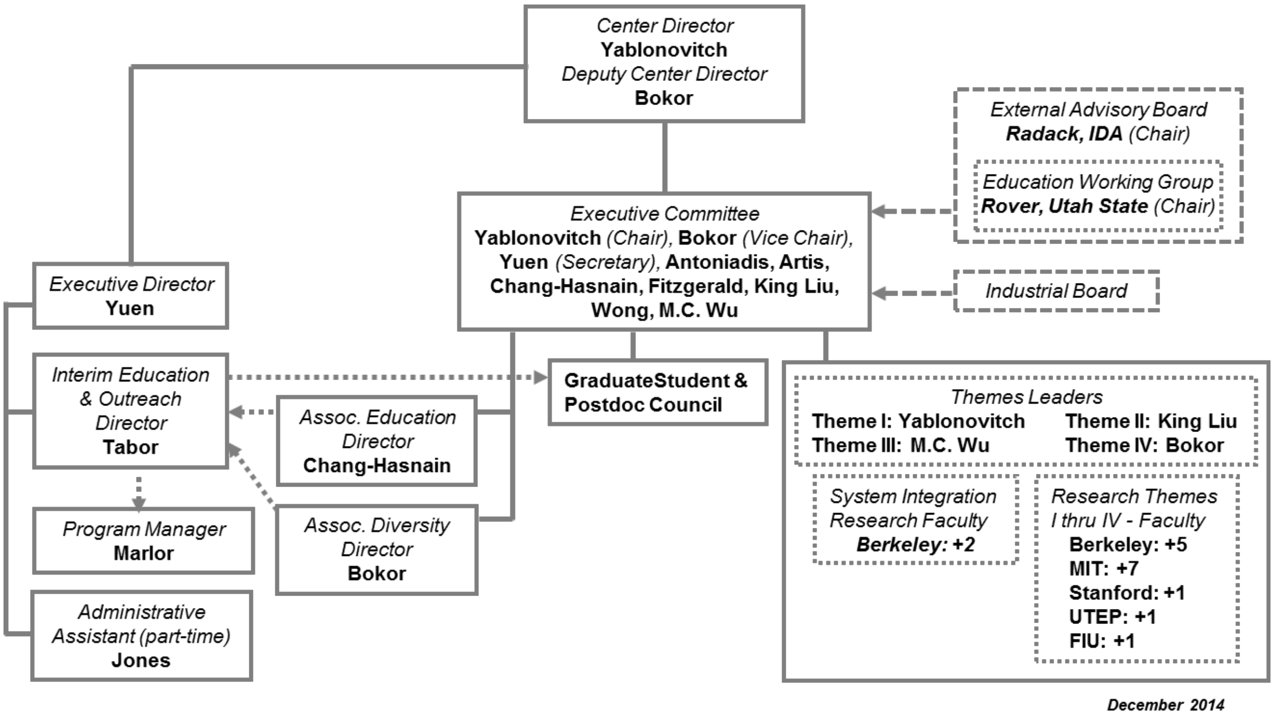
New Faculty in Period 6

- **Felix Fischer** is an Assistant Professor of Chemistry at the University of California Berkeley. His research interests focus on the design and the fabrication of atomically unambiguously defined nanomaterials and their incorporation into functional electronic devices such as organic field-effect transistors, photovoltaic cells, and integrated molecular circuits. A particular interested lies in the bottom-up synthesis of graphene heterostructures and the exploration of their unique properties emerging from quantum confinement effects at the nanometer scale. Felix received his Ph.D. in Organic Chemistry from the Swiss Federal Institute of Technology Zurich in 2008. Prior to joining the Faculty at UC Berkeley as an Assistant Professor (2011) he was a German National Academy of Sciences Leopoldina Postdoctoral Research Fellow at Columbia University New York, NY. He received the Packard Fellowship for Science and Engineering (2013), the DOE Early Career Award (2013), the ACS PRF Doctoral New Investigator Award (2012), and the Thieme Chemistry Journals Award (2011).

Appendix B: Organizational Chart

Center for Energy Efficient Electronics Science (E^{3}S)

December 1, 2014



Appendix C: 2014 External Advisory Board Meeting Agenda

November 5 (630 Sutardja Dai Hall)

Time	Duration	Topics	Presenter(s)
9:00 AM	0:30	*Continental Breakfast*	
9:30 AM	0:30	Introductions	**Yablonovitch**
		Research Updates	
10:00 AM	0:45	Theme I	**Yablonovitch, Zhao & Roy**
10:45 AM	0:15	Q&A	
11:00 AM	0:15	*Break*	
11:15 AM	0:40	Theme II	**King Liu & Lang**
11:55 AM	0:15	Q&A	
12:10 PM	1:10	*Lunch & Poster Session (550 Sutardja Dai Hall; Poster List on p2)*	
1:20 PM	0:30	Theme III	**Wu**
1:50 PM	0:15	Q&A	
2:05 PM	0:35	Theme IV	**Bokor**
2:40 PM	0:15	Q&A	
2:55 PM	0:25	System Integration	**Stojanovic**
3:20 PM	0:10	Q&A	
3:30 PM	0:15	*Break*	
3:45 PM	0:40	Education Update	**Artis**
4:25 PM	0:15	Q&A	
4:40 PM	0:30	Diversity Updates	**Artis**
5:10 PM	0:15	Q&A	
5:25 PM	1:10	Deliberations	
6:35 PM		*Leave for Dinner*	
7:00 PM		*Dinner at Comal*	

November 6 (400 Cory Hall)

Time	Duration	Topics	Presenter(s)
8:30 AM	0:30	*Continental Breakfast*	
9:00 AM	0:30	Center Management & KT	**Yuen**
9:30 AM	0:10	Q&A	
9:40 AM	0:20	Wrap-up Q&A Session	
10:00 AM	0:20	iLab Remote Demo	**Steinmeyer & del Alamo**
10:20 AM	0:15	*Break*	
10:35 AM	2:55	Deliberations	
1:30 PM	1:00	Readout & Dialog	
2:30 PM		Conclusion	

Appendix D: 2014 Research Seminars Attendance

Dates	Faculty	Postdocs	Graduate Students	Undergrad Students	Staff	Other
2014 Seminar Series						
February 6	4	3	18	3	4	0
February 20	1	1	16	2	3	0
March 6	1	4	6	21	4	0
March 20	0	5	11	0	1	0
April 3	2	2	11	0	2	0
April 16	4	3	12	0	4	1
June 12	7	3	12	19	4	3
June 26	8	5	24	16	4	2
July 10	5	3	5	13	5	3
July24	4	5	11	11	6	7
September 26	4	7	21	0	1	0
October 9	5	4	18	0	1	0
October 20	4	6	18	0	1	0
November 20	2	5	12	1	1	0
December 11	*Not Available*					

Appendix E: E^{3}S Professional Development Program

Objective: Equip E^{3}S students and postdoctoral researchers with the skills and experiences needed to maximize their potential and success in their professional careers.

Certificate Requirements: Formal, but flexible requirements

- At least one training in leadership, teaching **OR** mentoring
- Three other areas required

Training Areas: Leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship

Training Opportunities: Workshops and hands-on experience in training areas

Leadership*

- Complete online or in-person leadership training (1 hour)
- Complete diversity training (1 hour)
- Take lead in 1 leadership event *OR* supporting role in 3 events
- Opportunities: Graduate Student Postdoc Council, seminar coordinator, journal club coordinator, retreat committee, STC Directors Meeting, E^{3}S representative, theme meeting coordinator, REU selection committee, poster session evaluator

Teaching*

- Complete online or in-person teacher training (1 hour)
- Complete diversity training (1 hour)
- Practice teaching *OR* develop course curriculum at any academic level of your choice
- Opportunities: Curriculum development for outreach programs, E^{3}S summer school, online course development, MOSTEC instructor

Mentoring*

- Attend mentor training (1 hour)
- Complete diversity training (1 hour)
- Mentor an undergraduate or high school student
- Opportunities: E^{3}S REU, ETERN, TTE REU, MOSTEC, RET

Outreach

- Attend outreach training (1 hour)
- Take lead in 1 outreach event or supporting role in 3 events
  Opportunities: Research presentation for non-scientists & engineers, lead hands on project for high school students, Cal-Day, EECS Visit, Berkeley EDGE
- Conference, serve as judge at science fair, demonstrate research at science fair for k-12 students, laboratory tour

Science Communication

- Attend a science communication workshop (1 hour)
- Present research to center (1 hour)

- Present research to non-center audience (1 hour)
- Opportunities: Poster presented at annual retreat, EAB, Site Visit, or E^3S Symposium; presentation at annual retreat, EAB, Site Visit, Journal Club, Research seminar, or E^3S Symposium

Proposal Writing

- Attend a proposal writing workshop (1 hour)
- Write and submit proposal on research, education, and diversity activities
- Opportunities: proposal for E^3S education, diversity or research programs

Entrepreneurship

- Attend an entrepreneurship workshop (1 hour)
- Develop and submit a business plan *OR* complete innovation and commercialization course

**Leadership, teaching, and mentoring training areas include additional training on diversity.*

Appendix F: E^{3}S REU Joint Recruitment Calendar

2014 Joint Recruitment Calendar

for Summer Research Experiences for Undergraduates and Engineering Graduate Diversity

April 2014			
Women in Cyber Security	April 10-12	Nashville, TN	Trust
September 2014			
University of Puerto Rico, Mayaguez	September 16	Mayaguez, PR	COE
Massachusetts Institute of Technology	September 19	Cambridge, MA	COE
Morgan State University, Howard University,			
Norfolk State University, and Hampton University	September 22-25	DC/Maryland/Virginia	E^{3}S
October 2014			
Grace Hopper Conference	October 7-10	Phoenix, AZ	TRUST
Society for Advancement of Chicanos and			
Native Americans in Science (SACNAS) Conference	October 23-25	Los Angeles, CA	E^{3}S
University of California, Riverside	October 24	Riverside, CA	E^{3}S
November 2014			
Society of Hispanic Prof Engineers Annual Conf	November 7-8	Detroit, MI	E^{3}S
December 2014			
E3S Webinar: Program Overview and Q & A	December 10	Online	E^{3}S
E3S Webinar: Program Overview and Q & A	December 18	Online	E^{3}S
January 2015			
E3S Webinar: Program Overview and Q & A	January 19	Online	E^{3}S

Appendix G: TTE REU Recruitment Calendar

October 2014

UC-Berkeley's Community College Day	October 2	Berkeley, CA
El Camino College/ Southern California Transfer Alliance Project	October 15	Los Angeles, CA
Santa Monica Community College	October 16	Santa Monica, CA
Los Angeles Trade Technical College	October 17	Los Angeles, CA
Society for Advancement of Chicanos and Native Americans in Science (SACNAS) 2014 Conference	October 15-18	Los Angeles, CA
East Los Angeles College	October 24	Los Angeles, CA

November 2014

MESA Student Leadership Conference	November 1	San Diego, CA
Chabot Community College	November 25	Hayward, CA
Sacramento City College	November 25	Sacramento, CA

December 2014

UC Berkeley Transfer Alliance Project	December 2	Berkeley, CA
Webinar- Topic: Program Overview, Q & A	December 3	Online
Webinar- Topic: Program Overview, Q & A	December 18	Online

January 2015

Webinar- Topic: Program Overview, Q & A	January 19	Online

Appendix H: 2014 E^{3}S Annual Retreat Poster Session

	Title	Authors (*Poster Presenters)
Theme I		
1.	Piezoelectric Voltage Transformer for Low Voltage Transistors	**S. Agarwal*** and E. Yablonovitch
2.	InAs Bilayer Tunneling Field Effect Transistors	**J. Carter***, S. Agarwal, and E. Yablonovitch
3.	Tunnelling in Type-II and Type-III Heterojunctions	**R. Iutzi*** and E. Fitzgerald
4.	Fabrication of the 3Gate strained-Si/strained-Ge Bilayer TFET"	**J. Teherani***, W. Chern, T. Yu, D. Antoniadis, and J. Hoyt
5.	InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs Fabricated by a Top-down Approach	**X. Zhao*,** A. Vardi, and J. A. del Alamo
Theme II		
6.	NEM Relays Using 2-Dimensional Nanomaterials for Low Energy Contacts	**J. Cao***, S. Lee, and H.-S. P. Wong
7.	Nanomechanics for Energy Efficient Electronic Applications	**F. Niroui***, E. Sletten, A. Wang, W.J. Ong, P. Deotare, A. Murarka, W. Chang, T. Swager, J. Lang and V. Bulovic
Theme III		
8.	Methodology to Simulate Selective Area Growth	**S. Almeida***, E. Ochoa, J. Chavez, and D. Zubia
9.	InP Nanopillar PhotoBJT Integrated on Silicon Substrate	W. Ko, **I. Bhattacharya***, T. Tran, F. Lu, D. Skuridina, and C. Chang-Hasnain
10.	Electrically Injected nanoLED with Enhanced Spontaneous Emission from a Cavity Backed Optical Slot Antenna	**S. Fortuna***, M. Eggleston, K. Messer, E. Yablonovitch & M. C. Wu
11.	Germanium Phototransistors Integrated onto Silicon Photonics	**R. Going***, T. J. Seok, C. Keraly, and M. C. Wu
12.	Optical Antenna nanoLEDs for Efficient On-Chip Communication	**M. Eggleston***, S. Fortuna, K. Messer, E. Yablonovitch & M. C. Wu
Theme IV		
13.	Magnetic Tunneling Junction based Logic Devices	**J. Hong***, S. Khizroev, and J. Bokor
14.	Magneto-Electric Nanoparticle-Linked Spin-Transfer-Torque Magnetic Tunneling Junctions	**M. Stone***, **A. Hadjikhani***, R. Guduru, J. Hong, J. Bokor, P. Liang, and S. Khizroev
15.	Ultrafast Non-equilibrium Magnetic Switching	**Y. Yang***, J. Hong, Z. Gu, and J. Bokor
System Integration		
16.	Variability Considerations for Steeply Switching Logic Devices	**P. Lu***, and E. Alon

Appendix I: 2014 Student and Postdoc Survey

Year to Year Comparison of Survey Data

Number of Participants: 2014: 26; 2013 – 21; 2012 – 20; 2011 – 15

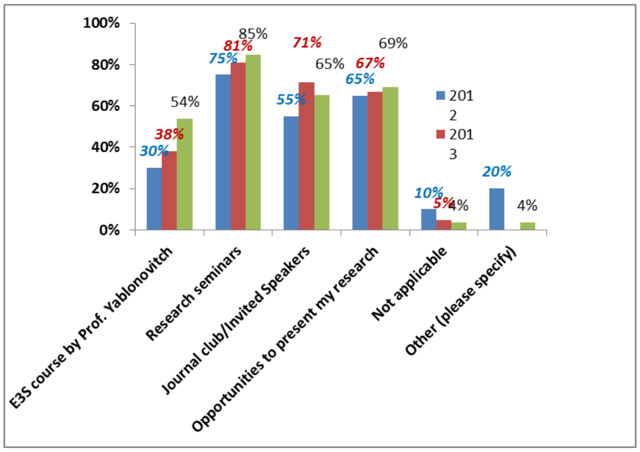
Part A: Teamwork, Inclusiveness, Leadership, Decision Making and Performance

Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree; 0=Cannot Rate

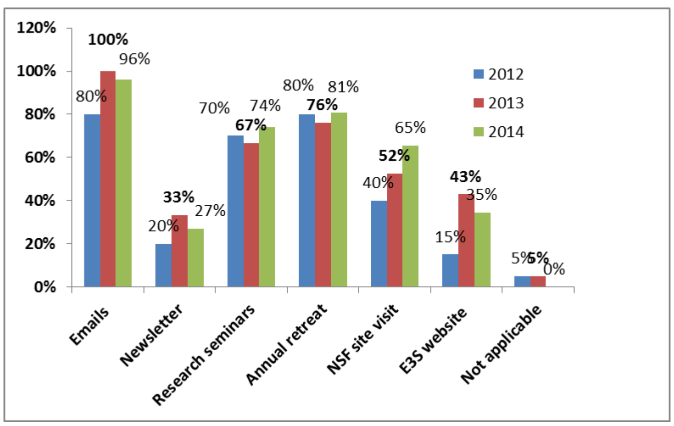
	Survey Question	**2014**	**2013**	**2012**	**2011**
Research	The Leadership Team identifies concepts and scientific principles that will enable fundamentally new and different science for digital information processing, in order to achieve a radical reduction in energy consumption in electronic devices.	4.6±0.6	4.4±0.5	4.2±0.7	4±1
	The Center is making progress in its research program.	4.5±0.6	4.1±0.9	4.2±0.5	
	I understand how my project will contribute to the goals and vision of the Center.	4.5±0.7	4.5±0.6	4.3±0.9	
Inclusiveness	The Leadership Team educates a diverse generation of scientists, engineers and technicians to be the future leaders, researchers, educators and workers of low energy consumption device science and technology.	4.6±0.5	4.1±0.8	4.1±0.6	4.1±0.6
	The Leadership Team provides a research environment that is inclusive of different institutions, research themes, science and engineering disciplines, and individual differences.	4.7±0.5	4.0±0.9	4.1±0.6	4±1.0
	The Leadership Team provides a research environment that crosses disciplinary and institutional boundaries.	4.5±0.7			
Communication	The Leadership Team keeps Center members well informed as there is a clear and timely communication on all Center activities.	4.7±0.6	4.2±0.6	4.2±0.5	4±0.7
Collaboration	The Leadership Team provides a research environment that is collaborative.		4.2±0.7	4.2±0.7	3.7±0.7
	The Leadership Team is providing a work environment that values and encourages teamwork.	4.6±0.5	3.9±0.8		
	The Leadership Team is providing opportunities to collaborate.	4.8±0.4	4.1±0.9		
Collaboration	The Leadership Team is providing tools that facilitate collaboration.	4.4±0.8	4.1±0.7		

Part B: Effectiveness of the Center's Activities

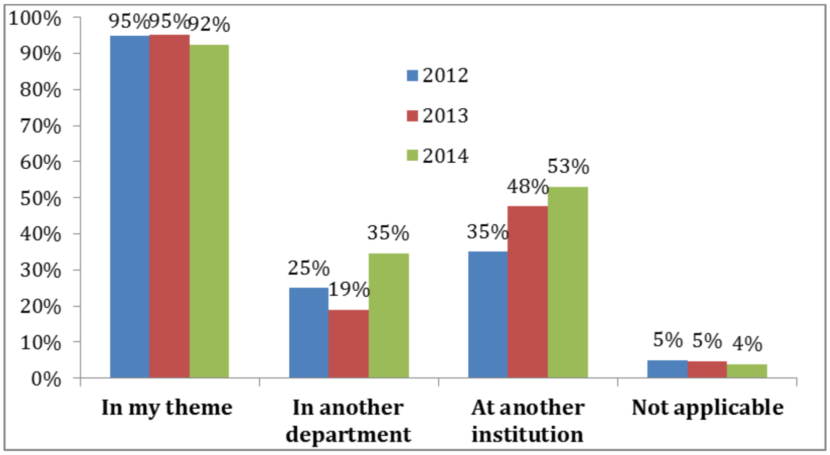
1. Respondent indicated the following activities are sharpening their understanding of low energy consumption device science and technology.



2. Respondent felt that the Center communicates with them effectively and in a timely manner using the following resources.



3. In terms of collaborating with other areas, respondent indicated that the following people by helped with their E^{3}S research through discussions, inputs, and general collaborations.



Part C: Ethics

When asked whether colleagues act in an ethical manner 96.2% (25) of respondents indicated that was the case. One respondent indicated that they were unable to respond. None of the respondents indicated they witnessed unethical behavior.

Appendix J: 2014 E3S Faculty Survey

Collaboration, Ethical Behavior, and Leadership

Part A: Collaboration

In terms of collaboration, faculty rated each faculty member in the Center on a scale of collaboration. Participants were instructed to not rate themselves. The scale was as follows:

0 = No interaction

1 = NETWORKING (For example, interaction limited to participation in Centerwide meetings)

2 = COOPERATION - Limited and informal interaction/collaboration on E3S research within a Theme or institution (For example, participation in Theme meetings mainly to present your own project, ad hoc sharing of research ideas/recipes/equipment with another E3S co-PI on as needed basis.)

3 = COORDINATION - Formalized collaboration on an E3S project within one institution (For example, formal division of responsibilities on the same E3S project; frequent project meetings to coordinate; students of each group recognizing that together, they are a project team.)

4 = COALITION - Formalized collaboration on an E3S project within one institution and limited, but sustained, contributing role on an E3S project that is mainly undertaken at another member institution (Same as level 3, PLUS significant technical participation on another E3S project)

5 = COLLABORATION - Formalized collaboration on an E3S project that has participation across multiple member institution and/or Themes (Multiple co-PIs from different institutions or Themes are on a project engaging at Level 3 or above)

In terms of how participants external to a theme rated the other themes, results revealed there is relatively minimal collaboration and interactions ranging in the networking (1) to cooperation (2) range

	Mean Score
Systems Integration	1.57
Nanoelectronics	1.29
Nanophotonics	1.44
Nanomagentics	1.09
Nanomechanics	1.31

Looking at the internal level of collaboration within theme, respondents indicated that within theme collaboration was relatively high for most research themes. However, some themes report interactions within the cooperation (2) range:

	Mean Score
System Integration (n=2)	4.50
Nanoelectronics (n=9)	2.24
Nanophotonics (n=2)	5.00
Nanomagentics (n=3)	3.50
Nanomechanics (n=5)	2.55

Part B: Leadership

Responses in Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree; 0=Cannot Rate

The E^{3}S leadership team is dedicated to:	**2013**	**2014**
Creating an inclusive work environment.	4.8±0.4	5.0±0
Promoting a work environment that values and encourages teamwork.	4.8±0.4	5.0±0
Providing open and timely communication to me.	4.7±0.5	4.9±0.3
Recognizing and evaluating me on my performance.	4.3±0.8	4.7±0.7
Making decisions that are in the best interest of the Center.	4.8±0.4	4.8±0.4
Promoting strong ethics and responsible conduct of scientific research.	4.9±0.3	
Providing opportunities to collaborate.	4.7±0.5	4.9±0.3
Providing tools that facilitate collaboration.	4.5±0.7	4.7±0.6
Educating a diverse generation	4.8±0.4	4.9±0.5
Identifying fundamentally new concepts and scientific principles	4.9±0.3	4.9±0.2
Number of Respondent	11	21