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Center for Energy Efficient
Electronics Science

Final

Period 6 Annual Report

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Berkeley University of California | Massachusetts Institute of Technology | Stanford University | The University of Texas at El Paso | Florida International University | California Community Colleges Chancellor's Office

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I. GENERAL INFORMATION

1a. Center Information

Date submitted	February 5, 2016
Reporting period	March 1, 2015– February 29, 2016
Name of the Center	Center for Energy Efficient Electronics Science (E^3S)
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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.

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

Institution Name	Stanford University H.-S. Philip Wong
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Role of Institution at Center	Stanford is a lead research, education, and outreach partner.

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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 Sakhrat Khizroev
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Role of Institution at Center	FIU is a research, education, and outreach partner.

Institution Name	California Community Colleges Chancellor's Office Pamela D. Walker
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Role of Institution at Center	California Community Colleges Chancellor's Office represents the California Community College system whose multiple member campuses are education and outreach partners to encourage greater women, minority and first generation college student participation in science, engineer and mathematics.

1b. Biographical Information of New Faculty

Please see Appendix A: Biographical Information of New Faculty for biographical information on two new faculty members. One was added to the Center in Period 6 and one will be added in Period 7.

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	Michael Bartl
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2. Context Statement

As it enters in its second five years as a NSF Science and Technology Center, the Center for Energy Efficient Electronics Science (E^3S) continues to work on bringing forth a broad-based effort aimed at making fundamental advances in physics, chemistry, and materials science to address the energy consumption in components for information processing. The need for such a scientific endeavor is as important now as it was in 2010, when the Center was founded.

The semiconductor industry has continued to be challenged by the power density of increasingly complex integrated circuit (IC) chips, projecting that practical limits would arise, despite continuous technological improvements. Owing to these improvements, the information processing technology sector that has enabled IC chips continues to experience explosive growth. In recent years, advancements such as cloud computing, social networking, mobile internet and data analytics have further accelerated demand for information processing. The increasing importance of mobile internet, wireless sensor swarms, and body-centered networks demands ever increasing functionality from a fixed amount of battery energy.

To address the power density challenge that can deter the continuing growth of information processing capacity, researchers, particularly those in industry and academia, are pursuing incremental approaches to address power density and the energy-per-bit challenge. The Center for E^3S, however, is continuing to seek opportunities for technological breakthroughs that rest in the fact that 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**.

The basic component of information processing is the transistor, which for all its splendor of having made the interconnected society of today, **suffers from a serious drawback**. Its conduction is thermally activated, and requires a powering voltage $>>kT/q = 26$ mVolt, 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 mVolt. **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.

The Center for E^3S concentrates on two fundamental components of digital information processing systems: the communications logic switch and the short-medium range communication of information between logic elements. The Center has brought together researchers from five institutions who have the complementary skills and expertise to pursue research opportunities in a broad-based effort aimed at making fundamental advances in the physics, chemistry, and materials science of communications logic switches. Our emphasis has been on identifying and addressing the 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 in the context of device and circuit performance 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. The need for basic science is supported by the continuing gap between the experimental results versus theoretical predictions. Much of the research in this area has been pursued by the engineering optimization or a technology development approach. But we seek basic scientific answers to approach the fundamental limits of energy consumption required to process information, to reduce the energy per operation by many orders of magnitude.

The five E^3S member institutions are: University of California, Berkeley (*Berkeley*), the lead, Massachusetts Institute of Technology (*MIT*), Stanford University, The University of Texas at El

Paso (*UTEP*), and Florida International University (*FIU*). Researchers from these institutions are engaged 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.

In addition to elucidating the underlying science, another objective 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. 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 or even by integrating one of the approaches with other functionalities that are not under research in the Center.

Overarching these four Themes is the System Integration research to ensure that the component research outcomes of the Center will be effective in enabling future ultra-low energy information systems. In the first five years of the Center, one System Integration research outcome is 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 adopted. In the Center's Performance during Period 6, the System Integration researchers have been fully integrated into Theme-specific collaborations guiding each Theme with a circuit/systems perspective.

Research Goals & Objectives: The research goals of the Center for E^3S have been set from fundamental consideration on the minimum energy needed per digital function. As we strive to reach the minimum energy per bit, part of the goal is to understand how low each approach can get compared to the fundamental limits, and to elucidate the factors that determine the minimum energy that each approach can reach.

The Center shares a common objective for a new switch in the form of the following specifications:

- Steepness (or sensitivity): ~1 mV/decade, allowing switches with a swing of only a few milli-Volts.
- On/Off current ratio: 10^6:1
- Current Density or Conductance Density (for miniaturization): 1 mSiemens/μm; i.e., a 1 μm device should conduct at ~1 kΩ in the on-state. (This requirement is given here in mSiemens/μm of conductance versus the traditional requirement of mA/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.

Research Strategic Plan and Rationale: As the Center embarks on its second five years, PI and Center Director, **E. Yablonovitch** led the Center's members (faculty, postdocs, students and staff) to review the accomplishments and challenges of the first five years and plan strategically for the Center to continue building a legacy in the coming years. Out of the discussions and sharing of perspectives, the Center is aligned to the following Theme strategies and approaches.

<u>Theme I – Nanoelectronics</u>: Led by Theme Leader, **E. Yablonovitch** (*Berkeley*), the goal of Theme I is to discover a solid-state switch that could replace the transistor switch that could be actuated in the milli-Volt range. Considerable research effort on alternate switching mechanisms have converged around the tunnel transistor, reasoning that Moore's Law will lead to devices so small as to require

the consideration of tunneling in any case. There are now many competing tunnel FET research groups, world-wide.

Two main tunnel modulation mechanisms are in play: tunnel-distance-modulation versus density-of-states modulation, which is also called energy filtering. Simple theory shows that the tunnel-distance-modulation is steep at low currents, but rather shallow at the high conductance (current) density needed for a competitive device. Conductance density is very important, since it determines how rapidly wires can be charged, which translates directly to clock speed.

While most researchers, including E^3S researchers, have emphasized the density-of-states modulation mechanism, the state of the art device results have continued to be disappointing and are more characteristic of the tunnel-distance-modulation mechanism, which works well only at low current density. Because of the Center's approach to elucidate the underlying device physics, versus simple device optimization, one of the key outcomes from the Center's Nanoelectronics research to date, is the understanding of the key reason for the discrepancy between experimental device performance and modelling predictions [1]. We have found that the preferred density-of-states, or energy-filtering mechanism, demands higher interface perfection than ever previously required in solid-state electronics.

The device fabrication efforts and simulation efforts of **D. Antoniadis**, **J. Hoyt** and **J. del Alamo** [2] (*all MIT*) and **E. Yablonovitch** [3] (*Berkeley*) have led to the discovery a particular requirement in the density-of-states switch, which is blocking progress (as outlined below):

Tunneling is an interfacial process, limited by the two-dimensional density of quantum states, which is $dN/dE \sim 10^{12}\,/cm^2/eV$. This desirable tunneling needs to compete with bandgap defect state density, D_{it}, which is a famous Figure-of-Merit in electronics science. For the materials that we have been considering, the defect density is $D_{it} \sim 10^{11}\,/cm^2/eV$ leads to "trap-assisted-tunneling". This means that, at best, we could look forward to only a 10× On/Off ratio in the density-of-states switch, even if everything else worked perfectly.

The tunnel distance modulation mechanism, does not need to satisfy this requirement, but it provides a limited performance improvement. A ~50% reduction in operating voltage might be achievable, compared to today's transistors, averaged over both low and high current density; at lowest a 250 mV operating voltage.

One of the key scientific question that the 2009 STC proposal that resulted in the Center for E^3S sought to answer is the sharpness of edge in the electronic bands involved in tunneling. At this point, however, the interfacial defect density $D_{it} \sim 10^{10}\,/cm^2/eV$, in the most favorable material system [4], trumps the band-edge sharpness. The challenge posed by this answer is that after decades of electronic material investigations, the best interface state density is far from being good enough. Thus we are obligated to obtain further major improvements in an important interface material property, beyond what decades of research have previously accomplished.

The concern for making perfect material interfaces led the Center's Nanoelectronics researchers to embark on research in two-dimensional semiconductor materials, particularly Chalcogenides, soon after the start of the Center. The early adoption by **A. Javey** (*Berkeley*) of a Chalcogenides research approach as part of the Center's Nanoelectronics Theme has allowed the Center to build a record of achievements both in materials and devices that is proving to have been a very important strategic response to interfacial traps in devices of traditional semiconductor materials. A very important new milestone in the research of **A. Javey**, in collaboration with **E. Yablonovitch**, is the demonstration of chemically-treated MoS_2 semiconducting monolayers with a photoluminescence quantum yield >95%, whereas untreated MoS_2 has a quantum yield <<1% [5]. This result indicates that we have the ability to passivate or repair imperfections! The high quantum yield reflects the significant reduction mid-gap traps to an ultra-low level. Defect traps, if present, would serve as recombination centers of the electrons generated by the probe light. Indeed, this result has affirmed our existing strategy for interfacial synthesis in new semiconductor materials, which are offering better prospects for controlling chemical bonds and energy levels. As such, the Center plans to expand the Chalcogenides research effort with the addition of a new faculty researcher, **J. Kong** (*MIT*), an authority on monolayer semiconductor synthesis in the coming Period 7. This expansion of Chalcogenides research in the Center will benefit not only the Nanoelectronics Theme but also the Nanophotonics and Nanomechanics Themes. The research of **A. Javey** in Theme I, has promoted the adoption of Chalcogenides in research of other parts of the Center; see subsequent discussions on Themes II and III.

The Center's transition to greater emphasis on new semiconductor materials has already begun. In the current Period 6, **F. Fischer** (*Berkeley*), a synthetic chemist, joined the Center to pursue a synthetic approach toward fabricating defect-free semiconductors. The synthetic bottom-up strategy for the synthesis of hybrid graphene nanoribbons (GNRs) heterostructures relies on lateral electron quantum confinement effects in the one-dimensional GNRs. We will expand this effort by engaging **T. Swager** (*MIT*). **Swager**, who has been with the Nanomechanics Theme at the Center since Period 2, will complement the surface directed synthesis of **Fischer** by recognition of the need for free-standing molecular scale devices supported only at the electrodes by rigid scaffolds that can preserve the electronic energy levels in the active center of the devices. The longer term goal is that the building of synthetic tools, molecular building blocks and purification techniques will enable highly reproducible fabrication of stable GNR heterojunction devices for advanced circuit architectures. To further strengthen this team, the Center plans to add **S. Louie** (*Berkeley*), who is an expert in simulation and modeling, to guide these chemical synthetic efforts of bottom-up graphene nanoribbon semiconductor-based research. In addition, **E. Yablonovitch** will continue to support these efforts with theoretical considerations as well as characterization.

At the same time, it must be emphasized that the Nanoelectronics Theme is not abandoning conventional III-V semiconductors, which can still help us in ferreting out the physics of tunneling devices, just as the III-V devices helped us to identify the D_{it} interfacial trap-density problem as being responsible for poor On/Off ratio. A major goal of the III-V nanowire TFET research of **del Alamo** (*MIT*) would be the identification of the band-edge spectroscopic sharpness in a single-channel quantum wire configuration, where inhomogeneous broadening from doping, thickness fluctuation, would be absent owing to the presence of only a single quantum channel. We still expect scientific results from the **D. Antoniadis** team (*MIT*) in the next Period, as their students complete their theses in device fabrication and modelling of traditional tunnel FETs.

<u>Theme II – Nanomechanics</u>: Led by **T.-J. King Liu** (*Berkeley*), the goal of Theme II is to demonstrate low-voltage switching with nano-electro-mechanical (NEM) relays as well as feasibility in a system application. At the start of the Center, the focus has been on voltage reduction through scaling and new device design to ensure reliability. This has led to the understanding that surface adhesion ultimately limits relay scaling and alternative approaches are needed. At the same time, the concept of a tunneling relay was pursued whereby the electrical activation will occur when the two electrodes are brought to close proximity, but not actually touch each other, the spacing of which is controlled by folding molecular chains [6]. The switching demonstration of the molecular switch, "the Squitch", by its research team, **J. Bulovic**, **J. Lang** and **T. Swager** (*MIT*), was a major milestone of Theme II in Period 5.

There are still remaining issues to be resolved with the Squitch to demonstrate the possibility of low dynamic power. This should be achievable by:

a) developing fabrication process to ensure sufficiently smooth surfaces inside the device;
b) reducing the area of tunnel contact;
c) increasing the area of the electrostatic actuator; and
d) striving for softer molecular structures

The key gating step to lowering the operating voltage has been determined to be the development of molecular structures, with low enough Young's modulus. Thus, the Nanomechanics Theme is putting significant emphasis on a device candidate for the circuit demonstration goal at the end of the Center's second five years.

In parallel, **T.-J. King Liu** developed and used an analytical model to assess the switching energy of a nano-mechanical switch. Modeling studies identified a tunneling switch in which the spring-restoring force could counterbalance contact adhesion force, reducing the depth of the potential energy well created by contact adhesion and thereby overcoming the contact adhesion energy limit. This is an alternative approach to the Squitch, but it might be difficult to achieve the force cancellation required. This work demonstrates that it is possible for tunneling or non-contact switches to overcome the previously perceived switching energy limit of a direct contact nano-mechanical switch. While this research finding of ultra-low switching energy in tunneling devices has reaffirmed the Center's Squitch program, the body biased approach can also be applied to a more traditional relay design. Thus, the broader concept of body-biased tunneling relays will be explored by **King Liu**, in collaboration with Material Scientists, **J. Wu** (*Berkeley*), who will provide the materials perspective in addressing issues like device reliability, and the practical incorporation of molecular spacers.

The off-state leakage current in tunneling relays provides major advantages in the anticipated "Internet of Things". In that application, the leakage current may be more important than the dynamic voltage. Circuit designer, **V. Stojanovic** (*Berkeley*) will collaborate with **King Liu** as she leads the relay design research and, together, they will identify the trade-off between these two requirements. The Center anticipates a working internet-of-things demonstration, a data compression circuit to save radio communication energy by pre-compressing the sensor data, by the end of the Center in 2020. This will require a meaningfully-sized circuit, to digitally compress sensor data, consisting of over 1000 MEM's gates; a goal that must be accompanied by the achievement of some reasonable mile-posts along the way.

At the same time, we must be open to new ideas in the second five years as a STC. For example, this past summer, we saw the first demonstration of piezoresistance in Transition Metal DiChalcogenides (TMDC) monolayers strained using a MEM actuator by **D. Zubia** (*UTEP*), supported by **Javey** and **King Liu**, opening up an intriguing avenue of exploration. This resulted from a 10-week residency of an UTEP postdoc at Berkeley, hosted by **Javey** and **King Liu,** an outcome that benefited from the Center format. Research in piezoresistive relays will be pursued.

Another example is **King Liu**'s proposal of hydraulic signaling. This contrasts well with our emphasis on wired signaling in Themes I, II, and IV. Hydraulic signaling is an innovative concept, that could have much lower dynamic power than electrical, but it is a low-speed technology in which dynamic power might not be all that important. Again, **Stojanovic** and **King Liu** will collaborate on systems analysis to identify the particular application area where this new type of signaling might have a role to play.

<u>Theme III – Nanophotonics:</u> Led by **M.C. Wu** (*Berkeley*), the goal for Theme III remains the reduction of the photons per bit in a data-link from 20,000 photons to 20 photons, the quantum limit at good bit-error-rate. The strategy remains to improve *both* energy efficiency and sensitivity by orders of magnitude in both the emitter and the photo-receiver and to miniaturize the components to be compatible with state-of-the-art transistors. Beginning in Period 1, the approach taken by **M.C. Wu**, in collaboration with **E. Yablonovitch,** has been on demonstrating that the spontaneous emission from antenna enhanced nano-LEDs can be faster than the stimulated emission of lasers and, ideally, be more energy efficient because it does not required in DC bias as in the case of the laser, the ubiquitous light source in optical communications today [7]. Indeed, in this current Period 6, the Theme III researchers achieved a big success: an electrically injected antenna-enhanced III-V nano-

LED showed increased spontaneous emission enhancement close to 200x, a result that places spontaneous emission rate on par with the stimulated emission rate [8]. Furthermore, an optically pumped antenna LED structure with WSe_2 monolayer light emitters yielded spontaneous emission rate enhancements of up to 320x, a result from the collaboration of **M.C. Wu**, **Yablonovitch** and **Javey**. These results have affirmed Theme III's strategy of introducing optical antenna enhanced spontaneous light emitters to allow energy efficient short distance on-chip optical interconnects. In addition, the important WSe_2 semiconducting monolayer result has shown the benefit of the Center format, as the Nanophotonics Theme III is leveraging the Chalcogenide research that has been undertaken for Nanoelectronics Theme I.

Antenna-enhanced light emission has become a hotly competitive field world-wide, but the Center recognizes that speed enhancement is meaningless, unless the optical antenna efficiency is simultaneously maintained above 50%. We are urging our competitors to set this as a ground rule for the reporting of antenna enhancement factor.

By retaining a systems viewpoint, we identified that the photo-receiver is of equal importance to the light source. The **Yablonovitch** and **Wu** groups have identified the device physics necessary for a photo-receiver to be sensitive at only 20 photons per bit. The key requirement is fast transit time of the transistor itself. Full performance requires integration of an optical cavity with photo-detector, and photo-receiver. At the same time, the detector function and the preamp function must be closely linked in space, to reduce stray capacitance. This pathway complements the approach of **C. Chang-Hasnain** (*Berkeley*) to minimize photo-receiver capacitance through monolithic InP on Si photo-transistor integration. Our short term goal is to interest the Si-photonics industry in adopting our more sensitive photo-receiver architecture.

We look forward to an optical antenna communications link demonstration by the end of the Center, 2020. Our existing Yagi antenna designs have demonstrated >70% coupling efficiency to silicon waveguides, [9] [10].

<u>Theme IV – Nanomagnetics</u>: Led by **J. Bokor** (*Berkeley*), the goal of Theme IV is to use current-driven magnetic elements for electrical communication and switching at sub-femto-Joules (sub-fJ) with fast switching speed, perhaps as low as < 10 psec. The primary approach is to take advantage of newly discovered ultra-sensitive, current-driven magnet switches employing Spin-Orbit Torque (Spin-Hall Effect), sensed by tunnel magneto-resistance to drive wires and to provide electrical gain and logic fanout. At the same time, we are showing that these magnetic switches can operate at ultra-high speed, employing a-thermal, non-equilibrium, magnetic phase transitions.

Since embarking in this strategy two Periods ago, significant progress has been made towards understanding the fundamental physics, including the demonstration of nanomagnets switching with an in-plane current without needing a symmetry breaking magnetic field by **S. Salahuddin** (*Berkeley*) [11] and observation by **J. Bokor** of magnetic "toggling" in GdFeCo indicating that magnetization reversal could occur in about 1 psec.

A secondary approach for Theme IV, pursued by **S. Khizroev** *(FIU*) in collaboration with **J. Bokor**, is the ultra-low sub-micro-Amp switching currents observed in sub-10-nm Spin Transfer Torque-Magnetic Tunnel Junctions. Further investigations to understand the physics is needed, like the need for a comprehensive set of field and temperature-dependent magneto-transport measurements, as well as investigations into alternative materials composition. A three-terminal device demonstration is one of the near term goals.

While magneto-electrical switching now benefits from very low switching current, the challenge in magnetic devices is the low I_{on}/I_{off} ratio of present magneto-resistors causing static leakage. Conversely, the non-volatility of magnets can be used to reduce the static power losses. With low dynamic power <u>and</u> low static power, the question arises: Where lies the problem? The problem is that signals might come in for switches that happen to be at rest, with the digital information is safely stored in the permanent nano-magnet. Unfortunately, it's hard to know which switches can be safely placed into hibernation, and which switches need to be awake in case a data signal comes in. **V. Stojanovic** (*Berkeley*) is addressing this circuit design and architectural problem. If we can establish a very fine-grained criterion for putting small numbers of components into hibernation, there could be a big benefit. The possibility of combining the advantage of good On/Off ratio in CMOS transistors, with the sensitivity and non-volatility of the magnetic switches, is attracting researchers. **H.-S.P. Wong** (*Stanford*) who has been working in Theme II (Nanomechanics) will transfer into Theme IV to collaborate with **S. Salahuddin** and **V. Stojanovic** to experimentally demonstrate the current reduction benefit of using spin-Hall switching in a circuit environment as originally conceived by **S. Salahuddin** [12] .

Education & Diversity Strategic Plan: A central pillar of the Center's mission is education and broadening participation. The Center's vision in Education and Human Development (EHD) is to set a legacy in the development of a next generation, engaged, skilled, and diverse workforce in energy efficient electronics that will last far beyond the sunset of this Center. The Center's primary goal is to develop Ph.D.- and M.S.-level scientists and engineers in energy efficient electronics science who: 1) are knowledgeable in the scientific approaches to energy efficient digital electronics systems; 2) understand that working in diverse teams enhances creativity; and 3) understand the process of innovation, entrepreneurship and the transition of research results to commercially viable products. Supporting this primary goal is the Center's EDH strategy of enhancing the number of students at all levels pursuing STEM education and in particular, technical disciplines related to energy efficient electronics science, so as to develop a pipeline of candidates for graduate studies. This pre-graduate level focus also serves to enhance a pipeline for technical disciplines beyond those in the Center, and for the future STEM workforce in general.

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.

<u>Graduate Education</u>: The Center provides formal and informal education. Since the start of the Center, E^3S Director, **E. Yablonovitch** biennially has been teaching a graduate level course on low energy electronics with a strong focus on E^3S topics and perspectives that the Center's students and postdocs can take either for credit or otherwise. In addition, the Center's faculty has incorporated into their courses general topics in low energy electronics, and in some cases, topics specific to the Center's research approaches and outcomes. Informal training occurs in form of numerous presentations, mentoring, science communications, and other leadership opportunities that the Center's students and postdocs participate in. Given the number of opportunities available, the Center has also developed the E^3S Professional Development Program (E^3S PDP) to guide students and postdocs to acquire a diverse and balanced set of experiences. With this program, students are able to earn a Leadership Certificate if they have participated in many of the professional development opportunities. Frequently, the Center also offers training in areas that it deems important in the development of a scientist/engineer. Incoming students and postdocs are required to complete online ethics training. All mentors of REU students receive training in project management and interactions between mentor and mentee. The Center has offered training in topics like Publishing Your Results, Entrepreneurship, Science Communications, Proposal Writing, and Best Practices to Promote Diversity.

<u>Undergraduate Education</u>: The Center uses Research Experiences for Undergraduates (REU) as the primary vehicle to engage undergraduates. There are three programs:

- ETERN provides paid internship during the academic year for undergraduates in E^3S member institutions to conduct research with E^3S faculty.

- E^3S REU provides paid summer internship primarily for students from 4-year institutions that are associated with the Center.
- Transfer-to-Excellence (TTE) REU provides paid summer internship for California community college students to conduct research with E^3S and E^3S-affiliated faculty at UC Berkeley.

The Center has relied on the latter two programs to build a diverse pipeline for graduate school and into the Center. In particular, the Center chose a California community college focus because the California community college system is the largest in the US and these schools have traditionally been the preferred first stop in undergraduate education for women, underrepresented minorities, and first generation college students. After five years of operation, the Transfer-to-Excellence (TTE) program has enabled not only higher transfer rates of California community college students to STEM baccalaureate programs, but has enabled its participants to transfer to top four-year institutions. TTE alumni, who were interns in the laboratories of E^3S or E^3S affiliated faculty, have been transferring to four-year institutions since Fall 2012 at a rate of 96%, with most transferring to Tier 1 academic institutions. Prompted by the E^3S External Advisory Board, the Center conducted a study in Period 6 that is intended to measure perseverance in pursuing a STEM education, comparing the TTE interns with those applicants who were not accepted. The study informs that the persistence of TTE interns at the beginning of their TTE internship aligns with that of the applicants who were not admitted to the program. However, at the conclusion of the internship, the TTE community college students reported a significantly higher level of confidence and interest in pursuing a STEM education.

The recruiting of underrepresented groups including women and racial minorities is also emphasized across the spectrum of the E^3S REU and education programs. While the rate of students entering graduate school among the E^3S REU program alumni is high (74%), the rate that students are transferring into the Center is still somewhat low. Even though a substantial percentage of alumni continue their graduate degree at an E^3S member institution, they do not pursue a thesis in an E^3S area of research. The Center recognized this difficulty and has made the first step in addressing the challenge through hiring and managerial changes. As additional interventions are likely needed to diversify the Center's demographics, in Period 6, the E^3S Executive Committee decided to separate the management of the function of Education and Diversity. Now, the Center has an Education Manager, who is responsible for Education, and a Diversity and Outreach Director who is responsible for Diversity.

The Center also seeks to impact community college education by offering professional development opportunities to community college faculty. Community college faculty members have conducted research at the laboratories of E^3S faculty. In addition, they also have the option to develop new teaching materials advised by E^3S graduate students or postdocs. The Center has augmented this professional development program by offering a series of pedagogy workshops in partnership with the Berkeley Center for Teaching and Learning. Regardless of whether the professional development experience is in research or curriculum development, the community college faculty participants are expected to implement new teaching materials in their classroom upon their return to their home institution.

<u>Online Education</u>: The Center looks to build its education legacy with online education and training materials that relate to the Center's research focus. This strategy was adopted in the Center's 4th year. This strategy is expected to impact all levels: developmental experiences for the Center' graduate students, postdocs and staff, as well as educational resources and knowledge transfer venue for a wide range of audiences. A 1.5-hour mini-course in Energy Efficient Electronics for entry level graduate students has been in development.

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 milli-Volt switching and few-photon communications. 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. The Center leverages the expertise and resources of its 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.

Summary of the Center in Period 6

Against the background on the Center for E^3S, this section offers a summary of the Center's progress in Period 6. In-depth discussions are found in the following sections of this report.

At the highest level, the status of the Center can be viewed through the metrics given in the E^3S Strategic Plan 2015-2020. The metrics were established to help track our performance in the various areas that make up the Center's mission as a NSF Science and Technology Center. While performance targets have been set for each Period, the Center has learned that the reporting of results has facilitated internal analysis and thereby, has impacted the Center's strategies and approaches.

Objective	Metric	Targets	Results				
			P 2	P 3	P 4	P 5	P 6
Research	Multi-PI projects	P 2: 30% P 5: 75% P 6: 50%	44%	67% (14)	55% (12)	64% (14)	65% (11)
	Multi-Institutional projects	P 2: 10% P 5: 30% P 6: 15%	4%	10% (2)	9% (2)	23% (5)	29% (5)
	Publications with authors from multiple institutions	P 3: 12 P 4: 3 P 5: 5 P 6: 5	0	1	1	1	3

	New joint research funding awards	P 6: 1	(new for P6-10)				0
Education	Center graduates completed E^{3}S training	P 2: Baseline P 3: 50% P 4: 50% P 5: 50% P 6: 15%	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)
	Students accessing online courses of the Center	P 6: 50	(new for P6-10)				TBD
	Undergraduates who pursue advanced degree in science and engineering	P 3: 5% P 4: 30% P 5: 35% P 6: 40%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	P 2: Baseline P 3: 5% P 4: 80% P 5: 80% P 6: 85%	n/a	3 (100%)	6 (100%)	7 (88%)	6 (100%)
	Pre-college students who pursue a bachelor's degree in science and engineering	P 3: Baseline P 4: 70% P 5: 70% P 6: 80%	n/a	31 (68%)	98 (75%)	162 (82%)	206 (75%)
	Students and postdocs serving in leadership roles in the Center	P 2: Baseline P 3: 15% P 4: 20%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)

		P 5: 25% P 6: 30%					
Diversity	Women in the Center's research programs	P 2: Baseline P 3: 5% increase P 4: 30% P 5: 20% P 6: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)
	Underrepresented minorities in the Center's research programs	P 2: baseline P 3: 15% increase P 4: 5% P 5: 10% P 6: 10%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)
	Participants from underrepresented* groups in the Center's Diversity programs	P 3: Baseline P 4: 80%	n/a	93 (82%)	Women 37 (44%)	Women 26 (41%)	Women 29 (40%)
		P 5: 85%			URM: 58 (68%)	URMs: 36 (56%)	URMs: 49 (67%)
		P 6: 85%			**Total: 73 (86%)**	**Total: 49 (77%)**	**Total: 66 (90%)**
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center	P 6: 40%	(new for P6-10)				17 (55%)
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate	P 6: 85%	(new for P6-10)				16 (70%)

	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering	P 6: 80%	(new for P6-10)				TBD
Knowledge Transfer	Center publications	P 2: 18	17	17	19	39	45
		P 3: 18					
		P 4: 18					
		P 5: 18					
		P 6: 25					
	Talks at peer-reviewed conferences	P 6: 12	(new for P6-10)				14
	Center sponsored symposia & workshops	P 2: Baseline	1	0	1	0	1
		P 3: 0					
		P 4: 1					
		P 5: 0					
		P 6: 2					
	External citations of publications *(cum)*	P 3: 10	15	178	393	719	1724
		P 4: 100					
		P 5: 100					
		P 6: 25% increase					
	Contacts with industry:						
	• Talks & Meetings	P 6: 36	66	20	42	62	35
	• Industry Presentations	Yearly: 2	4	2	6	3	5
	Research collaboration with industry	P 4: 1	0	1	1	4	6
		P 5: 2					
		P 6: 3					
	Patent disclosures	P 3: 3	1	0	1	0	2

	• Disclosure/Provisional	P 4: 3					
		P 5: 5					
		P 6: 2					
	• Patent Application Filed	P 4: 0	1	0	0	0	4; 1 granted
		P 5: 3					
		P 6: 1					
	Technologies attributable to Center's research		(new for P6-10)				0
	• Low energy devices	P 6: 0					
	• Enabling other applications	P 6: 0					
	Center's alumni into relevant industries	P 5: 50%	Student: 0%	Student: 64% (7)	Student: 16% (2)	Student: 16% (6)	Students: 50% (12)
		P 6: 30%	Postdoc: 100% (1)	Postdoc: 33% (2)	Postdoc: 20% (2)	Postdoc: 40% (4)	Postdoc: 13% (1)
	Center's alumni pursuing research in academia & research labs in disciplines related to the Center	P 6: 30%	(new for P6-10)				Student: 38% (9)
							Postdocs: 88% (7)
Management Center	Annual Surveys:	Likert Scale:					
	• Students /Postdocs	P 2: 3 or higher	Ave: 3.9±0.2	Ave: 4.0±0.3	Ave: 4.2±0.2	Ave: 4.5±0.2	Ave: 4.3±0.2
	• Co-PIs	P 3: 3 or higher	No survey in P 2	Leader-ship: 4.46	Leader-ship: 4.7±0.5	Leader-ship: 4.9±0.1	Leader-ship: 4.6±0.1
		P 4: 3 or higher		Collabo ration 3.25	Collabo ration n/a	Collabor ation	
		P 5: 3 or higher				Outside Theme: 1.3+/-0.1	

		P 6: 4 or higher				Within Theme: 3+/-1	
	• External Advisory Board		Strategic Plan: 4.18	Strategic Plan: 4.07	Strategic Plan: 4.6	Strategic Plan: 4.7±0.5	Center Legacy: 4.8±0.4
			Center Status: 4.01	Center Status: 3.96	Center Status: 4.6	Center Status: 4.7	
	Authorship disputes	P 2: 20% decrease	0	0	0	0	0
		P 3: 20% decrease		Faculty Ethics Survey: 4.39	Ethics Survey: not on Likert scale		
		P 4: 20% decrease					
		P 5: 20% decrease					
		P 6: 0					
	Plagiarism		0	0	0	0	0
	Changes in Center processes made in response to evaluation results	Timely closure of action items **	(new for P6-10)				0

* underrepresented groups: racial minorities, women, 1st generation college students, veterans, and students with disabilities

** 3 months for closure of regular Action; 1 week for closure of time-sensitive Action

Research Accomplishments in Period 6

The Center brought together faculty researchers in five academic institutions: UC Berkeley, MIT, Stanford, The University of Texas at El Paso (UTEP), and Florida International (FIU). In Period 6, the co-PI's are:

- UC Berkeley: E. Alon, J. Bokor, C. Chang-Hasnain, F. Fischer, A. Javey, T.-J. King Liu, S. Salahuddin, V. Stojanovic, J. Wu, M.C. Wu, and E. Yablonovitch.
- MIT: D. Antoniadis, V. Bulović, J. del Alamo, E. Fitzgerald, J. Hoyt, J. Lang and T. Swager
- Stanford: H.-S. P. Wong
- UTEP: D. Zubia
- FIU: S. Khizroev

All but one faculty researchers were with the Center in the previous Period 5; F. Fischer joined the Center in the beginning of Period 6 to start a new Theme I project.

Theme I – Nanoelectronics: The key accomplishments in the Nanoelectronics Theme are:

- III-V Tunneling FET: As previously stated, in the last Period 5, the device fabrication efforts and simulation efforts of **D. Antoniadis**, **J. Hoyt** and **J. del Alamo** [2] (*all MIT*) and **E. Yablonovitch** [3] (*Berkeley*) have led to the discovery that poor device performance of TFET obtained by TFET researchers can be explained by a trap-assisted mechanism. In Period 6, the **Yablonovitch** group modeled the experimental data of the **del Alamo** group to explain that the trap-assisted mechanism is a two-step process. A carrier first tunnels from the source valence band to an interface trap state in the bandgap. The relevant trap states are those at the p-n junction between III-V semiconductors, as well as the traps at the interface between the semiconductor and the gate dielectric (Al_2O_3). After the tunneling event, the carrier can be thermally excited above the conduction band edge by a thermal Shockley-Reed-Hall (SRH) process. The thermal activation energy ΔE required for the trapped carriers is the separation between the source Fermi level and the channel conduction band, which is controlled by the voltage V_{DS}. Extraction of the activation energy shows that ΔE decreases linearly with the applied voltage, as expected, within a certain voltage range. In this range, the current is dominated by the thermal excitation rate, which grows as exp ($-\Delta E/kT$). At a certain voltage, the tunneling rate into the trap states becomes the limiting step of the conduction process and the conductance of the device follows the density of states. At a still larger voltage, the conduction band and the valence band overlap, and band-to-band tunneling begins.

- Chalcogenides Tunnel FETs: The goal of this project in the **Javey** group (*Berkeley*) is two-fold: Establishing the materials science as well as demonstrating devices. In this Period 6, there have been successes in both accounts. In collaboration with **E. Yablonovitch**, the photoluminescence quantum yield of MoS_2, the prototypical two-dimensional material, which is reported to have a maximum quantum yield of 0.6% was investigated. Quantum yield is a measure of the quality of these materials and the question was whether active defects can be passivated/repaired [13]. Using an organic superacid treatment, the photoluminescence and minority carrier lifetime of MoS_2 monolayers is improved by more than two orders of magnitude. The treatment eliminates defect-mediated radiative recombination, thus resulting in a final quantum yield of 95%.

  The **Javey** group also achieved several device demonstrations, one of which is the first TFET with two different layered semiconductors. A heterojunction device using WSe_2 as the gated p-layer and $SnSe_2$ as the degenerately n-type layer was fabricated. This structure did not have physical dopants that may smear out the band edges at the heterojunction. Vertical tunnel transistors were realized with a minimum subthreshold swing of 100 mV/dec. The best case I_{ON}/I_{OFF} was 10^7. Negative differential resistance was observed at low temperatures, confirming that the current obtained across the $WSe_2/SnSe_2$ heterojunction is due to band-to-band tunneling. Also, the subthreshold swing was observed to be independent of temperature.

- Bottom-Up Fabrication of Semiconductors: **F. Fischer** has synthesized p-doped graphene nanoribbons (GNRs) featuring an atomically defined pattern of boron atoms along the backbone of the GNRs. Low-temperature scanning tunneling microscopy (STM) imaging of fully cyclized B-doped 7-AGNRs (B-7AGNRs) reveals a unique, characteristic stripe pattern along the length of the ribbon with a period corresponding to the distance between the expected position of dopant atoms in the molecular repeat unit.

Theme II – Nanomechanics: The key challenge towards the goal of demonstrating sub-0.1 Volt switching with nano-electro-mechanical (NEM) relays is to minimize or even eliminate the contact adhesion energy. The last annual report (Period 5) presented a strategy that continued to emphasize both non-contacting and contacting switches; the former, the Squitch project [6], pursued by **V. Bulović**, **J. Lang** and **T. Swager** at MIT, and the later, van der Waals (vdw) switches, pursued by **T.-J. King Liu** at Berkeley and **H.-S.P. Wong** at Stanford. Progress in the Nanomechanics Theme has caused a change in the Theme's strategy.

- Device Designs to Overcome the Contact Adhesion Energy Limit: Further analytical studies by **T.-J. King Liu** identified that a bistable nanomechanical tunneling switch requires even lower operating energy than the normally-on tunneling switch, which was presented in last year's annual report. The energy required to operate either the tunneling switch or the bistable (body-biased) tunneling switch, 18.12 aJ or 7.61 aJ, respectively, are lower than the contact adhesion energy [13]. These switch designs leverage the spring-restoring force to counterbalance contact adhesion force, reducing the depth of the potential energy well created by contact adhesion and thereby overcoming the contact adhesion energy limit. This work demonstrates that it is possible for tunneling or non-contact switches to overcome the previously perceived switching energy limit of a NEM switch, and thereby paves a pathway to ultimately energy-efficient NEM switches. The new research finding of ultra-low switching energy in tunneling devices is influencing the strategy of the Nanomechanics Theme, resulting in de-emphasizing van der Waals (vdw) switches, which require processes for nano-gaps formation – a development in which the **Wong** group (*Stanford*) did not make sufficient progress.
- Squitch: In the previous Period 5, the team effort of **Bulović**, **Lang** and **Swager** (*MIT*) demonstrated tunneling nanoelectromechanical switches ("Squitches") fabricated with metal-molecule-graphene tunneling junctions that exhibited sub-2-V actuation voltages [6]. The device performance obtained, including the differences in performance among devices, may be attributed to variations in molecular layer thickness and packing density, roughness of the electrode, which may result in variations in the effective thickness of the switching gap, as well as the properties of gold or graphene layers. Thus, in this Period 6, the focus has been on the development of new fabrication processes to enable fabrication of squitches at the size scale and with the geometry required for low-voltage switching. The needed processes and metrology tools for a vertically activated Squitch have been developed and we expect to have device results by the end of this Period 6.
- Novel Concept for Nanomechanical Switching: New research on the role of strain in 2D materials for band gap modulation was initiated by **D. Zubia** (*UTEP*) in this Reporting Period. In this project, a 2D material was transferred onto a MEM actuator to study the role of strain in the 2D material. Experimental studies, conducted in collaboration with the **Javey** and **King Liu** groups have shown four orders of magnitude change in resistivity in tensile-strained MoS_2 via AFM.

<u>Theme III – Nanophotonics</u>: The Nanophotonics researchers, **M. Wu**, **E. Yablonovitch**, **C. Chang-Hasnain** at Berkeley and **E. Fitzgerald** at MIT have continued to focus on advancing *both* the energy efficiency and sensitivity in the emitter and detector as part of the goal of achieving data transmission at the quantum limit.

Emitters: The biggest accomplishment is the demonstration that antenna-enhanced spontaneous emission in LEDs can indeed be a lower energy and faster light source as compared to lasers. The **M. Wu** group achieved an electrically injected nanoLED that showed an order of magnitude increase in spontaneous emission enhancement as measured by taking the ratio of antenna and orthogonal polarization components (from 8X to upwards of 200X). The large boost in measured enhancement factor in the electrically-injected nanoLED was enabled by significant fabrication improvements: 1) A high aspect ratio ridge dry etch was developed to replace the wet etch; 2) The gold antenna was replaced with less lossy silver; 3) An in-situ tilting technique was developed to coat ridge with conformal silver; and 4) A low-index spin-on-glass layer was inserted between antenna and high index substrate for reduced electrical leakage and increased antenna performance.

Improvements to device fabrication of Chalcogenide Nano-LEDs, a collaborative project of **M. Wu** and **E. Yablonovitch** that was initiated in the last Reporting Period, have enabled WSe_2 monolayers that are coupled to slot antennas to yield spontaneous emission rate enhancements up to 320x. Analysis of time resolved measurements showed carrier lifetimes of ~1 psec. This is more than an order of magnitude faster than unprocessed flakes. These measurements have led to the identification of edge recombination as the dominant recombination mechanism in all of our devices.

Phototransistors: The **M. Wu** group has been working with the **Yablonovitch** group on Ge Bipolar Phototransistors, while the **Chang-Hasnain** group has been exploring Bipolar Phototransistor of InP nanopillars. The approach of both groups has been to minimize the total capacitance of the photodectector and the drive electronics via optoelectronic integration.

In Period 6, the **Yablonovitch** group developed a simulation method to express the sensitivity in terms of fundamental device characteristics and signal-to-noise ratio (SNR). This derivation, which can easily be generalized to most phototransistor types, shows that the electron transit time of the device as well as the capacitance of the base are crucial in determining the sensitivity of the device. This rules out many phototransistor topologies that have been considered and explored in the past and points out that one may not design a phototransistor without these factors in mind. This simulation work points to the need to explore the possibility of building transistors as close as possible in proximity to the photodiodes rather than directly integrating the photonic and electronic function together, a strategy that the Center's Nanophotonics researchers have pursued to date.

The Chang-Hasnain group has demonstrated a highly sensitive homojunction photo-BJT with a high current gain of 53.6 and a bandwidth of 7 GHz for a gain bandwidth product of 375 GHz. The device also showed an external quantum efficiency of 28% and extremely low dark current of 3 pA.

<u>Theme IV – Nanomagnetics</u>: Led by **J. Bokor** (*Berkeley*), the Nanomagnetics researchers, including **S. Salahuddin** (*Berkeley*) and **S. Khizroev** (*FIU*) are pursuing the goals of magnetic switching with ultra-low switching energy in the order of sub-femto-Joules (sub-fJ) and fast switching speed in the order of <10 psec. The focus has been to understand the fundamental physics and the switching dynamics of the spintronic phenomena that underlie magnetic switching with the desired attributes. In addition, a key detractor with all currently known magnetic materials is the low On/Off ratio of present magneto-resistors and the matter is being addressed in the Center from the circuit design and architectural perspective through the research of **V. Stojanović** (*Berkeley*). Significant progress has been made towards understanding the fundamental physics of spintronics. The key findings in Period 6 are as follows.

- The **Salahuddin** group has demonstrated the elimination of the need for an external magnetic field to switch a perpendicularly polarized magnet with an in-plane current, which can significantly reduce the power dissipation. The Berkeley team has accomplished this by engineering an anisotropy in the magnets such that the magnetic easy axis slightly tilts away from the direction normal to the film plane. Such a tilted anisotropy breaks the symmetry and makes it possible to switch the magnet deterministically without needing the external magnetic field [11]. These results are significant for the field of spintronics as the symmetry breaking provides new insight into the physics of spin orbit torque and the switching without a magnetic field could lead to significant impact in high-density storage applications.
- The **Khizroev** group observed spin-torque switching at anomalous low current density in sub-10-nm devices, which is in agreement with the hypothesis of dramatically increased spin relaxation in this size range. The observation is explained by the fact that the collective behavior of spins in such small devices dominates over the effects due to the spin-orbit (L-S) interaction.
- Optical measurement of spin accumulation at non-magnetic heavy metal surfaces was achieved by **J. Bokor** and **S. Salahuddin**. This effect is due to spin-Hall effect with a build-up and decay time of the spin accumulation of <200 psec. This result has direct impact on the question of the speed of response of magnetic memory and switches based on spin-Hall effect. In addition, this direct probe method promises to be simpler than magnetization-based approaches because it allows separation of the effect of the spin-current in the non-magnetic metal from the spin-transport across the non-magnetic/magnetic interface.
- Direct observation of magnetic "toggling" in GdFeCo samples by fsec laser pulses indicates that the magnetization reversal occurs in about 1 psec. These results independently confirm prior results

[14] and, therefore open the possibility to generate ultrafast switches for memory and logic gated by a single stimulus, without the need of polarization modulation.

- Circuit modeling by **V. Stojanović** to provide circuit perspectives of magnetic logic devices has provided initial conclusions that magnetic logic can be optimized at very low supply voltage and the energy dissipation can be reduced infinitesimally toward zero at the expense of the time delay. However, energy scaling is limited by noise at low throughputs.

Education and Diversity Accomplishments in Period 6

Since the start of the Center, E^3S Director, **E.Yablonovitch** has been teaching biennially a graduate level course on low energy electronics with a strong focus on E^3S topics and perspectives. In Period 6, the UC Berkeley listed course, was taken by eleven graduate students from four of the five E^3S member institutions, and four postdocs from two member institutions. In addition, curriculum has been implemented into courses taught by E^3S faculty that focuses on low energy electronics, the Center's approaches, and some of the research outcomes. Nine E^3S faculty at FIU, MIT, and UC Berkeley taught courses in Period 6. A total of 15 courses have included the addition of E^3S content. Of these, two of the courses are at the undergraduate level, ten are graduate level, and three are both undergraduate and graduate level courses. Unfortunately, due to staffing limitations, progress towards the release of education videos on low energy electronics has been delayed.

The Center also offers a variety of practical training opportunities for graduate students and postdocs, including both oral and poster presentations; presenting at seminars and during Center events; mentoring of undergraduates; group analysis of competing research; participating in the REU intern selection process; serving as poster judges; and conducting scientific demonstrations at outreach events. Given the number of opportunities available, the Center has developed the E^3S Professional Development Program (E^3S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences. Upon completing four development areas, a student/postdoc will receive a Leadership Certificate. Thus far, sixteen students have earned a certificate of completion, of these, six were awarded in Period 6. Approximately half, 29 (46%) of the E^3S students participated in a training area in Period 6.

The Center also offers training in areas that it deems important for developing scientists/engineers. For example, all new incoming students and postdoc are required to complete online ethics training. Additionally, mentors of REU students receive training in project management, diversity, and interactions between mentor and mentee. In Period 6, 14 students and postdocs received training in these areas. In addition, in Period 6, the Center offered a workshop on proposal writing that was attended by 16 students and postdocs.

Intended to be pathway programs, the E^3S and TTE REU Programs, are designed to continue engagement after the internships end, a design informed by the Jolly model for student success [15]. Post program engagement comes in three ways: 1) a travel award to present the research outcomes of the internship at a conference; 2) advice and support through the application process for either transfer admissions to a four-year institution and/or graduate school; and 3) annual surveys to track the progress of the program alumni. In Period 6, two REU alumni presented their research with one at the 2015 APS March Meeting and another presenting at the UT-LSAMP Student Research Conference. Four TTE alumni made poster presentations at SACNAS and CUR Undergraduate Research Symposium. The Center has a strong record of REU program alumni going on to transfer and further their careers in graduate education. In Period 6, nine undergraduates have enrolled in a graduate program in science or engineering and six (100%) community college students have transferred to a 4-year institution to major in a STEM field. To date, 31 undergraduate REU alumni have enrolled in a graduate program in science or engineering and 23 (96 %) community college students who did research with E^3S or E^3S affiliated faculty have transferred to a 4-year institution. Among these participants, eleven (35%) of our undergraduates who are now enrolled in a graduate program are women and eight (26%) are from an underrepresented minority group. The demographics of those going to graduate school are exceeding the benchmarks the Center has set as references. For the community college students who have transferred to a 4-year institution, seven (30%) are women, seven (30%) are from an underrepresented minority group, and 13 (57%) are first-generation college students.

Knowledge Transfer Accomplishments in Period 6

Center's researchers have continued to support information dissemination and knowledge exchanges with communities of peers through publications in peer-reviewed journals, presentations both at peer-reviewed conferences and other forums, and private meetings with companies. A key knowledge transfer activity was the 4th Berkeley Symposium for Energy Efficient Electronic Systems, which was organized by the Center. The IEEE co-sponsored event brought together researchers from around the world who are working from devices to systems to provide researchers an integrated perspective of the challenges and advances in energy efficiency for information processing systems. Of the 119 registered attendees, 23 were from industry and 28 were from academic institutions that are not a part of the Center. The program consisted of 28 presented papers, two of which were from industry and 17 were invited papers, and three panels. The Center contributed seven talks and eleven posters.

The Center's Knowledge Transfer mission also includes the application of knowledge gained from the Center's research to other applications. Continuing the momentum from the last Period 5, new uses for three technologies are being pursued by E^3S faculty with external partners for broader application: i) InGaAs/GaAsSb QWTFET for RF Applications; ii) Squitch Switches as Analog Valves; and iii) RIE process with Digital Etch Technology for III-V Features of High Aspect Ratios. The first two uses are being further developed, while the third has been under evaluation at three companies.

Center Management Changes in Period 6

The Center's leadership, management team, and advisory board all underwent changes during Period 6. The E^3S Executive Committee welcomed new members, new roles, as well as new bylaws. The new members include **V. Bulovic** as the new MIT Site PI, **D. Zubia** (*UTEP*) joined to provide additional perspectives on Diversity, and **T.-J. King Liu** assumed the role of Associate Education Director.

The Center also welcomed a new Executive Director, **M. Bartl**, as the founding Executive Director, **J. Yuen** announced her retirement. **A. Tabor** joined as the new Diversity and Outreach Director in December. Tragically, Dr. Tabor passed away only nine days after she started her position.

As required by its charter, a new chairperson was appointed for the External Advisory Committee with an outgoing chairperson upon the completion of the 2-year term. **P. Gargini** replaced **D. Radack** and will serve the 2015-2016 term.

Center Output in Period 6

Publications		
	Peer Reviewed Journal Publications	31
	Submitted for Review	10
	Peer Reviewed Conference Proceedings	23
	Books and Books Chapters	5
Conference Presentations		45
Other Dissemination Activities		23
Awards and Honors		16
Ph.D. and M.S. Graduates		13
Postdoc Alumni		7
Patents and Patent Disclosures		6

Summary of Plans in Period 7

Research Plan for Period 7: Following the Research Strategic Plan as presented above, there will be changes in faculty participation. This will include new faculty joining the Center, current faculty members working in another Theme, as well as transition of faculty out of the Center. In particular, the Center will welcome the participation of **J. Kong** (*MIT*) as she joins E^3S to work on two-dimensional materials research that will initially target goals of Theme I - Nanoelectronics, but it is expected to have impact in other Themes. In addition, the Center will welcome **S. Louie** (*Berkeley*), who will add simulation and modeling expertise to the bottom-up graphene nanoribbon semiconductor-based research efforts in Theme I. The Center will bid goodbye to **J. Hoyt** (*MIT*), who is on official long-term disability leave from MIT, and to one of its two circuit designers, **E. Alon** (*Berkeley*), who has chosen to take a leave of absence from the Center in Period 7 to allow more time for his undergraduate curriculum re-engineering activities and his entrepreneurial endeavors.

The Nanoelectronics research portfolio will change in the upcoming Reporting Period 7 in response to the understanding of the role of interfacial traps as detractors to band-to-band tunneling at low turn-on voltage in traditional semiconductors. Research in traditional TFETs will be reduced in favor of additional research efforts in Chalcogenide TFETs and bottom-up semiconductors. The ongoing vertical nanowire TFET of **J. del Alamo** (*MIT*) will continue to serve as a venue for elucidating the physics of tunneling. Device fabrication projects of **D. Antoniadis** (*MIT*) with traditional semiconductor materials will be ramped down over the next period. The Chalcogenide TFET research will expand as the research group of **J. Kong** (*MIT*) joins the Center, complementing the research efforts of **A. Javey** (*Berkeley*). **T. Swager** (*MIT*) will apply his synthetic chemistry expertise to the issue of bottom-up semiconductors expanding the graphene nanoribbon-based research of **F. Fischer** (*Berkeley*). This group will be supported by simulations and modeling work of newly added physicist **S. Louie** (*Berkeley*). Theme Leader, **E. Yablonovitch** will continue to support these efforts with simulation and characterization in all three areas, and in particular, in the Graphene Nanoribbons project.

Research towards the goal of demonstrating sub-0.1 Volt nanomechanical relay switches will continue. The E^3S faculty participating in the Nanomechanics Theme will be **King Liu**, **J. Wu** and **Stojanović** (*Berkeley*), **Bulovic, Lang** and **Swager** (*MIT*) and **Zubia** (*UTEP*). The Berkeley researchers will continue to establish a robust process for fabricating body-biased NEM relays to achieve sub-0.1 V switching with high device yield, while the MIT researchers will continue to further reduce the operating voltage of the Squitch. New Theme II research efforts planned for the upcoming Period 7 are:

- The **Zubia** (*UTEP*) group will extend the initial proof-of-concept of strained 2D layers to the development of piezoresistive switches, in collaboration with Berkeley researchers.
- The **King Liu** group will collaborate with **V. Stojanović** (*Berkeley*) to experimentally demonstrate relay integrated circuits operating at very low voltage (< 0.1 V).
- The **Wong** group (*Stanford*) will no longer participate in Nanomechanics research, as the Nanomechanics research is moving away from van der Waals contacting switches. Instead, the **Wong** group will migrate its research activities to the Nanomagnetics Theme.

The Nanophotonics researchers, **M. Wu**, **C. Chang-Hasnain**, **E. Yablonovitch** (*Berkeley*) and **E. Fitzgerald** (*MIT*) will continue advancing the antenna enhanced LED emitters and phototransistors for their integration into waveguides. **M. Wu** will collaborate with **E. Fitzgerald** to demonstrate an electrically injected nanoLED with InP re-growth of the active region with the goal of achieving micro-Watt output power and >100x spontaneous emission advancement. As part of the development of an electrically injected WSe_2 Nano-LED, **M. Wu** will collaborate with **A. Javey** to address the need to passivate the edge of the chips. **Chang-Hasnain** will be working on increasing the sensitivity and gain of InP phototransitors with a hetero-junction.

The Nanomagnetics researchers, **J. Bokor** and **S. Salahuddin** (*Berkeley*) and **S. Khizroev** (*FIU*) will continue their research in achieving a magnetic switch with ultra-low energy at atto-Joule level and at speeds of a few picoseconds. They will continue to elucidate the underlying physics and materials science and demonstrate ultrafast magnetic switching enabled by electrically stimulated non-equilibrium switching. **Khizroev** (*FIU*) will also extend his research efforts to increase the magnetoresistance value of spintronic devices including developing graphene-based spin materials.

With the progress already made in understanding the underlying science, this Theme will increase its research towards understanding the application of magnetic devices. Towards that end, **H.-S. P. Wong** (*Stanford*) will join this Theme to collaborate with **S. Salahuddin** and **V. Stojanovic** (both *Berkeley*) to embark on a new effort: The fabrication, design, and integration of in-memory and normally-off computing using magnetic non-volatile devices. One application venue being considered is to turn off large portions of the computer that are not in use as a means to reduce power consumption. The use of non-volatile memory can make normally-off computing viable, since the shut-down part of the computer can be restored to its original state once it is needed, without needing to write to or read from external storage. By distributing the memory over the circuit (memory-in-logic), there can be additional power savings due to reduced interconnect length [16]. Magnetic devices such as spin-Hall and spin torque switches are particularly suitable for normally-off computing, since they are high-speed, non-volatile, have sufficient endurance, are scalable, and their fabrication is compatible with CMOS and 2D Transition Metal Dichalcogenide (TMD) FETs. Spin-Hall switching reduces the write current by adding a torque to the magnet [17]. The goal is demonstrate the large (> 10×) current reduction benefit [18] of using spin-Hall switching in a circuit environment.

Education and Diversity Plans for Period 7:

In Period 7, the Center will be staffed with an Education Manager **L. Marlor** and a new (soon-to-be-hired) Diversity and Outreach Director, and the Center will strive to attract diverse candidates to its education programs. They will receive faculty support from **T.-J. King Liu** and **J. Bokor**, in their roles as Associate Director of Education and Associate Director of Diversity, respectively. In addition, they will seek the advice of the Education Working Group that is part of the E^3S External Advisory Board.

Much of Period 7 will be spent in continuing to strengthen internship programs with recruiting emphasis on attracting women and underrepresented minorities. For the REU program, we plan to utilize leveraged funding from the UC Office of the President to attract students from HBCUs. Through the activities of the UCB-HBCU program, led by Theme Leader **T.-J. King Liu,** as well as the development of institutional ties to HBCUs, we hope to build a legacy of engagement in energy efficient electronic science. The new Diversity and Outreach Director will be tasked with working with the UCB-HBCU program and its faculty to recruit qualified applicants and build strong working relationships with faculty at the HBCUs. **T.-J. King Liu** will work with the new Diversity and Outreach Director in the planning of a workshop to host HBCU faculty in Spring 2016 and further build upon these relationships.

By analyzing the data on REU alumni attending graduate school and joining the Center as graduate students, we recognized that interventions are necessary. The new Diversity and Outreach Director will lead a review of the Center's Diversity strategy and identify new approaches to be adopted, if appropriate. It will take a few months to complete the review and yet, the process to select REU interns for Summer 2016 will likely start before the completion of the strategy review. Thus, the selection process for Summer 2016 will put 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 with a choice of E^3S faculty to serve as their advisors.

For Education, emphasis will be placed on re-energizing the Center in executing on its online education plans. Besides fast-tracking the release of videos that have already been created, an action plan for publicizing the videos to its target audiences will be developed and implemented. This action plan will also include implementation of assessment tools to study the efficacy of the online teaching modules, particularly the collection of mini-course modules on Energy Efficient Electronics for new Center members. A longer term development plan for additional online education videos, and possibly e-books, will be established before the end of Period 7.

Knowledge Transfer Plans for Period 7:

The key initiative is the release of a new website for the Center. While a prototype of a website with new navigational organization as well as look and feel has been available since the end of Period 5, much work needs to be done in developing updated content. In addition, the Center must address whether the existing hosting platform will continue to best serve the needs of the Center through 2020 and beyond.

II. RESEARCH

1a. Goals and Objectives

The Center for E^3S concentrates on two fundamental components of digital information processing systems: the communications logic switch and the short-medium range communication of information between logic elements. We continue to pursue three approaches, or Themes, for switching: Nanoelectronics (I), Nanomechanics (II), and Nanomagnetics (IV); and an optical approach for communication: Nanophotonics (III). The research goals for all approaches have been set from fundamental consideration on the minimum energy needed per digital function. While we strive to reach to the minimum energy per bit, part of the goal is to understand how low each approach can get compared to the fundamental limits, and to elucidate the factors that determine the minimum energy that each approach can reach.

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 [19]. An oft-quoted result is that a computer operating at temperature T must dissipate at least kTln(2) (about 18 meV at room temperature) per logical operation. This is frequently referred to as the "Landauer limit" [20]. However, for reversible, or adiabatic operations, in fact the minimum dissipation can even be made much less than kT [21]. For reference, leading edge CMOS today dissipates a minimum of ~400,000 kT per digital function, when the energy required to charge the wires is included. The ITRS Roadmap [22] projects a goal for this value to be reduced to ~40000 kT/digital function in 2022.

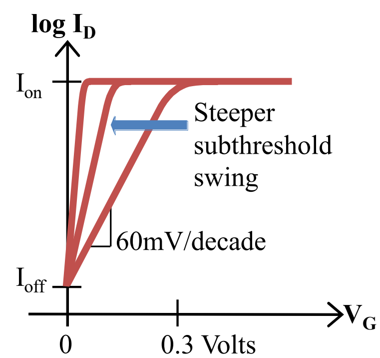


Figure 1: Current (logarithmic scale) vs. voltage V_G (linear scale) characteristics of a logic switch. The subthreshold swing (S) is conventionally limited by the Boltzmann factor to be no steeper than $ln(10)kT/q$ = 60 mV/decade at room temperature

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 ~0.7 V. 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 ~1 mV, good Signal-to-Noise ratio can be maintained even while lowering the powering voltage below 10 mV. 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.

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 1 milli-S/µm rather than 1 mA/µm.

Thus these three basic requirements, sub-threshold swing, On/Off ratio, and conductance, are directly applicable across the three Themes that are addressing the communications digital switch.

Theme III, Nanophotonics, is addressing the need for ultra-low energy alternative to the current metal wires or interconnects with an optical approach. In that approach, the lowest energy per bit is the quantum limit: 20 aJ/bit or 20 photons/bit.

1b. Performance Metrics

Objective	Metrics	Frequency	Targets
Integrative Research	Multi-PI Projects	Yearly	P2: 30% P5: 75% P6: 50% P7: 60% P8: 70% P9: 70% P10: 70%
	Multi-Institutional Projects	Yearly	P2: 10% P5: 30% P6: 15% P7: 20% P8: 25% P9: 25% P10: 25%
	Unplanned research projects *(discontinued in the 2nd five years)*	Yearly after Period 2	P3: 1 P4: 3 P5: 0
	New joint research funding opportunities *(replaced)*	Beginning in Period 3	P3: 1 P4: 2 P5: 2
	Publications with authors from multiple institutions	Yearly beginning in Period 2	P3: 12 P4: 2 P5: 4 P6: 5 P7: 5 P8: 5 P9: 5 P10: 5
	New joint research funding awards *(new, as replacement)*	Yearly	P6: 1 P7: 0 P8: 1 P9: 1 P10: 1

As we developed the Center's Strategic Plan 2015-2020 that was submitted to NSF in July 2014, we re-examined the purpose of the metrics and reviewed what we had learned from the metrics and other forms of input we had to track the Center's progress.

In the first five years, the Research metrics were set to measure: a) center synergy as in whether the Center members are forming and norming, in the lingo of group development; and b) performing as in whether new ideas that are generated from the interactions. But, after five years, the Center must be in the performing stage of group development and thus, we concluded that the Research metrics should put more focus on the tangible results from the collaborations, as in joint publications and the new funding the Center's faculty jointly receive in support of expanding and sustaining the collaborations.

Even though the Center has struggled to meet the targets set with the metric, publications with joint authors from multiple institutions, it is being continued after much consideration. We conclude that the metric is likely the best for measuring the value of NSF STC program as a catalyst. One can argue that research collaborations are formed among faculty colleagues outside a center environment, but it is more difficult with increasing physical distance and institutional boundaries. Having tangible outcomes as in joint publications will truly indicate the quality of those collaborations.

1c. Problems Encountered

The problems encountered in this Period 6 have been typical of research programs that rely on the need to develop novel device fabrication processes, metrology tools and simulation tools to make progress. The advantage of working in a center format is that as a whole, the Center has made significant progress towards the goals of all four Themes, although individual projects within a Theme may have encountered delays. In some cases, the progress made by one project within a Theme either creates or affirms one of the multiple pathways under investigation in the Center.

Theme I: In the previous Reporting Period, the Center's Nanoelectronics researchers identified interfacial traps as a key detractor to device performance in tunnel FETs. The strategy to be used for reducing these electrically active materials imperfections has been debated in the Center.

- One approach is to focus on using well-established, and thus, well controlled material systems and processes to minimize the traps. The **Antoniadis and Hoyt** team (*MIT*) has been following this approach with the fabrication of an electrostatically doped bilayer tunneling FET with Si/Ge. The fabrication, however, has been delayed considerably due to unanticipated problems with some of the necessary process development for the unconventional bilayer structure.

Theme II: The last annual report, for Period 5, reported that the Center's Nanomechanics research efforts, focused on overcoming the fundamental energy-efficiency limit of a mechanical switch, have included research into the formation of sub-lithographic contact gaps. Challenges to forming nanometer-scale gaps have emerged. The need to overcome this fabrication challenge has been ameliorated by the Period 6 findings of **T.-J. King Liu** (*Berkeley*) that body-biased tunneling switches, which do not need nanogaps, can provide a pathway to overcome the limitations posed by adhesion forces on the contacts.

- The **H.-S.P. Wong** group (*Stanford*) continued to fabricate and characterize switches using carbon nanotubes (CNTs). The distance between the CNT and drain has been reduced, resulting in a reduction in switching voltage from 16 V to just below 12 V. This research direction has proven to be difficult, with relatively slow progress toward mV switching. Hence, it will not be pursued further.
- The planned partnership with MIT Lincoln Laboratory that will allow the use of a SEM-guided ALD system to form gaps as small as ~4 nm was delayed to Fall 2015 due to the reassignment of research personnel at MIT Lincoln Laboratory. This caused a delay in achieving the milestones set forth for this Reporting Period for laterally actuated switches, which require equipment and deposition process development by the partner. Nevertheless, the Nanomechanics researchers at MIT are making significant progress in defining the process steps to enable the demonstration of Squitches with reduced operating voltage.
- Last year's annual report included what was expected to be the closing report on the study of Electro-Mechanical Memory Devices Integrated on Top of CMOS NEMory array, a project the research of Circuit Designer **E. Alon** (*Berkeley*) in Co-Design for Emerging Devices for Theme II. Unfortunately, this closing of this work required significant more time and a new student had to be introduced to the project.

Theme III: To achieve optical communications at the photon limit of 20 photons per bit, the Center's Nanophotonics researchers have been researching into ultra-high efficient sources as well as ultra-sensitive photo-receivers. One research approach for nano-LED is the use a family of two dimensional materials, Transition Metal Dichalcogenides (TDMs). New materials science has to be established to support the advancement of this approach.

- Results obtained in Nano-LED built from WSe_2 monolayers by the **M. Wu** group (*Berkeley*) indicated that edge-recombination is the dominant recombination mechanism. To move towards a more efficient emitter this loss pathway must be mitigated. Work is currently in progress in the **A. Javey** group (*Berkeley*) to passivate the edges of monolayer flakes to improve quantum yield. In addition, devices are being investigated that will not require the damaging reactive ion etching that is currently used for device fabrication.
- It was stated in our Period 5 Annual Report that the main bottleneck is the supply of Chalcogenide materials. To address this difficulty, the **Zubia** group (*UTEP*) has been developing a CVD process for monolayers of such materials. The initial work with MoS_2 growth is intended to lay the foundation for growth of WSe_2. Initial research was undertaken in the deposition of MoS_2 films under various conditions. However due to a lack of photoluminescence (PL) and Raman characterization equipment at UTEP, the research progress has been slow. While E^3S has provided funding toward the acquisition of a high performance Raman/PL system, the system will not be installed until November 2015. Meanwhile, the **Zubia** group is giving preference to its research of TMD monolayer under-strain that has implications for Theme I & II, because of the promising results that the group has achieved in this Period 7; *see Research Thrusts in Period 6 - Nanomechanics*.

  The Center's research portfolio has seen an expanding role of chalcogenide materials. The continuing lack of a method for larger area chalcogenide materials affects Themes I, II and III. This will be addressed as part of the changing Theme I research strategy with the addition of a new faculty to the Center; see *Research Thrusts in Period 7*.
- Ge Phototransistor: One goal is to characterize the system level sensitivity of the fabricated Ge Phototransistor to demonstrate the effect of integrating photodiode and amplifying transistor in a single device. To achieve the goal, a 3-terminal Ge n-p-n Phototransistor on silicon photonics was fabricated using the Rapid Melt Growth (RMG) method. Unfortunately, during the process, the Phosphorus used to implant the emitter and the collector of the devices n-type diffused far further than expected, effectively shorting out the device and rendering it useless. Plans for addressing this problem include using a different material than Germanium, for which we know how to control the diffusion more effectively (such as Silicon, as a demonstration).

Theme IV: The Center's Nanomagnetics researchers have continue to elucidate the physics and dynamics associated with magnetic switching.

- The **Bokor** group (*Berkeley*) has continued to make progress in studying ultrafast magnetization dynamics induced by picosecond duration optical pulses. However, looking towards future practical device implementation, his efforts have included the development of a picosecond current pulse source. Progress has been hampered by the difficulty in integrating the fragile cantilevered based probes with integrated switches to form the optoelectronic switches that will produce the picosecond current pulse. In addition, quantification of the magnitude of the current pulses has not been achieved so as to allow a determination whether the electrical pulses are large enough to cause measurable dynamics. To overcome these issues, experimental techniques to address the probe fragility are being developed and experiments have been designed to measure the current/voltage magnitude of pulses injected into suitable strip-lines. The implementation of electrical pumping will be delayed to the next Period 7.

- The Nanomagnetic research of **S. Khizroev** (*FIU*) has been in sub-10nm nanodevices which are fabricated and manipulated in cleanrooms with ultra-low particulate levels. Progress in the research efforts has been hampered by the higher than desired down-time for the needed equipment for sputtering and FIB fabrication in an open-access cleanroom facility. The FIU researchers have been addressing the issue of cleanroom maintenance with the FIU university administration.

2a. *Research Thrusts in Period 6*

E^{3}S Research Strategic Plan: Understanding the status of the Center's research in Period 6 is best done in the context of the Center's research strategic plan. This plan can be found in the section, Context Statement, at the beginning of this Period 6 Annual Report.

E^{3}S Researchers: The Center brought together faculty researchers in five academic institutions: UC Berkeley, MIT, Stanford, The University of Texas at El Paso (UTEP), and Florida International. The co-PI's are:

- UC Berkeley: E. Alon, J. Bokor, C. Chang-Hasnain, F. Fischer, A. Javey, T.-J. King Liu, S. Salahuddin, V. Stojanovic, J. Wu, M. C. Wu, and E. Yablonovitch.
- MIT: D. Antoniadis, V. Bulović, J. del Alamo, E. Fitzgerald, J. Hoyt, J. Lang and T. Swager
- Stanford: H.-S. P. Wong
- UTEP: D. Zubia
- FIU: S. Khizroev

All but one faculty researchers were with the Center in the previous Period 5. **F. Fischer** (*Berkeley*) joined the Center in the beginning of Period 6 to start a new Theme I project; his biosketch is given in Appendix A. In Period 6, **E. Alon** (*Berkeley*), one of the two circuit design faculty in the Center, reduced his involvement in the Center's research due his departmental responsibility to re-engineer the undergraduate electrical engineering curriculum.

The following table identifies faculty participation in the four research Themes in Period 6. We provide the following guide on faculty participation by Theme to facilitate the understanding of each Theme through the Theme narratives given in the upcoming sections of this report. Note that *x** indicates the Theme Leader. The Research status report is organized by Themes; the research on devices and the associated circuit studies are discussed within the section applicable to the Theme.

Faculty Participation by Theme in the Current Period 6

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

	Fitzgerald			*x*	
	Hoyt	*x*			
	Lang		*x*		
	Swager		*x*		
Stanford	Wong		*x*		
UTEP	Zubia		*x*	*x*	
FIU	Khizroev				*x*

Legend: x = Theme Leader*

Center Synergy: The Center's four research Themes are made up of 17 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. Approximately 65% of the projects involve more than 1 faculty group, while about 30% has multi-institutional engagement.

In Period 6, there are two new collaborations that we would like to highlight.

- Piezoresistance in Chalcogenide Monolayers: This new collaboration among **D. Zubia** (*UTEP*), **A. Javey** and **T.-J. King Liu** (*both Berkeley*) was implemented with the E^{3}S Rotation Program supporting a 10-week internship of a UTEP postdoc at Berkeley. Earlier in Period 6, **D. Zubia** proposed the concept of straining Chalcogenide monolayers with a MEMS device to change the bandgap and thus affect switching. However, the laboratory at UTEP had insufficient equipment and experience in Chalcogenide materials and MEMS device fabrication. To help accelerate the demonstration of feasibility, **S. Almeida** (*UTEP*) spent 10 weeks in Summer 2015, hosted by **Javey** and **King Liu** in Berkeley. The technical results were very encouraging and plans, including funding of new equipment at UTEP by the Center as well as continuing collaboration on MEMS between the **Zubia** and **King Liu** groups, will continue; see Theme II Research in Periods 6 & 7.
- New Nanomagnetics Collaborations: The informal faculty interactions in the Center led to the invitation of **H.-S. P. Wong** (*Stanford*) to **S. Salahuddin** (*Berkeley*) to co-author an invited commentary paper on the role of memory in computing that was published in Nature Nanotechnology. This interaction has led to the start of a new circuit level demonstration initiative in the Nanomagnetics Theme in Period 7. Accordingly, **S. Wong** will move from Theme II – Nanomechanics to Theme IV – Nanomagnetics.

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

The goal of the Nanoelectronics Theme is to discover a solid-state switch that could replace the transistor switch, but at a much lower voltage. Both academia and industry have spent considerable efforts on the mechanisms of the tunnel transistor, reasoning that Moore's Law has led to devices so small as to require the consideration of tunneling. While there are many research groups in this field, world-wide, experimental results still failed to yield devices with the promised steepness, On/Off ratio and conductance, even though theory has predicted excellent results [1]. Simple theory shows that the tunnel-distance-modulation is steep at low currents, but rather shallow at the high conductance (current) density needed for a competitive device. Conductance density translates directly to clock speed.

There are two main tunnel modulation mechanisms in play: tunnel-distance-modulation versus density-of-states modulation, which is also called energy filtering. While most researchers are attracted to the density-of-states modulation mechanism, the leading device results are more characteristic of the tunnel-distance-modulation mechanism, which works well only at low current density [23] [24] [25] [26]. Averaged over both low and high current density, under the distance modulation mechanism, a ~50% reduction in operating voltage might be achievable, compared to today's transistors, (at best 250 mV).

The Center's focus in voltage reduction is well beyond what industry is currently aiming. Since the inception of the Center, the Nanoelectronics researchers of the Center at MIT and Berkeley, led by Theme Leader, **E. Yablonovitch** (*Berkeley*), have focused on elucidating the underlying physics of the density-of-states switch. In the last Reporting Period, we reported the discovery of a particular requirement in the density-of-states switch, which is blocking progress.

Tunneling is an interfacial process, limited by the two-dimensional density of quantum states, which is $dN/dE = \sim 10^{12}\ /cm^2/eV$. This desirable tunneling needs to compete with bandgap defect state density, D_{it} which is a very important Figure-of-Merit in electronics science. For the materials that we have been considering for density-of-state switches, the defect density is $D_{it} \sim 10^{11}\ /cm^2/eV$, leading to "trap-assisted-tunneling". This means that, at best, we could look forward to only a 10x On/Off ratio in the density-of-states switch, even if everything else worked perfectly. The challenge here is that after decades of research, the best D_{it} is $\sim 10^{10}\ /cm^2/eV$, in the most favorable material system [4].

In this Reporting Period 6, further investigations into trap-assisted tunneling, both through modeling and experiments, have continued in **Antoniadis**, **Hoyt** and **del Alamo** groups (*MIT*) and the **Yablonovitch** group (*Berkeley*). The key conclusion is that the modeling by the **Yablonovitch** group using the experimental data of the **del Alamo** group shows that temperature dependent data of tunneling FETs can be explained by a two-step switching process: thermal activation at low drain-source voltage to be followed by band-to-band tunneling at higher voltage.

The recognition of potential need for higher level of materials perfection has been a concern of the Center since its early years and thus, research into semiconductors based on two dimensional (2d) materials, particularly Transition Metals Dichalcogenides (TMDs) has been part of the Theme I research approaches since Period 3 and reported in past Annual Reports. TMD is a good material system because of its fundamental layered structure, minimum surface roughness, lack of dangling bonds and surface defects at extremely thin body (~1 nm for single layer). The identification of the importance of interfacial trap in the switching mechanism of tunneling FETs places additional importance on the Center's TMDs research effort. Indeed, a key accomplishment of the Nanoelectronics Theme is the results from the **Javey** group (*Berkeley*) on quality of TMD materials. Using photoluminescence quantum yield as probe of material quality, the **Javey** group demonstrated 95% photoluminescence quantum yield in chemically treated MoS_2, indicating that it is possible to achieve materials where the traps can be passivated or repaired.

In support of the Center's strategy on semiconductor materials of near perfection quality, **F. Fischer** (*Berkeley*), a synthetic organic chemist, joined the Center at the beginning of this Reporting Period 6 initiating research that takes a bottom-up approach in fabricating semiconductors, versus the top-down approach in traditional semiconductors. The **Fischer** group has developed a synthetic bottom-up strategy for the synthesis of hybrid graphene nanoribbons (GNRs) heterostructures to exploit the possibilities that arise from lateral electron quantum confinement effects in the one-dimensional GNRs. Many of these properties can directly be correlated to the absolute dimensions, the intramolecular symmetry and the edge-structure. The initial strategy is to incorporate molecular quantum dots lined on either side by a narrow tunneling barrier into individual GNRs as a means to control the bandgap. The initial goal is to develop a fundamental understanding of how to modulate the band structure at the interface between a molecular quantum dots and the extended bands of a GNR. This work will be crucial for the rational design of functional device architectures relying on quantum tunneling junctions. The longer term goal is the building of synthetic tools, molecular building blocks and purification techniques that will enable the bulk and highly reproducible fabrication of GNR heterojunction devices for advanced circuit architectures.

Details of Theme I research efforts for Period 6 are provided below.

InAs/InGaAs Nanowires TFETs: The research efforts of the **del Alamo** group (*MIT*) in InGaAs/InAs heterojunction vertical nanowire (NW) TFETs has continued as the key venue to study the underlying physics of tunneling in semiconductors. The vertical nanowire tunnel FET with a superlattice can enable energy filtering in density of state switching. In this Reporting Period 6, the research has proceeded to: 1) complete characterization and data analysis of the >10 nm nanowire device structure that was fabricated in the last Reporting Period 5; 2) develop a simulation model that will account for band-to-band tunneling; 3) develop processes for fabricating narrow nanowires that can support a single 1D sub-band.

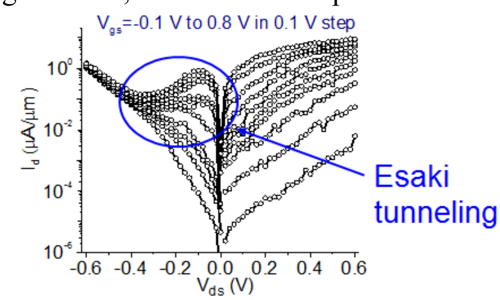


Figure I-1: I-V characteristics of Vertical Nanowire InGaAs Tunnel FETs showing Esaki tunneling regime.

The InGaAs Vertical Nanowire Tunnel FETs (VNW-TFETs), fabricated in the previous Reporting Period, were fully characterized and Esaki tunneling under forward-biased diode conditions was unmistakably observed (Figure I-1) [2]. Severe clipping of ON current in InGaAs VNW-TFETs was observed, which is a common problem in all TFETs of every design. In the case of the MIT VNW TFETs, this limitation in the ON current is tentatively attributed to the modulation of the hole concentration at the source by the gate, which partially overlaps it. As the gate voltage is made more positive, the hole concentration is reduced and the density of states available at the source for tunneling also goes down. This prevents the tunneling current from increasing.

In Period 6, the **Yablonovitch** group (*Berkeley*) reported the analysis of the measured characteristics of the nanowire TFET fabricated by the **del Alamo** group, and identified the specific role of interface traps on the device On/Off ratio [3]. The physical illustration of the nanowire TFET is given in

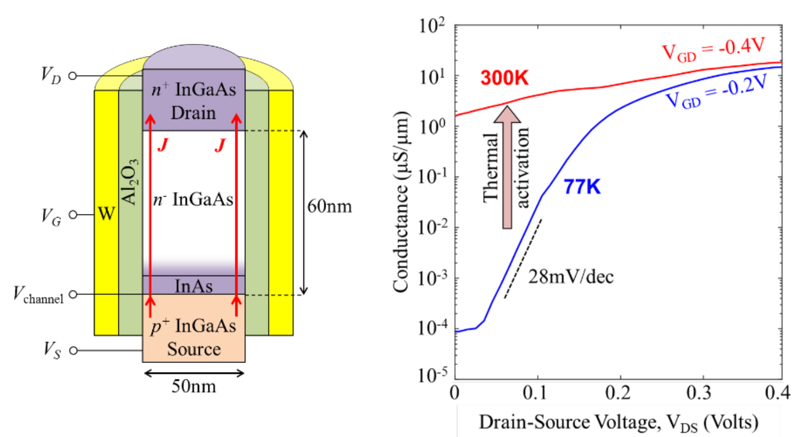


Figure I-2: Schematic (Left) and conductance characteristics at two temperatures (Right) of the InGaAs nanowire TFET from the **del Alamo** group [11]. The tunneling junction lies between the p+ InGaAs source and the InAs notch in the channel.

Figure I-2, *left*. Two-terminal conductance measurements were performed with varying drain-source voltage and fixed gate-drain voltage (biasing the device as a backward diode) in order to observe the intrinsic turn-on steepness. By comparing the measurements at two temperatures, the electrical characteristics can be separated into a thermally-limited regime and a tunneling-limited regime Figure I-2, *right*.

The trap-assisted tunneling mechanism, which conducts current prior to the band overlap condition, can be viewed as a two-step process. A carrier first tunnels from the source valence band to an interface trap state in the bandgap. The relevant trap states are those at the p-n junction between III-V semiconductors, as well as the traps at the interface between the semiconductor and the gate dielectric (Al_2O_3). After the tunneling event, the carrier can be thermally excited above the conduction band edge by a thermal Shockley-Reed-Hall (SRH) process (Figure I-3, *left*). The thermal activation energy ΔE required for the trapped carriers is the separation between the source Fermi level and the channel conduction band, which is controlled by the voltage V_{DS}. Extraction of the activation energy from the results in Figure I-3 *right* shows that ΔE decreases linearly with the applied voltage, as expected, within a certain voltage range (Figure I-4). In this range, the current is dominated by the thermal excitation rate, which grows as exp ($-\Delta E/kT$). At a certain voltage, the tunneling rate into the trap states becomes the limiting step of the conduction process and the conductance of the device follows the density of states. At a still larger voltage, the conduction band and the valence band overlap, and band-to-band tunneling begins (Figure I-3, *right*).

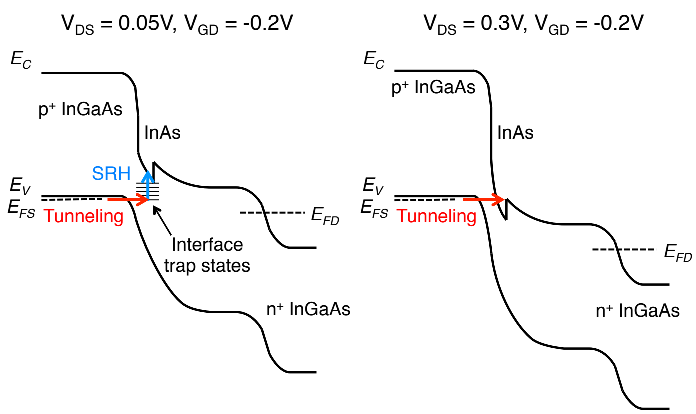


Figure I-3: (a) Band diagram at the tunneling interface in the subthreshold regime, $V_{DS} = 0.05V$. (b) Band diagram in the On state, $V_{DS} = 0.3V$. (Band diagram not to scale)

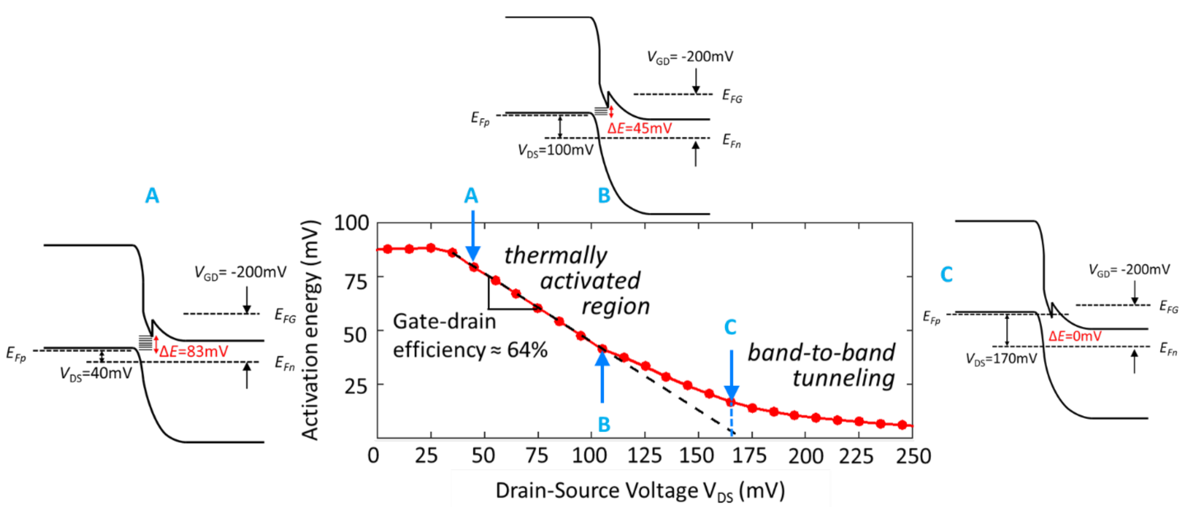


Figure I-4: Thermal activation energy (ΔE) and band diagrams at different drain-source voltages. ΔE decreases linearly with voltage in the thermally activated regime (A to B), but tends toward zero as the device becomes tunneling-limited. Point C is the onset of band-to-band tunneling.

The low-temperature conductance measurements are fit to a two-step trap-assisted tunneling model and a band-to-band tunneling model (from the 3D bulk nanowire source to a 2D sheet of current in the channel), as shown in Figure I-5. From the difference in the rate of tunneling into the traps and into the conduction band, we can approximately extract the ratio of the density-of-states between the bandgap and the conduction band. The density-of-states ratio is roughly ~10^2, four orders of magnitude smaller than the required conductance On/Off ratio of 10^6. Without vastly improving the density-of-states ratio, a steep response over the desired six decades of current cannot be achieved.

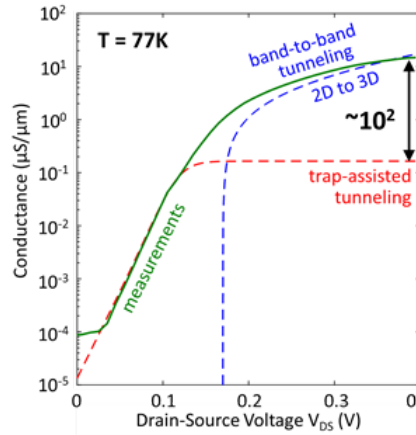


Figure I-5: Trap-assisted tunneling and 3D-to-2D band-to-band tunneling conductance characteristics are compared to the measured conductance at 77 K.

Towards the goal of elucidating the fundamental physics of tunneling devices, the **del Alamo** group has been focusing on the fabrication of InGaAs vertical nanowires with sub-10 nm dimensions that can support a single 1D subband. The biggest challenge lies in the need to refine the etching technology and develop a new isolation scheme for the nanowire. Towards that goal, the **de Alamo** group has refined its etching technology and demonstrated InGaAs FinFETs with fin widths as narrow as 5 nm (Figure I-6). In these devices, prominent quantum effects were observed at room temperature. The threshold voltage of these devices exhibits a marked dependence on the fin width that arises from electron quantization. This is confirmed by self-consistent Poisson-Schrodinger simulations. This demonstration gives us confidence that using these fabrication techniques, it should be possible to achieve single-mode InGaAs vertical nanowires to be used in Tunnel FETs and Superlattice Source MOSFETs.

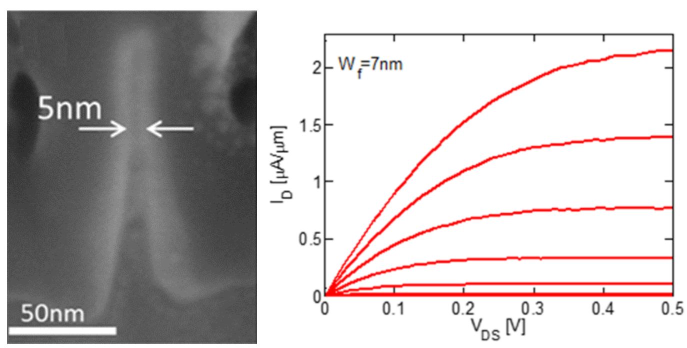


Figure I-6: *Left* **-** Cross-section of InGaAs FinFET with 5 nm fin width; *Right* - I-V characteristics of 7 nm fin-width InGaAs FinFET.

Chalcogenides Tunnel FETs: The goal of this project in the **Javey** group (*Berkeley*) is two-fold: establish the materials science as well as demonstrate devices. In this Period 6, there have been successes in both accounts.

As previously stated, Chalcogenides are an attractive materials system partly due to the potential of having materials closer to perfection. Two dimensional layered materials have pristine interfaces and surfaces due to the absence of out-of-plane dangling bonds. As recently reported, the **Javey** group, in collaboration with **E. Yablonovitch** used photoluminescence quantum yield to probe the quality of MoS_2 to demonstrate that if there are active defects, they can be passivated/repaired [27].

$$\text{Quantum Yield} = \frac{\mathit{Radiative\ Decay\ Rate}}{\mathit{Non{-}Radiatiive\ Decay\ Rate} + \mathit{Radiative\ Decay\ Rate}}$$

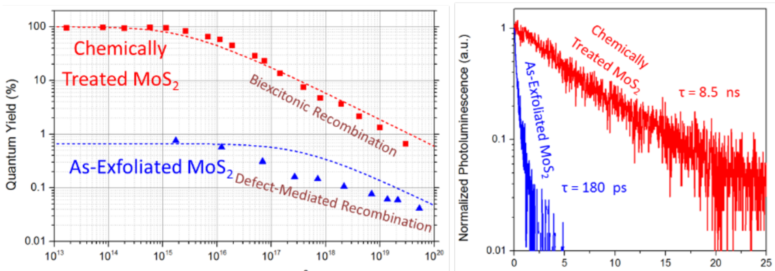


Figure I-7: Quantum yield and the associated lifetime of the photoluminescence from MoS_2 samples: chemically treated (red); as-exfoliated (blue)

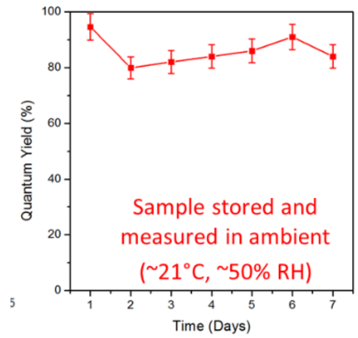


Figure I-8: Quantum yield of chemically-treated MoS_2 samples that has been stored in air

Quantum yield is a highly sensitive indicator of material quality, as lower quality materials will have midgap defects that act as non-radiative recombination centers. We measured the photoluminescence quantum yield of exfoliated MoS_2 and chemically treated MoS_2. Figure I-7 shows that the MoS_2 samples that have been chemically treated exhibit >95% quantum yield compared to the as-exfoliated samples which have quantum yields of <1%. Furthermore, Figure I-8 shows that the chemically treated samples continued to show high quantum yield when stored for more than one week in air.

These quantum yield data reflect the low level of traps and lend support to the Center's strategy of pursuing chalcogenides as a materials system for tunnel semiconductors.

The device demonstration goal of this project is to build a tunnel field effect transistor with a subthreshold swing of 1 mV/decade. Heterostructure devices with layered materials are being explored towards the application of tunnel transistors. Both lateral and vertical heterostructures are being investigated. Homojunction tunnel FETs are also being explored. The heterojunction device structure involves gating of the individual constituents of the heterostack. Thus, electrostatic doping and tuning of band alignment are possible. This rules out the use of physical dopants that may smear out the band edges at the heterojunction. Principally, extremely steep switching can be obtained.

In this Period 6, the first TFET with two different layered semiconductors was achieved. A heterostructure using WSe_2 as the gated p-layer and $SnSe_2$ as the degenerately n-type layer was fabricated (Figure I-9). The van der Waals gap at the hetero-interface prevents the Fermi level from being pinned at the interface. Thus, gate-controlled tunneling can be obtained without the use of an additional tunneling barrier. The band alignment of WSe_2 and $SnSe_2$ was experimentally obtained using X-ray photoelectron spectroscopy to be close to type III. This helps in the realization of a tunnel FET without having to apply large electric fields across the heterojunction to control tunneling.

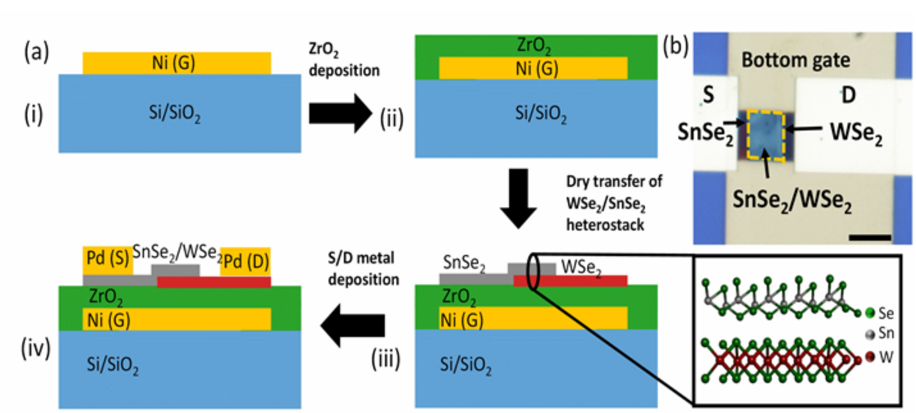


Figure I-9: a) Schematic of the fabrication process for a WSe_2/$SnSe_2$ TFET; b) a top down view of the active area.

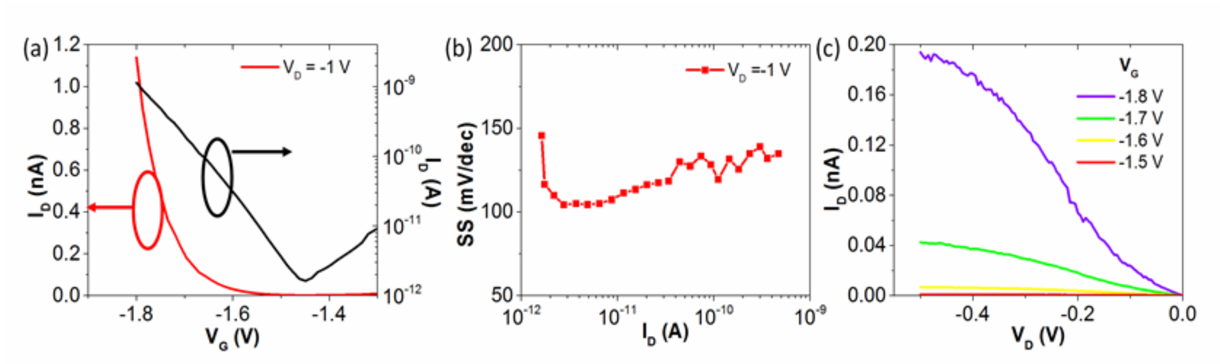


Figure I-10: Characteristics of $WSe_2/SnSe_2$ heterojunction TFET at room temperature (295 K), in vacuum-.a) I_D-V_G at V_D = -1 V; b) Subthreshold swing *vs*. I_D; c) I_D-V_D for varying gate voltages.

$WSe_2/SnSe_2$ vertical tunnel transistors were realized with a minimum subthreshold swing of 100 mV/dec. The best case I_{ON}/I_{OFF} was 10^7 (Figure I-10).

Negative differential resistance was observed at low temperatures (Figure I-11), confirming that the current obtained across the $WSe_2/SnSe_2$ heterojunction is due to band-to-band tunneling. Also, the subthreshold swing was observed to be independent of temperature.

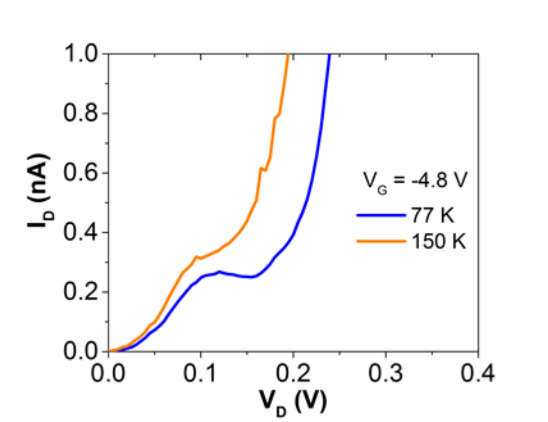


Figure I-11: Data from a $WSe_2/SnSe_2$ at two different temperatures show negative differential resistance as well as temperature-independent sub-threshold swing

Quantum Tunneling Devices from Graphene Nanoribbons:

F. Fischer (*Berkeley*) has synthesized p-doped graphene nanoribbons (GNRs) featuring an atomically defined pattern of boron atoms along the backbone of the GNRs. Low-temperature scanning tunneling microscopy (STM) imaging of fully cyclized B-doped 7-AGNRs (B-7AGNRs) reveals a unique, characteristic stripe pattern along the length of the ribbon with a period corresponding to the distance between the expected position of dopant atoms in the molecular repeat unit (**Figure I-12**). This is consistent with the empty p-orbitals of boron conjugating to the extended π-system of the 7-AGNR and acting as substitutional dopants. Density functional theory (DFT) calculations reveal that B-7AGNRs have a deep acceptor band at energies within the gap of undoped 7-AGNRs, which is localized along the backbone of a B-7AGNR and verified experimentally through *dI*/*dV* imaging.

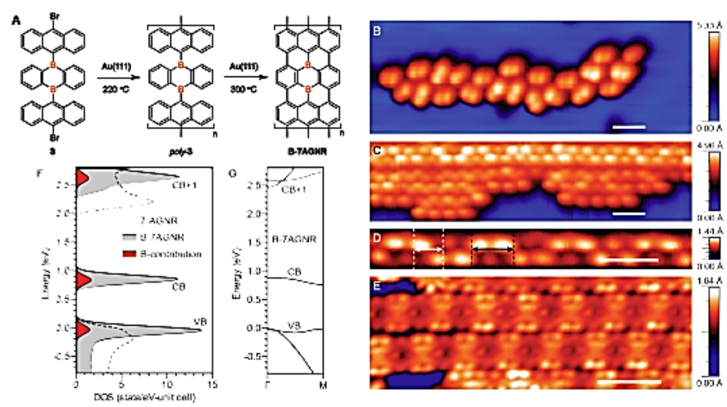


Figure I-12: A) Schematic representation of the bottom-up synthesis of B-7AGNRs; B) STM topographic image of the building block 3 (right); C-D) STM topographic image of poly-3 (middle); and E) fully cyclized B-7AGNRs (left).

Center for Energy Efficient Electronics Science

The key challenge towards the goal of demonstrating sub-0.1 Volt switching with nano-electro-mechanical (NEM) relays is to minimize or even eliminate the contact adhesion energy. In Period 6, the Nanomechanics researchers at UC Berkeley, MIT and Stanford University have continued to pursue complementary approaches to address this technical challenge.

In the last Reporting Period, the research group of **T.-J. King Liu** *(Berkeley)*, Theme Leader, developed an analytical model to assess the switching energy of a NEM switch. In this Reporting Period, further studies using the analytical model resulted in the identification of a bistable nanomechanical tunneling switch that requires even lower operating energy than the normally-on tunneling switch which was presented in last year's annual report. The energy required to operate either the tunneling switch or the bistable (body-biased) tunneling switch, 18.12 aJ or 7.61 aJ, respectively, are lower than the contact adhesion energy [13]. These switch designs leverage the spring-restoring force to counterbalance contact adhesion force, reducing the depth of the potential energy well created by contact adhesion and thereby overcoming the contact adhesion energy limit. This work demonstrates that it is possible for tunneling or non-contact switches to overcome the previously perceived switching energy limit of a NEM switch, and thereby paves a pathway to ultimately energy-efficient NEM switches.

The new research finding of ultra-low switching energy in tunneling devices is influencing the strategy of the Nanomechanics Theme. The last annual report presented a strategy that continued to emphasize both non-contacting and contacting switches; the former, the Squitch project [6], pursued by researchers at MIT, and the later, van der Waals (vdw) switches, pursued by researchers at Berkeley and Stanford. Also new in this Period 6 is the first demonstration of piezoresistance in Transition Metal DiChalcogenide (TMD) monolayers strained using a MEM actuator. Thus, Theme II has begun to de-emphasize vdw switches, and to look ahead to the upcoming Period 7 to focus on the Squitch and other tunneling switches as well as Piezoeresistive NEM switches.

Details of the Theme II research efforts are provided below.

Ultra-Low-Voltage Switch Designs: The **King Liu** group (*Berkeley*) proposed new tunneling switch designs in which the actuator electrode and contacting electrode are located on opposite sides of the suspended electrode [13]. In these designs, the movable electrode has lower stiffness so that the force of adhesion (F_{adh}) actuates it into the ON state without an applied voltage; F_{adh} is balanced by the spring restoring force (F_{spring}) within 1 Å of contact to allow for significant electron conduction via tunneling. To turn OFF the switch, electrostatic force (F_{elec}) is applied to actuate the suspended electrode away from the contacting electrode and thereby reduce the tunneling current. Since F_{elec} and F_{spring} work together to counterbalance F_{adh}, less electrostatic force (hence less energy) is needed to operate the switch. Calculated reductions in operating voltage and energy for conventional *vs*. tunneling switch designs are provided in Table II-1, demonstrating the potential for tunneling-based NEM switches to achieve very low switching energy, albeit at the tradeoff of reduced ON/OFF current ratio ($\sim 10^4$).

The **King Liu** group (*Berkeley*) also investigated the fundamental tradeoff between relay switching energy and switching delay, for contacting switches. Figure II-1 shows the structure of the planar 6-terminal (6-T) micro-electro-mechanical (MEM) relay design used in this study [28]. It comprises one gate electrode, one body electrode, and two pairs of output (source/drain) electrodes. When the magnitude of the gate-to-body voltage (V_{GB}) is larger than that of the pull-in voltage (V_{PI}), the electrostatic force (F_{elec}) is sufficient to actuate the body downward (toward the gate electrode) such that each of the channels (narrow metal strips attached to the underside of the body via an insulating dielectric layer) contacts with its respective pair of source/drain electrodes (which are co-planar with the gate electrode) so that output current (I_{DS}) suddenly can flow. When V_{GB} is reduced below the release voltage (V_{RL}), the spring restoring force (F_{spring}) of the folded-flexure suspension beams actuates the body upward, such that contact between the channels and their respective source/drain electrodes is broken and I_{DS} suddenly drops to zero. It should be noted that F_{spring} must be greater than the sum of F_{elec} and the contact adhesive force (F_{adh}) to switch off the relay.

Symbol	Description	Unit	Conventional (Sec. II)	Tunneling (Sec. III-A)	Bistable Tunneling (Sec. III-B)
A_{act}	Actuation area	μm^2	0.7	0.7	0.16
A_c	Real contact area	nm^2		10	
g_{act}	Fabricated actuation gap	Å		17	
g_{cont}	Fabricated contact gap	Å		5	
k_{eff}	Effective spring constant	N/m	195	172	182
γ	Surface energy density	J/m^2		1.1	
λ_M	Characteristic decay length	Å		1.2	
V	Switching voltage	V	0.2	0.1	0.1
E_{switch}	Total energy consumed during one switching cycle	aJ	102.44	18.12	7.61
E_{limit}	Switching energy limit for a conventional switch	aJ		88	

Table II-1: Design parameters and comparison of calculated switching voltage and energy values for conventional vs. tunneling NEM switch designs.

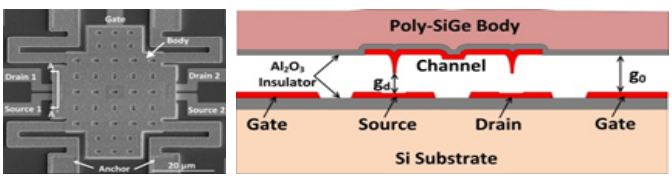


Figure II-1: (a) Plan-view scanning electron micrograph of 6-T MEM relay (b) Schematic cross-sectional view along the cut-line A-A'. The as-fabricated contact gap thickness g_d = 135 nm and the actuation gap thickness g_0 = 260 nm.

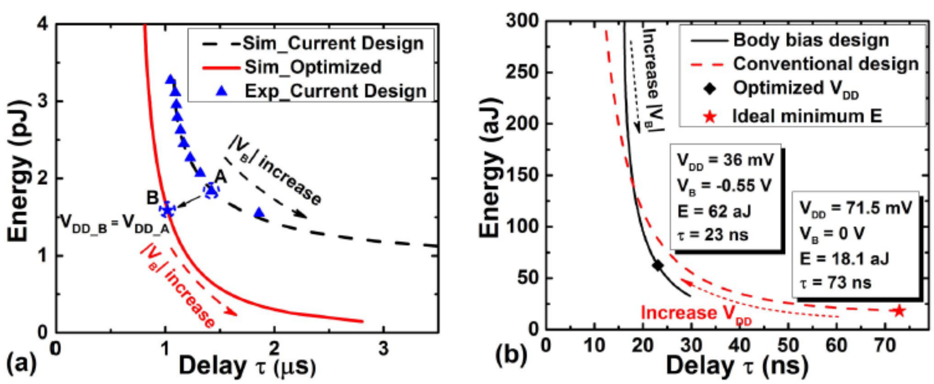


Figure II-2: (a) Measured switching energy *vs.* turn-on delay for a MEM relay (b) calculated energy-delay curves for two NEM relay designs: one optimized for minimum switching energy but with relatively long switching delay; the other optimized for lower switching energy with a shorter delay.

Figure II-2(a) shows the relationship between switching energy and delay for a MEM relay. The triangular symbols represent experimental data for different values of body voltage (V_B) with the same value of V_{GB} (= V_{PI}). As $|V_B|$ increases, the gate voltage swing (*i.e.* the operating voltage V_{DD}) required to switch the relay on/off decreases and hence the switching energy decreases. This improvement in energy efficiency comes at the cost of longer switching delay, however, because the average velocity decreases more quickly than the contact gap thickness with increasing $|V_B|$. To further improve the energy efficiency of a relay, the actuation gap size (g_0) and contact gap size (g_d) should be optimized so that the off-state gate capacitance approaches the on-state gate capacitance. The solid line in Figure II-2(a) is the calculated energy-delay curve for a relay that is identical to the fabricated device except with $g_0 = 3g_d$ = 405 nm instead of 206 nm. It can be seen that the energy-delay trade-off is significantly improved for this theoretical design, even though it has a larger value of V_{PI}. As shown in Figure II-2(b), an optimally designed NEM relay with 1 μm^2 actuation area, 15 nm actuation gap, and 3 N/m effective spring constant is projected to operate with less than 50 mV and ~60 aJ switching energy, which is lower than that required for CMOS transistors at sub-10 nm technology nodes.

With ultra-low-voltage operation enabled by the body-biased relay design, functional relays will be provided to Theme II researchers in the **Bulovic/Lang/Swager** groups (*MIT*) for coating with molecular monolayers to produce low-voltage "squitches" and to the **Zubia** group (*UTEP*) for additional processing with 2-D materials to form piezoresistive switches. See below for the status of the MIT and UTEP research efforts.

In addition, normally-off MEM relays with various contacting electrode materials were systematically characterized by the **King Liu** group (*Berkeley*) to investigate the effects of contact material, relay design and relay operating conditions on contact resistance and contact-opening delay, to assess the trade-off between these performance parameters in minimizing contact adhesion energy. The contact detachment delay (τ_{CD}), i.e. the time required for the spring restoring force to actuate the movable electrode out of contact – which is correlated with contact adhesive force – was systematically characterized for various contact materials. In contrast to the turn-on or "pull-in" delay (τ_{PI}), i.e. the time required for the electrostatic force to actuate the movable electrode into contact, τ_{CD} varies with the contact material, as shown in Figure II-3. It can be reduced by using a contact material with lower normalized adherence force, but at the trade-off of larger contact resistance.

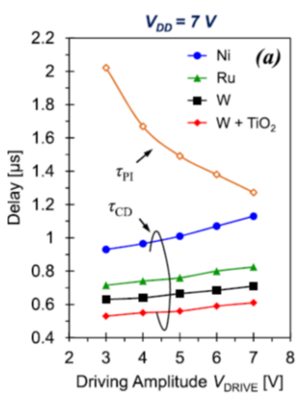


Figure II-3: Measured contact detachment delay (τ_{CD}) and pull-in delay (τ_{PI}) of microrelays with different contact electrode materials. Measured values of relay ON-state resistance were ~700 Ω for W, ~480 Ω for Ru, and ~250 Ω for Ni. These results indicate that lower adherence force is beneficial for higher-speed (and lower-energy) operation, but comes at a cost of increased ON-state resistance; this should not be a significant issue for relay-based integrated circuits, however, whose performance is limited by mechanical delay rather than electrical delay.

Squitch: In the previous Period 5, the team effort of **Bulović**, **Lang** and **Swager** (*MIT*) demonstrated tunneling nanoelectromechanical switches ("squitches") fabricated with metal-molecule-graphene tunneling junctions that exhibited sub-2 V actuation voltages [6]. The device performance obtained, including the differences in performance among devices, may be attributed to variations in molecular layer thickness and packing density, roughness of the electrode, which may result in variations in the effective thickness of the switching gap, as well as the properties of gold or graphene layers. Thus, in this Period 6, we have focused on the development of new fabrication processes to enable fabrication of squitches at the size scale and with the geometry required for low-voltage switching.

Towards that end, we have development in the following processes to enable very flat and very smooth drain, gate and source electrodes:

- Drain and Gate electrodes to be formed by very-flat and very-smooth thin gold crystalline nanoplates: Crystalline nanoplates, shown in Figure II-4, are chemically grown and exhibit less than 0.5 nm roughness over a span of several microns or more. In contrast, the evaporated gold electrodes used in the device demonstration of the last Reporting Period exhibited about 4-nm roughness, a roughness that exceeded the squitch gap.

- Source electrode to be formed by very-flat and very-smooth gold nanocubes or very smooth graphene sheets: The crystalline nanocubes are chemically grown to sizes that can be tuned through synthesis, and exhibit sub-nm surface roughness over their full size. A collection of 100-nm gold nanocubes is shown in Figure II-5. Alternatively, we have also demonstrated the ability to use very-smooth graphene sheets as the source electrode.

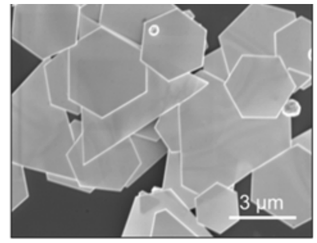


Figure II-4: Chemically synthesized single-crystal gold nanoplates

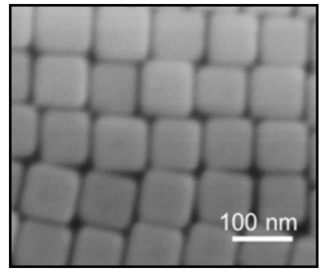


Figure II-5: Chemically synthesized 100-nm single-crystal gold nanocubes

We have used these elements to build a multi-step assembly process by which: (1) gold nanoplates are first brought closely together as neighboring electrodes on a substrate; (2) elements of the molecular monolayer are attached to the plates and/or nanocubes; and (3) gold nanocubes (or graphene sheets) are assembled above the gold electrodes with the molecular monolayer in between. To illustrate, Figure II-6 shows two gold nanoplates on a substrate aligned side by side but separated by a 20 nm gap (left image). The right image is an expanded view of the left in the vicinity of the yellow circle. Gold bonding pads, for example, would be deposited over the nanoplates at their far extremes to provide for connectivity. To further illustrate, Figure II-7 shows a (colorized) gold nanocube located over a gap between two neighboring plates. In this case, the gold nanocube is suspended above the plates by a molecular monolayer that has chemically assisted in locating the nanocube. We have developed several strategies for locating nanocubes. One is physical, and involves using templates that preferentially guide the nanocubes to the desired location. The others are chemical, and involve the molecular layer in the form of noncovalent click chemistry, directed chemical bond formation, and electrostatic attraction of chemical groups. Alternatively, the suspended source electrode could be a graphene sheet. In this case, the graphene sheet is located through manual manipulation.

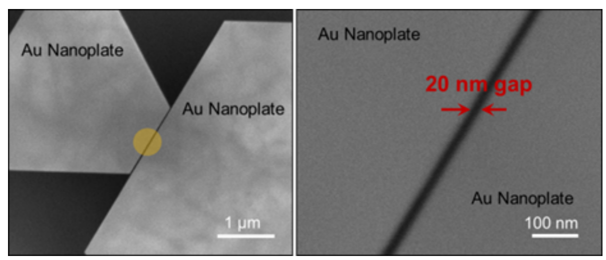


Figure II-6: (*Left*) Two gold nanoplates side-by-side on an oxidized silicon substrate. (*Right*) An expanded view of the left-hand figure showing plate-to-plate alignment and the plate-to-plate gap in detail.

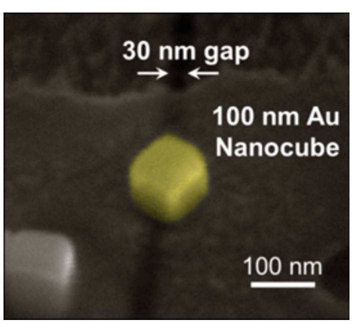


Figure II-7: A (colorized) 100-nm gold nanocube located over a plate-to-plate gap as would be required for the fabrication of a squitch. A molecular monolayer anchors the nanocube to the nanoplates.

To summarize, the fabrication process outlined above should enable fabrication of squitches at the size scale and with the geometry required for low-voltage switching. Further, the squitches will facilitate source motion measurement during switching, which is critical to characterizing the mechanical behavior of the molecular monolayer and squitch physics in general. Squitches fabricated with gold nanocubes should exhibit a plasmonic resonance in their gaps that varies with source motion. The variation should be observable through a change in color of scattered light. Squitches fabricated with graphene sheets should exhibit Raman scattering off the graphene having peaks that shift in frequency with source motion. Finally, the fabrication process is expected to yield a sufficient number of squitches to permit the construction of simple digital circuits, such as a ring oscillator, through which dynamics and circuit behavior can be studied. By the end of this Period 6, we expect to have preliminary device data from squitches fabricated with these processes.

Materials Engineering & Process Development: In collaboration with these device efforts, the **J. Wu** group (*Berkeley*) has continued to engineer the surface of the contact to minimize adhesion and friction. Particularly, ways to implant, oxidize, coat, or plasma-treat the contact surface, and to measure the effects on adhesion and lateral friction were sought. The goal of this work also includes understanding surface degradation during NEM switch operation, particularly materials issues such as oxidation, fatigue, charge tunneling and charge trapping.

The commonly used processes for depositing contact metals (like Ru and W), dc-sputtering techniques, have uniformity issues. In a typical batch of devices, due to the variations of the Ru/W metal uniformity and thickness, reliability has been poor. Instead, in this Reporting Period, we have developed an ALD process to deposit uniform Ru metal films on Si_3N_4/Si substrates. Using Auger Electron Spectroscopy, we have demonstrated that the ALD process does result in metallic Ru films with a surface native conducting oxide that are 1-2 nm thick. The oxygen peak is seen to be diminishing as the material is sputtered exposing the inner region. The electrical quality of the ALD films is comparable to the currently used sputtered Ru films; see Figure II-8. These results demonstrate that ALD deposited Ru films are indeed good-quality Ru metals rather than RuO_2. The surface of the films, however, has a native RuO_2 layer with a thickness of 1-2 nm. The resistivity measurements also show that the ALD deposited films have resistivity of 113 nΩ-m, which is consistent with the literature values of the pure Ru film.

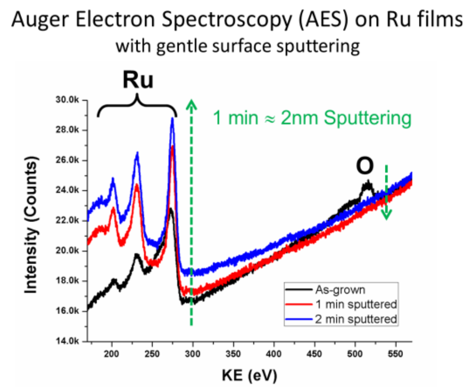


Figure II-8: Auger electron spectrum of ALD deposited Ru films. Gentle surface sputtering was conducted for 1 and 2 minutes to understand the composition of the inner film regions. The sputtering rates are approximately 2-3 nm/sec. The oxygen peak, which was present at the surface of the film, vanishes as we go inside.

Ion-beam synthesis is also being investigated as a method for synthesizing ultrathin layers of RuO_2/WO_2 on Ru/W metals, respectively. Stiction force and energy on these metal and oxide surfaces have been determined with an AFM. In anticipation of research in nano-actuators that will be initiated by the **King Liu** group in the upcoming Period 7, the **J. Wu** group has investigated the nanotribological and electrical properties of vanadium dioxide across its thermal-driven metal-insulator transition, discovering the combined dissipative effects of phonons and electrons in friction in the material [29]. It was learned that the friction decreases with temperature on the insulating domains, which is consistent with thermal lubricity. Further increasing the temperature shows an increase in the friction coefficient, which is associated with electronic contributions to friction from the metallic phase. These results are important in controlling friction that can be used for nano-actuators and micro- and nanomechanical devices.

New research on the role of strain in 2D materials for band gap modulation was initiated by **D. Zubia** (*UTEP*) in this Reporting Period. In this project, a 2D material was transferred onto a MEM actuator to study the role of strain in the 2D material, for applications in switches relevant to Themes 1 and 2. Published reports of MoS_2, WS_2 and WSe_2 indicate that the band structure can be transformed from semiconducting to metallic through strain. For example, theoretical studies predict a large reduction in band gap with application of 11% strain in 2D TMDs [30]. Moreover, experimental studies have shown 4 orders of magnitude change in resistivity in tensile-strained MoS_2 via AFM. This suggests that strain engineering can be used to modify band gaps, carrier effective masses and mobilities. The goal of this research is to explore the fabrication and characterization of a band gap modulated switching device in collaboration with researchers from Theme 1 (**Javey**) and Theme 2 (**King Liu**). The device will use a

MEMS cantilever to strain a 2-dimensional TMDC to change its band gap and hence its resistance, to achieve an energy-efficient switch. We also anticipate this device to serve as a platform for the study of free-standing monolayer physics under strain.

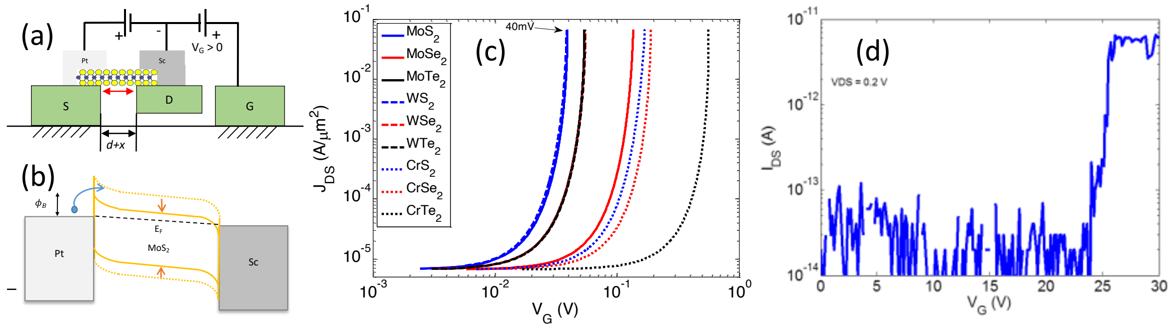


Figure II-9: (a) Schematic representation of the TMD/MEMS device. (b) Band diagram for the OFF and ON state. (c) Modeled and (d) experimental drain current versus gate voltage of the device.

NEM-Relay Based VLSI Circuits: The last annual report, Period 5, reported a study by the group of **V. Stojanović** (*Berkeley*) of the energy-delay performance of a floating-point unit (FPU) implemented with NEM relays vs. CMOS transistors at the 90 nm technology node, to assess the energy-efficiency benefits of NEM relay technology at the system level. This study was concluded in this Period 6 with the evaluation of the efficiency of the scaled-relay floating-point unit (single-precision multiple-add) by benchmarking against the near-V_{th} FPUs reported by Intel Corporation in 2012 (32 nm technology), adjusted for single-precision, for an apples-to-apples comparison [31]. Figure II-10 shows the advantage of relay technology for low-throughput applications where near-Vth or subthreshold CMOS is orders of magnitude less energy-efficient.

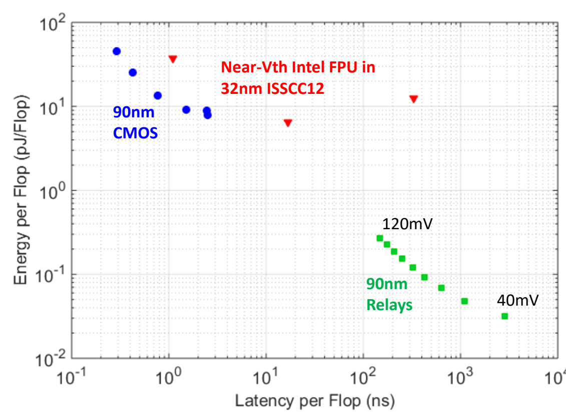


Figure II-10: Comparison of the data on 90nm scaled NEM relay model with Intel's FPU, adjusted for single precision, shows energy per operation with the trade-off of higher latency.

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

The goal of the Nanophotonics theme remains the reduction of the photons per bit in a data-link from 20,000 photons to 20 photons, the quantum limit. The strategy, to improve *both* energy efficiency and sensitivity by orders of magnitude in the emitter and detector and miniaturize the components to sizes comparable to state-of-the-art transistors, has been in place since the start of the Center. By virtue of the radical reduction of the dimensions of the components, Theme III researchers can apply photonic phenomena that are applicable only in nanoscale dimensions to overcome the fundamental trade-off between energy efficiency and sensitivity. Beginning in Period 2, the approach taken by **M.C. Wu**, in collaboration with **E. Yablonovitch** (*both Berkeley*), has been on demonstrating that the spontaneous emission from antenna enhanced nano-LED can be stronger and faster than the stimulated emission of a laser and be ideally more energy efficient because it does not required in DC bias as in the case of the laser, the ubiquitous emitter in data communications of today [7]. This Theme has had a big success in demonstrating that antenna-enhanced spontaneous emission in LEDs can indeed be a lower energy and faster light source as compared to lasers. Moreover, from the overall systems viewpoint, we have identified that the photo-receiver is equally important as the light source for data links to achieve the near quantum limit of 20 photons per bit.

Key accomplishments for the Nanophotonics theme in this Reporting Period are:

- Demonstration of an electrically injected antenna-enhanced nanoLED with increased spontaneous emission enhancement; upwards of 200x.
- Demonstration of nanoLEDs with WSe_2 monolayers that are coupled to slot antennas yielding spontaneous emission rate enhancements up to 320x.
- Demonstration of a compact InP bipolar junction phototransistor with a current gain of 53.6, 3-dB bandwidth of 7 GHz and an external quantum efficiency of 28% for the same device. Both the gain-bandwidth, f_T, of 375 and, particularly, the external quantum efficiency are the highest for a device directly grown on silicon.

Modeling of a photodetector circuit that expressed detector sensitivity in terms of device characteristics has led to the understanding that the primary figure of merit is the quality of the transistor itself. This has led to reconsideration of our phototransistor strategy: integrating a low capacitance photodiode in close proximity of a high performance transistor versus integrating them in a single device. The former allows us to separately optimize the photodiode and the transistor.

Details of the Center's nanophotonics research in this Reporting Period are given below.

NanoLED: The **M. Wu** group (*Berkeley*), in collaboration the **Fitzgerald** group (*MIT*) and the **Yablonovitch** and **Javey** groups (*Berkeley*), are pursuing research in nanoLEDs made with traditional III-V materials and the newer Chalcogenide materials.

<u>III-V Nano-LED</u>: After several process and design improvements to the electrically injected nanoLED, we have demonstrated an order of magnitude increase in spontaneous emission enhancement as measured by taking the ratio of antenna and orthogonal polarization components (from 8X to upwards of 200X). This is the largest spontaneous emission enhancement reported for any antenna-coupled electrically-injected device and a result that places spontaneous emission rate on par with the stimulated emission rate (Figure III-1). This was first reported at IEEE Photonics Conference, in which the student's (**S. Fortuna**) talk has been "updated" to an invited talk [8].

The large boost in measured enhancement factor in the electrically-injected nanoLED was enabled by significant fabrication improvements: 1) A high aspect ratio ridge dry etch was developed to replace wet etch; 2) The gold antenna was replaced with less lossy silver; 3) An in-situ tilting technique was developed to coat ridge with conformal silver; and 4) A low-index spin-on-glass layer was inserted

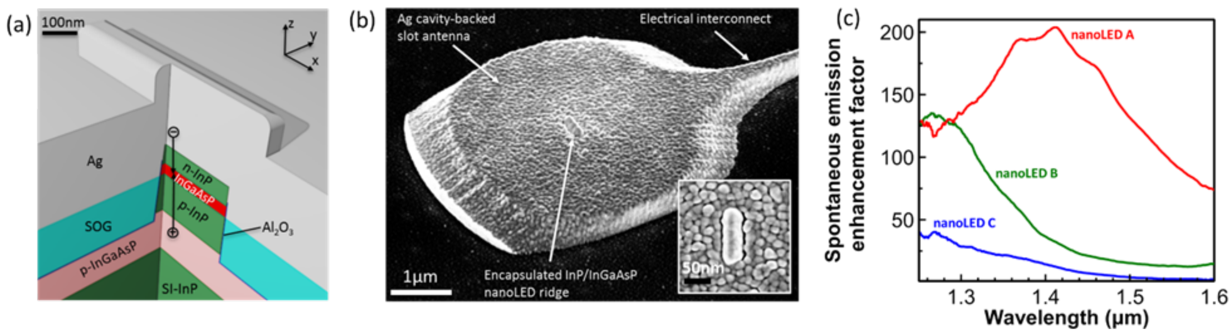


Figure III-1: (a) Cutaway drawing of electrically-injected InP/InGaAsP nanoLED design; (b) Oblique angle SEM image of nanoLED with silver (Ag) cavity-backed slot antenna. Inset shows top-view close-up of encapsulated nanoLED ridge; (c) Measured spontaneous emission enhancement factor for three nanoLED devices with different antenna resonance wavelengths.

between antenna and high index substrate for reduced electrical leakage and increased antenna performance.

One of the challenges is the pronounced impact of surface recombination on the small nanoLEDs, which have large surface-to-volume ratios. The **Fitzgerald** group (*MIT*) has continued to work on materials challenges in support of the **M. Wu** group's efforts to fabricate energy-efficient optoelectronic devices. In the last Reporting Period, research in the growth of InGaAs/InP nanoLED structures via MOCVD was initiated at MIT. In this Reporting Period, characterization by cross-sectional TEM was undertaken, verifying the target film thicknesses as well as excellent interface abruptness. Photoluminescence measurements at both MIT and Berkeley showed good agreement with TEM for the active quantum well thickness. InP was re-grown via MOCVD on blanket InGaAs/InP films after being exposed to atmosphere. Cross-sectional TEM shows an abrupt and clean re-growth interface. Photoluminescence intensity of the InGaAs increased by a factor of 7x with the InP cap vs. without (Figure III-2).

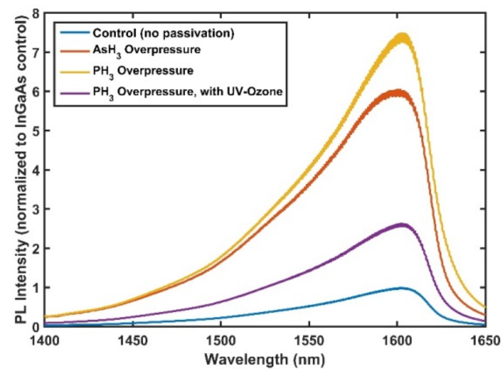


Figure III-2: Photoluminescence Intensity as of InGaAs with MOCVD grown InP layer, overgrown under different conditions.

<u>Chalcogenide Nano-LED</u>: Research into Chalcogenide Nano-LED, which was initiated in the last Reporting Period, has continued. Improvements to device fabrication have enabled WSe_2 monolayers that are coupled to slot antennas to yield spontaneous emission rate enhancements up to 320x. The raw photoluminescence data showed enhancements greater than 1000x because of the higher collection efficiency of the nanoLED emission (Figure III-3).

Improvements to the measurement setup performed in collaboration with the **Yablonovitch** group have allowed measurement of scattering properties and photoluminescence emission from individual antennas. This has greatly improved the ability to characterize our devices and probe the different mechanisms for enhanced light emission. In particular, we are able to distinguish from enhanced pumping and enhanced emission of our WSe_2 monolayers. Scattering measurements also allow us to characterize antennas without the presence of an active material, which significantly speeds up device prototyping.

Further analysis of time resolved measurements performed in external collaboration with **X. Zhang** (*Berkeley*) has shown carrier lifetimes of ~1 psec; see Figure III-4. This is more than an order of magnitude faster than unprocessed flakes. These measurements have led to the identification of edge recombination as the dominant recombination mechanism in all of our devices.

Efforts are underway to investigate the effect of helium ion milling as a high-resolution fabrication technique to increase antenna quality that will be part of the electrically injected test structures. The new fabrication technique will be used to develop optically pumped antenna devices using un-etched MoS_2 monolayers.

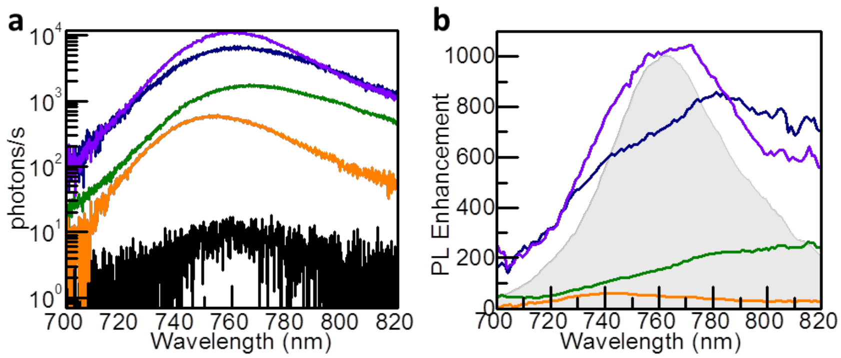


Figure III-3: (a) Total emitted light from five different etched WSe_2 monolayers: resonantly pumped antenna (purple); non-resonantly pumped antennas: on-resonance (blue), slightly-off resonance antenna (green), far-off resonance antenna (orange); bare flake not coupled to antenna (black). (b) PL enhancement of the four devices from (a) calculated by normalizing total light emission to the total light emission from a bare flake. Bare flake emission spectra shown in grey.

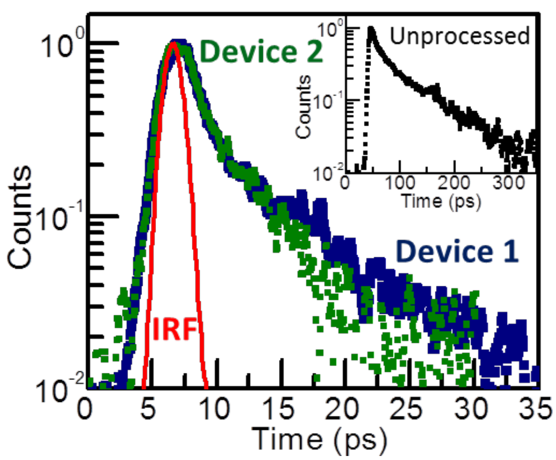


Figure III-4: Time resolved measurements of two different antenna devices (blue and green curves) and an unprocessed monolayer (black, inset). All devices measured have a decay lifetime of ~1ps, which is just above the instrument response (red curve) of our measurement system.

Phototransistors: At UC Berkeley, the **M. Wu** group has been working with the **Yablonovitch** group on Ge Bipolar Phototransistors that are fabricated with the Rapid Melt Growth (RGM) method, while the **Chang-Hasnain** group has been exploring Bipolar Phototransistor of InP nanopillars. The approach of both groups has been to minimize the total capacitance of the photodectector and the drive electronics via optoelectronic integration. Detection sensitivity, as expressed by maximizing the gain bandwidth product, f_T, improves as the capacitance of the device is reduced by shrinking the device size, and as the transit time of the carriers is reduced by shortening the base length. Both these factors, however, are tradeoffs with optical absorption, which reduces as the device is shrunk in size.

To further explore the achievable sensitivity of a bipolar phototransistor, we have developed a simulation to express the sensitivity in terms of fundamental device characteristics and signal-to-noise ratio (SNR).

This derivation, which can easily be generalized to most phototransistor types, shows that the electron transit time of the device as well as the capacitance of the base are crucial in determining the sensitivity of the device. This rules out many phototransistor topologies that have been considered and explored in the past and points out that one may not design a phototransistor without these factors in mind.

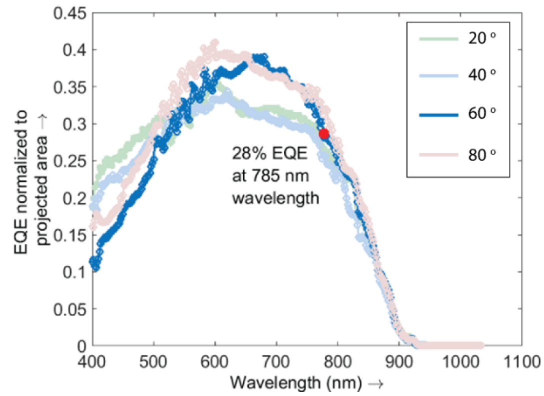


Figure III-5: Measured external quantum efficiency for angled illumination of nanopillar devices. The efficiency was calculated with respect to all the light incident on the projected cross section of the pillar, resolved vs. wavelength. The angle is with respect to the vertical (device growth axis).

<u>InP Phototransistor</u>: In the last performance period the **Chang-Hasnain** group reported that an InP Bipolar Phototransistor (photo-BJT) with very linear photo response and responsivity approaching 4 A/W at low bias voltage of 0.5 V was achieved, indicating that the device with re-grown junctions for low dark current facilitating very low voltage operation. In this Period 6, we have performed a detailed characterization of a fabricated Bipolar p-n-p InP phototransistor.

By decoupling light absorption from the carrier transit direction using a core-shell growth mode (similar to a waveguide geometry) and enhancing the absorption using a dielectric antenna effect, an external quantum efficiency of 28% was achieved, as determined from measurements on a p-i-n junction device with similar dimensions as the phototransistor but with no gain; see. Figure III-5.

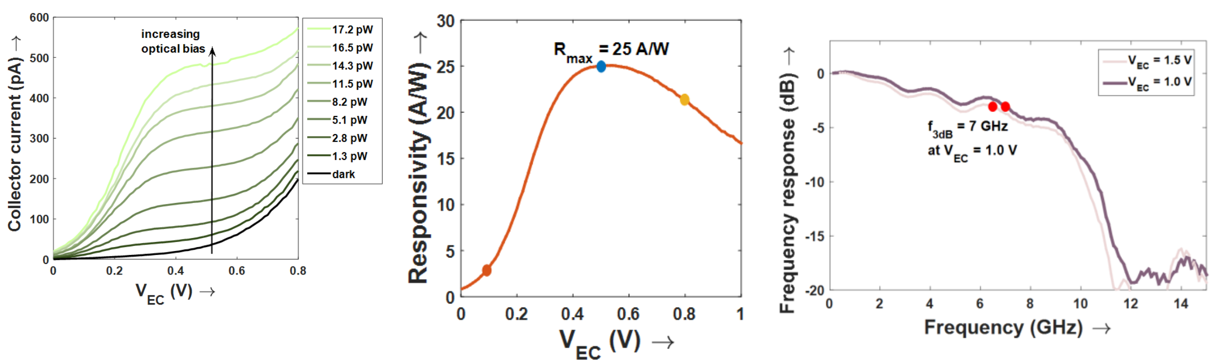


Figure III-6: (a) Light dependent i-v characteristics show a response down to pico-Watt levels of illumination. The dark current at 0.5 V is only 33 pA. (b) The responsivity vs. bias shows a peak of 25 A/W at 0.5 V (blue dot), indicating the possibility of operation at CMOS line voltage. (c) The pulsed response was de-embedded from the pad capacitance to obtain a 3 dB frequency of 7 GHz at 1 V bias. The same device had responsivity of 9.5 A/W – leading to gain bandwidth product of 105 GHz, and electronic transition frequency of 375 GHz.

The output characteristic of the photo-BJT, along with illumination dependence shows the relatively flat collector current, with a high output impedance of approximately 10 GΩ when operated at 0.5 V emitter-collector bias. At the optimum bias point of 0.5 V (indicated by the arrow), the responsivity can be as high as 25 A/W, with a linear response over more than one order of magnitude of input power.

Extremely low dark current of 33 pA was demonstrated in the device, which has its outer shell layers of the device grown after the lower half of the pillar was coated with an oxide sleeve. This electrically isolates the active region from the substrate and allows a low dark current.

The device, with an excellent gain bandwidth product of 375 GHz, has both a high current gain of 53.6 and a bandwidth of 7 GHz. High speed measurements with a pulsed excitation source indicated a 3-dB frequency of 7 GHz and responsivity of 9.5 A/W on the same device; see Figure III-6.

In summary, these results must be compared to the prior photodetector results, as seen in Table III-1 which compares III-V based phototransistors from the reported literature and explains the contextual significance of the Center's results [32] [33] [34] [35] [36]. While it is possible to build a device with extremely high electronic gain bandwidth product, f_T (column 3, left), such a scaled down device often has a very poor external quantum efficiency (column 8 from left). Novel approaches for light management are required to maintain a high absorption while deeply scaling the device. We have used a nanoresonator to achieve both high f_T as well as good efficiency.

	Electronic Gain bandwidth product f_T	Optical gain bandwidth product, accounting for EQE	Technology	Emitter-base junction dimensions	Collector current	EQE
J. C. Campbell *et al.*, 1981	1.7 GHz	1.19 GHz	InP/InGaAs, 1.154 μm	10 μm radius	0.5 mA	70%
S. Chandrasekhar *et al.*, 1993	52 GHz	27.0 GHz	InP/InGaAs, 1.5 μm	$3 \times 8\ \mu m^2$	5 mA	52%
H. Kamitsuna *et al.*, 2000.	82 GHz	16.4 GHz	InP/InGaAs double heterostucture, 1.55 μm	$24\ \mu m^2$	20 mA	20%
A. Leven *at al.*, 2004	135 GHz	8.64 GHz	InP/InGaAs double heterostructure, 1.55 μm	$2.6 \times 7.8\ \mu m$	20 mA	6.4%
V. E. Houtsma *et al.*, 2006	447 GHz	17.88 GHz	InP/InGaAs double heterostructure, 1.55 μm, waveguide coupled	$0.7 \times 4\ \mu m^2$	19.5 mA (calc*)	4%
This Work – Chang-Hasnain, 2015	375 GHz	105 GHz	InP homojunction BJT with nano-resonator geometry	Cylinder: 0.5 μm (r) & 1 μm (h)	Pulsed with ~2.8fJ **	28%

Table III-2: Comparison of InP Photodetector results.

* Calculated based on current at base given as 0.65μA and gain of 10

** Pulsed operation at ~2.8fJ energy per pulse received at device

Ge Phototransistor: Since the last Annual Report, Period 5, the **M. Wu** group has designed and simulated a 100+ GHz separate absorption and gain germanium photo-BJT; see Figures III-7 & 8. The device allows for optimization of transistor gain region, reducing size and increasing doping concentration, for a fast, high f_T transistor. Simultaneously, the separate absorption region can remain large for good optical

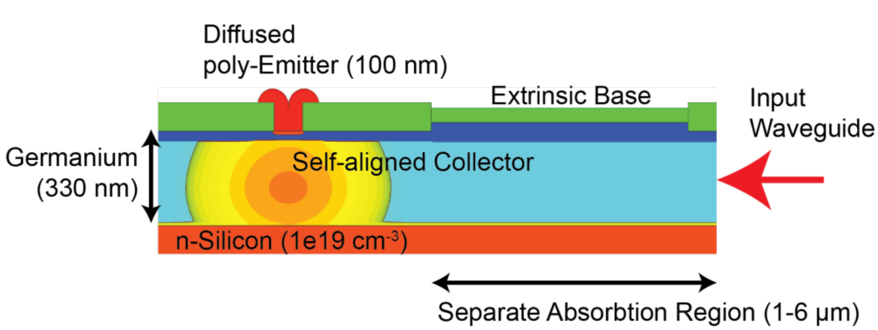


Figure III-7: Schematic showing a simulated separate absorption and gain phototransistor with 330 nm thick germanium on silicon and an input from a silicon waveguide on the right. It is assumed to be 1 μm width into the page.

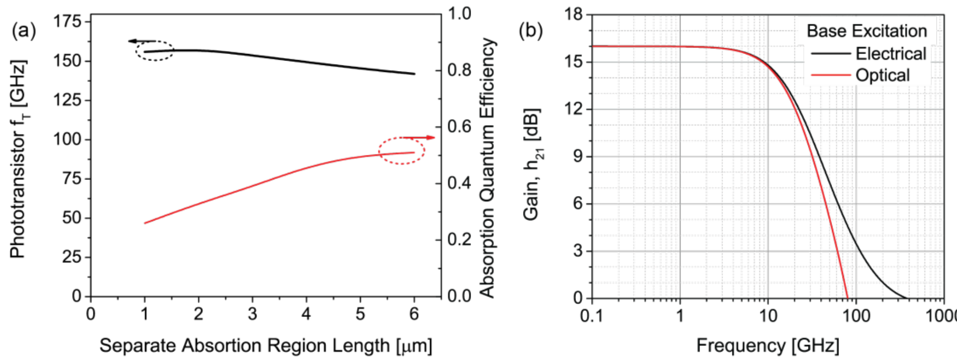


Figure III-8: (a) Simulation results showing little change in f_T when extending the separate absorption region (SAR), but tremendous gains in absorption quantum efficiency. (b) Simulated gain frequency response for a 1 μm SAR showing almost identical frequency response when the phototransistor has an optical input signal, demonstrating fast photocarrier collection into the base.

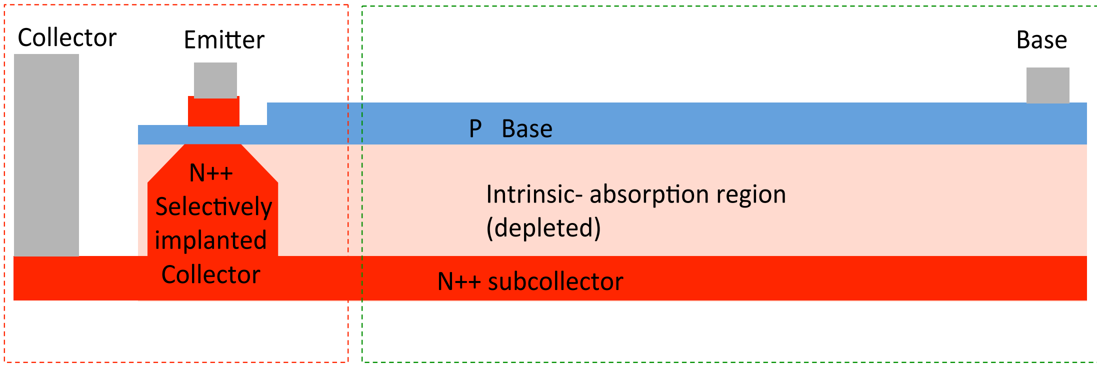
absorption, and with low doping for fast photocarrier collection. Combined, these form a highly absorbing and fast phototransistor.

Using the rapid melt growth method, a 3-terminal Germanium n-p-n phototransistor on silicon photonics was fabricated. The device was a lateral n-p-n transistor with critically aligned emitter/base/collector implants, 500 nm emitter width, and designed with a 60 nm thick emitter and 100 nm thick base. The devices showed the emitter had diffused through the base into the collector and no transistor performance could be measured. This issue is discussed in the earlier Problems Encountered section on challenges encountered.

Circuit Modeling: In addition to the device work, the **Yablonovitch** group also developed an advanced circuit model to incorporate high f_T and low capacitance phototransistor in a low energy receiver circuit. An analysis was performed to determine the critical characteristics of the phototransistor to realize a low energy receiver, and determine the ultimate energy sensitivity limit given the most advanced available BJT technology. The simulation, pursued to elucidate the achievable sensitivity of a bipolar phototransistor, expressed the energy sensitivity in terms of fundamental device characteristics. This derivation, which can easily be generalized to most phototransistor types, showed that the transit time of the amplified electrons through the device, as well as the capacitance of the base are crucial in determining the sensitivity of the device. This rules out many phototransistor topologies that have been considered and explored in the past and points out that one may not design a phototransistor without these factors in mind.

Applying the understanding gained by the derivation of the sensitivity, we were able to design a novel phototransistor architecture where the light absorption and the gain mechanisms are decoupled, and can be separately optimized. The design is inspired by modern heterojunction bipolar technology, and involves the modulation of the base collector junction depth across the device, as shown in Figure III-9. This enables the device to have a large absorption region, while ensuring that the capacitance and the transit time can stay low, resulting in a high sensitivity device.

This simulation work points to the need to explore the possibility of building transistors as close as possible in proximity to the photodiodes rather than integrated directly into them, a strategy that the Center's Nanophotonics researchers have pursued to date. This results from the realization that the primary figure of merit is the quality of the transistor itself. From an implementation perspective, it may be more beneficial to build the transistors out of Silicon rather than Germanium, and leverage the immense amount of research and knowledge of Silicon transistors.



Transistor region
- Short depletion region
- Short transit time (large ft)
- Small Area (low capacitance)

Photodiode region
- Long depletion region
- Low capacitance/Area
- Drift driven carrier collection (fast)
- Large Area (more absorption)
- Thicker base for less resistance

Figure III-9: New Bipolar Phototransistor Topology

The main approach of the Nanomagnetics Theme is taking advantage of ultra-sensitive current driven switches employing actuated Spin-Orbit Torque (Spin Hall Effect) to switch a magnet, which in turn changes a voltage-biased magneto-resistor, producing output current. Such a component can have current in/current out gain, as well as fanout. Since the constituents tend to be metallic, the voltage requirement is low, compatible with the goal of low dynamic power as the digital circuits switch. At the same time, the non-volatility of magnets can be used to reduce the static power losses. Another approach under research for magnetic logic is spin-transfer-torque (STT) in magnetic tunnel junctions (MTJs) in sub-10 nm devices. Led by **J. Bokor** (*Berkeley*), the Center's Nanomagnetics researchers, including **S. Salahuddin** (*Berkeley*) and **S. Khizroev** (*FIU*), are pursuing the goals of magnetic switching with ultra-low switching energy in the order of sub-femtojoules (sub-fJ) and fast switching speed in the order of <10 picoseconds (psec). The focus has been to understand the fundamental physics and the switching dynamics of the spintronic phenomena that underlie magnetic switching with the desired attributes. In addition, a key detractor with all currently known magnetic materials is the low On/Off ratio of present magneto-resistors and the matter is being addressed in the Center from the circuit design and architectural perspective through the research of **V. Stojanović** (*Berkeley*).

Significant progress has been made towards understanding the fundamental physics of spintronics. The new findings include:

- Experimental demonstration of a new way of switching perpendicular nanomagnets with an in-plane current without needing a symmetry breaking magnetic field was completed. These results are significant for the field of spintronics as the symmetry breaking provides new insight into the physics of spin orbit torque and the switching without a magnetic field could lead to significant impact in high-density storage applications.
- Experimental observation of an anomalous low switching current density in STT-MTJs when the planar sizes are reduced substantially below 10 nm, and related, the observation to reduced damping in magnetic nanoparticles through ab initio calculations.
- Optical measurement of spin accumulation at non-magnetic heavy metal surfaces due to spin-Hall effect with a build-up and decay time of the spin accumulation to be <200 psec. This result has direct impact on the question of the speed of response of magnetic memory and switches based on spin-Hall effect.
- Direct observation of magnetic "toggling" in GdFeCo allow samples by fsec laser pulses indicating that the magnetization reversal occurs in about 1 psec.

In addition, modeling to provide circuit perspectives of magnetic logic devices has provided initial conclusions that magnetic logic can be optimized at very low supply voltage and the energy dissipation can be reduced infinitesimally toward zero at the expense of the time delay. However, energy scaling is limited by noise at low throughputs.

Details of the Center's Nanomagnetics research in the Reporting Period 6 are given below.

Physics of Spin Hall Effect: The spin-orbit torque effect, typically identified as a spin-Hall effect, which arises from the spin current transverse to an applied charge current in a non-magnetic metal as a result of spin-orbit coupling, has emerged as a promising new low current magnetization switching technique. When a spin-orbit-torque is applied to a magnet with perpendicular anisotropy, the induced spin accumulation is completely symmetric with respect to the magnetization. As a result, previous work has shown that a deterministic switching cannot be achieved unless an external magnetic field is applied to break the symmetry. The **Salahuddin** group (*Berkeley*) has demonstrated the elimination of this external magnetic field to switch a perpendicularly polarized magnet with an in-plane current, which can significantly reduce the power dissipation. The Berkeley team has accomplished this by engineering an anisotropy in the magnets such that the magnetic easy axis slightly tilts away from the direction normal to the film plane. Such a tilted anisotropy breaks the symmetry and makes it possible to switch the magnet deterministically without needing the external magnetic field [11].

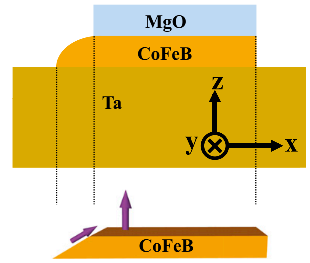


Figure IV-1: Schematic showing the structure and the tilt coming from the spins aligning to the wedge.

The experimental demonstration was conducted with nanomagnetic devices that are built from a stack of Ta /CoFeB/ MgO/Ta thin films with a CoFeB wedged thickness profile (Figure IV-1). To experimentally assess the impact of the wedge, they have performed anisotropic magnetoresistance (AMR) measurements at ambient room temperature to investigate potential tilting of the easy axis. Figures IV-2a and 2b show the dependence of resistivity on the rotation angle θ of the in-plane magnetic field (H_{inp}) in the initial polarization of up and down, respectively.

Starting from an initially up position, the resistance is larger when H_{inp} is in the +x direction compared to when it is in the opposite direction and the resistance goes down away from the x-axis (Figure IV-2c). On the other hand, starting from an initial down position, the resistance is larger when H_{inp} is in the -x direction (Figure IV-2d). These data show that the easy-axis of the magnetization is slightly tilted from the z-axis and lies along the (x,z) quadrant to the (-x,-z) quadrant. The observed behavior matches well with modeling data, including the fact that the lowest value of resistance arises slightly away from the y-axis and the sign of the shift depends on the starting polarization of the magnet, i.e. 'up' or 'down'. In addition, Figure IV-2e & f show measured AMR data at higher in-plane field starting from up and down positions respectively. No asymmetry is observed between the AMR recorded for H_{inp} applied in the +x and –x direction. This is expected because now H_{inp} is strong enough to overcome the tilted anisotropy and the magnet follows the magnetic field. Thus, from the symmetric AMR along the x-axis at high field and asymmetric AMR at low field, the existence of a tilted easy axis in the nanodots is confirmed. From AMR measurement, we can also estimate the angle of the tilt which comes to be ~2˚ with an error of 1˚ due to the uncertainty in the angle of the in-plane field. With such a tilted easy axis of the nanodots, a deterministic switching from up to down with a current in the y direction and from down to up with a current in the –y direction should be possible.

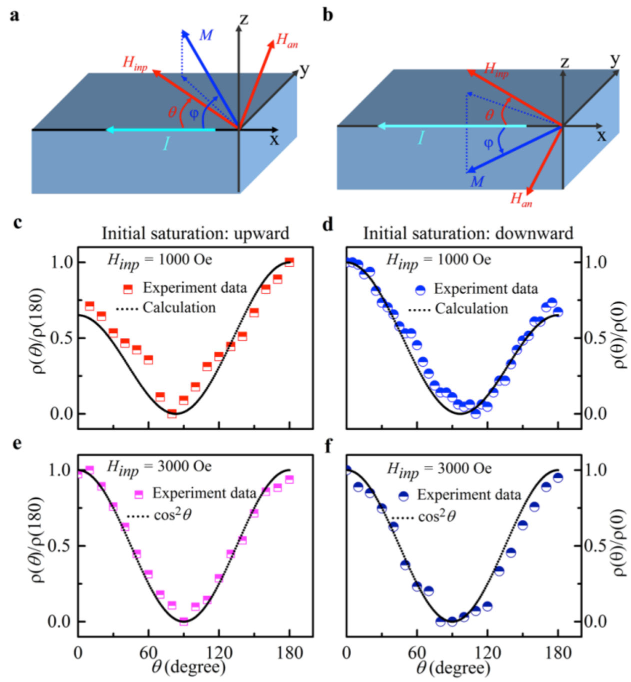


Figure IV-2. AMR data. (a) and (b) show the configurations for the initial polarization of up and down respectively. Calculated and measured values of AMR resistivity are shown when $|H_{inp}|$=1000 Oe and the magnet was initially polarized (c) upward and (d) downward. Calculated and measured values of AMR resistivity are shown when $|H_{inp}|$=3000 Oe and the magnet was initially polarized (e) upward and (f) downward.

Room temperature Anomalous Hall Effect (AHE) measurements, presented in Figures IV-3a & b, show that full switching of the magnet has taken place. Figure IV-3b shows switching data in the presence of zero external field. The reproducibility of the switching process was tested by repeatedly reinitializing and subsequently switching the nanodot in the upward direction 10 times. Figure IV-3c shows 100% switching for the 4 tested devices. Among the 4 different devices, each going through 10 repeated trials, only 1 device shows a small probability (0.2) of switching with current below the switching threshold. We attribute this to thermal heating of the dots due to repeated pulsing. Figure IV-3d shows the data on the same 4 devices but now starting from an initial down position and applying a current, $-I_y$. Again small switching error is observed since application of a $+I_y$ is not expected to induce any switching in this case. Once again, the small errors in device 1(0.3) and device 3(0.1) is attributed to heating due to repeated pulsing. Figures IV-3b, c & d indeed demonstrate deterministic switching of the magnetization without any external magnetic field by a current flowing along the y-axis.

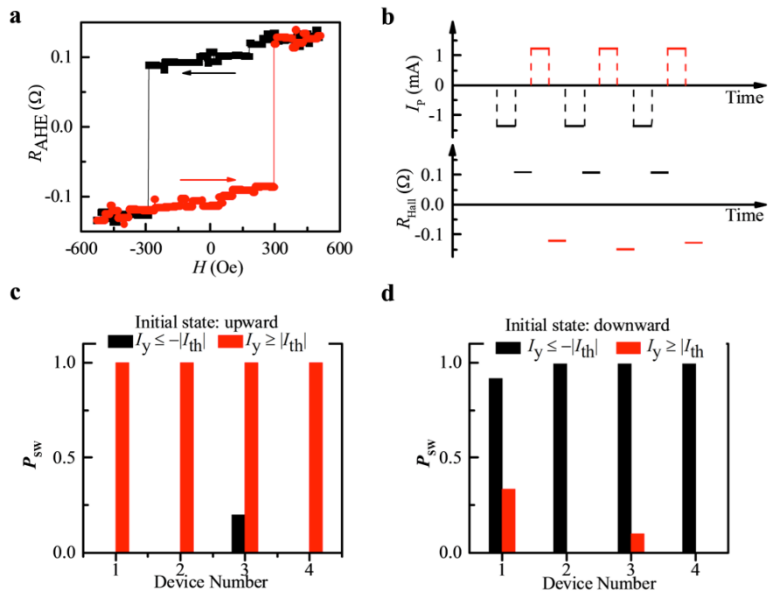


Figure IV-3: (a) AHE loop of the nanomagnet. (b) AHE resistance showing switching of the magnet due to changing polarity of the current pulses. (c) and (d) switching probability starting from initially up in (c) and down in (d).

Physics of Spin Switching in Sub-10nm STT Magnetic Tunneling Devices: Another significant Theme IV accomplishment is contributed by the **Khizroev** group (*FIU*) with the observation of spin-torque switching at anomalous low current density in sub-10-nm devices, which is in agreement with the hypothesis of dramatically increased spin relaxation in this size range. The observation is explained by the fact that the collective behavior of spins in such small devices dominates over the effects due to the spin-orbit (L-S) interaction.

For “larger” device sizes (>~10 nm), the elastic modulation of exchange interaction and crystalline fields creates a coupling to phonons; L-S interactions contribute to fast and slow spin-lattice relaxation mechanisms. The resulting spin-lattice relaxation and thermal fluctuations result in magnetic damping. However, the physics dramatically changes when the lateral device dimension is reduced below ~ 10 nm. In the sub-10-nm range, ab initio calculations were performed that directly account for all the quantum-mechanical interactions between adjacent spins [37]. According to the calculations, the spin relaxation time can be expressed as

$$\tau_s \sim d/((1\text{-}N_s/N_v)\,\Delta g_v^2 + (N_s/N_v)\,\Delta g_s^2)V_F), \qquad (1)$$

where d is the nanostructure diameter, Δg_v and Δg_s stand for the g-factor shifts for the bulk and surface electrons, respectively, and N_v and N_s stand for the volume and surface electron concentrations, respectively. Typically, the surface shift is much smaller than the volume shift, Δg_v. Therefore, when the size is reduced below the value at which the surface effects are dominant, the spin relaxation time could increase by orders of magnitude.

Structures with sub-10-nm magnetic nanoparticles as junctions were fabricated (Figure IV-4a to c). Figure IV-5 shows increased magnetoresistance for 2-nm as compared to the 4-nm nanoparticles sandwiched between tow ferromagnetic layers.

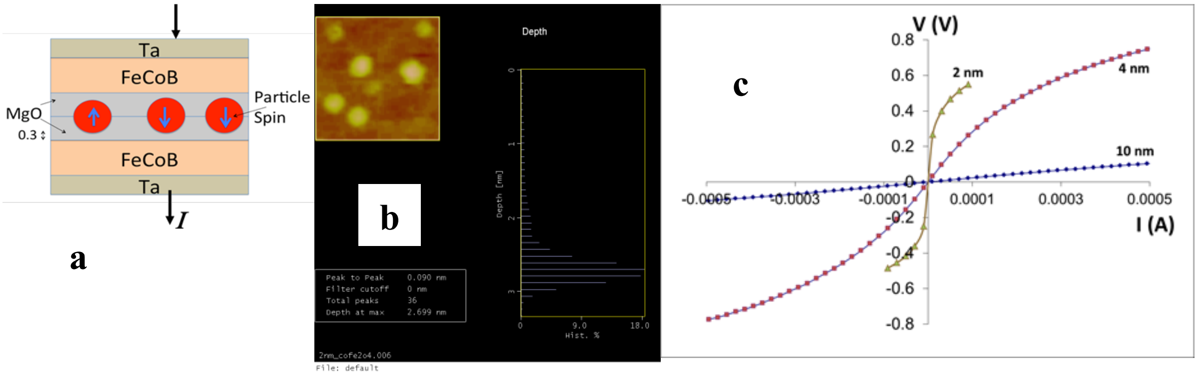


Figure IV-4: a) Schematic of **a test structure with** a nanoparticle junction. b) AFM image of 2-nm nanoparticles deposited on a 0.3-nm MgO layer on a CoFeB ferromagnetic layer. (b) I-V curves measured via STS probe technique for nanoparticles of different sizes: 2-nm (green), 4-nm (brown), and 10-nm (blue).

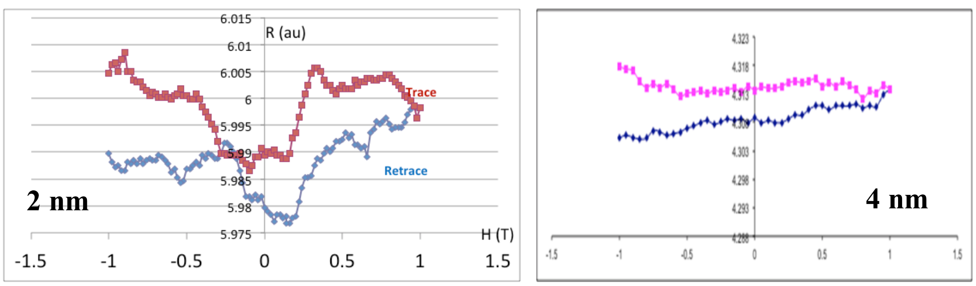


Figure IV-5: Magnetoresistance for 2-nm (*left*) and 4-nm (*right*) nanoparticles sandwiched between two ferromagnetic layers.

In other experiments the **Khizroev** group (*FIU*) collaborated with the **Bokor** group (*Berkeley*), to study sub-10 nm diameter devices fabricated by using focused ion-beam (FIB) etching of magnetic tunnel-junction thin-film stacks. The well-known Ta(5 nm)/CoFeB(1 nm)/MgO(0.9 nm)/CoFeB(1 nm)/Ta(5 nm) trilayer material composition was chosen since it is known that this composition provides an adequately high tunneling magnetoresistance (TMR) ratio, a relatively high anisotropy energy, and a relatively small switching current. A perpendicular tunneling junction with a side of a few microns was first patterned through a standard lithographic process. Then, FIB etching from the top surface was used to trim the devices down to sub-10-nm sizes. The trimming was performed with an Orion NanoFab system with three FIB sources, Ga+, Ne+, and He+ ions. A scanning electron microscopy (SEM) image of a typical FIB-trimmed STT MTJ is shown in Fig. IV-6a. The red square in the middle of the image shows the location of the final FIB trimmed MTJ.

The smallest device measured had a planar side on the order of 5 nm. The precision of the measurement is limited by the resolution of SEM used in the study to approximately 2 nm. The value was estimated also from the resistance value which scales with the cross-sectional area. The switching current curve and the magnetoresistance for the device are shown in Figs. IV-6b and c, respectively. The measured switching current of approximately 0.6 μA corresponds to a switching current density of ~2.4 MA/cm^2, about 4x lower compared to previous reports for 20 nm junctions [38].

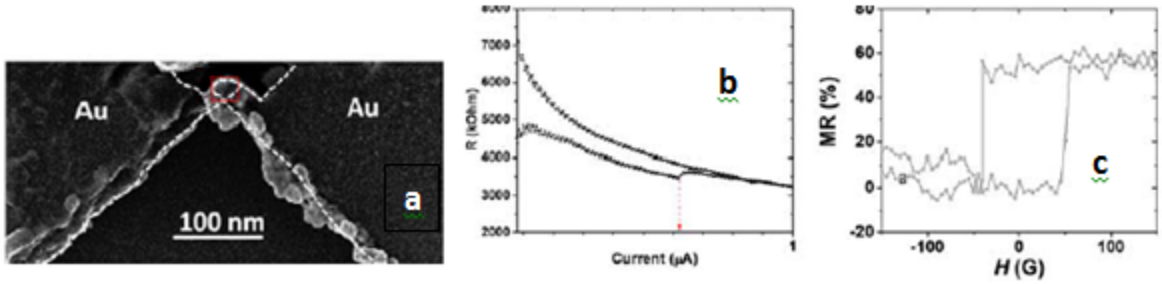


Figure IV-6: a) He-ion image of a FIB fabricated junction. The red square shows the junction location. b) I-V curve of a 5-nm junction. c) magnetoresistance of the junction.

Spin Dynamics: Conventional magnetic switching is governed by precession dynamics that sets a minimum switching time of ~100 psec [39], but to have practical application in logic, a switching speed in the range of a few psec would be far more attractive. In laser-based ultrafast magnetic switching experiments, the 'heating' is with a 60 fsec laser pulse that initially 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 1000-2000 K. 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 [40]. 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.

In this Reporting Period 6, the **Bokor** group (*Berkeley)* has continued to study the fast magnetic switching in three different materials systems, with an ultimate goal to trigger ultrafast magnetic switching using short electrical current pulses in the place of short laser pulses.

Direct Optical Study of Current Induced Spin Accumulation Dynamics in Metals*:* **J. Bokor** and **S. Salahuddin** (both *Berkeley*) have been collaborating to study the dynamics of spin accumulation due to the spin-orbit torque effect in metals. Also identified as a spin-Hall effect, this spin current causes the accumulation of spins of opposite orientations at opposite faces of the metal, transverse to the charge current direction.

Until recently, the spin current in metals was studied exclusively by electronic methods [41] or by the study of its interaction with an adjacent magnetic layer [42]. A direct optical probe of the effect in non-magnetic metals promises to be simpler than magnetization-based approaches because it allows separation of the effect of the spin-current in the non-magnetic metal from the spin-transport across the non-magnetic/magnetic interface. Here, magnetization induced optical second harmonic generation (MSHG) [43] is demonstrated as a promising new technique to detect the spin accumulation at normal metal surfaces and interfaces owing to the surface/interface sensitivity of MSHG, and report for a Pt film the sub-nanosecond time-dynamics of the spin accumulation that follows a short current pulse.

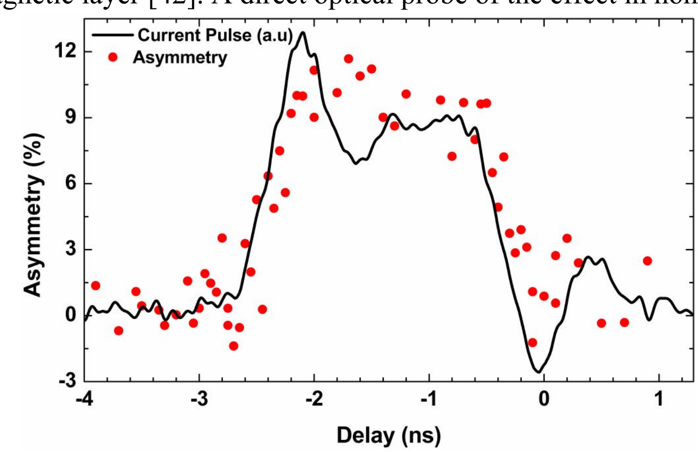


Figure IV-7: Spin accumulation at the surface of the 10 nm Pt sample as a function of the probing time of the laser pulse relative to the 2 ns current pulse.

MSHG was used to study the time dynamics of the spin accumulation due to spin-Hall effect in a 10 nm Pt sample using a unipolar, 2 ns wide current pulse. The relative time of arrival of the laser and current pulses at the sample were varied using a delay generator, and at each delay time the magnetic asymmetry was measured. As shown in Figure IV-7, the spin accumulation pulse follows the current pulse. Similar results were observed in 20 nm Pt films.

These results demonstrate that the MSHG technique can probe spin accumulation resulting from the spin-orbit effect at the surface of metallic thin films. MSHG has the ability to detect spins directly, independent of spin transport into an adjacent magnetic layer, and offers the promise of performing detailed time-dependent dynamic studies of spin accumulation. Measurements of the spin dynamics in these samples on psec time scales are in progress.

Ultrafast Laser Pulse Assisted Magnetization Reversal by Spin-Orbit Torque Effect*:* In heavy metals like W and Ta, the injection of an electrical current generates a large transverse spin current due to the spin-orbit torque effect. By exploiting the spin-transfer torque (STT) induced by this spin current, the magnetization of an out-of-plane magnet on top of the heavy metal can be reversed [42]. This is particularly interesting since critical switching currents are lower than injecting current directly into a magnet like conventional STT-MRAM. In recent years, heat-assisted magnetic recording in hard disk drive media has been pursued in order to lower the switching field [44]. In this work, the two methods are combined to demonstrate that by applying a single ultrafast laser pulse, the current needed to switch a magnet with spin-orbit torque effect can be further lowered. This could have an important impact in the development of even more energy efficient spintronic devices.

Experiments were carried out on a $50x50$ μm^2 channel of Si/SiO_2 (100 nm)/Ta(10 nm)/CoFeB(1 nm)/MgO(2 nm)/Ta(2 nm). The CoFeB film exhibits perpendicular magnetic anisotropy. An external in-plane field of 185 Oe was applied along the current direction to break the symmetry in order to switch the magnetization. A laser pulse of 70 fsec duration was used in combination with a magneto-optic Kerr effect (MOKE) microscope. Figure IV-8 (*left*) shows magnetic hysteresis loops obtained by sweeping the current in the Ta layer under varying laser pulse fluence. The laser spot was around 80 μm in diameter, covering the whole magnetic channel, and had a 252 kHz repetition rate. As we increased the laser fluence, the coercive current I_c of the hysteresis loops decreased (Figure IV-8 *right*). When the laser fluence reached 1.5 mJ/cm^2, a reduction of 5x of I_c was observed.

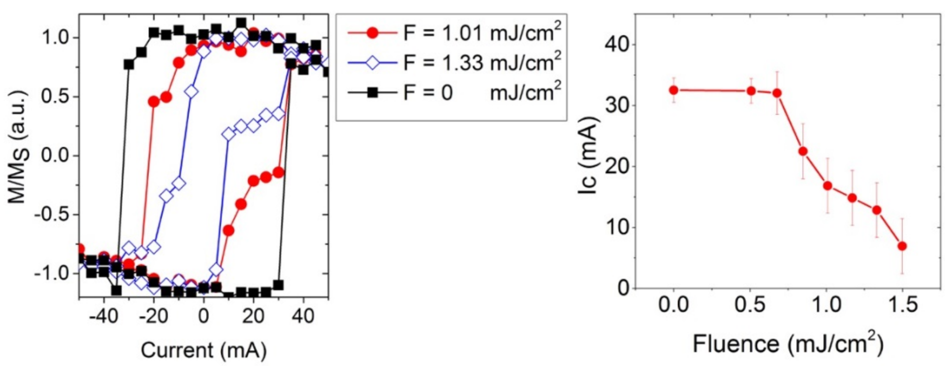


Figure IV-8: Hysteresis loops measured with different laser fluences (*Left*). Coercive current for different laser fluences (*Right*).

To understand how each laser pulse affects the magnetization reversal, single-shot experiments were performed. A current lower than the switching threshold was maintained on the sample and then an individual laser pulse was fired. After each pulse, a MOKE image was taken to check the final magnetic state, where the optical contrast represents the magnetic contrast. As shown in Fig.IV-9, as the pulse energy was increased, the final state was seen to evolve from non-switching to partially switching and eventually to fully switching.

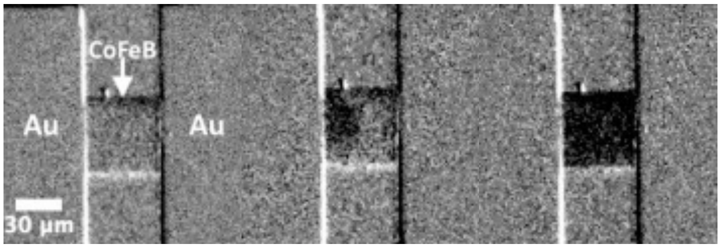


Figure IV-9: MOKE images after single shots of different fluences. From left to right, 0.67 mJ/cm^2, 0.84 mJ/cm^2, 1.05 mJ/cm^2. Channel is the center square and current of -20 mA is flowing from left to right. Dark and white represent different magnetization state “up” or “down”.

Single-Shot Helicity Independent All-Optical Switching in GdFeCo: In 2007 the ability to deterministically switch the magnetization of a ferrimagnetic GdFeCo film on a subpicosecond timescale was reported [14] and has since been extensively studied. All-optical switching (AOS) can be classified in two groups as a function of the influence of the laser polarization: helicity dependent (HD) and independent (HI). HI-AOS opens the possibility to generate ultrafast switches for memory and logic gated by a single stimulus, without the need of polarization modulation. HD-AOS has since been reported in various materials [43]; however, although a wide variety of GdFeCo compositions were studied in [43], HI-AOS was not reported. The **Bokor** group (*Berkeley*) has confirmed the phenomenon of HI-AOS and measured the ultrafast dynamics of this process.

The experiments were carried out on $Gd_x(Fe_{90}Co_{10})_{1-x}$ of concentrations x = 24.5%, 27.5%, 28% and 28.2% grown by co-sputtering on the following stacks: Si/SiO_2(300 nm)/Ta(4 nm)/GdFeCo(20 nm)/Ta(4 nm). The sample with x = 24.5% was the only one to have a compensation temperature below room temperature. All samples exhibited perpendicular magnetic anisotropy. An amplified Ti:sapphire laser with 70 fsec pulse duration and single-shot capabilities was used in combination with a MOKE microscope and the energy of each pulse was monitored with a fast photodiode.

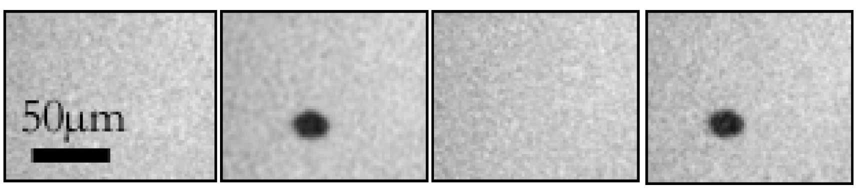


Figure IV-10: MOKE images showing the AOS of a domain. The left image shows the homogeneous initial magnetization of the x = 28% film. A single left circularly polarized laser pulse of fluence ~2.3 mJ/cm2 is shot between images, resulting in the successive reversal of a magnetic domain.

Single shot experiments at various fluences were performed without external magnetic fields and could demonstrate reproducible HI switching in all of the samples with all combinations of linear, right circular or left circular polarized light and an initial sample magnetization “up” or “down”. This is shown in Fig.IV-10, where with each successive laser shot the magnetization in a small region “toggles”. This behavior is consistent with that reported in [45]. Reliable toggling was observed in single-shot mode for more than 100 successive laser shots.

In order to verify the speed of the reversal, time-resolved pump-probe MOKE measurements were performed. In this experiment, a constant, perpendicular external field of 20 mT was applied to reset the magnetization between excitation pulses. The pump spot radius was ~200 µm, whereas the probe spot size remained smaller than 20 µm. As shown in Fig.IV-11, the reversal occurs against the external magnetic field in less than a picosecond. This result is comparable to the previously reported switching speeds in HI-AOS experiments on GdFeCo [14].

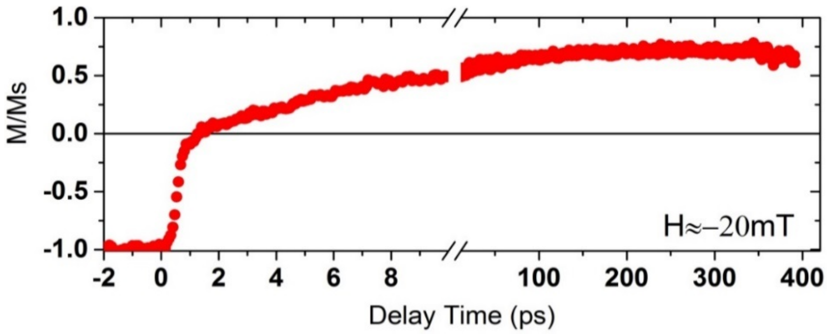


Figure IV-11: Evolution of the magnetization after a linearly polarized ~2mJ/cm2 pulse.

These results independently confirm the HI-AOS process and, therefore open the possibility to generate ultrafast switches for memory and logic gated by a single stimulus, without the need of polarization modulation. Our goal will be to demonstrate similar ultrafast magnetic switching using this mechanism, but using fast electrical current pulses rather than laser pulses to induce the switching. In this way, psec magnetic switching could be implemented in monolithic magnetic memory and logic devices.

Circuit Architectures with Nanomagnetic Switches: The **V. Stojanović** group (*Berkeley*) has continued to provide the understanding of the circuit implications of the low I_{on}/I_{off} ratio of nanomagnetic switches, yet leveraging the low supply voltage operation of these devices. In collaboration with **J. Bokor**, circuit modeling has been undertaken based on a magnetic logic device, "mLogic", composed of two nanowires, namely read path and write path (Figure IV-12). The current flowing thru the write path drives the domain wall motion in the write path via both spin-transfer torque and spin-Hall effect. The domain wall in the read path follows that in the write path via exchange coupling between the two nanowires. The resistance seen at the read ports depends on the magnetic configuration of the read path, since the read ports are connected to the read path thru magnetic tunnel junctions. So, depending on the position of the read path domain wall, the resistance can be either anti-parallel state resistance (high resistance) or parallel-state resistance (low resistance).

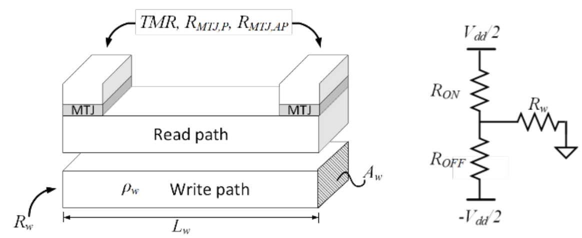


Figure IV-12: Schematic of mLogic (*Left*) and its circuit elements (*Right*)

The device was modelled by the circuit elements as given in Figure IV-13. Since the read path domain wall speed is approximately linearly dependent on the write path current density, we can define a performance-related parameter called "current domain-wall mobility" by the ratio between the read path domain wall speed and the write current density.

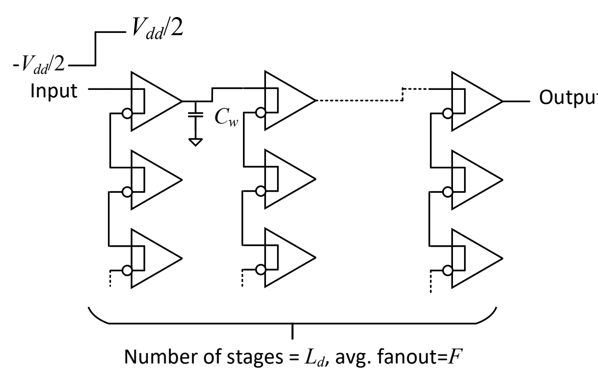


Figure IV-13: Magnetic logic pipeline setup

To assess energy-performance of a logic pipeline implemented with mLogic, the energy-delay of a simple buffer chain of the device (Figure IV-14) was analyzed. The implications on the optimization results are the following: a) mLogic can be optimized for ultra-low supply voltage, which is different from the CMOS case in which the threshold voltage is optimized differently for each supply voltage; and b) The optimization result shows that the energy dissipation can be reduced infinitesimally toward zero at the expense of the time delay.

Further comparison between mLogic and CMOS is modeled by comparing a 32nm CMOS inverter chain and a 32 nm mLogic buffer chain (Ld = 10, F = 4, sw = 0:05) using device parameters given in [46]. The shaded region shows the region where the circuit error probability p is larger than 3 x 10^{-20} with varying tunneling magneto-resistance (TMR) from 0.2 to 106 and a fixed µDW. Note that the entire region in the CMOS graph is noise-free as the supply voltage for CMOS is not smaller than 0.2 V which is larger than the minimum noise-immune supply voltage for CMOS: sqrt(kT/C) ~ O(10 mV).

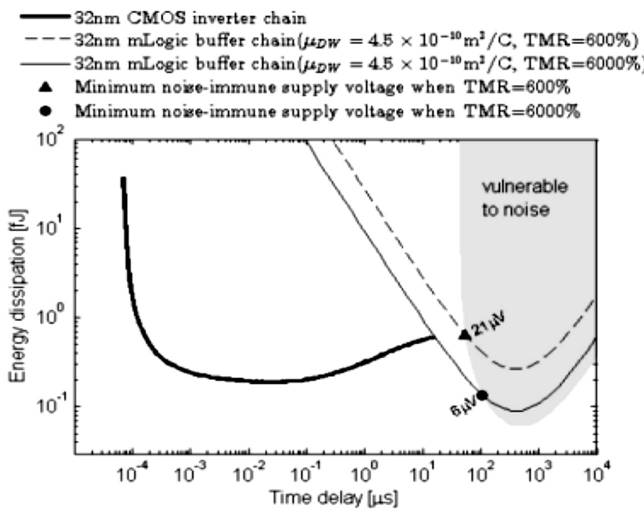


Figure IV-14: Energy dissipation of a 32 nm CMOS chain inverter (*bold dark line, left*) and a 32 nm mLogic buffer chain (*two right lines*).

2b. Performance Against Metrics

Objective	Metric	Targets	Results				
			P 2	P 3	P 4	P 5	P 6
Research	**Multi-PI projects**	P 2: 30% P 5: 75% P 6: 50%	44%	67% (14)	55% (12)	64% (14)	65% (11)
	Multi-Institutional projects	P 2: 10% P 5: 30% P 6: 15%	4%	10% (2)	9% (2)	23% (5)	29% (5)
	Publications with authors from multiple institutions	P 3: 12 P 4: 3 P 5: 5	0	1	1	1	3
	New joint research funding awards	P 6: 1	*(new for P6-10)*				0

The Center's faculty researchers have organized themselves to be highly collaborative, exceeding the targets in the Strategic Plan. The highly collaborative environment applies across institutional as well and has translated into co-authorship among faculty of the same institutions. Of the journal articles published to date in 2015, 45% have two or more faculty authors. However, the Center still needs to significantly improve co-authorship from multi-institutional projects. To date, only six papers (three in period 6) were published with E^{3}S faculty authors from different institutions; however, there are several manuscripts in preparation with multi-institutional authors. In addition, in response to this low number of multi-institutional papers, the Center leadership will initiate a new program of multi-institutional postdocs to foster publications between research groups at different institutions.

This new program is also supported by our finding that collaborations happen primarily at the level of graduate students and postdocs. The Students and Postdoc Survey have included questions on cross-institutional collaborations. In 2015, 67% of the respondents said that they have developed a working relationship with someone from another institution, while 45% said that their research was helped by someone from another institution. We are hopefully that out of these interactions, there will be tangible outcomes as reflected by upcoming publications. Forty-five percent of the 2015 respondents said that their cross institutional interactions are expected to lead to at least one publication.

2c. Research in Period 7

Research in the coming Period 7 will be guided by the Strategic Research Plan that is given in the Context Statement. There will be changes including changes in faculty participation. Again, the following faculty participation table is to serve as a guide for the following narratives on the Research in the coming Period 7. The table informs that all Themes have multi-institutional participation.

Faculty Participation by Theme in Period 7

Institution	Faculty	Theme I	Theme II	Theme III	Theme IV
UC Berkeley	Bokor				*x**
	Chang-Hasnain			*x*	
	Fischer	*x*			
	Javey	*x*		*x*	
	King Liu		*x**		
	Louie	*x***			
	Salahuddin				*x*
	Stojanovic		*x*		*x*
	J. Wu		*x*		
	M.C. Wu			*x**	
	Yablonovitch	*x**		*x*	
MIT	Antoniadis	*x*			
	Bulović		*x*		
	del Alamo	*x*			
	Fitzgerald			*x*	
	Kong	*x***			
	Lang		*x*		
	Swager	*x***	*x*		
Stanford	Wong				*x***
UTEP	Zubia		*x***		
FIU	Khizroev				*x*

Legend: x - Theme Leader; x** - New to the Theme; Name x = Ramp-Down Phase*

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

The Nanoelectronics research portfolio will change in the upcoming Reporting Period 7 in response to the understanding of the role of interfacial traps as detractors to band-to-band tunneling at low turn-on voltage in traditional semiconductors. Research in traditional TFETs will be reduced in favor of additional research efforts in Chalcogenide TFETs and bottom-up semiconductors. The ongoing vertical nanowire TFET of **J. del Alamo** (*MIT*) will continue to serve as a venue for elucidating the physics of tunneling. Device fabrication projects of **D. Antoniadis** (*MIT*) with other traditional semiconductor materials will be ramped down over the next period. The Chalcogenide TFET research will expand as the research group of **J. Kong** (*MIT*) joins the Center, complementing the research efforts of **A. Javey** (*Berkeley*). **T. Swager** (*MIT*) will apply his synthetic chemistry expertise to the issue of bottom-up semiconductors expanding the graphene nanoribbon-based research of **F. Fischer** (*Berkeley*). This group will also be supported by simulations and modeling work of newly added physicist **S. Louie** (*Berkeley*). Theme Leader, **E. Yablonovitch** will continue to support these efforts with simulation and characterization in all three areas, and in particular, in the Graphene Nanoribbons project.

Specifically, the Nanoelectronics research plan for Reporting Period 7 is as follows.

- *III-V Nanowire TFET*: The goal is to demonstrate single-channel III-V VNW TFETs and Super-Lattice Source FETs with reduced interface state density at the sidewalls as a means to further elucidate the fundamental physics of tunneling. To achieve this goal, the **del Alamo** group (*MIT*) will refine its RIE + digital etch technology to fabricate sub-10 nm diameter InGaAs nanowires with high aspect ratio and smooth sidewalls. Techniques will be investigated to reduce interface state density at the etched sidewalls through fin-sidewall capacitors, a special test structure that was demonstrated in the recent past. The **del Alamo** group has recently demonstrated that RIE + digital etched fins in the InGaSb system exhibit a D_{it} in the mid 10^{11} /cm^2/eV range. This makes this an attractive material for VNW TFETs. As it turns out, the InAs/GaSb system features a type II broken-gap band alignment that favors TFETs. Incorporating this material system into our VNW FETs will be investigated. Under a separate project, RIE and digital etch technology will be developed for InGaSb fins and nanowires. This has already yielded sub-20 nm fins with an aspect ratio of around 10 and smooth surfaces, and further development of this technology so that it can be utilized to demonstrate InAs/GaSb VNW TFETs and MOSFETs will be conducted.

- *Chalcogenides TFETs*: At Berkeley, the **A. Javey** group will continue its efforts to improve the device performance in WSe_2/$SnSe_2$ heterojunction tunnel FETs. This will include improving subthreshold swing by improving gating methodology as well as development of reliable methods to improve overall 2D layer material quality before fabrication.

  The Center's researchers with projects using Chalcogenide materials have been doing so with exfoliated flakes. The need for high quality larger area Chalcogenides is of high importance. Thus one of Period 7 goals of the Nanoelectronics Theme is the development of a process for highly optimized surfaces with chemical vapor deposition (CVD) growth 2D semiconductors. MoS_2 will be used as a model system for this investigation. The **Kong** group (*MIT*) has developed a CVD synthesis method for monolayer MoS_2 deposition during the past few years. Aromatic molecules such as perylene-3,4,9,10-tetracarboxylic acid tetrapotassium salt (PTAS) were found to facilitate the synthesis, and single crystalline triangular flakes of tens of microns in size can be reliably obtained. These single crystalline flakes will be used for the investigation of minimizing surface defects. High quality hexagonal Boron Nitride (hBN), either by exfoliation or CVD growth, will be used as substrate and dielectric capping layer. Various transfer procedures will also be explored to ensure high quality surfaces. The **Kong** group (*MIT*) plans to collaborate with the **Javey** group (*Berkeley*) for surface treatment to improve the MoS_2 surface quality. The **Kong** group also plans to collaborate with the **Yablonovitch** group for D_{it} characterization. Such evaluation, together with other characterization results, such as photoluminescence to Raman ratio (or PL quantum yield) and high resolution TEM imaging, identifying defect types and locations, will be used as feedback to optimize the synthesis/processing to achieve lowest possible D_{it}.

- *Bottom-up Graphene Nanoribbons (GNRs) Semiconductors*: Towards building a GNRs based molecular materials platform for semiconductors, the near-term goal is to develop a fundamental understanding of how to modulate the band structure at the interface between a molecular quantum dot and the extended bands of a GNR. This work will be crucial for the rational design of functional device architectures relying on quantum tunneling junctions. Given that the synthesized molecular structures are expected to be fragile, investigations into isolation schemes to preserve electronic coherence will be part of the research plan in Period 7.

The goal of the **Fischer** group (*Berkeley*) research program is to develop a rational bottom-up strategy towards integrating molecularly defined quantum dots (QD) that are flanked by two atomically defined tunneling barriers into a semiconducting GNR. Based on expertise with bottom-up fabricated graphene nanostructures the **Fischer** group will synthesize molecular precursors for QDs derived from porphyrins that are structurally compatible with a series of molecular precursors for 7- and 9-AGNRs. The unique molecular structure and highly tunable electronics of porphyrin derived QDs will enable to rationally adjust the band alignment between the semiconducting GNR and the inserted QD. High resolution scanning probe microscopy (STM and non-contact AFM) and spectroscopy will be used to probe the local electronic structure and the alignment of energy states in GNR quantum tunneling junctions. In collaboration with the **Salahuddin** group (*Berkeley*), the **Fischer** group will use computational methods to analyze the performance of the fabricated device architectures. These calculations in discussion **E. Yablonovitch** will serve as the foundation to rationally guide the design of improved generations of bottom-up fabricated QD tunneling junctions. In collaboration with the **Bokor** group (*Berkeley*) samples of the most promising surface fabricated GNR-QD will be transferred onto insulating supports, deposit metal contacts and evaluate the device performance of GNR-QD tunneling junctions.

T. Swager (*MIT*) will develop solution phase syntheses of graphene nano-ribbons (GNRs) that will complement the surface directed synthesis of the **Fischer** group. These methods will target integrating nitrogen atom substitutions for carbon atoms of the GNRs. Chemically, the structures will initially be produced as cationic semiconducting structures, which upon reduction to a neutral state generate a metallic ground state. In GNR a metallic ground state is produced when highest energy electrons occupy a half filled orbital that extends over the entire structure. It is expected that the metallic character will be fragile and contact of the GNR's π-system with incommensurate surfaces will create inhomogeneous electrostatic potentials that localize the electrons. To avoid quenching of the metallic state, GNRs are ideally suspended over the substrate. Top-down fabrication of wells under each GNR is impractical and a bottom-up chemical design is preferable. The **Swager** group has developed rigid scaffolds that can effectively isolate π-systems; similar structures will be developed for GNRs in order to preserve electronic coherence over the entire structure in surface immobilized devices.

S. Louie (*Berkeley*) will perform theoretical studies on the structural, electronic, and optical properties of GNRs in different geometric and doping configurations. The general aim is to obtain basic understanding of the influence of structural modifications and of dopants on the electronic and optical properties of GNR systems for applications in nanoelectronics. Calculations will be performed to determine: 1) structural and related ground-state properties using density functional theory, 2) quasiparticle band structure using the first-principles GW method, and 3) optical properties, including excitonic effects, using the GW plus Bethe-Salpeter equation (GW-BSE) approach. The **Louie** group will work in close interaction with the synthesis work of both the **Fischer** and the **Swager** groups. Particular focus will be directed on exploring the effects of edge modifications, interfacial atomic arrangements, substrate screening, and dopants on the electronic structure of the GNRs.

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

Research towards the goal of demonstrating sub-0.1 Volt switches will continue. The E^3S faculty participating in the Nanomechanics Theme will be **King Liu**, **J. Wu** and **Stojanović** (*Berkeley*), **Bulovic, Lang** and **Swager** (*MIT*) and **Zubia** (*UTEP*). The Berkeley researchers will continue to establish a robust process for fabricating body-biased NEM relays to achieve sub-0.1 V switching with high device yield,

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while the MIT researchers will continue to further reduce the operating voltage of the Squitch.

New Theme II research efforts planned for the upcoming Period 7 are:

- The **Zubia** group will extend the initial proof-of-concept of strained 2D layers to the development of piezoresistive switches, in collaboration with Berkeley researchers.
- The **King Liu** group will collaborate with **V. Stojanović** (*Berkeley*) to experimentally demonstrate relay integrated circuits operating at very low voltage (< 0.1 V).
- The **Wong** group (*Stanford*) will no longer participate in Nanomechanics research, as the Nanomechanics research is moving away from van der Waals contacting switches. Instead, the **Wong** group will migrate its research activities under the Nanomagnetics Theme.

Further details of Period 7 Theme II research plans are as follows.

Body-Biased Switch Design: At UC Berkeley, the focus in the coming months is to establish a high-yield (>99.9%) manufacturing process for NEM relays operating with gate voltage less than 100 mV. This will include the identification of key technical challenges for body-biased relay technology and experimental study of the reliability/endurance of body-biased relays operating with very low voltage.

One aspect of device reliability lies on proper optimization of the metal-metal contacts. The **King Liu** group will utilize the outcomes of the materials research of the **J. Wu** group. For example, metals are relatively soft so that metal-metal contacts are inherently unreliable. To mitigate that challenge, ion-beam synthesis techniques will be used to form uniformly thin layers (1-2 nm thick) of RuO_2 on Ru films. Such a thin layer of RuO_2 is expected to reduce possible mechanical damage of the contacting surfaces.

Squitch: Efforts to lower the actuation voltage of the squitch will include a combination of the following activities. First, synthesis of candidate molecular monolayers and/or composite layers designed to enable lowering of the actuation voltage. Second, use of the squitch as an in-situ metrology tool to characterize the electrical tunneling and mechanical behavior of candidate molecular layers. Third, with the metrology data in hand, a model-based optimization of the squitch to produce designs with lower actuation voltage will be carried out. The optimized designs will be fabricated and characterized, and the process will be iterated. The stretch goal by the end next Reporting Period, in early 2017, includes the characterization of dynamic Squitch performance.

Piezoresistive NEM Switch: The **Zubia** group (*UTEP*) will work closely with Berkeley research groups of **King Liu** and **Javey**, to continue investigations of the electronic properties (bulk and interface) of TMDCs under strain via MEM actuation for low-voltage switching. Bulk and interface switching mechanisms will be studied using the most promising TMDC material. The MEM actuator will be redesigned and fabricated to optimize device switching. The device fabrication can be divided into three steps: MEM fabrication, TMDC transfer, and contact deposition. Device modeling will be continued by the UTEP researchers. The goal is to experimentally assess how close the performance of a piezoresistive NEM switch can approach the modelling prediction of 40 mV activation voltage and an ON/OFF ratio of 4 orders of magnitude using MoS_2 or WS_2.

Sub 0.1V Circuit Demonstration: Relay IC circuit demonstration will be undertaken by the researchers at Berkeley. A collaboration between the **King Liu** and **Stojanović** groups will work toward the first goal of experimentally demonstrating a circuit with NEM relays to operate below 0.1 V. Beyond low-energy switch operation, low-energy signal communication is necessary for energy-efficiency computing. Therefore, technical approaches to mechanical signaling for reduced communication energy will be investigated via three-dimensional modeling and simulation. For example, hydraulic interconnects will be investigated using molecular dynamics simulations to analyze tradeoffs between speed and energy-efficiency, and between surface hydrophobicity and ease of fabrication. Pivoting beam interconnect structures may be explored, as well. The materials issues will be addressed in collaboration with the **J. Wu** Group. This work is highly novel and likely will require additional collaboration with other experts in nanofluidics.

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

The Nanophotonics Theme will continue to make progress towards few-photon optical communications. Antenna enhanced LED emitters, ultra-sensitive phototransistors, and their integration into waveguides will continue.

III-V Nano-LED: The next major goal for the III-V Nano-LED research program, a collaborative effort between the **M. Wu** and **Fitzgerald** groups, is the demonstration of a nanoLED that has microwatt output power. Towards that end, two key approaches are being pursued:

- Optimizing epitaxial LED structure that will increase the internal quantum efficiency (IQE) of the device; and
- Passivating the nanoLED active region with MOCVD re-grown semiconductor material.

In addition, the possibility of using epitaxial quantum dot active layers will also be explored. To enable a proof of concept, Prof. J.P. Reithmaier, University of Kassel, will provide test epitaxial materials that will be fabricated into LED devices.

The major milestone in the coming Period 7 is the first demonstration of electrically injected nanoLED with InP re-growth passivation of active region. The goal is to achieve micro-watt output power and >100X spontaneous emission enhancement with an electrically injected nanoLED.

Chalcogenide Nano-LED: A key goal for the next Period is the first demonstration of an electrically injected WSe_2 Nano-LED. Towards that end, the **M. Wu** group will develop enhanced fabrication techniques to improve the device structure, such as investigating the effect of helium ion milling to increase antenna quality, and in collaboration with the **Javey** group, addressing the need to passivate the WSe_2 chips. Efforts to achieve optically pumped antenna-enhanced LEDs with high efficiency will also be pursued as such improvements will lead to additional processing and device design knowledge that will enable the demonstration of an electrically injected WSe_2 Nano-LED.

InP Phototransistors: Given the progress in InP phototransistors during the past year, we expect that InP based phototransistors will be a key approach in the Center towards an ultra-high sensitive monolithically integrated phototransistor.

The **Chang-Hasnain** group's demonstration of an InP bipolar phototransistor reported for Period 6 is a homo-junction device without doping concentration optimization. In this coming year, hetero-junction for the base junction will be introduced to increase the sensitivity and gain. The resonator effect can be used to enhance absorption in the base junction, with optimized placement of the junction. This will also be one of the next year's research foci to enable yet a higher gain. In addition, we will optimize the doping density of the layers, particularly the layer directly grown on the silicon substrate to avoid a type-II hole-blocking junction. This will reduce the junction and parasitic capacitance and increase device speed, leading to >100 GHz operation. The device performance goal by the end of the next Reporting Period 7, is a significant increase in 3-dB bandwidth and gain-bandwidth product, but with similar external efficiency and gain as the 2015 device. The goal is to reach >25 GHz 3-dB bandwidth and a gain-bandwidth product, f_T, >1000 GHz.

Complementing the InP phototransitor research at Berkeley will be the emerging GaAsP/InGaP based phototransitor efforts in the **Fitzgerald** group at MIT. GaAsP/InGaP structures will be grown epitaxially on Si substrates via MOCVD and fabricated into HBTs and photoHBTs. These devices will allow the direct correlation of crystalline defects (such as threading dislocations, stacking faults, interface roughness, etc.) to both electrical properties and device performance. Different compositions of emitter and base materials ($In_xGa_{1-x}P$ and $GaAs_yP_{1-y}$, respectively) can be explored to tailor the band alignment of the heterostructure, thereby improving the gain and frequency response of the photo-HBTs. By reducing the lattice constant of the active materials (i.e. reducing x and y), integration with Si will be made easier.

The Nanomagnetics researchers, **J. Bokor** and **S. Salahuddin** (*Berkeley*) and **S. Khizroev** (*FIU*) will continue their research in achieving a magnetic switch with ultra-low energy at atto-Joule level and at speeds of a few picoseconds. They will continue to elucidate the underlying physics and materials science and demonstrate ultrafast magnetic switching enabled by electrically stimulated non-equilibrium switching. **Khizroev** (*FIU*) will also extend his research efforts to increase the magnetoresistance value of spintronic devices including developing graphene based spin materials.

With the progress already made in understanding the underlying science, this Theme will increase its research towards understanding the application of magnetic devices. Towards that end, **H.-S. P. Wong** (*Stanford*) will join this Theme to collaborate with **S. Salahuddin** and **V. Stojanovic** (both *Berkeley*) to embark on a new effort: The fabrication, design, and integration of in-memory and normally-off computing using magnetic non-volatile devices. One application venue being considered is to turn off large portions of the computer that are not in use as a means to reduce power consumption. The use of non-volatile memory can make normally-off computing viable, since the shut-down part of the computer can be restored to its original state once it is needed, without needing to write to or read from external storage. By distributing the memory over the circuit (memory-in-logic), there can be additional power savings due to reduced interconnect length [16]. Magnetic devices such as spin-Hall and spin torque switches are particularly suitable for normally-off computing, since they are high-speed, non-volatile, have sufficient endurance, are scalable, and their fabrication is compatible with CMOS and 2D Transition Metal Dichalcogenide (TMD) FETs. Spin-Hall switching reduces the write current by adding a torque to the magnet [17]. The goal is demonstrate the large (> 10×) current reduction benefit [18] of using spin-Hall switching in a circuit environment.

Further details of Period 7 Theme IV research plans are as follows.

- The **Salahuddin** group (*Berkeley*) will continue to explore the fundamental science of the spin orbit torque induced magnetic switching. Building on the recent work has shown that spin currents generated by dissimilar materials do not add algebraically, and that bulk spin-Hall effect cannot be the only source of the spin current. A key milestone is the demonstration of ferromagnetic switching with spin orbit coupling in various magnetic materials and with different heavy metals that show a pathway to improve the efficiency such that the total current and therefore, the necessary voltage needed for switching can be reduced. The **Bokor** and **Stojanović** groups (both *Berkeley*) will collaborate to evaluate the efficacy of the switching mechanisms in terms of a system level function.
- **S. Khizroev** (*FIU*) will continue to study the physics of the anomalous magnetoresistance measured in sub-10-nm STT MTJs by conducting a comprehensive set of field and temperature magneto-transport measurements from helium to above room temperature. They will also study the possibility of using functionalized graphene nanostructures as the material of choice. One goal for the next Period is the demonstration of a 3-terminal device. They will also explore a number of alternative device configurations, e.g. ferromagnetic and magnetoelectric nanoparticle based systems.
- Towards elucidating the fast dynamics of spins in spin-Hall effect, the **Bokor** group will extend the MSHG technique used in Period 6 to the psec time scale experiments. The technique that has been used to detect the spin accumulation at normal metal surfaces is also sensitive to interfaces. They will use the technique next to directly measure the spin accumulation in the non-magnetic metal at the interface with a ferromagnetic layer. Comparison of the magnitude of the spin accumulation at the free non-magnetic metal with the magnitude at the interface will provide direct information about the spin transport across the interface, which thus, far has not been possible to obtain. Using ultrafast techniques, they will study the ultimate speed for spin-Hall effect switching. They plan to

explore spin-Hall switching to ferrimagnet systems such as GdFeCo, which are expected to show much faster switching than ferromagnet systems. The unique ultrafast dynamics in GdFeCo will play a critical role in this work. This effort is aimed at bringing the switching speed of magnetic memory and logic devices from the nsec range down to the psec range, which will greatly expand the applicability of magnetic devices. It is expected that the on-going efforts in the **Bokor** group to produce purely electrical current pulses with psec duration using ultrafast optoelectronics techniques will be successfully completed and the new capability will be used to drive suitable magnetic structures such that ultrafast hot-electron demagnetization and switching is observed. This is essential for translating the physics of ultrafast switching triggered by fsec laser pulses to practical applications in fast electronic circuits.

- To be initiated by **H.-S.P. Wong** (*Stanford*), in collaboration with **V. Stojanović** and **S. Salahuddin** (*both Berkeley*), a new project will integrate spin-Hall devices with FETs to build SRAM cells and flip-flops to demonstrate that the circuits are non-volatile and that such integration will have no impact on the circuit area. The integration of spin-Hall memory devices on CMOS as well as 2D FETs will be a collaborative effort in Si CMOS and 2D FET device fabrication involving the **Wong** group and the **Salahuddin** and **Javey** groups. The integration will require device engineering to properly match the FET current drive with the required spin-Hall switching current. In addition, new circuit structures need to be invented and their behavior properly modeled. The device groups will collaborate with the **Stojanović** group will design the non-volatile circuits. Device level simulations will provide the initial memory cell design. Circuit simulations at the macro and functional block level, including the overhead from power-gating, will allow them to quantify the system-level benefit from normally-off computing.

III. EDUCATION

1a. Goals and Objectives

The primary element of the Education goal is the training of Ph.D.- and M.S.-level scientists and engineers in energy efficient electronics science who: 1) are knowledgeable in the scientific approaches to energy efficient digital electronics systems; 2) understand that working in diverse teams enhances creativity; and 3) understand the process of innovation, entrepreneurship and the transition of research results to commercially viable products. In addition, the Center also aims to prepare high school and undergraduate students to pursue studies and research in the energy efficient electronics field to increase the number of students pursuing technical disciplines, contributing to an engaged, skilled and diverse technical workforce in energy efficient electronics science. The Center integrates research and education to stimulate and prepare students and postdocs to pursue careers in energy efficient electronics science.

The 2015 E^3S Annual Retreat included a breakout session on Education and Legacy. Led by **T. King Liu**, Associate Education Director, the Center members reaffirmed the Education strategy that builds on the development of a pipeline of undergraduates who will be interested in research and graduate education. Developing online training materials on the Center's research will be emphasized in the Center's second five years and will serve as the venue to establishing the Center's Education legacy.

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	Center graduates completed E^3S training	Yearly beginning in Period 3	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50% Period 6: 15%
	Students and postdocs participating in education and diversity programs *(discontinued in the 2nd five years)*		
	Students accessing online courses of the Center *(new)*	Yearly beginning in Period 6	Period 6: 50
	Undergraduates who pursue advanced degree in science and engineering	Yearly beginning in Period 3	Period 3: 5% Period 4: 30% Period 5: 35% Period 6: 40%
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Yearly beginning in Period 3	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80% Period 6: 85%
	Pre-college students who pursue a bachelor's degree in science and engineering	Yearly beginning in Period 3	Period 3: Baseline Period 4: 70% Period 5: 70% Period 6: 80%

	Students and postdocs serving in leadership roles in the Center	Yearly beginning in Period 2	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Period 6: 30%

In the E^3S Strategic Plan 2015-2020, the organization of metrics for Education and Diversity changed. Three metrics that measure the progression of students in the pipeline are now tracked under Education, while metrics for the underlying demographics are tracked under Diversity. One metric on graduate student and postdoc participation the Center's activities has been dropped, given that the participation is organized under the E^3S Leadership Program.

1c. Problems Encountered

In November 2014, the E^3S Education and Outreach Director, **S. Artis**, left the Center. In Period 6, much of the time was focused on the renewal grant, and therefore this position was left unfilled until December 2015. The Center's greatest challenge during Period 6 was balancing the existing education and diversity programs while being understaffed. The Center decided to concentrate its efforts on undergraduate education programs that are also diversity programs in order to ensure no disruption in the pipeline of diverse graduate students. As a consequence, progress in development of online modules and courses has been delayed. The Center created videos during Period 5 that were to be released during Period 6; however, in order to be released, the videos must undergo reviews on content and usability. Being understaffed prevented the Center from going through these reviews, and therefore the videos have not yet been published. With the onboarding of **A. Tabor** into the Center's Diversity Director position in December 2015, the focus of the Center was to renew its focus on creating and disseminating online educational videos and modules. Tragically, however, **Dr. Tabor** unexpectedly passed away only nine days after joining the Center. This left a tremendous hole in our renewed Diversity and Outreach activities and current efforts are underway to re-fill this position as soon as possible.

2. Educational Activities

During Period 6, the Center graduated 12 graduate students and 7 postdocs. In addition, 14 undergraduates who were research interns with the Center, either through one of the REU programs (E^3S REU or ETERN) also received their baccalaureate. To date, E^3S has graduated 114 graduates (41 undergraduates, 47 graduates, and 26 postdocs). These students and postdocs have gone on to pursue careers in industry, academia, and national research laboratories around the globe (see Graduates Table, Centerwide Output). These Center alumni have benefited from the Center's formal and informal training programs and opportunities.

Since the start of the Center, E^3S Director, **E. Yablonovitch** has been teaching biennially a graduate level course on low energy electronics with a strong focus on E^3S topics and perspectives. In Period 6, the course, a listed UC Berkeley course, was taken by 11 graduates students from four of the five E^3S member institutions, and 4 postdocs from 2 member institutions. In addition, low energy electronics, the Center's approaches, and some of the research outcomes have also been implemented by 9 E^3S faculty into courses they teach. Currently, this curriculum is being taught at FIU, MIT, Stanford, and UC Berkeley. A total of 15 courses have had E^3S content added. Of this, two of the courses are at the undergraduate level, ten are graduate level courses, and three are both undergraduate and graduate level courses. As indicated in the section on Problems Encountered, progress towards the release of education video on low energy electronics has been delayed due to staff limitations.

The Center also offers a variety of informal training opportunities for graduate students and postdocs including: presenting, both oral and poster, at seminars and during Center events; mentoring of undergraduates; group analysis of competing research; participating in the REU intern selection process;

serving a poster judges, and conducting scientific demonstrations at outreach events. In Period 6, 23 graduate students and 6 postdocs took advantage of these practical training opportunities.

These informal training opportunities are part of the professional development opportunities of the Center. Given the number of opportunities available, the Center has also developed the E^3S Professional Development Program (E^3S PDP) to guide the students and postdocs to acquire a diverse and balanced set of experiences. Upon completing enough areas, a student/postdoc will receive a Leadership Certificate. Thus far, sixteen students have earned a certificate of completion, of these, 6 were awarded in Period 6. Approximately half, 29 (46%) of the E^3S students participated in a training area in Period 6.

The Center also offers training in areas that it deems important in developing a scientist /engineer. Incoming students and postdoc are required to complete an online ethics training. All mentors of REU students receive training in project management and interactions between mentor and mentee. In Period 6, 14 students and postdocs received training in these area. In addition, in Period 6, the Center offered a workshop on proposal writing that was attended by 16 students and postdocs.

The recent 2015 survey of graduate students and postdocs identified the impact of the Center's education programs on increasing the respondents' understanding of low energy consumption device science and technology (**Figure 1).** Students also indicated that the Center has positively impacted their professional development and interests in energy efficient electronics (**Figure 2**).

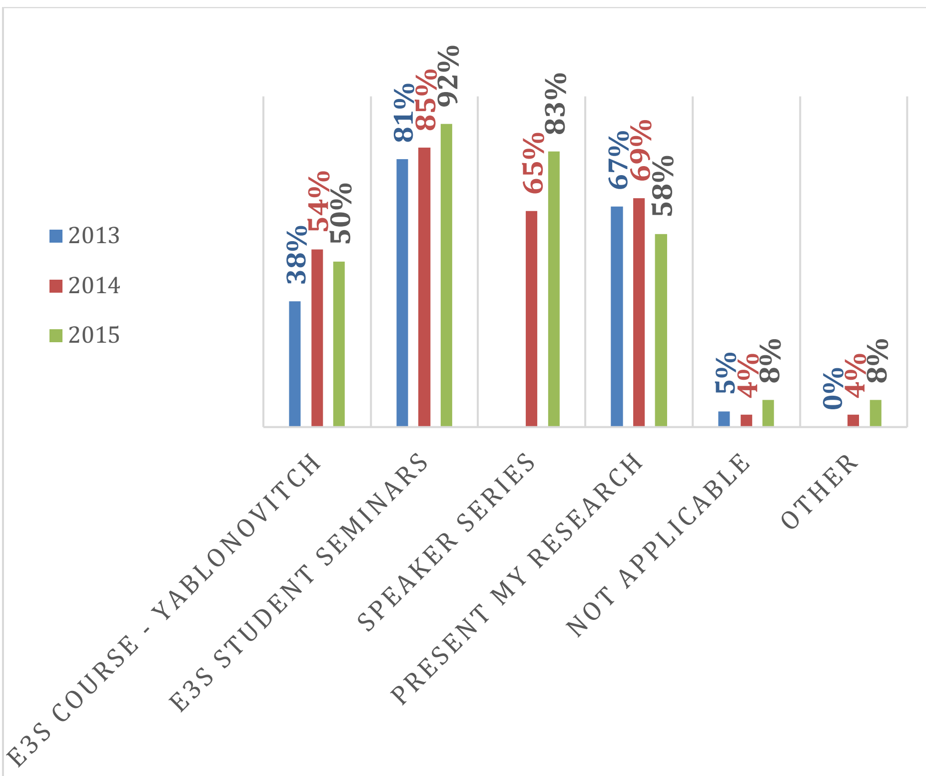

Figure 1: Graduate students and postdocs indicated the Center's educational activities are sharpening their understanding of low energy consumption device science and technology

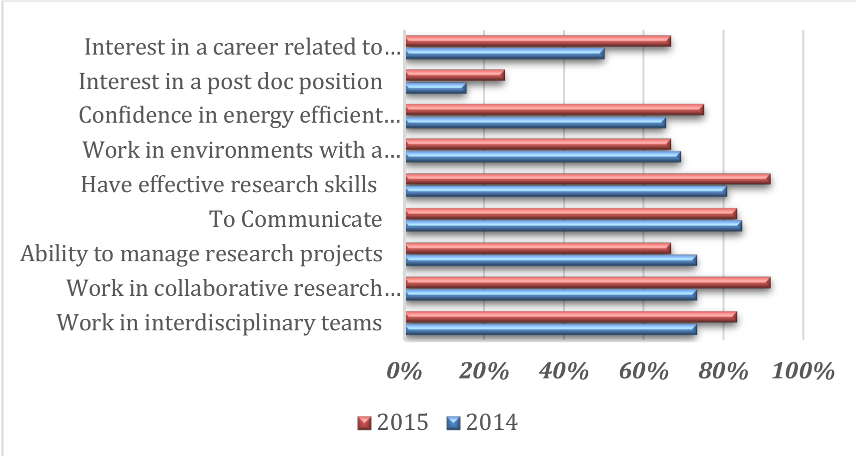

Figure 2: Graduate Students and postdocs indicated that the Center has positively impacted their professional development and interests

The Center is also impacting undergraduate education by offering research opportunities. Students of the member institutions participate in the ETERN program that offers paid 10 week internships during the academic term. In Period 6, there were 3 ETERNs at FIU and UTEP. ETERNs have the opportunity to continue their research in the summer at either an alternate E^{3}S member institution or at CEA-Leti in France, an E^{3}S education partner. In Summer 2015, one ETERN from UTEP conducted 9 weeks of research in France.

The Center also manages three REU programs for undergraduates from 4 year institutions and community colleges. Five community college students and 15 undergraduates from 4 year institutions were hosted in E^{3}S or E^{3}S affiliated research groups at four of the five E^{3}S member institutions. In alignment with the Center's focus community college education, two E^{3}S faculty supported the professional development of community college teachers in Period 6 with the goal of enhancing STEM classroom instructions. One community college professor develop teaching materials for two courses: Materials Science and Electrical Engineering. Another community college instructor, after 8 weeks of hands-on research, developed a new teaching module on Nanotechnology for an introductory Chemistry course.

The following sections provide details in support of the above summary of the state of Education in Period 6.

2a. Internal Educational Activities

The internal educational activities that were initiated in previous reporting periods continued in Period 6. Seminars, external speaker series, poster sessions, and the Center's Annual Retreat are all informal education venues for undergraduates, graduate students and postdocs. The research internship program, ETERN, for early engagement of undergraduates involved 3 interns conducting research during the academic terms at 2 institutions.

Activity Name	E^{3}S Course – EE 290B: Advanced Topics in Solid State Devices
Led by	**E. Yablonovitch** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 14 Graduate Students: 5 Berkeley, 1 MIT, 3 FIU, 1 UTEP Postdocs: 3 Berkeley, 1 UTEP

One of the Center's goals for its members is to receive formal training in technical topics that are applicable to the Center. **E. Yablonovitch,** Center Director, developed a UC Berkeley, EE 290: Advanced Topics in Solid State Devices, to be the key training venue. This course was first taught in Fall 2010, at the inception of the Center. In the spring of Period 6, **E. Yablonovitch** taught EE 290 again. This course covers the following topics: solid-state switching devices that operate in the milli-Volt regime, nano-transistor options with steeper sub-threshold slope, nano-optical links, novel nano-scale impedance matching transformers, including plasmonics, new forms of amplification using giant magneto-resistance and other spintronic effects, nano-mechanical switching elements that are capable of very low voltage operation, low-temperature electronics, and electro-chemical switching elements. This course was taught at UC Berkeley and offered to members at all institutions through videoconferencing technology and online posting of course material. The enrollment count for this course was 32, including 14 E^3S members from Berkeley, MIT, FIU, and UTEP; and 18 non-E^3S members.

Activity Name	E^3S Research Seminars
Led by	**T. Yu** (MIT) and **P. Zhao** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 364 Undergraduate Students: 41 Berkeley, 2 MIT, 2 UTEP Graduate Students: 81 Berkeley, 23 MIT, 1 Stanford, 5 FIU Postdocs: 73 Berkeley, 1 Stanford, 9 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 present the progress of their research. Occasionally, E^3S faculty present new projects, and industry partners have presented the research efforts in their company. Period 6 is expected to conclude with 13 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	Sixth 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 – 53 Graduate Students: 13 Berkeley, 7 MIT, 3 FIU Postdocs: 2 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 13 posters at the 2015 Annual Retreat presented by 9 graduate students (7 Berkeley, 2 MIT), 3 postdocs (2 Berkeley, 1 Stanford), and 1 faculty (Berkeley). For a list of posters, please see Appendix I.

Activity Name	Poster Presentation at the External Advisory Board Meeting
Led by	**J. Yuen** (Berkeley)
Intended Audience	External Advisory Board
Approx. Number of Attendees (if appl.)	Total – 7 Graduate Students: 3 Berkeley Postdocs: 2 Berkeley, 1 Stanford Faculty: 1 Berkeley

This year, 6 students and postdocs from 2 member institutions were given the opportunity to present their research to the external advisory board.

Activity Name	Fifth Annual Student and Postdoc Retreat
Led by	**L. Marlor** (Berkeley)
Intended Audience	Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 9 Graduate Students: 3 Berkeley, 2 MIT, 3 FIU Postdocs: 1 MIT

In August, the Center hosted its 5th Annual Student and Postdoc Retreat for graduate students and postdocs. Graduate students and postdocs spent the day in breakout sessions organized by research themes. This year the students focused on creating presentations to give at the E^3S Annual Retreat that would serve as feedback to the faculty on the direction in which the research of the Center should be headed.

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

The ETERN program is an academic-year program for undergraduates at all of the Center's institutions. The primary goal is to attract students to energy-efficient electronics science by providing research experiences to lower-division undergraduate students of member institutions. The major aim is to enhance the pipeline of students interested in graduate studies in the science and engineering disciplines of relevance to the Center. In Period 5, we had 3 participants. These students were advised by E^3S faculty and mentored by E^3S graduate students. They also had the opportunity to participate in Center-wide activities for students and postdocs such as research seminars. In Period 6, 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^3S 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^3S Leadership Certificate that students receive after completing enough areas in the Professional Development Program (E^3S PDP) with the goal of guiding the students and postdocs to acquire a diverse and balanced set of experiences.

Activity Name	E^3S Professional Development Program (E^3S PDP)
Led by	**L. Marlor** (Berkeley)
Intended Audience	All Graduate Students and Postdocs
Approx. Number of Attendees (if appl.)	Total – 29 Graduate Students: 13 Berkeley, 7 MIT, 1 FIU, 1 UTEP, 1 Stanford Postdocs: 2 Berkeley, 2 MIT, 2 Stanford

Students and postdocs are provided with a number of programmatic activities within the Center aimed at professional development. These programs offer different areas of development: leadership, teaching, mentoring, outreach, science communication, proposal writing, and entrepreneurship. E^3S PDP 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). Thus far, sixteen students have earned a certificate of completion, of these, 6 were awarded in Period 6. Approximately half, 29 (46%) of the E^{3}S students participated in a training area in Period 6.

Activity Name	Analysis of Competing Research Programs
Led by	**W. Chern** (MIT), **M. Stone** (FIU), **T. Xiao** (Berkeley), **C. Keraly** (Berkeley)
Intended Audience	E^{3}S Center members at the Center's Annual Retreat
Approx. Number of Attendees (if appl.)	Total – 53 Graduate Students: 13 Berkeley, 7 MIT, 3 FIU Postdocs: 2 Berkeley, 2 MIT, 1 Stanford, 1 UTEP

At the 2015 Annual Retreat, the Center had students create competitive analysis research presentations according to their 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)
Intended Audience	Graduate Student and Postdoc Mentors
Approx. Number of Attendees (if appl.)	Total – 14 Graduate Students: 8 Berkeley Postdocs: 6 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	Proposal Writing Training
Led by	**L. Marlor** (Berkeley)
Intended Audience	Graduate Student and Postdoc Mentors
Approx. Number of Attendees (if appl.)	Total – 16 Graduate Students: 7 Berkeley, 3 MIT, 1 FIU Postdocs: 2 Berkeley, 1 MIT, 1 UTEP, 1 Stanford

Additional opportunities for leadership experiences for graduate students and postdocs were provided at this year's annual retreat in form of a proposal writing workshop. The training, conducted by former NSF Program Officer, **S. Sorby** (The Ohio State University), discussed the NSF organizational structure, how proposals are reviewed, and strategies for submitting proposals.

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

Approx. Number of Attendees (if appl.)	Total – 17 Graduate Students: 8 Berkeley, 4 MIT, 1 FIU Postdocs: 2 Berkeley, 1 Stanford, 1 UTEP

Special emphasis is given to recruit postdocs to serve on the selection committee for the E^{3}S Research Experience for Undergraduates (REU) program. Due to the substantial increase in the number of applications received, graduate students were also invited to participate in 2015. Each member of the selection committee reviews the application material, including personal statement, transcript, and letters of recommendations of ~5 applicants. Based on their review process, the postdocs and graduate students provided a list of applicants that should be considered for placement in a REU summer research project.

Activity Name	REU Poster Review
Led by	**L. Marlor** (Berkeley)
Intended Audience	Undergraduate Students at Center's Institutions
Approx. Number of Attendees (if appl.)	Total – 5 Graduate Students: 3 Berkeley Postdocs: 1 Berkeley, 1 UTEP

The Center hosted three REU programs, one for upper division undergraduates, one for students attending an HBCU institution, and another for community college students 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 6, 5 graduate students and postdocs evaluated the posters based on the following criteria: presentation skills, poster layout, and content (problem, methods, results & understanding). Each member of the review panel evaluated 4-5 posters so that all of the summer students had at least one evaluation of their work. At the conclusion of the poster session, assessments were anonymously shared with the REU intern to provide them feedback on their performance.

2c. External Educational Activities

Activity Name	E^{3}S Teacher Fellows Program
Led by	**J. Yuen** (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 of low-energy electronic devices. In Period 6, 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. Leveraging a 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 (LATTC), one of the Center's education partners, was hosted by Prof. **T.-J. King Liu** and mentored by graduate student, **I. Bhattacharya**. **A. Navarro** created a new online curriculum for his Materials of Engineering Course (ENG GEN 151) as well as instructional materials for a new introductory electrical engineering course that has been approved for implementation at LATTC. Prof. **E. Alon** also advised on electrical engineering curriculum development, including sharing the approach that he has been using as part of the re-engineering of UC Berkeley electrical engineering freshmen curriculum. Online materials that have been in use in Berkeley's introductory electrical engineering courses were made available as reference materials for the visiting faculty.

S. Beaver, a chemistry instructor of the Peralta Community College District, conducted nine weeks of research in the laboratory of Prof. **J. Wu** in Berkeley, mentored by postdoc, **H. S. Choe**. The RET program calls for the introduction of new curricular materials that incorporate some of the new concepts in the summer research. In Fall 2015, the visiting chemistry instructor implemented an introduction of nanotechnology to his teaching of introductory chemistry.

Activity Name	Introduction to Electronics Mini-course
Led by	**J. Teherani** (MIT)
Intended Audience	K-12, General Public
Approx. Number of Attendees (if appl.)	Graduate Students- 1 Berkeley

The Center has partnered with the MIT's Office of Digital Learning Science Out Loud program to design two free, easily accessible videos: How Computers Compute (https://www.youtube.com/watch?v=8cVsgFN3hSM) (Published: November, 2014, 15,000 views) and What is a Semiconductor? (https://www.youtube.com/watch?v=gUmDVe6C-BU) (Published: May 2015, 16,000 views).

Activity Name	Bay Area Science Festival
Led by	**F. Li** (Berkeley)
Intended Audience	The San Francisco Bay Area Community
Approx. Number of Attendees (if appl.)	Total- 9 Undergraduate Students: 1 Berkeley Graduate Students: 8 Berkeley

Each fall, a science festival is held at AT&T Park in San Francisco that showcases fun and exciting science to the general population. This year was the third year that E^3S participated in the event. **F. Li** led 9 students in demonstrating how 2D materials (graphene) conduct electricity. More senior participants were also introduced into the Center's goal of 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 500 people participated in the E^3S demonstration.

2d. Integration of Education and Research

Research is the driving force behind all of our educational programs and activities. As in previous years, the Center continues to integrate its research mission into its educational 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 educational programs with the Period 5 targets. The table below displays these data and future metrics to measure education success.

Objective	Metric	Targets	Results				
			P 2	P 3	P 4	P 5	P 6
Education	Center graduates completed E^3S training	Period 2: Baseline Period 3: 50% Period 4: 50% Period 5: 50% Period 6: 15%	n/a	3 (17%)	3 (14%)	3 (33%)	7 (35%)
	Students accessing online courses of the Center	Period 6: 50	*(new for Period 6-10)*				TBD
	Undergraduates who pursue advanced degree in science and engineering	Period 3: 5% Period 4: 30% Period 5: 35% Period 6: 40%	n/a	0 (0%)	5 (38%)	20 (71%)	31 (74%)
	Community college participants who transferred to 4 year universities to pursue a science and engineering baccalaureate	Period 2: Baseline Period 3: 5% Period 4: 80% Period 5: 80% Period 6: 85%	n/a	3 (100%)	6 (100%)	7 (88%)	6 (100%)
	Pre-college students who pursue a bachelor's degree in science and engineering	Period 3: Baseline Period 4: 70% Period 5: 70% Period 6: 80%	n/a	31 (68%)	98 (75%)	162 (82%)	206 (75%)
	Students and postdocs serving in leadership roles in the Center	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Period 6: 30%	11%	11 (19%)	20 (34%)	20 (34%)	20 (32%)

2f. Education Activities in Period 7

Much of Period 7 will be spent in continuing the established education programs.

As we will have newly released online modules on electronics, we will use Period 7 for assessment and promotion. We will 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 colleges and conduct follow-up interactions 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 goals of the Center for E^3S are to establish partnerships that will accelerate the Center's research and programmatic endeavors, create venues for introducing new and more efficient electronics technologies, and enable workers at all levels to participate in the new opportunities. We think of knowledge transfer as the cross-fertilization of ideas within the Center, as well as throughout the ecosystem 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.

Knowledge transfer occurs when:

- The Center's research, education and programmatic activities and outcomes are shared and made widely accessible;
- The research and programmatic outcomes are accelerated by collaborations;
- The outcomes are recognized to be impactful through citations;
- The alumni who are trained through research experiences continue to participate in the industries and technical disciplines related to the Center; and
- Outreach to the general public stimulates support for STEM education and research related to the Center's scope.

1b. *Performance Metrics*

Objective	Metrics	Frequency	Targets
Knowledge Transfer	Center publications	Yearly	Periods 2 – 5: Yearly: 18 Period 6: 25
	External citations of publications *(cum)*	Yearly	Period 3: 10 Period 5: 100 Period 6: 25% yearly increase
	Talks at peer-reviewed conferences ***(new)***	Yearly	Period 6: 12
	Center sponsored symposia & workshops	Bi-annually	Period 2: baseline Period 3: 0 Period 4: 1 Period 5: 0 Period 6: 2
	Website hits & unique visitors *(discontinued)*	Yearly	Period 2: Baseline Period 3: 20% increase
	Contacts with industry • Talks & Meetings • Presentations by industry	Yearly	Period 2: 18 Period 3+: 36 yearly Yearly: 2
	Research Collaboration with industry	Yearly	Period 4: 1 Period 5: 2 Period 6: 3
	Patents Disclosures/Provisional	Yearly	Period 3: 3 Period 4: 3

			Period 5: 5 Period 6: 2
	• Patent Application Filed/Granted	Yearly	Period 4: 0 Period 5: 3 Period 6: 1
	• Center's alumni into relevant industries	Yearly	Period 5: 50% Period 6: 30%
	Center's alumni pursuing research in disciplines related to the Center at academia & research labs ***(new)***	Yearly	Period 6: 30%
	Technology development attributable to Center's research • Low energy devices Enabling other applications	Yearly	Period 6: 0
	• Number of external articles on the Center *(discontinued)*	Yearly beginning in Period 3	Period 2: Baseline Period 3: 100% increase Period 5: 50% increase

Knowledge Transfer is a very important indicator of the Center's success. Because Knowledge Transfer has many venues, both versions of the E^3S Strategic Plan, the first and the current 2015 – 2020 version, have many metrics. We have continued to keep the same number of metrics, but have replaced two with new ones. The information that are needed for "new" metrics are already being collected, even though they had not been considered to be officially performance indicators. One is the number talks at peer-reviewed conferences and the other, the number of Center graduates going to academia and research centers. Tracking conference presentation is very important as some conferences are very influential, like IEDM. The Center's alumni are the Center's human legacy and thus, we should not only focus on those who go on to industry, but also those who become educators and researchers outside industry.

1c. Problems Encountered

The last annual report shared that a new website will be released. Due to the lack of staff in the Center, the release has been delayed significantly. This gap will be addressed by the beginning of Period 7.

2a. Knowledge Transfer Activities

Center's researchers have also 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 with many companies. A key knowledge transfer activity was the 4th Berkeley Symposium for Energy Efficient Electronic Systems that was organized by the Center. The IEEE co-sponsored event brought together researchers from around the world who are working from devices to systems to provide researchers an integrated perspective of the challenges and advances in energy efficiency for information processing systems. Of the 119 registered attendees, 23 were from industry and 28 were from academic institutions that are not a part of the Center. The program consisted of 28 presented papers, 2 of which were from industry and 17 were invited papers, and 3 panels. The Center contributed 7 talks and 11 posters.

Since the last annual report, the Center researcher have published 29 papers, and 12 are under review. Moreover, the papers from 23 talks, presented at peer reviewed conferences, have newly been published as conference proceedings. In addition, Center members presented 39 papers at other peer review conferences, including presentations by REU program alumni.

The Center's two-way knowledge transfer calls for soliciting information generated external to the Center. As such, we continued to seek input from the Center's Industrial Science Board which are made up of company that the Center considers to be members, invite external speakers to be seminar speakers and organize group activities for the Center's students and postdocs to learn about other low energy electronics programs.

The Center's Knowledge Transfer mission also includes the transfer of knowledge gained from the Center's research on low energy electronics to other applications. Three technologies of the technologies identified in last year's report are being pursued by E3S faculty with external partners: i) InGaAs/GaAsSb QWTFET for RF Applications; ii) Squitch Switches as Analog Valves; and iii) RIE process with Digital Etch Technology for III-V Features of High Aspect Ratios. The first two technologies are being further development to enable the new application, while the third has been under evaluation at three companies.

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

- The formal Knowledge Transfer venue has continued to be dissemination of research results by E^{3}S researchers through journal and talks at peer-reviewed journal and conferences. The Center's REU interns also gave talks and presented posters at peer review conferences. In addition, as the Center embarks into its 2nd five years, there are also increasing patent applications and patents.

Dissemination of the Center's Research Results in Journals		
Led by	E^{3}S Faculty	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Stanford	Stanford, CA
4.	UTEP	El Paso, TX

To date, the Center's faculty, students and collaborators have published 31 papers, all in peer-reviewed journals. All, but one, are scientific papers; one paper on education. The lead faculty author of 20 technical papers is from Berkeley, 8 from MIT faculty, 2 from Stanford and 1 from UTEP. In addition, 10 papers have been submitted for review.

One performance metric in the Strategic Plan is the number of citations of the Center's publications. The cumulative citations for the 112 papers attributed to the Center was 1724, increase of 240%.

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

23 talks by researchers from Berkeley, MIT, Stanford, and UTEP were published in conference proceedings in Period 6. 14 were in proceedings of major conferences, like IEEE International Electron Devices Meeting, Device Research Conference and IEEE Int'l MEMS conference.

Berkeley Symposium on Energy Efficient Electronic Systems		
Led by	E. Yablonovitch, J. Bokor and H.-S.-P. Wong	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	Stanford University	Stanford, CA

The 4th Berkeley Symposium on Energy Efficient Electronic Systems offered technical sessions that range from devices to systems to provide researchers an integrated perspective of the challenges and advances in energy efficiency for information processing systems (Appendix H – Symposium Program). IEEE Electron Devices Society was a technical co-sponsor of the Symposium, while Applied Materials and Lam Research were industry sponsors. The Organizing Committee was co- chaired by E. Yablonovitch and J. Bokor, who together established the Symposium in 2009, before the Center was started. The organizing committee also included A. Amerasekera (TI); E. Sangiorgi (U of Bologna); J. Bowers (UC Santa Barbara); J. Shalf, (LBL); O. Faynot (CEA-Leti); M. Tabib-Azar (U of Utah); R. Huang (Peking U.), T. Theis (IBM & SRC); L. Pileggi (Carnegie Mellon U.); K. Wang (UCLA); J. P. Reithmaier, (U. Kassel); H.-S. P. Wong (Stanford U.); J.-B. Yoon (KAIST).

Of the 119 registered attendees, 23 were from industry and 28 were from academic institutions that are not a part of the Center. The program consisted of 28 presented papers, 2 of which were from industry and 17 were invited papers, and 3 panels. The contributed talks and posters were selected through a peer-reviewed selection process. The Center contributed 7 talks and 11 posters.

Presentation by REU alumni		
Led by	L. Marlor	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	APS March Meeting, March 2015	San Antonio, TX
3.	CUR Research Experiences for Undergraduates Symposium	Arlington, VA
4.	SACNAS Annual Conference	Washington, D.C.
5.	UT-LSAMP Student Research Conference	El Paso, TX
6	APS March Meeting, March 2016	Baltimore, MD

REU alumni are provided funding in order to present their summer research at conferences. During Period 6, one 2014 E^3S REU alumna, B. McLellan, presented the research she did in the J. Bokor group at the APS March meeting. Two 2015 community college students presented their work at SACNAS and one presented his work at the CUR Research Experiences for Undergraduates Symposium. One 2015 E^3S REU alumnus presented his work at the UT-LSAMP Student Research Conference. One 2015 E^3S REU alumna has been accepted to present her research in next year's APS March meeting.

Patent & Patent Applications		
Led by	**Various**	
Organizations Involved		
	Name	*Address*
1.	UC Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3.	Florida International University (FIU)	Miami, FL

There were 2 provisional applications; 1 from Theme III researchers at Berkeley, 1 related to Theme IV from FIU. MIT researchers was granted a patent on nanomechanical switch using a composite material. 3 additional patent applications were filed from MIT researchers.

- 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. Several efforts to develop applications outside the scope of the Center that were mentioned in the last annual report have continued in Period 6.

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 showed remarkable sensitivity as a tunable microwave detector. A collaboration to exploit the approach for RF application has continued. In Period 6, the collaboration has been focused on modeling the device.

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. 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 and for access to the monolayers of MIT. The processes being developed at Lincoln Labs will also support the fabrication of horizontal switches being in development in the Center. While there was an approximately half a year delay in the start of the project, the MITLL technical partner, J. Chou, is making progress in developing critical processes for fabricating horizontally-actuated Squitches using their unique fabrication tools. The E^{3}S Squitch team has already synthesized the appropriate molecules in anticipation that the Squitch researchers will participate in the assembly of the molecules within the devices fabricated by MITLL.

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.	Lam Research	Fremont, CA
3.	Applied Materials	Santa Clara,CA
4.	Northrup Grunman	Sacramento CA

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 6, J. del Alamo has been working with three companies to assess the technology for broader semiconductor applications.

- Knowledge transfer in terms of materials and processing knowledge can also occur within the Center.

Materials Processing and MEMS Device Fabrication		
Led by	D. Zubia, J. Javey, T.-J. King Liu	
Organizations Involved		
	Name	*Address*
1.	University of Texas, El Paso	El Paso, TX
2.	UC Berkeley	Berkeley, CA

D. Zubia (UTEP) is using the opportunity to collaborate with J. Javey and T.-J. King Liu (*Berkeley*) on an E^{3}S project to transfer the practical skills and understanding of 2d materials and MEMS processing to the Electrical Engineering Department of UTEP. As such, he requested a 10-week internship for the postdoc to be embedded in the Berkeley laboratories to have hands off experience.

- 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.

Annual Research Briefing for Industry Partners		
Led by	**E. Yablonovitch** (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	MIT	Cambridge, MA
3	Applied Materials	Santa Clara, CA
4.	IBM	Yorktown Heights, NY
5.	Intel Corp.	Hillsboro, OR
6.	Lam Research	Fremont, CA

Five companies are considered E^{3}S members because of the support they have pledged to provide. These companies form the E^{3}S Industrial Research Board, which advises on the Center's Research to ensure that the Center's approaches are practical. In past years, these companies were invited to the Center's Annual Retreat as members. However, this year, the Center tried a new approach, Instead, a joint review session was held for the Industrial Research Board and the External Advisory Board. While both were attended the same presentation and discussion of Research, the Industrial Research Board met separately with the E^{3}S leadership. At the meeting, each participating company representative provide input on the Research Themes and directions and status of each. This year, the input was very detailed with the corporate partners discussing many of the projects within the Theme and their companies' interests.

Seminars by Invited Speaker		
Led by	**J. Yuen** *(Berkeley)*	
Organizations Involved		
	Name	*Address*
1.	HPE	San Jose, CA
2	CEA- Leti	Grenoble, France

3.	U of Utah	Salt Lake City, UT
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 three seminars by external speakers: S. Williams, HPE; O. Faynot, CEA-Leti; and M. Tabib-Azar, U. of Utah; see http://www.e3s-center.org/research/rsh-seminars.htm. While attendees at these seminars consisted of Center members from the five academic institutions of the Center, the seminars also attracted attendees who are not Center members.

Competitive Analysis – 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.	Florida International University	Miami, FL

At the 2015 Annual Retreat, the Center had students create competitive analysis research presentations according to their theme. The students in Themes I, III and IV made presentation of the competitive landscape and identify similarities and differentiation in the approaches of the programs, including those of the Center.

- 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.

Presentation at ASEE		
Led by	**L. Marlor**	
Organizations Involved		
	Name	*Address*
1.	U of California, Berkeley	Berkeley, CA
2.	ASEE Conference, June 2015	Seattle, WA

L. Marlor, E^3S Education Manager, presented a paper at the peer-reviewed conference, ASEE, in June 2015 on "The Impact of Summer Research Experiences on Community College Students' Pursuit of a Graduate Degree in Science and Engineering." This paper was co-authored with C. Amelink, External Evaluator, and S. Artis, previously, E^3S Education & Diversity Director.

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	Metric	Targets	Results P 2	Results P 3	Results P 4	Results P 5	Results P 6
Knowledge Transfer	**Center publications**	Periods 2 – 5: Yearly: 18 Period 6: 25	17	17	19	30	45
	External citations of publications *(cum)*	Period 3: 10 Period 5: 100 Period 6: 25% yearly increase	15	178	393	719	1724
	Talks at peer-reviewed conferences *(new)*	Period 6: 12	*(new for P6-10)*				10
	Center sponsored symposia & workshops	Period 2: baseline Period 3: 0 Period 4: 1 Period 5: 0 Period 6: 2	1	0	1	0	1
	Contacts with industry • **Talks & Meetings**	Period 2: 18 Period 3+: 36 yearly	66	20	42	62	35
	• **Presentations by industry**	Yearly: 2	4	2	6	3	5
	Research Collaboration	Period 4: 1 Period 5: 2 Period 6: 3	0	1	1	4	6
	Patents • **Disclosures/ Provisional**	Period 3: 3 Period 4: 3 Period 5: 5 Period 6: 2	1	0	1	0	2
	• **Patent Application Filed/Granted**	Period 4: 0 Period 5: 3 Period 6: 1	1	0	0	0	4; 1 granted
	Center's alumni into relevant industries	Period 5: 50% Period 6: 30%	Student 0%	Student 64% (7)	Student 16% (2)	Student 16% (6)	Student 50% (12)
			Postdoc 100% (1)	Postdoc 33% (2)	Postdoc 20% (2)	Postdoc 40% (4)	Postdoc 13% (1)

	Center's alumni pursuing research in disciplines related to the Center at academia & research labs *(new)*	Period 6: 30%	*(new for P6-10)*	Student 38% (9) Postdoc 88% (7)
	Technology development attributable to Center's research • **Low energy devices** • **Enabling other applications**	Period 6: 0	*(new for P6-10)*	0

2d. Transfer Activities in Period 7

The key initiative is the release of a new website for the Center. While a prototype of a website with new navigational organization as well as look and feel has been available since the end of Period 5, much work is needed to develop updated content. In addition, the new management team of the Center must address this issue in the context of its approaches to information dissemination and assess whether the existing hosting platform will continue to best serve the needs of the Center through 2020 and beyond.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

The basic rationale for a center is to enable collaborations. The collaborations that the Center seeks to enable go beyond its boundaries. External partners have been critical to the success in every aspect of the Center: research, education, knowledge transfer and broadening participation. The Center's researchers have also established both formal and informal partnerships with researchers in academia and industry as they pursue their scientific investigations. Industry partnerships also serve as the cornerstone in the execution of E^{3}S' two-way knowledge transfer strategy. The education and diversity programs leverage the experience, expertise and resources of campus partners at the lead and subaward institutions to deliver highly successful programs. In period 6, 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
	- Talks given to and meetings with industry		
	- Talks given by industry		
	Research Collaborations (new)	Yearly	

The Center engages external partners to accelerate its work towards the Center's goals. While external partnerships have helped in all aspects of the Center's work, industry partnerships are critical to the success of practical implementation of the Center's research outcomes. As such, the metrics for partnerships are tied in with knowledge transfer with industry.

As in the past Reporting Periods, the Center will continue to track the number of contacts with industry in two categories: i) talks given to and meetings with industry; ii) presentations by industry. The two metrics, in place since the start of the Center, measure the sharing of information. In the next years, more importantly, the partnerships must go beyond information sharing outcomes. The metric, number of research collaborations, is added to measure the depth of engagement with industry.

1c. Problems Encountered

In early 2015, two companies expressed interest in membership in the Center. As the Center's proposal for new funding was still under consideration at NSF, the Center management decided that a delay in engagement would be appropriate. Nevertheless, there were informal discussions and both companies sent representatives to the 4th Berkeley Symposium on Energy Efficient Electronics Science that the Center organized in October 2015.

As shared in the last annual report, the E^{3}S Squitch team entered into a formal 1-year joint development partnership with MIT Lincoln Labs (MITLL). However, due to MITLL personnel shifts, the project was suspended and did not resume until July 2015. This delayed the research in horizontally-actuated Squitch designs. Nevertheless, as reported in the Research section, E^{3}S researchers at MIT have made significant progress on a vertically actuated approach that did not require the unique fabrication tools at MITLL. With the partnership being active again, MITLL and the E^{3}S Squitch team at MIT are in good communication with biweekly phone conferences.

2a. Activities in Period 6

The Center primarily engages industry partners in order to accelerate research and facilitate knowledge transfer.

- The primary route for companies to engage with the Center on a sustained basis is through formal participation as a member in the E^{3}S Industrial Research Board; see Center Management. In Period 6, like recent prior Periods, there are five member companies: Applied Materials, Hewlett-Packard Enterprise, IBM, Intel and Lam Research. Besides serving as advisors to provide the Center with industry perspectives, these companies support the Center's activities, including financial support in limited cases. In Period 6, four of the five member companies had additional engagement with the Center beyond an advisory level.
    - Applied Materials served as a co-sponsor of the 4th Berkeley Symposium on Energy Efficient Electronic Systems. In addition to five participants from Applied Materials, **N. Kim** was a session moderator. The company has also been evaluating the potential of the high aspect ratio digital edge technology that was developed by the group of **J. del Alamo** *(MIT)* for nanowire semiconductors for broader semiconductor applications.
    - Lam Research was another industry co-sponsor of the 4th Berkeley Symposium on Energy Efficient Electronic Systems. **N. Draeger** served as a session moderator. Lam Research is also conducting laboratory evaluation of the high aspect ratio digital etch technology of the **J. del Alamo** group for broader semiconductor applications.
    - Hewlett Packard Enterprise supported the Center by providing its members an education in industry research perspectives. Dr. **S. Williams**, CTO, was an E^{3}S seminar speaker in Summer 2015; his seminar was on the "Foundational Technologies at HP Labs".
    - IBM Zurich, in its second year as a research partner, provided III-V on insulator wafers for bilayer TFETs being fabricated by the **Antoniadis/Hoyt** team (*MIT*).

- Other companies work with the Center in focused and limited manner.
    - Western Digital provided funding for early access to the sub-10µm STT-MTJ spintronics research in the **S. Khizroev** group (*FIU*).
    - Northrop Grumman is another company evaluating the digital etch technology broader semiconductor applications.

E^{3}S faculty have primarily been engaged in ad hoc research collaborations with other researchers, the most substantive being the partnership between MIT Lincoln (MITLL) and the E^{3}S Squitch team of **Bulović, Lang** & **Swager** (*MIT*) that includes funding from MITLL. While the start of the joint development was delayed, as we shared in the Problems Encountered section, the agreed upon program is now in progress. The MITLL technical partner, J. Chou is developing critical processes for fabricating horizontally-actuated Squitches using their unique fabrication tools; see Knowledge Transfer section on MITLL's application of the Squitch technology. The E^{3}S Squitch team has already synthesized the appropriate molecules in anticipation that the Squitch researchers will participate in the assembly of the molecules within the devices fabricated by MITLL.

The Center's biennial Berkeley Symposium on Energy Efficient Electronic System became an IEEE Electron Device Society (EDS) co-sponsored knowledge dissemination venue in 2013. This relationship provides publicity and free publication of the Symposium's proceedings. Once again, in 2015, the 4th Symposium received IEEE EDS endorsement. E^{3}S faculty, **E. Yablonovitch**, **J. Bokor** and **H.-S.P. Wong** reached out to both academic and industry partners to be part of the Organizing Committee, so as to get broad support for the event. The Organizing Committee, which includes the following individuals, advised on invited speakers and served as reviewers of this peer-reviewed venue.

A. Amerasekera, *Texas Instruments*
J. Bowers, *UC Santa Barbara*
O. Faynot, *CEA-Leti*
E. Sangiorgi, *University of Bologna*
J. Shalf, *Lawrence Berkeley Laboratory*
M. Tabib-Azar, *University of Utah*

R. Huang, *Peking University*
L. Pileggi, *Carnegie Mellon University*
J. P. Reithmaier, *Universität Kassel*
T. Theis, *IBM & SRC*
K. Wang, *UCLA*

In addition, the organizers invited A. Seabaugh (*Notre Dame University*), and A. Krishnamoorthy (*Oracle Corp.*) to moderate the Tunnel FET and Silicon Photonics Panels, respectively. The Center also received publicity support before the Symposium from the Bay Area IEEE Chapter and the Semiconductor Research Corporation (SRC). For the first time, we coordinated the timing of this Symposium with two other related knowledge dissemination events, S3S Conference, where the lead technical organizer was O. Faynot, and the Steep Transistor Workshop, where the lead organizer was A. Seabaugh. The purpose was to jointly attract attendees, particularly those coming from outside the US. The two other venues supported the 4th Berkeley Symposium with publicity and the Center, in turn, provided similar support for the other two venues.

Among the organizations in the above list is CEA Leti, a French government laboratory, in Grenoble, France. E^{3}S' engagement with CEA-Leti started in 2014 with an education partnership. This education partnership has continued with **L. Hutin** (*CEA-Leti*) hosting E^{3}S ETERN, **A. Vidãna** (*UTEP*) as a student researcher for 9 weeks in Summer 2015. **O. Faynot** (*CEA-Leti*) was a speaker at an E^{3}S seminar, providing a European perspective of low-energy device research to the Center's students, postdocs and faculty.

In Period 6, the Center engaged new partners to enhance its organized education and diversity programs.

- The E^{3}S REU program strives to provide REU internships with all E^{3}S faculty spread across five campuses. We have been able to support REU internships with MIT faculty since the start of the Center because of the partnership with the MIT Summer Research Program (MSRP), a program currently under Assistant Dean for Graduate Education, Diversity Initiative, **E. Hearn**. In Summer 2015, the E^{3}S REU program hosted the first intern at UTEP in the laboratory of **D. Zubia**. This was made possible as the intern was embedded in the University of Texas System LSAMP program that is managed by **A. Arciero,** who provided the local support and included the E^{3}S intern in LSAMP enrichment activities.
- Recognizing the need to offer broad perspectives in STEM for community college interns, the Center's Transfer to Excellence (TTE) REU program developed a partnership with **C. Raferty**, physicist and science educator, UC Berkeley Space Science Laboratory. This partnership provided mutual support for both parties. The Center's TTE community college interns were hosted by the Space Science Laboratory where they learned a new area of research they have not been exposed to in the TTE program. The undergraduate interns of the Space Science Laboratory joined the REU interns of the Center's programs for science communications training.
- The Center has partnered with the Graduate Division of the UC Office of the President (UCOP) to start a research internship program for undergraduates from Historically Black Colleges and Universities, the UCB-HBCU program in Summer 2015. This program offers paid research experiences at UC Berkeley and at the HBCU home institution for a duration of 15 months. The program, which is managed by E^{3}S as an extension of the E^{3}S REU program, is partially funded by UCOP and the E^{3}S REU program. In Summer 2015, **P. Jenkins**, Director of Graduate Studies, UCOP, joined the HBCU interns for their graduation ceremony. She also participated in the joint poster session of all summer research interns, 28 in total, where she served as a poster judge. This provided her the opportunity to meet undergraduates from 4-year institutions from around the country and community college students and faculty from across California.
- The Center addressed the need for additional support to interns with backgrounds traditionally under-represented in STEM by partnering with the Berkeley Graduate Engineering and Science Students (BGESS). With funding from Berkeley's College of Engineering Student Services,

BGESS, a networking event was held for all African-American REU interns who were hosted by E^{3}S managed programs, as well as interns from all summer research programs.

- The Center is continuing its tradition of including Leadership Day as part of the programming of the summer internship programs. On Leadership Day, the undergraduates have the opportunity to serve as mentors to middle school students. This year, **A. Dayal**, Program yoUr Future, arranged a joint Leadership Day participation between middle school students of her program and the E^{3}S interns. All participants learned about the experiences of colleges students pursuing science and engineering majors and observed demonstration of science principles by community college students.
- The Center provided Diversity training by inviting **M. Platt**, Professor of Bioengineering at Georgia Tech, and Diversity Director of EBICS, to give a talk on Diversity that included discussion of micro-aggression.

The above discussions of partnership activities are not intended to be inclusive of all partnerships that the Center relies on as it works towards its goals. A summary list of all partners are given in the Centerwide Output section of this report.

2b. Outcomes

The outcomes and impact are given above and in the Knowledge Transfer section.

2c. Performance Against Metrics

Objective	Metric	Targets	Results				
			P 2	P 3	P 4	P 5	P 6
Knowledge Transfer	Contacts with industry:						
	• Talks & Meetings	Period 6: 36	66	20	42	62	35
	• Industry Presentations	Yearly: 2	4	2	6	3	5
	Research collaboration with industry	Period 4: 1	0	1	1	4	6
		Period 5: 2					
		Period 6: 3					

2d. Partnerships Plans for Period 7

The Center expects that there should be increasing research outcomes that will attract industry engagement. In Period 7, efforts will be made to deepen the engagement level with the existing industry members, as well as recruiting additional industry members.

Some research partnerships in place in Period 6 will extend to Period 7, while new ones will be formed as needed. Despite the formal agreement to end in 2015, the joint development partnership with MITLL on horizontally activated Squitch device may extend into 2016, as the delayed start will result in the delayed completion of the research activities. The partnership with IBM Zurich on engineering substrates for the tunnel FET project at MIT is expected to ebb as the Center de-emphasizes its III-V materials approach to tunnel semiconductors.

During Summer 2016, the education partnership with CEA-Leti is expected to see an increase in the number of undergraduate interns at CEA-Leti, sponsored by E^{3}S. The Center received a NSF supplement to provide second REU internships to two targeted populations of Center's REU alumni, women and racial minorities who are majoring in Electrical Engineering. CEA-Leti will be one of the sites for the second REU. This will provide the selected candidates not only in-depth research experiences, but also a global experience.

VI. DIVERSITY

1a. Goals and Objectives

To enable the vision of contributing to a diverse workforce in energy efficient electronics science, the Center for E^3S strives to broaden participation by recruiting and retaining individuals from groups underrepresented in the disciplines represented in the Center, and fostering their development and successful maturation into a new generation of scholars, researchers and workers. In particular, the Center focuses on participation by individuals with underrepresented racial/ethnic backgrounds, women, veterans, and first-generation college attendees.

The goal is to broaden participation of underrepresented groups (URGs: e.g., URMs, women, disabilities, first-generation, veterans) among students, faculty, and the STEM workforce in E^3S disciplines by implementing programs that allow them to be introduced and engaged in E^3S research. We cultivate an inclusive environment that intellectually and socially engages, embraces, and values all members of the E^3S community in order to promote retention and academic excellence.

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 at many levels: postdocs, graduate students, undergraduate students, and high school students. In Period 6, the Center concentrated on further strengthening 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. The Center has also continued to track past participants and provide advising, support, and preparation for applying for transfer admissions to a four-year institution or for graduate school.

In Period 6, nine undergraduates have enrolled in a graduate program in science or engineering and six (100%) 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 31 undergraduates have enrolled in a graduate program in science or engineering and 23 (96 %) community college students have transferred to a 4-year institution majoring in STEM. Among these participants, eleven (35%) of our undergraduates who are now enrolled in a graduate program are women and eight (26%) are from an underrepresented minority group. For the community college students who have transferred to a 4-year institution, seven (30%) are women, seven (30%) are from an underrepresented minority group, and 13 (57%) are first-generation college students. Preliminary data for our pre-college programs, shows that 206 (75%) of past participants have self-reported that they are currently enrolled in a baccalaureate degree program.

Online Laboratory for High School Students: This period, the Center decided to increase student engagement in E^3S topics by providing a more hands-on activities. MOSTEC students were provided with breadboards, Raspberry Pi, and additional electrical components to complete their final projects. These hands-on activities, a best practice, are an effective way to increase engagement among all students including those from diverse background [47]. In addition to new projects, students conducted Electrical Engineering and Computer Science (EECS)-themed lab assignments and projects and received college coaching and workshops on E^3S topics.

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 **L. Marlor** expanded the E^3S REU program to offer undergraduate students from HBCU institutions a second summer experience through the Center. This expansion is funded by the University of California Office of the President (UCOP) and provided two years of summer funding. In continuation of this new initiative and its partnerships, **L. Marlor** traveled to four HBCUs (Hampton University, Norfolk State University—also in conjunction with graduate student,

B. Osoba, Morgan State University, and University of the District of Columbia) to conduct recruiting seminars and introduce the Center's research opportunities for students at HBCUs. Also discussed were opportunities to work more closely in the future with faculty and department chairs. It is expected that continuous engagement with students and faculty from HBCUs will enhance the students' experience and preparation for graduate school at UC Berkeley and other E^{3}S Schools. In addition to student engagement, the awards fund faculty development workshops, in which Berkeley and HBCU faculty come together to cultivate research collaborations, discuss research interests, identify research synergies, and share projects the undergraduate researcher can work on at UC Berkeley and the HBCU home institution.

In Period 6, the Center aimed to increase diversity by participating in several recruiting events across the United States. This year, **L. Marlor** attended the Society of Women Engineers (SWE), Society of Hispanic Professional Engineers (SHPE), and Society for Advancement of Chicanos and Native Americans in Science (SACNAS) to provide information about E^{3}S research topics and graduate programs to a diverse group of students. This period, a blind review process was introduced, in conjunction with diversity recruiting, to impact the number if URGs that were offered research spots in the Center's education and diversity programs. In addition, E^{3}S has been an active participant in the Berkeley Edge Conference that brings underrepresented students who are competitively eligible for our Ph.D. programs to the Berkeley campus. **L. Marlor** arranged faculty visits and one-on-one sessions to help students with application preparation. E^{3}S also aims to incorporate diversity into the awareness and cultural climate of the Center. At this year's annual retreat, the Center organized a presentation by **M. Platt**, Assistant Professor of Bioengineering, Georgia Tech, and Director of Diversity, EBICS STC about implicit bias and microaggression as well as best practices for diversity within a research center and provided diversity training for E^{3}S faculty and students.

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

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

1b. Performance Metrics

E^{3}S Strategic Plan 2015-2020 includes 3 new Diversity performance metrics to track the persistence of the alumni from under-represented groups of the Center's undergraduate programs in pursuing STEM education. This would further allow the Center to understand the long term impact of the programs that are primarily intended to promote broader participation. Below are the benchmarks and targets for the diversity performance indicators and metrics for the Center.

Objective	Metrics	Frequency	Targets
Diversity	Women in the Center's research programs	Annually	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 20% Period 6: 25%
	Underrepresented minorities in the Center's research programs	Annually	Period 2: baseline Period 3: 15% increase Period 4: 5% Period 5: 10% Period 6: 10%

	Participants from underrepresented* groups in the Center's Diversity programs	Annually	Period 3: Baseline Period 4: 80% Period 5: 85% Period 6: 85%
	Pre-college students who pursue a bachelor's degree in science and engineering *(transferred to Education)*		Period 3: Baseline Period 4: 70% Period 5: 70%
	Community college students who transfer from 2-year institutions to 4-year universities to pursue a bachelor's degree science and engineering *(transferred to Education)*		Period 3: 5% Period 4: 30% Period 5: 35%
	Undergraduates who pursue advanced degree in science and engineering *(transferred to Education)*		Period 3: 5% Period 4: 30% Period 5: 35%
	Undergraduate participants from underrepresented* groups pursuing advanced degrees in disciplines related to the Center *(new)*	Annually beginning in Period 6	Period 6: 40%
	Community College students from underrepresented* groups pursuing a science or engineering baccalaureate *(new)*	Annually beginning in Period 6	Period 6: 85%
	Pre-college participants from underrepresented* groups pursuing a bachelor in science or engineering *(new)*	Annually beginning in Period 6	Period 6: 80%

1c. Problems Encountered

In Period 6, the Center is most challenged by the low number of women and underrepresented minorities at the graduate student level. The Center's diligent work to increase the number of women and underrepresented minorities in the Center is showing progress, however a 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^{3}S 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^{3}S project. Instead they are pursuing graduate research in another STEM area.

The Center faced a second challenge during Period 6, balancing the existing education and diversity programs while being understaffed. In November 2014, the E3S Education and Outreach Director, **S. Artis**, left the Center. In Period 6, much of the time was focused on the renewal grant, and therefore this position was left unfilled until December 2015.

The E^{3}S demographic data have informed the need for a sharper focus in the Center's approach to Diversity. Taking advantage of the opening resulting from the departure of the Center's first Education & Outreach Director, E^{3}S Executive Committee decided to restructure the Center to have dedicated and separate staff positions for Education and Diversity.

A. Tabor assumed the position of E^{3}S Diversity Director, on December 1, 2015. One of her first responsibilities was to review the Center's established strategies and programs for promoting broadening participation. The planned next steps were to establish optimized strategies, approaches, and plans for the Center's 2nd five years. Tragically, however, **Dr. Tabor** unexpectedly passed away only nine days after joining the Center. This left a tremendous hole in our renewed Diversity and Outreach activities and current efforts are underway to re-fill this position as soon as possible.

2a. Development of US Human Resources

In Period 6, the Center has ensured that its diversity programs include a strong integration with the Center's research activities. 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 6, 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. The Center's main 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 6.

Activity Name	MIT Online Science, Technology, and Engineering Community (MOSTEC)
Led by	**S. Young** (MIT) and **L. Marlor** (Berkeley)
Intended Audience	Rising 12^{th} grade high school students
Approx. Number of Attendees (if appl.)	Total: 57 Females: 23 (40%), URMs: 45 (79%)

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 fifth 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 6, the Center supported 57 students, 22 who participated in the three-week online electronics course project and 35 who participated in the electronics workshop at the MOSTEC Conference. Of the students, 40% were females and 79% were from underrepresented racial groups. MOSTEC held its second online three-week electronics project course in Period 6. For the MOSTEC course, students conducted EECS-themed lab assignments and projects using breadboards and Raspberry Pis. During the weeklong conference, the Center sponsored an electronics workshop and a 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:

- A stipend paying for 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. This program has had limited numbers since its inception (typically 1 student/year), and thus was discontinued in Period 6.

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	**L. Marlor** (Berkeley) and **J. Bokor** (Berkeley)
Intended Audience	Community college students
Approx. Number of Attendees (if appl.)	Total: 5 Females: 1 (20%), URMs: 1 (20%), 4 (80%) First Gen

During summer 2015 (Period 6), E^{3}S at UC Berkeley hosted five of the 14 community college students in the TTE REU program (TTE REU Recruitment Flyer: http://www.e3s-center.org/education/2016_TTE_Flyer.pdf). These students completed nine weeks of research in the laboratories of E^{3}S faculty, **T.-J. King Liu**, **J. Bokor**, and **S. Salahuddin**; and E^{3}S Education Affiliates, **J. Clarkson** and **A. Zettl**. Education Affiliates are not part of the Center's research team, but their research disciplines are similar to those of the Center. **J. Clarkson** and **A. Zettl** joined the Center as affiliates in Period 5.

In Period 6, the TTE REU experience started 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 attended 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/2015_TTEREUcalendar.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 (2011-2014 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 19 (3 females, 4 URMs) are pursuing B.S. degrees in STEM fields at UC Berkeley (16), UCLA (2), and UC San Diego (1). Among this group, five of the students transferred to a 4-year institution in Period 6, two (40%) are women, and two (40%) are URMs. The Center is actively conducting research to determine the impact of TTE on transfer rates. This project led by L. Marlor and we hope to have concrete results to report in Period 7.

- *Summer Research Programs for Undergraduate Students 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 studies 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	**L. Marlor** (Berkeley) and **E. Yablonovitch** (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx. Number of Attendees (if appl.)	Total: 11 Female: 5 (45%), URMs: 3 (27%)

The Center's 9-week E^3S REU program received approximately 115 applications (E^3S Recruitment Flyer: http://www.e3s-center.org/education/2015-E3SREU_Flyer.pdf). Seven of these students were matched with Center faculty at Berkeley, two were matched with faculty at MIT, and one was matched with a faculty at Stanford. This is the first year the E^3S REU has also placed a student at the UTEP campus and the student was hosted by **D. Zubia**. The Center partnered with LSAMP to host this student for workshops and programmatic support while at UTEP. At MIT, students were hosted by **T. Swager** and **J. Hoyt/D. Antoniadis**. At Berkeley, students were hosted by E^3S faculty **J. Wu**, **S. Salahuddin**, **T-J. King Liu**, **J. Bokor**, **M.C. Wu**, **E. Yablonovitch**, and **V. Subramanaian** (affiliate). At Stanford, one student was hosted by E^3S faculty **P. Wong.** In addition to research activities, 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 **L. Marlor**, the Center's Education Manager. For calendar of events and activities, see: http://www.e3s-center.org/education/2015_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. The poster was presented at a joint poster session that featured over 35 posters from several REU programs. **T. King Liu**, the Associative Education Director, interviewed the students about his/her research project during the poster session.

In order to attempt to increase diversity in the E^3S REU program, this was the first year that a blind application review was used in the selection process. A blind review consists of taking out the name and any demographic information of an applicant (gender, race, veteran status, etc.). Blind reviews are a best practice approach to achieve more gender and racial parity. This practice has a strong research foundation to support its use [48]. In Period 6, this practice increased offers for research internships for underrepresented groups from 63% in Period 5 to 83% in Period 6. E^{3}S plans to continue the use of this practice in future years.

- *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 present 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 6, the Center targeted students at institutions that may not offer, or have limited offerings in, courses and research on energy efficient electronics science.

  This fall, E^{3}S collaborated with UC Berkeley's College of Engineering to recruit for the Center's diversity programs, targeting students at 4-year institutions. Together, four universities were visited and six diversity conferences were attended (see Appendix F: E^{3}S 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 successfully apply to the Center's research internship programs. During these webinars, **L. Marlor** provided students with application tips, the importance of research for graduate school applications and transfer applications, and tips on how to get good letters of recommendation. In addition, the webinar included ample time for students to ask questions.

  L. Marlor visited four 4-year universities: Norfolk State University, Morgan State University, Hampton University, and University of the District of Columbia. During these visits, the Center conducted graduate school workshops, information sessions, and/or faculty meetings. 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 helped sponsor a booth at the graduate fairs for prospective undergraduate and graduate students to meet Center members. These booths also offered the chance to learn about the Center's research areas and opportunities for undergraduates, as well as graduate students and postdocs.

  For the community college programs, **L. Marlor** and **F. Li** visited seven 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. For a complete list of recruitment for the community college program, please see Appendix G. The Center also supported three students from its summer TTE research program to present their research in a poster session 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. One of the student posters won an award, and one student also won the SACNAS conference travel award.

2b. Impact on the Center's Diversity

In Period 6, the Center has committed available resources for the recruitment of graduate and undergraduate students from underrepresented groups into the Center activities. We believe active recruitment ensures that E^{3}S programs will have access to competitive candidates and highly qualified participants, regardless of race, color or gender. 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. These students have been exposed to energy efficient electronics science through research or lecture. To date, approximately 56% (51) 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 75% (206) are pursuing a bachelor's degree in science and engineering.

For our undergraduate programs targeting community college students, we have seen a significant impact on diversity. 23 (96%) of the Center's alumni from the TTE programs have transferred to a 4-year institution. 20 (87%) of these students became undergraduate students at UC Berkeley. For our upper-division undergraduate programs for juniors and seniors, 42 (64%) of our students have graduated with a Bachelor's degree. 31 REU alumni are pursuing graduate degrees in science and engineering. Of the 31 graduate students, eighteen are students at E^3S schools, including four that are part of the Center as graduate students.

In summary, the Center has continued to make diversity a high priority in Period 6. 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	Metric	Targets	Results				
			P 2	P 3	P 4	P 5	P 6
Diversity	Women in the Center's research programs	Period 2: Baseline Period 3: 5% increase Period 4: 30% Period 5: 20% Period 6: 25%	13 (22%)	15 (25%)	13 (19%)	24 (21%)	27 (19%)
	Underrepresented minorities in the Center's research programs	Period 2: Baseline Period 3: 15% increase Period 4: 5% Period 5: 10% Period 6: 10%	2 (2%)	1 (2%)	5 (7%)	12 (11%)	20 (14%)
	Participants from underrepresented * groups in the Center's Diversity programs	Period 3: Baseline Period 4: 80% Period 5: 85% Period 6: 85%	n/a	93 (82%)	Women 37 (44%) URM: 58 (68%) Total: 73 (86%)	Women 26 (41%) URMs 36 (56%) Total 49 (77%)	Women 29 (40%) URMs 49 (67%) Total 66 (90%)
	Undergraduate participants from underrepresented * groups pursuing advanced degrees in disciplines related to the Center *(new)*	Period 6: 40%	*(new for Period 6-10)*				17 (55%)

	Community College students from underrepresented * groups pursuing a science or engineering baccalaureate *(new)*	Period 6: 40%	*(new for Period 6-10)*	16 (70%)
	Pre-college participants from underrepresented * groups pursuing a bachelor in science or engineering *(new)*	Period 6: 40%	*(new for Period 6-10)*	TBD

2d. Plans in Period 7

In Period 7, the Center will be staffed with an Education Manager **L. Marlor** and a new (soon-to-be-hired) Diversity and Outreach Director. E^3S will strive to attract diverse candidates to its education programs. For the REU program, we plan to attract students from HBCUs through the activities of the UCB-HBCU program of which Theme Leader **T.-J. King Liu** is the PI. The new Diversity and Outreach Director will be tasked with working with the UCB-HBCU program and its faculty to recruit qualified applicants and build strong working relationships with HBCU faculty. **T.-J. King Liu**, in collaboration with the new Diversity and Outreach Director, plans to host a workshop in the Spring 2016 to further build upon these relationships.

By analyzing the data on REU alumni attending graduate school and joining the Center as graduate students, we recognized 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 with 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. The new Diversity and Outreach Director will work with **L. Marlor** and **J. Bokor** to utilize best practices in recruitment to increase diversity of the pool of applicants E^3S programs. Additionally, to further increase diversity, the new Diversity and Outreach Director will work more closely with UTEP and FIU to enable students from these schools to intern at other E^3S schools.

VII. MANAGEMENT

1a. *Performance Metrics*

Objective	Metrics	Frequency	Targets
Center Management	Centerwide Communications *(discontinued)*		
	Annual Surveys:		
	• Students /Postdocs	Annually	According to Likert scale: Period 2: 3 or higher Period 3: 3 or higher Period 4: 3 or higher Period 5: 3 or higher Period 6: 4 or higher
	• Co-PIs	Annually beginning in Period 3	
	• External Advisory Board	Annually	
	Authorship disputes	Annually beginning in Period 3	Period 2: 20% decrease Period 3: 20% decrease Period 4: 20% decrease Period 5: 20% decrease Period 6: 0
	Plagiarism	Annually	Period 2: 0 Period 3: 0 Period 4: 0 Period 5: 0 Period 6: 0
	Changes in Center processes made in response to evaluation results *(new)*	Annually	Period 2: Baseline Period 3: 15% Period 4: 20% Period 5: 25% Period 6: 30%
	Assessment of goals, objectives, and outcomes – Strategic Plan Review		

1b. *Organizational Structure and Underlying Rationale*

The organizational structure of the Center for E^3S changed in Period 6 in anticipation of the Center's needs in the remaining five years. The new organizational chart is given in Appendix C. Below we highlight and provide the rationale for the changes.

- Executive Committee:

  a) The by-laws of the E^3S Executive Committee, the Center's leadership body, was revised.

  - In the by-laws for the Center's first five years, the ex-officio positions for co-principal investigators were for those who were identified as Principal Investigators and co-Principal Investigators on the cover page of the 2009 NSF STC proposal. Recognizing changes in the interests and thus, roles, of the Center's faculty in support of the Center's operations, the Executive Committee by-laws were changed for ex-officio positions to be tied to the working positions in the Center: Center's Principal Investigator, Center Director, Deputy Center

Director, Executive/Managing Director, Research Theme Leaders, Education Director, Diversity Director, and the site head of its largest subaward research institution.

- The revised by-laws provide for elected positions for institutions with one or no representatives on the leadership committee. This change was intended to expand the participation of subaward institutions in the Center's leadership.

b) The new leadership team consists of:

- Ex-officio members:
  E. Yablonovitch - Principal Investigator and Center Director
  J. Bokor – Deputy Center Director, Theme Leader and Associate Director for Diversity
  T.-J. King Liu – Theme Leader and Associate Director for Education
  M. C. Wu – Theme Leader
  M. Bartl – Executive Director
  Diversity Director (to be hired)
  V. Bulovic – Site Head, MIT, the largest subaward institution

- Elected members:
  H.-S.P. Wong, Stanford, elected to ensure continued subaward participation
  D. Zubia, University of Texas at El Paso (UTEP), elected to provide deeper perspectives on broadening participation issues.

The new Executive Board ratified the revised charter at its September 14, 2015 meeting with 100% of the vote in favor of the new by-laws.

- E^{3}S Management and Operations Team:
  - E^{3}S continues to be led and managed by an Executive Director as provided by the STC award. Beginning on November 16, 2015, the Executive Director position was assumed by Dr. **M. Bartl**, replacing the founding Executive Director, Dr. **J. Yuen** who announced her retirement, due in early 2016 at the end of this Reporting Period. Dr. Bartl will receive direct support from the PI and Center Director, E. Yablonovitch. Dr. Bartl's biosketch is given in Appendix B.
  - The Center's programmatic efforts in Education and Diversity was previously the responsibility of the E^{3}S Education and Outreach Director. With the resignation of Dr. **S. Artis** towards the end of the last Reporting Period, and upon analyzing the Center's diversity record and progress towards executing its online education strategy, the E^{3}S leadership concluded that the responsibility for Education and Diversity is best split in two positions. Dr. **A. Tabor** joined the Center as Diversity Director to enhance the Center's approaches towards broadening participation, especially at the graduate and postdoctoral level and implement the associated programmatic efforts; see Appendix B for Dr. **Tabor**'s biosketch. Tragically, Dr. **Tabor** unexpectedly passed away only nine days after joining the Center. This left a tremendous hole in our renewed Diversity and Outreach activities and current efforts are underway to re-fill this position as soon as possible. **L. Marlor**, previously Education Program Manager and now Education Manager, will accelerate the implementation of the Center's online education strategy as well as manage education programs. As previously structured, the Diversity and Education efforts of the Center will continue to receive faculty support through the two Associate Director positions; **J. Bokor** for Diversity and **T.-J. King Liu** for Education. **King Liu** is new to the role in this Reporting Period 6, replacing **C. Chang-Hasnain**, who has left the Executive Committee.

1c. Performance Against Metrics

Objective	Metric	Targets	Results P 2	P 3	P 4	P 5	P 6
Center Management	Annual Surveys:	*Targets*	3 or higher on Likert Scale				
	• Students /Postdocs	*Results*	Average 3.9±0.2	Average 4.0±0.3	Average 4.2±0.2	Average 4.5±0.2	Average 4.3±0.2
	• Co-PIs	*Results*	No survey in Period 2	Leadership 4.46 Collaboration 3.25	Leadership 4.7±0.5 Collaboration not available	Leadership 4.9±0.1	Leadership 4.6±0.1
	• External Advisory Board	*Results*	Strategic Plan: 4.18 Accomplishment: 4.01	Strategic Plan 4.07 Accomplish-ments: 3.96	Strategic Plan 4.6 Center Status: 4.6	Strategic Plan: 4.7±0.5 Center Status: 4.7	Center Legacy: 4.8±0.4
	Authorship disputes	*Targets*	20% decrease annually				
		Results	0	0 Faculty Ethics Survey: 4.39	0 Ethics Survey: no longer on Likert scale	0	0
	Plagiarism	*Targets*	20% decrease annually				
		Results	0	0	0	0	0
	Changes in Center processes made in response to evaluation results	*Targets*	3 months for closure of regular Action; 1 week for closure of time-sensitive Action				
			(new for P6-10)				0

The Center measures the effectiveness of its leaders through two perception surveys of: 1) postdocs and graduate students and 2) faculty. Both surveys are designed to assess the performance of the Center's leadership on what are considered the Center's values:

- Inclusiveness
- Teamwork
- Open and Timely Communications
- Agility
- Focus on Performance
- Ethical Conduct

2015 is the 5th year that the Graduate Students & Postdocs Survey has been conducted. The overall average leadership rating of 4.3 on the Likert scale is indicating that the Center's graduate students and postdocs have continued to view the Center's leadership positively and there has been no substantive changes in overall rating from year to year.

By looking at the responses to the individual questions, we can further learn how the graduate students and postdocs in the Center perceive the E^{3}S leadership team's performance with each value (see

Appendix K). It must be noted that the set of survey questions for each value has not stayed identical from year to year, but the question set of the past three years have by enlarge been similar. The mean scores on questions that probe different values by year are as follows.

	2011	2012	2013	2014	2015
Inclusiveness	3.8	4.1	4.1	4.6	4.4
Teamwork	3.7	3.6	4.0	4.6	4.2
Open and timely communications	4.0	4.2	4.2	4.7	4.2
Agility/Decision Making	4.0	4.1	4.2	4.5	4.4
Focus on Performance	3.8	4.1	4.1	4.5	4.2

While year to year differences are likely to be within the range of data uncertainties, when comparing the data over time, the Center's graduate students and postdocs view the Center's leadership in creating a positive climate more favorably in recent years as compared to when the Center was founded.

As in past years, the externally administered anonymous survey also asked for incidents that can be considered to be unethical conduct. Again, continuing the previous trend, no unethical incidents were reported.

The Faculty Survey revealed that the Center faculty view the Center leadership very positively, as indicated by an overall average leadership rating of 4.8 on the Likert scale. The detailed responses to leadership questions are given in Appendix L. In addition, all faculty respondents answered the question "*I feel that my E^3S colleagues act in an ethical manner*" with YES.

1d. Problems Encountered

The Center operated with 50% of its full time staff for most of this Reporting Period 6. This has resulted in delays in implementing activities that were planned for this Reporting Period. Particularly impacted were plans in Online Education (Problems Encountered, Section III) and the ability to fully engage the Center's External Advisors in the Education Working Group of the E^3S External Advisory Board. With Dr. **A. Tabor** joining the Center in December 2015, we expected that the gaps would be addressed quickly. Due to Dr. **Tabor**'s unexpected passing only nine days after she joined the Center, we had to re-start the search for our new director for diversity and outreach. We expect the search to be concluded by February 2016, with a new director in place by March 2016.

Being in its sixth year, the Center's first graduate students have completed their Ph.D. studies and left the Center. We believe that additional effort is now needed to engage the newer graduate students to build yet another strong student community for the coming years. We recognize that the number of respondents to this year's survey being the lowest since the survey was first conducted is a warning indicator; twelve respondents in 2015 versus 26 in 2014, the year with the highest number of respondents.

2. Management and Communications Systems

Communications and Planning: While the Center has a variety of venues to communicate with its members, the key communication and planning event is the center-wide annual retreat, where all Center faculty, students, postdocs and staff gather to review the Center's progress towards its goals, re-assess its approaches, and set the strategies and plans for next year and beyond. Each retreat adopts a theme or focus so as to help guide a successful outcome for the meeting. The E^3S center-wide retreat of 2015 took place at MIT on Sep 13 and 14 with the Theme: *Building a Legacy of Home Runs*. The agenda (Appendix I) provides opportunities for presentations, not only of faculty, but also students and postdocs. The agenda included breakout sessions for planning, time for faculty-only discussions, training in diversity for all Center members, and a proposal writing workshop for students and postdocs.

A major outcome of the retreat are the changes in the Center's research strategy, which is articulated in this annual report.

Management: The E^3S Executive Committee was scheduled to meet five times in 2015; all but one of the meetings have taken place. All but the September 14 meeting, which took place following the Annual Retreat, took place through remote participation. Below is the high level agenda of each meeting.

Executive Committee – Period 6 Meetings	
Meeting Dates	**Agenda Topics**
May 7, 2015	Budget Review, Site Visit Recommendations, Award Status, Berkeley E^3S Symposium, External Advisory Board Membership
June 23, 2015	*Carry-over items*: External Advisory Board Membership, Berkeley E^3S Symposium *New items*: Revision of Executive Committee By-Laws, Status of E^3S Renewal, Annual Retreat Planning, Review of Research Direction
September 14, 2015	Debrief of Annual Retreat, Ratify Executive Committee By-Laws, Annual Meeting of Advisory Boards
October 29, 2015	Centerwide Annual Proposal Review
December 18, 2015	Review of the Center's results versus the Strategic Plan, Review of Preliminary Feedback from External Advisory Board, Review of Feedback from Industrial Research Board, Site Visit Planning

To ensure that the Center is progressing effectively towards its goals, the Executive Committee conducts an annual review of all its programs. It was decided that this year, the review will focus mainly on Research given the major changes that resulted from the Annual Retreat. Also this year, the process was more structured. The process began with a written document released by **E. Yablonovitch**, PI and Center Director, Strategic Direction of E^3S Research that provided written guidance to the faculty proposers on the Center. The document also served as a formal guide to the Executive Committee members who were the proposal reviewers. The review ended with agreement on the program and faculty member changes that are articulated in this Annual Report.

3. Internal and External Advisory Bodies

The Center for E^3S has two advisory boards:

1. External Advisory Board with members who have arms-length relationships with the Center; and
2. Industrial Research Board which is made up of representatives from companies that have expressed their intention to collaborate through letters to the Vice Chancellor of Research Office, UC Berkeley.

E^3S External Advisory Board: The members, who are from both academia and industry, are appointed by the E^3S Executive Committee for limited terms:

- Chair: one 2-year term
- Members: one 3-year term to be followed by, at the discretion of the E^3S Executive Committee, a second appointment of 2 years.

Membership terms were implemented in the early years of the Center, as a means to ameliorate the concern that an engagement as an E^3S External Advisor can be onerous. This provision also allows the Center to bring in new advisors, and therefore, new perspectives.

In 2015, **D. Radack** (*IDA*) completed his 2-year term as Chair, but will stay on as an advisor. The E^3S Executive Committee appointed **P. Gargini** as the Chair of the External Advisory Board with a 2015-2016 term at the 2015 annual meeting of the Board. Three External Advisors, **J. Chen** (*Nvidia*), **L. Colombo** (*Texas Instruments*) and **W. Maszara** (*GlobalFoundries*) completed their 3 year terms and were excused from the Board. The current members are given below.

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
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		
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

A subset of External Advisors has formed the *Education Working Group* as a subcommittee within the External Advisory Board. This education group has the responsibility to advise and guide in matters of education and diversity, but it does not assess. The assessment of the Center's Education and Diversity efforts are done as part of the annual evaluation by the entire External Advisory Board. As previously indicated, in Reporting Period 6 the Center has not been able to take full advantage of this advisory group that is chaired by **D. Rover** (*Iowa State*).

Industrial Research Board: The Center for E^3S continues to have receive strong support from four leaders in the semiconductor industry even before its inception. The Industrial Research Board monitors, advises and participates in the Center's research. As part of the STC renewal process, the following companies and their representatives sent letters of collaboration that in some cases, not only included interest in participating in research, but also financial support, in akin and otherwise, and non-financial support of E^3S activities.

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

2015 Joint Meeting of Advisors: Both the External Advisory Board and the Industrial Research Board convene annually to be updated on the Center. Industry partners have been treated as members and thus, were invited to the Center's Annual Retreat in past years. However, in Reporting Period 6, the timing and location prohibited the attendance of the 2015 E^3S Annual Retreat by the industry partners. Instead, on November 20, a joint meeting of the External Advisory Board and the Industrial Research Board was held; see Appendix J for the agenda of the 2015 Joint Meeting of Advisors. The joint meeting had a shared briefing session on Research while sessions on Center Management, Education, Diversity and Knowledge Transfer were held solely for the benefit of the External Advisory Board members. Each board held its own deliberations and feedback session.

External Advisors and industry partners had the option to participate in person at UC Berkeley or via Webex. Attendance of this joint meeting by industry partners are as follows:

- N. Draeger, Lam Research
- N. Kim, Applied Materials
- I. Young, U. Avci, D. Nikonov, Intel
- P. Solomon, IBM

Attendance by the External Advisory Board was unfortunately less than expected as two individuals cancelled within days of the meeting. The attendees were:

- P. Gargini, ITRS (*Chair*)
- E.-W. Chang, Mercer County Community College
- E. Garmire, Dartmouth College
- J. Heritage, UC Davis
- M. Pinto, Blue Danube Labs

Despite a small group, the External Advisors who participated came from a broad background and together had the necessary skills to provide the feedback on all elements of the Center. Because the Research session was jointly attended by the industry partners, the External Advisory Board also had the benefit of the questions and comments offered by industry.

Like prior years, the Center leadership held a meeting with the industry partners as a group following the Research session, where the industry partners provided detailed comments on each of the themes and the approaches that we had shared. This year's meeting with the industry partners was by far the most engaging and interactive feedback session in which highly specific suggestions and comments were made in regard to the Center's Research.

Separately, the External Advisory Board deliberated and worked on their written report to the Center which we expect to be made available before the upcoming NSF Site Visit. Before their exit, however, the External Advisors met briefly with the Center leadership providing supportive comments, particularly with respect to the student speakers and poster presenters. This year, instead of relying solely on the Center's faculty to present, the Center featured several students to present their own research results. This change was especially well-received by the External Advisors.

4. *Changes in the Strategic Plan*

A new Strategic Plan that covers the next 5 years of the Center was submitted to NSF in July 2014. The metrics reported in this Annual Report are part of the E^3S Strategic Plan of 2015 to 2020.

In 2014, as the Strategic Plan 2015-2020 was in development, we re-examined the purpose of the metrics and reviewed what we had learned from the metrics and other forms of input we had to track the Center's progress. This led to discontinuation of some metrics and adoption of new metrics.

In each Performance Metrics section of this annual report, we have identified the metrics that are discontinued and those that are new. We will provide the rationale behind the metrics for the next five years; why certain metrics are discontinued, retained or adopted. We are continuing to carry results from prior years should the metric be applicable in Period 6 and beyond.

VIII. CENTERWIDE OUTPUT

1a. Publications

1ai. Peer Reviewed

<u>Journal Articles</u> *(Chronological)*

1. E. M. Sletten and **T. M. Swager**, "Fluorofluorophores: Fluorescent Fluorous Chemical Tools Spanning the Visible Spectrum," *J. Am. Chem. Soc.*, vol. 136, no. 39, pp. 13574–13577, Oct 2014.
2. B. Koo, E. M. Sletten, and **T. M. Swager**, "Functionalized Poly (3-hexylthiophene)s via Lithium-Bromine Exchange," *Macromolecules*, vol. 48, pp. 229-235, Jan 2015.
3. 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," *Nat. Commun.*, vol. 6, p. 5969, Jan 2015.
4. M. S. Eggleston, K. Messer, L. Zhang, **E. Yablonovitch**, and **M. C. Wu**, "Optical Antenna Enhanced Spontaneous Emission," *PNAS*, vol. 112, no. 6, pp. 1704–1709, Feb 2015.
5. A. Vardi, W. Lu, X. Zhao, and **J. A. del Alamo**, "Nano-Scale Mo Ohmic Contacts to III-V Fins," *IEEE Electron Device Lett.*, vol. 36, no. 2, pp. 126-128, Feb 2015.
6. T. Roy, M. Tosun, X. Cao, H. Fang, D.-H. Lien, P. Zhao, Y.-Z. Chen, Y.-L. Chueh, J. Guo, and **A. Javey**, "Dual-Gated MoS_2/WSe_2 van der Waals Tunnel Diodes and Transistors," *ACS Nano*, vol. 9, no. 2, pp. 2071-2079, Feb 2015.
7. **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 Coll. J. Research and Practice*, vol. 39, no. 7, pp. 1111-1124, Mar 2015.
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9. Z. Gu, 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," *Nat. Commun.*, vol. 6, p. 6466, Mar 2015.
10. H. Sohn, M. E. Nowakowski, C. 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**, and R. N. Candler, "Reversible Electrically-Driven Magnetic Domain Wall Rotation in Multiferroic Heterostructures to Manipulate Suspended On-Chip Magnetic Particles," *ACS Nano*, vol. 9, pp. 4814-4826, May 2015.
11. J. Lin, **D. A. Antoniadis**, and **J. A. del Alamo**, "Physics and Mitigation of Excess Off-State Current in InGaAs Quantum-Well MOSFETs," *IEEE Trans. on Electron Devices*, vol. 62, no. 5, pp. 1448-1455, May 2015.
12. R. Going, T. J. Seok, J. Loo, K. Hsu, and **M. C. Wu**, "Germanium Wrap-Around Photodetectors on Silicon Photonics," *Opt. Express*, vol. 23, pp. 11975-11984, May 2015.
13. M. S. Eggleston and **M. C. Wu**, "Efficient Coupling of an Antenna-Enhanced nanoLED into an Integrated InP Waveguide," *Nano Lett.*, vol. 15, no. 5, pp. 3329–3333, May 2015.
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Field by Engineering a Tilted Anisotropy," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 112, pp. 10310-10315, Aug 2015.

17. C. Qian, A. P. Peschot, I-R. Chen, Y. Chen, N. Xu, and **T.-J. K. Liu**, "Effect of Body Biasing on the Energy-Delay Performance of Logic Relays," *IEEE Electron Device Lett.*, vol. 36, no. 8, pp. 862-864, Aug 2015.
18. F. Niroui, A. I. Wang, E. M. Sletten, Y. Song, J. Kong, **E. Yablonovitch**, **T. M. Swager**, **J. H. Lang** and **V. Bulovic**, "Tunneling Nanoelectromechanical Switches Based on Compressible Molecular Thin Films," *ACS Nano*., vol. 9, no. 8, pp. 7886-7894, Aug 2015.
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21. A. P. Peschot, C. Qian and **T.-J. K. Liu**, "Nanoelectromechanical Switches for Low-Power Digital Computing," *Micromachines*, vol. 6, pp. 1046-1065, Aug 2015.
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24. A. Pattabi, Z. Gu, J. Gorchon, Y. Yang, J. Finley, O. J. Lee, H. A. Raziq, **S. Salahuddin**, and **J. Bokor**, "Direct Optical Detection of Current Induced Spin Accumulation in Metals by Magnetization-Induced Second Harmonic Generation," *Appl. Phys. Lett.*, vol. 107, no. 15, p. 152404, Oct 2015.
25. K. Liu and **J. Wu**, "Mechanical Properties of Two-Dimensional Materials and Heterostructures," *J. Mater. Res.*, Oct 2015. doi: 10.1557/jmr.2015.324.
26. 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," *Adv. Mater. Interfaces*, pp. 1500388 (1-7), Nov 2015.
27. M. Amani, D.-H. Lien, D. Kiriya, J. Xiao, A. Azcatl, J. Noh, S. R. Madhvapathy, R. Addou, S. K. C., M. Dubey, K. Cho, R. M. Wallace, S.-C. Lee, J.-H. He, J. W. Ager III, X. Zhang, **E. Yablonovitch**, and **A. Javey**, "Near-Unity Photoluminescence Quantum Yield in MoS_2," *Science*, vol. 350, no. 6264, pp. 1065-1068, Nov 2015.
28. J. Lin, **D. A. Antoniadis**, and **J. A. del Alamo**, "Impact of Intrinsic Channel Scaling on InGaAs Quantum-Well MOSFETs," *IEEE Trans. on Electron Device*, vol. 62, no. 11, pp. 3470-3476, Nov 2015.
29. M. M. Sabry Aly, M. Gao, G. Hills, C.-S. Lee, G. Pitner, M. M. Shulaker, T. F. Wu, M. Asheghi, **J. Bokor**, F. Franchetti, K. E. Goodson, C. Kozyrakis, I. Markov, K. Olukotun, L. Pileggi, E. Pop, J. Rabaey, C. Re, **H.-S. P. Wong**, and S. Mitra, "Energy-Efficient Abundant-Data Computing: The N3XT 1,000x," *Computer*, vol. 48, no. 12, pp. 24-33, Dec 2015.
30. R. M. Iutzi and **E. A. Fitzgerald**, "Conductance Slope and Curvature Coefficient of InGaAs/GaAsSb Heterojunctions at Varying Band Alignments and its Implication on Digital and Analog Applications," *J. Appl. Phys.* vol. 118, no. 23, p. 235702, Dec 2015.
31. K. Kimhiko, **T.-J. K. Liu**, and **V. Stojanovic**, "Non-Volatile Nano-Electro-Mechanical Memory for Energy-Efficient Data Searching," *IEEE Electron Device Lett.*, vol. 37, no. 1, pp. 31-34, Jan 2016.

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

1. S. Dutta, and V. Stojanović, "Floating-Point Unit Design with Nano-Electro-Mechanical (NEM) Relays," submitted to *IET Circuits, Devices & Systems*, 2015.
2. J. Hong, A. Hadjikhani, M. Stone, F. Allen, V. Safonov, P. Liang, J. Bokor, and S. Khizroev, "The Physics of Spin-Transfer Torque Switching in Magnetic Tunneling Junctions in Sub-10-nm Size Range," submitted to *IEEE Trans. Magn*., 2015.
3. J. Hong and S. Khizroev, "3D Self-Assembled Shape Transformation of Iron Oxide Nanoparticles for Applications in Biological Systems," submitted to *IEEE Trans. Magn.*, 2015.
4. J. Hong, B. Lambson, S. Dhuey and J. Bokor, "Experimental Test of Landauer's Principle in Single-Bit Operations on Nanomagnetic Memory Bits," submitted to *Science*, 2015.
5. Y. Kang, J. Bokor, and V. Stojanovic, "Design Requirements for a Spintronic MTJ Logic Device for Pipelined Logic Applications," submitted to *IEEE Trans. on Electron Devices*, 2015.
6. J. Lin, D. A. Antoniadis, and J. A. del Alamo, "InGaAs Quantum-Well MOSFET Arrays for Nanometer-Scale Ohmic Contact Characterization," submitted to *IEEE Trans. on Electron Devices*, 2015.
7. J. Lin, X. Cai, Y. Wu, D. A. Antoniadis, and J. A. del Alamo, "Record Maximum Transconductance of 3.45 mS/μm for III-V FETs," submitted to *IEEE Electron Device Lett.*, 2015.
8. J. Lin, Y. Wu, J. A. del Alamo and D. A. Antoniadis, "Analysis of Resistance and Mobility in InGaAs Quantum-Well MOSFETs from Ballistic to Diffusive Regimes," submitted to *IEEE Trans. on Electron Devices*, 2015.
9. T. Roy, M. Tosun, M. Hettick, G. H. Ahn, C. Hu, and A. Javey,"2D-2D Tunneling Field Effect Transistors using WSe_2/$SnSe_2$ Heterostructures," submitted to *Appl. Phys. Lett.*, Jan 2016.
10. N. Xu, C. Qian, I-R. Chen and T.-J. K. Liu, "Hybrid CMOS/NEMS for Non-Volatile SRAM," submitted to *IEEE Trans. on Electron Devices*, 2015.

Conference Proceedings *(Chronological)*

Presented

1. S. A. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch, and M.C. Wu, "Electrically Injected NanoLED with Enhanced Spontaneous Emission from a Cavity Backed Optical Slot Antenna," *IPC*, Oct 2014.
2. 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," *MMM Conference*, Nov 2014.
3. J. A. del Alamo, "InGaAs MOSFET Electronics," *17th ISPSA-2014*, Dec 2014.
4. 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 IEDM*, Dec 2014.
5. 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," *2014 IEEE IEDM*, Dec 2014.
6. X. Zhao, A. Vardi and J. A. del Alamo, "InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs Fabricated by a Top-down Approach," 2014 *IEEE IEDM*, Dec 2014.
7. J. Lin, D. A. Antoniadis and J. A. del Alamo, "Novel Intrinsic and Extrinsic Engineering for High-Performance High-Density Self-Aligned InGaAs MOSFETs: Precise Channel Thickness Control and Sub-40-nm Metal Contacts," *2014 IEEE IEDM*, pp. 574-577, Dec 2014.
8. 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," in Ultrafast Magnetism I, vol. 159, J. Y. Bigot, W. Hubner, T. Rasing, and R. Chantrell, (Ed.), *Springer International Publishing AG*, Cham, Jan 2015, doi: 10.1007/978-3-319-07743-7.

9. F. Niroui, E. M. Sletten, P. B. Deotare, A. I. Wang, T. M. Swager, J. H. Lang and V. Bulovic; "Controlled Fabrication of Nanoscale Gaps using Stiction," Proceedings: *IEEE MEMS Workshop*, Jan 2015.
10. R. Going, C. Keraly, T. J. Seok, E. Yablonovich, M. C. Wu, "32 GHz Germanium Bipolar Phototransistors on Silicon Photonics," *IEEE OI Conference*, May 2015.
11. M. S. Eggleston, S. Desai, K. Messer, S. Madhvapathy, J. Xiao, X. Zhang, E. Yablonovitch, A. Javey and M. C. Wu, "Enhanced Spontaneous Emission from an Optical Antenna Coupled WSe_2 Monolayer," *CLEO*, May 2015.
12. J. Lin, D. A. Antoniadis, and J. A. del Alamo, "A CMOS-compatible Fabrication Process for Scaled Self-Aligned InGaAs MOSFETs," *30th International Conference on Compound Semiconductor Manufacturing Technology (CS MANTECH)*, p. 12.2, May 2015.
13. I. Bhattacharya, W. S. Ko, F. Lu, S. Gerke, and C. J. Chang-Hasnain, "III-V Nanopillar Phototransistor Directly Grown on Silicon," *CLEO*, *OSA Technical Digest* (online), paper SW4N.2, May 2015.
14. L. K. Marlor, S. Artis, and C. T. Amelink, "The Impact of Summer Research Experiences on Community College Students' Pursuit of a Graduate Degree in Science and Engineering," *ASEE*, Jun 2015.
15. T.-J. K. Liu, P. Zheng, D. Connelly, K. Kato, R. Nguyen, C. Qian and A. Peschot, "Sustaining the Si Revolution: from 3D Transistors to 3D Integration," *SOI-3D-Subthreshold Microelectronics Technology Unified Conference*, Paper 1.3, Oct 2015.
16. S.A. Fortuna, M.S. Eggleston, K. Messer, E. Yablonovitch, and M.C. Wu, "Large Spontaneous Emission Rate Enhancement from an Electrically-injected nanoLED Coupled to an Optical Antenna," *IPC*, Oct 2015.
17. C. Keraly, R. Going, M. Wu, and E. Yablonovitch, "Ultra-Sensitive Detector for Silicon Photonics; a Photodiode Incorporating Integrated Bipolar Gain," *IPC*, Oct 2015.
18. J. A. del Alamo, D. A. Antoniadis, J. Lin, W. Lu, A. Vardi and X. Zhao, "III-V MOSFETs for Future CMOS," *Compound Semiconductor Integrated Circuit Symposium (CSICS)*, New, Oct 2015.
19. A. Vardi, X. Zhao and J. A. del Alamo, "Quantum-Size Effects in Sub 10 nm Fin Width InGaAs FinFETs," 2015 *IEEE IEDM*, Dec 2015.
20. I. Ouerghi, M. Sansa, W. Ludurczak, L. Duraffourg, K. Benedetto, P. Besombes, T. Moffitt*, B. Adams*, D. Larmagnac*, P. Gergaud, C. Poulain, A.-I. Vidana, C. Ladner, J.-M. Fabbri, D. Muyard, G. Rodriguez, G. Rabille, O. Pollet, P. Brianceau, S. Kerdiles, S. Hentz, and T. Ernst, CEA LETI, MINATEC, *Applied Materials, "Polysilicon Nanowire NEMS Fabricated at Low Temperature for Above IC NEMS Mass Sensing Applications," *2015 IEEE IEDM*, Dec 2015.
21. T. Yu, U. Radhakrishna, J. L. Hoyt, and D. A. Antoniadis, "Quantifying the Impact of Gate Efficiency on Switching Steepness of Quantum-Well Tunnel-FETs: Experiments, Modeling, and Design Guidelines," *IEDM Tech. Dig.*, pp. 22.4.1-22.4.4, Dec 2015.
22. C. Qian, A. Peschot, D. J. Connelly, and T.-J. K. Liu, "Energy-Delay Performance Optimization of NEM Logic Relay," *IEDM Tech. Dig.*, Paper 18.1, Dec 2015.
23. P. Zhao, S. Desai, M. Tosun, T. Roy, H. Fang, A. Sachid, M. Amani, C. Hu, A. Javey, "2D Layered Materials: From Materials Properties to Device Applications," *IEEE IEDM Tech. Dig.*, pp. 27.3.1 - 27.3.4, Dec 2015.

1aii. Books and Book Chapters (Chronological)

<u>*Published*</u>

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, April 2015, ISBN: 978-1-107-04318-3.

2. E. Alon, “Energy-Efficiency Limits of Digital Circuits based on CMOS Transistors,” in *Beyond CMOS*, T.-J. King Liu & K. Kuhn, (Ed.), Cambridge University Press, April 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, April 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, April 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, April 2015, ISBN: 978-1-107-04318-3.

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

1. N/A

1b. Conference Presentations (Chronological)

Presented Talks: *(does not include 2015 talks that have published proceedings by 12/31/2015; see Conference Proceedings section above.)*

1. M. E. Nowakowski, Z. Gu, D. B. Carlton, R. Storz, M. Im, J. Hong, W. Chao, B. Lambson, P. Bennett, M. T. Alam, M.A. Marcus, A. Doran, A.T. Young, A. Scholl, P. Fischer, and J. Bokor, “Sub-nanosecond Signal Propagation in Anisotropy Engineered Nanomagnetic Logic Chains,” *59th Annual Conference on Magnetism and Magnetic Materials*, Honolulu, HI, November 2014.
2. M. E. Nowakowski , H. Sohn, C. Liang, J.L. Hockel, K. Wetzlar, S. Keller , M.A. Marcus , A. Doran , A.T. Young , M. Kläui , C.S. Lynch , G.P. Carman , J. Bokor and R.N. Candler, “Deterministic, Strain-based, Electric Field Control of Magnetic Domain Wall Rotation in Patterned Ring,” *59th Annual Conference on Magnetism and Magnetic Materials*, Honolulu, HI, November 2014.
3. 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,” *59th Annual Conference on Magnetism and Magnetic Materials*, Honolulu, HI, November 2014.
4. E. Yablonovitch, “The Low Voltage TFET Demands Higher Perfection than Previously Required in Electronics,” *ITRS Emerging Research Device (ERD) Meeting*, Palo Alto, CA, February 2015.
5. T.-J. K. Liu, “Sustaining the Si Revolution: From 3D Transistors to 3D Integration,” *SPIE Advanced Lithography Symposium*, San Jose, CA, February 2015.
6. B. McLellan, M. Nowakowski, J. Bokor, C. Liang, J. Hockel, K. Wetzlar, S. Kellar, H. Sohn, G. Carman, A. Young, A. Doran, M. Marcus, M. Klaui, R. Candler, “Calculating a Parameter Space to Smoothly Transport Magnetically-trapped Suspended Superparamagnetic Microbeads with Electric-field Domain Wall Control,” *APS March 2015 Meeting*, San Antonio, TX, March 2015.
7. S. Salahuddin, “Controlling Magnetization using Spin Orbit Torque” *APS March Meeting*, San Antonio, TX, March 2015.
8. J. A. del Alamo, “III-V FETs for Future Logic Applications,” *CS International Conference*, Frankfurt, Germany, March 2015.
9. T. Roy, M. Tosun, X. Cao, H. Fang, D.-H. Lien, P. Zhao, Y.-Z. Chen, Y.-L. Chueh, J. Guo, and A. Javey, “Tunable van der Waals Heterojunction Tunnel Diodes,” *2015 MRS Spring Meeting*, San Francisco, CA, April 2015.
10. R. M. Iutzi, “Materials Structure and Performance of Epitaxial III-V Heterojunctions for Tunnel Field Effect Transistors,” *2015 MRS Spring Meeting*, San Francisco, CA, April 2015.
11. J. A. del Alamo, “Nanometer-Scale III-V Electronics,” *Workshop on Nanomaterials*, Real Colegio Complutense, Harvard University, Cambridge, MA, May 2015.

12. E. Yablonovitch, “The Challenge of a New Low-Voltage Switch that is Much More Sensitive than the Transistor,” *11th International Nanotechnology Conf. on Communication & Coop.*, Fukuoka, Japan, May 2015.
13. E. Yablonovitch, “The Search for a New Low-Voltage Switch that is Much More Sensitive than the Transistor,” *CMOS Emerging Technology Research*, Vancouver, BC, May 2015.
14. H.-S. P. Wong, “Memory Leads the Way to Better Computing: the N3XT 1,000X in Energy Efficiency,” invited paper in Session 2W, “Workshop 2: Design Automation for Beyond-CMOS Technologies, *Design Automation Conference (DAC)*, San Francisco, CA, June 2015.
15. E. Yablonovitch, “Nano-Photonic Devices: Spontaneous Emission Faster than Stimulated Emission,” *Metamaterials Science & Technology Workshop*, San Diego, CA, July 2015.
16. S. Lee, A. Tang, and H.-S. P. Wong, “Making Electrical Contacts to Large-Area, CVD Grown 2D Layered Materials,” invited paper, *International Symposium on Physics and Device Application of Two-dimensional Materials*, Nanjing, China, July 2015.
17. T.-J. K. Liu, “NEM Switches for Ultra-low-power Computation and Information Storage,” *ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK)*, San Francisco, California, July 2015.
18. E. Yablonovitch, “Confronting the Scientific Challenges,” *NSF S&T Center Directors Meeting*, Honolulu, HI, August 2015.
19. E. Yablonovitch, “Optical Antennas: Spontaneous Emission Faster than Stimulated Emission,” *Pacific CLEO*, Busan, Korea, August 2015.
20. J. Boco, D. Zubia, J. Chavez, “Molecular Dynamics Study of Cadmium Selenide as Buffer Layer in CdTe/CdS Solar Cells,” *2015 UT-LSAMP Student Research Conference*, El Paso, TX, September 2015.
21. I. Garduno and J. Clarkson, “Optimization of Patterned Thin Films of Photoresist for Plasma Etching Applications,” *CUR's Research Experiences for Undergraduates Symposium*, Cheney, WA, October 2015.
22. J. Gorchon, Y. Yang, R. Wilson, J. Chen, L. He, J.-P. Wang, M. Li and J. Bokor, “Single-Shot Helicity Independent All-Optical Switching & Domain Wall Dynamics in GdFeCo,” *Ultrafast Magnetism Conference*, Nijmegen, Netherlands, October 2015.
23. J. A. del Alamo, “Nanometer-Scale III-V Electronics,” *6th RIEC-RLE Meeting on Research Collaboration in Photonics*, Tohoku University, Sendai, Japan, October 2015.
24. A. Peschot, C. Qian, D. J. Connelly and T.-J. K. Liu, “Body-biased Operation for Improved MEM Relay Energy Efficiency,” *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
25. M. Stone, et al, “Anomalous Properties of Sub-10-nm Magnetic Tunneling Junctions,” *Fourth Berkeley Symposium on Energy Efficient Electronics Systems*, Berkeley, CA, October 2015.
26. J. T. Teherani, W. Chern, S. Agarwal, J. L. Hoyt, and D. A. Antoniadis, “A Framework for Generation and Recombination in Tunneling Field-Effect Transistors,” *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
27. V. Stojanovic, “High-density 3D Electronic-Photonic Integration,” *Fourth Berkeley Symposium for Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
28. T. Xiao, X. Zhao, S. Agarwal and E. Yablonovitch, “Impact of Interface Defects on Tunneling FET Turn-on Steepness”, *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
29. F. Niroui, E. M. Sletten, Y. Song, A. I. Wang, W. J. Ong, J. Kong, T. M. Swager, J. H. Lang, and V. Bulović; “Tunneling Nanoelectromechanical Switches,” *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
30. A. Peschot, C. Qian, D. J. Connelly and T.-J. K. Liu, “Body-biased Operation for Improved MEM Relay Energy Efficiency,” *Fourth Berkeley Symposium on Energy Efficient Electronic Systems,* Berkeley, CA, October 2015.

31. C. L. Keraly, R. Going, M. C. Wu and E. Yablonovitch, “Low Capacitance, High Speed Phototransistors with a Large Absorption Region,” *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
32. D. Kumar, R. Wilson, and J. Bokor, “Ultrafast Magnetization Switching of Ferromagnetic Alloys Through Optically Generated Spin Current,” *SACNAS Annual Conference*, National Harbor, MD, October 2015.
33. L. Ruwanpathirana and M. Gilbert, “Optimization of Hexagonal Boron Nitride for 2D Electronics,” *SACNAS Annual Conference*, National Harbor, MD, October 2015.
34. T.-J. K. Liu, “Material Requirements and Challenges for NEM Logic Relays,” *AVS 62nd International Symposium*, San Jose, CA, October 2015.
35. E. Yablonovitch, “t-FET's as a Dit Versus dN/dE Problem!” *Steep Transistors Workshop*, South Bend, IN, October 2015.
36. E. Yablonovitch, “The Low Voltage T-FET Demands a More Perfect Interface than Previously Required in Electronics: t-FET's as a Dit Versus dN/dE Problem!,” *Beyond CMOS Workshop*, Leuven, Belgium, October 2015.
37. E. Yablonovitch, “Optical Antennas: Spontaneous Emission Faster than Stimulated Emission,” *Workshop on “Quantum Information on a Chip,”* Univ. of Padua, Italy, October 2015.
38. E. Yablonovitch, “Photonic Crystals—Inhibited Spontaneous Emission; Optical Antennas—Enhanced Spontaneous Emission,” *Royal Swedish Academy of Sciences Jubilee Symposium*, Lund, Sweden, October 2015.
39. Y. Yang, J. Gorchon, R. Wilson, A. Pattabi, H. Abdel-Raziq, D. Bhowmik, O. Lee, S. Salahuddin, and J. Bokor, “Ultrafast Laser Pulse Assisted Magnetization Reversal by Spin-orbit Torque Effect,” *Ultrafast Magnetism Conference*, Nijmegen, Netherlands, October 2015.

<u>*Accepted Talks*</u>

1. F. Niroui, P. Todorović, E. M. Sletten, Y. Song, A. I. Wang, J. Kong, T. M. Swager, J. H. Lang, and V. Bulović; “Self-assembled Molecular Films as Nanoscale Springs to Modulate Tunneling Gaps,” *Material Research Society Conference*, Boston, MA, December 2015.
2. L. Marlor and C. Amelink, “The Impact of Summer Research Experiences on Community College Students' View of Self Efficacy,” peer-review paper presentation, *ASEE*, June 2016.

<u>*Presented Posters*</u>

1. F. Niroui, E. Sletten, P. B. Deotare, A. I. Wang, T. M. Swager, J. H. Lang, and V. Bulović, “Controlled Formation of Nanoscale Tunneling Gaps with Self-assembled Molecular Layers,” *Material Research Society Conference*, Boston, MA, December 2014.
2. X. Zhao, A. Vardi, and J. A. del Alamo, “InGaAs/InAs Heterojunction Vertical Nanowire Tunnel FETs Fabricated by a Top-Down Approach,” *MTL Annual Research Conference*, Quincy, MA, January 2015.
3. K. Messer, M.S. Eggleston, S. Fortuna, M. C. Wu, E. Yablonovitch, “Limits to Efficient Enhancement of Spontaneous Emission using Optical Antennas,” *Metamaterials Science and Technology Workshop*, La Jolla, CA, July 2015.
4. I. Bhattacharya, W. S. Ko, T. Tran, K.W. Ng, H. Sun, and C. J. Chang-Hasnain, “Illumination Angle Insensitive Indium Phosphide Nanopillar Solar Cell Grown on a Silicon Substrate,” *International Nano-Optoelectronic Workshop (iNOW)*, Tokyo, Japan, August 2015.
5. S.A. Fortuna, M.S. Eggleston, K. Messer, E. Yablonovitch, and M. C. Wu, “Large Spontaneous Emission Rate Enhancement from an Electrically-injected nanoLED Coupled to an Optical Antenna,” *International Nano-Optoelectronics Workshop (iNOW)*, Tokyo, Japan, August 2015.
6. S. Almeida and David Zubia, “Monolayer Strain by NEMS for Low Power Applications,” *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.

7. J. Cao, L. Li, K. Kato, T.-J. K. Liu, H.-S. P. Wong, "Sub-5 nm Gap Formation for Low Power NEM Switches", *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
8. R. M. Iutzi, C. Heidelberger, E. A. Fitzgerald, "Defect and Temperature Dependence of Tunneling in InGaAs/GaAsSb Heterojunctions with Varying Band Alignments," *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
9. K. Messer, M. Eggleston, S. B. Desai, S. A. Fortuna, S. Madhavapathy, P. Zhao, J. Xiao, Z. Xiang, A. Javey, M. C. Wu, E. Yablonovitch, "Optical Slot Antennas for Enhancement of WSe_2 Spontaneous Emission Rate," *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
10. J. Suh, B. Saha, J. Wu, "Novel Device Functionalities Enabled by Substitutional Doping in 2D Semiconductors," *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
11. W. J. Ong, E. M. Sletten, F. Niroui, J. H. Lang, V. Bulovic and T. M. Swager, "Electromechanically Actuating Molecules," *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
12. B. Osoba, C. Qian, A. Peschot and T.-J. K. Liu, "MEM Diode for Energy-Efficient Power Conversion," *Fourth Berkeley Symposium on Energy Efficient Electronic Systems*, Berkeley, CA, October 2015.
13. A. Pattabi, Z. Gu, J. Gorchon, Y. Yang, J. Finley, O. Lee, S. Salahuddin, J. Bokor, "Direct Optical Study of Current Induced Spin Accumulation Dynamics in Metals," *Ultrafast Magnetism Conference*, Nijmegen, Netherlands, October 2015.

Accepted Posters

1. Z. Xu, K. Messer, E. Yablonovitch, "Radiation Pattern and Scattering Properties of Optical Antennas," poster, *APS March 2016*, March 2016.

1c. Other Dissemination Activities (Chronological)

1. J. A. del Alamo, "InGaAs MOSFET Electronics," TSMC, Hsinchu, Taiwan, December 2014.
2. J. A. del Alamo, "InGaAs MOSFET Electronics," National Chiao Tung University, Hsinchu, Taiwan, December 2014.
3. J. A. del Alamo, Panelist at "60 Years of IEDM and Counting," Evening Panel Discussion at International Electron Devices Meeting, San Francisco, CA, December 2014.
4. H.-S. P. Wong, "Monolithic 3D Integration of 1D/2D Transistors with Resistive Memories – the N3XT Frontier," Materials and Technologies for Beyond CMOS Workshop, SEMATECH, San Francisco, CA, December 2014.
5. J. A. del Alamo, "III-V CMOS," Qualcomm, San Diego, CA, January 2015.
6. E. Yablonovitch, "The Low Voltage T-FET Demands Higher Perfection than Previously Required in Electronics," *Online Intel Webinar*, February 2015.
7. J. A. del Alamo, "III-V MOSFET Electronics," IMEC, Leuven, Belgium, March 2015.
8. T.-J. K. Liu, "Sustaining the Si Revolution: From 3D Transistors to 3D Integration," Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan R.O.C., May 2015.
9. T.-J. K. Liu, "Sustaining the Si Revolution: From 3D Transistors to 3D Integration," Institute for Advanced Study Distinguished Lecture at Hong Kong University of Science and Technology, Hong Kong, China, May 2015.
10. T.-J. K. Liu, "Sustaining the Si Revolution: From 3D Transistors to 3D Integration," Samsung Semiconductor, Inc., Milpitas, California, CA, May 2015.
11. E. Yablonovitch, "What Does the Clock Speed of My Computer Have to do With the Fundamental Constants of Nature, h, c, q, m?," *Electrical Engineering Dept. Colloquium*, Technion, Haifa Israel, June 2015.

12. E. Yablonovitch, "What Does the Clock Speed of My Computer Have to do With the Fundamental Constants of Nature, h, c, q, m?," *HKUST IAS Distinguished Lecture*, Clear Water Bay, Hong Kong, July 2015.
13. T.-J. K. Liu, "Sustaining the Si Revolution: From 3D Transistors to 3D Integration," presented at Technical Advisory Board meeting, Ultratech, Inc., San Jose, California, July 2015.
14. E. Yablonovitch, "Optical Antennas: Spontaneous Emission Faster than Stimulated Emission," *1st International POSTECH Nanophotonics Workshop*, Pohang, Korea, August 2015.
15. E. Yablonovitch, "The Challenge of a New Low-Voltage Switch that is Much More Sensitive than the Transistor," *HP Labs Seminar*, Palo Alto, CA, September 2015.
16. J. A. del Alamo, "Nanoscale III-V Electronics: from Quantum-Well Planar MOSFETs to Vertical Nanowire MOSFETs," Northrop Grumman, El Segundo, CA, September 2015.
17. J. A. del Alamo, "Nanoscale III-V Electronics: from Quantum-Well Planar MOSFETs to Vertical Nanowire MOSFETs," Purdue University, West Lafayette, IN, September 2015.
18. J. A. del Alamo, "Nanoscale III-V Electronics: from Quantum-Well Planar MOSFETs to Vertical Nanowire MOSFETs," SunEdison Semiconductor, St. Peters, MO, October 2015.
19. E. Yablonovitch organized the Fourth Berkeley Symposium on Energy Efficient Electronic Systems, October 2015.
20. E. Yablonovitch, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?," *SystemX Seminar*, Stanford Univ., Palo Alto, CA, October 2015.
21. E. Yablonovitch, "Center for Energy Efficient Electronics Science; Searching for the Milli-Volt Switch," *Interdisciplinary Instrumentation Colloquium*, LBL Berkeley, CA, October 2015.
22. E. Yablonovitch, "What Does the Clock Speed of My Computer Have to do with the Fundamental Constants of Nature, h, c, q, m?," *Univ. College London Seminar*, London, UK, November 2015.
23. E. Yablonovitch, "Photonic Crystals—Inhibited Spontaneous Emission; Optical Antennas—Enhanced Spontaneous Emission," *Isaac Newton Lecture*, Institute of Physics, London, UK, November 2015.

2. *Awards & Honors*

Recipient	**Reason for Award**	**Award Name**	**Sponsor**	**Date**	**Award Type**
Jesús del Alamo	For recognition as an honorary doctorate	Doctor *Honoris Causa*	Universidad Politécnica of Madrid	November 2015	Academic
Michael Eggleston	Outstanding Research in dissertation	David J. Sakrison Memorial Prize	UC Berkeley EECS	May 2015	Scientific
Seth Fortuna	Outstanding research	Best Poster Award	iNOW (International Nano-Optoelectronics Workshop)	August 2015	Scientific
Ryan Going	Innovative technical achievement with potential for entrepreneurial success	Sevin Rosen Funds Award for Innovation	Sevin Rosen Funds through UC Berkeley EECS	May 2015	Scientific
Connie Chang-Hasnain	For the Development of Nanoscience and Nanotechnologies	UNESCO Medal	United Nations	April 2015	Scientific

Christopher Heidelberger	Merit-based	IBM PhD Fellowship	IBM	2014-2015	Fellowship
Ali Javey	For innovative contributions in integrating nanomaterials into device applications	Outstanding Young Investigator Award	Materials Research Society (MRS)	April 2015	Scientific
Jianqiang Lin	Best Student Paper Award	Roger A. Haken Best Student Paper Award	International Electron Devices Meeting 2014	December 2014	Scientific
Jianqiang Lin	Outstanding Student	Chinese Government Award for Outstanding Self-Financed Student Abroad	Chinese Ministry of Education	2015	Academic
Jianqiang Lin	Outstanding research	Dimitris N. Chorafas Foundation Award	Dimitris N. Chorafas Foundation	2015	Scientific
Benjamin Osoba	Academic achievement	Ford Foundation Fellowship	Ford Foundation	August 2015	Fellowship
Benjamin Osoba	Electrical Engineering; "Development of Nanoscale NEM Relays for Energy Efficient Switching Applications"	NSF Graduate Research Fellowship Program (GRFP)	Professor Tsu-Jae King Liu	March 2015 (Award period began Fall 2015)	Academic
Junqiao Wu	Recognition	Outstanding Alumni	Peking University, China	Summer 2015	Academic
Eli Yablonovitch	For visionary and foundational contributions to photonic nanostructures	Isaac Newton medal of the Institute of Physics	Institute of Physics	July 2015	Scientific
Eli Yablonovitch	For seminal achievements in solar cells and strained quantum well lasers, and especially for creating the field	Oliver E. Buckley Condensed Matter Prize	AT&T Bell Laboratories (now Bell Laboratories, Alcatel-Lucent) & co-sponsored with the HTC-VIA Group	2015	Scientific

	of photonic crystals				
Eli Yablonovitch	For recognition as an honorary professor	Honorary Professor	Nanjing U.	July 2015	Academic

3. *Graduates*

Undergraduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Carlos Asuncion	B.S. EE, UC Berkeley	Spring 2015	4	Graduate Student at UC Berkeley
Channell Boyd	B.S. Chemistry, Howard University	Spring 2015	4	Graduate Student at Uniformed Services University of the Health Sciences
Neil Cammardella	B.S. EE, University of South Florida	Spring 2015	4	Graduate Student at University of Florida
Johanna Chen	B.S. EE, MIT	Spring 2015	4	United States Navy
Joseph Finley	B.S.; EECS	May 2015	2	MIT – Sep 2015
Satcher Hsieh	B.S. Physics, Washington University at St. Louis	Spring 2015	4	Graduate Student at UC Berkeley
Ibrahim Iskender Kushan	B.S., EE	June 2015	2	Co-term MS program
Justin Laguardia	B.S. EE, UC Davis	Spring 2015	4	N/A
Augustus Lang	B.S. EE, USC	Spring 2015	4	Graduate Student at UC Berkeley
Brenda McLellan	B.S. Physics, Polytechnic Institute of NYU	Spring 2015	4	Graduate Student at the University of Rochester
Morgan Monroe	B.S. MSE and ChemE, UC Berkeley	Spring 2015	4	Graduate Student at UC Berkeley
Lawrence Pan	B.S. MSE, UC Berkeley	Spring 2015	4	N/A
C. Shane Strickland	B.S. Physics, Polytechnic Institute of NYU	Spring 2015	4	Graduate Student at Rutgers
Joeson Wong	B.S. EE, University of Michigan	Spring 2015	4	Graduate Student at Caltech
Aldo Vidana	B.S. MME, UTEP	Winter 2015	4	Graduate Student at UTEP

Graduate Students

Name	Degree(s)	Degree Date & Year	Years to Degree	Placement
Haron Abdel-Raziq	M.S., EECS	2015	2	FORD Motor Corp.
Franiece Bennett	N/A	Withdrawal; EECS	1	Company in Atlanta
Jared Carter	EECS	2014	2	Went into industry
I-Ru Chen	Ph.D., EECS	Dec 2014	5	Xilinx, Inc.
Yenhao Chen	Ph.D., EECS	Aug 2015	6	Knowles
Ryan Cloke	Chemistry	Oct 2015	4.5	IBM
Michael Eggleston	Ph.D., EECS	Dec 2014	5.5	Alcatel Lucent Bell Labs
Ryan Going	Ph.D., EECS	Aug 2015	5	Infinera
Ryan Iutzi	Ph.D., DMSE	Aug 2015	5	Applied Materials
Cem Koc	Ph.D., EECS	Dec 2014	5	Applied Materials
Jianqian Lin	Ph.D.	May 2015	5	MIT
Fanglu Lu	Ph.D., EECS	2015	5	Exponent (consulting firm, Shanghai)
Jamie Teherani	Ph.D.	May 2015	6	Columbia

Postdocs

Name	Departure Date	Placement (where did they go?)
OukJae Lee	Aug 2015	KAIST
Parag Deotare	August 2015	Asst. Prof; U Michigan Department of Electrical and Computer Engineering
Rakesh Guduru	June 2015	Director of Research, Vapor Shark
Mohammed Najmzadeh	September 2015	-
Daria Skuridina	June 2015	Technical Assistant, Dr. Tüerck Ingenieürburo, Berlin
Ellen Sletten	June 2015	Asst. Prof; UCLA Department of Chemistry and Biochemistry
Long You	Aug 2015	HUST

4a. General Outputs of Knowledge Transfer Activities

Patents:

	Inventors/Authors	Number	Publication Type	Application Date	Receipt Date
Electronically Controlled Squishable Composite Switch (First squitch concept using nano-composite)	V. Bulovic, J. H. Lang, S. Paydavosi, A. I.-J. Wang, T. L. Andrew, A. Murarka, F. Niroui, F. Yaul, J. C. Grossman	8933496	Application	Nov 7, 2011	Jan 13, 2015
Tunneling Nanoelectromechanical Switches	Bulovic, Lang, Niroui, Sletten and Swager	62252771	Application	Nov 9, 2015	
Tunable Plasmonic Nanogaps	Bulovic, Lang, Niroui, Sletten and Swager	62252762	Application	Nov 9, 2015	
Electrically-Driven Light-Emitting Tunnel Junctions	Bulovic, Lang, Niroui, Mahony	62264042	Application	Dec 07, 2015	
Decoupled Absorption/Gain Region Bipolar Phototransistor	C. Keraly, R. Going, E. Yablonovich, M. Wu	BK-2015-111-1	Provisional	April 22, 2015	
Energy-efficient Super computer Inside a Nanoparticle	S. Khizroev, R. Guduru, P. Liang	FIU disclosure	Provisional	May 28, 2015, filed at FIU	

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

Period 6	**Summer**	**Summer + Academic**	**Academic**	**No Salary**	**Total**
Faculty	7	4	3	9	23

	Funded by E^3S			**Other Funding Source**	**Total Participants**
Category	50% or more	Less than 50%	**Total**		
Postdocs	10	4	14	6	20
Grad Students	13	10	23	20	43
Undergrads		23	23	2	25
TOTAL	**23**	**37**	**60**	**28**	**88**

The demographics of all participants are given on the following page.

PARTICIPANTS - PERIOD 6

Category	Institutional Affiliation	Department	Gender	Disability Status	Ethnicity	Race	Veteran	Citizenship
23 Faculty	11 Berkeley	18 E.E.	20 M	0 Hearing Impairment	2 Hispanic or Lantino	0 American Indian or Alaskan Native	0 Yes	18 US Citizens
	7 MIT	2 Mats Sci	3 F	0 Visual Impairment	18 Not Hispanic or Latino	5 Asian	23 No	5 Permanent Resident
	1 Stanford	2 Chemistry		0 Mobility/Orthopedic Impairment	3 Decline to State	0 Black or African American		0 Other non-US Citizen
	1 UTEP	1 Other		0 Other	0 Not Available	0 Native Hawaiian or Other Pacific Islander		0 Decline to State
	1 LATTC			21 None		16 White		0 Not Available
	1 FIU			2 Decline to State		2 Decline to State		
	1 Other			0 Not Available		0 Not Available		
20 Postdocs	13 Berkeley	18 E.E.	14 M	0 Hearing Impairment	2 Hispanic	0 American Indian or Alaskan Native	0 Yes	4 US Citizens
	3 MIT	0 Mats Sci	6 F	0 Visual Impairment	18 Not Hispanic or Latino	11 Asian	20 No	1 Permanent Resident
	2 Stanford	0 Physics		0 Mobility/Orthopedic Impairment	0 Decline to State	0 Black or African American		14 Other non-US Citizen
	1 UTEP	2 Chemistry		0 Other	0 Not Available	0 Native Hawaiian or Other Pacific Islander		0 Decline to State
	1 FIU			20 None		9 White		1 Not Available
				0 Decline to State		0 Decline to State		
				0 Not Available		0 Not Available		
43 Graduate Students	30 Berkeley	32 E.E.	37 M	0 Hearing Impairment	1 Hispanic	1 American Indian or Alaskan Native	0 Yes	24 US Citizens
	9 MIT	4 Mats Sci	6 F	0 Visual Impairment	41 Not Hispanic or Latino	21 Asian	43 No	1 Permanent Resident
	2 Stanford	0 Physics		0 Mobility/Orthopedic Impairment	1 Decline to State	1 Black or African American		17 Other non-US Citizen
	0 UTEP	0 ME		0 Other	0 Not Available	0 Native Hawaiian or Other Pacific Islander		1 Decline to State
	2 FIU	6 Chemistry		41 None		18 White		0 Not Available
		1 Other		2 Decline to State		2 Decline to State		
				0 Not Available		0 Not Available		
25 Undergraduate Students	3 Berkeley	20 E.E.	17 M	0 Hearing Impairment	6 Hispanic	0 American Indian or Alaskan Native	1 Yes	20 US Citizens
	0 MIT	1 Mats Sci	8 F	0 Visual Impairment	19 Not Hispanic or Latino	4 Asian	24 No	4 Permanent Resident
	0 Stanford	1 Physics		0 Mobility/Orthopedic Impairment	0 Decline to State	4 Black or African American		1 Other non-US Citizen
	6 UTEP	1 ME		0 Other	0 Not Available	0 Native Hawaiian or Other Pacific Islander		0 Decline to State
	1 LATTC	2 ChemE		25 None		11 White		0 Not Available
	0 CCC	0 Engr Phys		0 Decline to State		4 Decline to State		
	1 FIU			0 Not Available		2 Not Available		
	14 Other							
9 Staff	8 Berkeley	0 E.E.	3 M	0 Hearing Impairment	0 Hispanic	0 American Indian or Alaskan Native	0 Yes	8 US Citizens
	1 MIT	0 Mats Sci	6 F	0 Visual Impairment	8 Not Hispanic or Latino	3 Asian	9 No	0 Permanent Resident
	0 Stanford	0 Physics		0 Mobility/Orthopedic Impairment	0 Decline to State	1 Black or African American		0 Other non-US Citizen
	0 UTEP	8 E3S		0 Other	1 Not Available	0 Native Hawaiian or Other Pacific Islander		0 Decline to State
	FIU	1 Other		6 None		5 White		1 Not Available
				0 Decline to State		0 Decline to State		
				1 Not Available		1 Not Available		
120 TOTAL PARTICIPANTS								

5b. Affiliates

AFFILIATES - PERIOD 6

Category		Institutional Affiliation		Department		Gender		Disability Status		Ethnicity		Race		Citizenship	
3	Faculty	2	Berkeley	1	E.E.	2	M	0	Hearing Impairment	0	Hispanic or Lantino	0	American Indian or Alaskan Native	3	US Citizens
		0	MIT	0	Mats Sci	1	F	0	Visual Impairment	3	Not Hispanic or Latino	2	Asian	0	Permanent Resident
		0	Stanford	1	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	1	Chemistry			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			3	None			1	White	0	Not Available
		1	CCC	0	Other			0	Decline to State			0	Decline to State		
		0	Other					0	Not Available			0	Not Available		
1	Research Scientists & Visiting Faculty	1	Berkeley	1	E.E.	1	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	1	US Citizens
		0	MIT	0	Mats Sci	0	F	0	Visual Impairment	1	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Other			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU					1	None			1	White	0	Not Available
								0	Decline to State			0	Decline to State		
								0	Not Available			0	Not Available		
10	Postdocs	6	Berkeley	9	E.E.	10	M	0	Hearing Impairment	1	Hispanic	1	American Indian or Alaskan Native	2	US Citizens
		3	MIT	1	Mats Sci	0	F	0	Visual Impairment	8	Not Hispanic or Latino	5	Asian	1	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	0	Decline to State	0	Black or African American	6	Other non-US Citizen
		1	UTEP	0	Chemistry			0	Other	1	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	FIU	0	ME			9	None			2	White	1	Not Available
				0	Other			0	Decline to State			1	Decline to State		
								1	Not Available			1	Not Available		
14	Graduate Students	5	Berkeley	13	E.E.	13	M		Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	7	US Citizens
		4	MIT	0	Mats Sci	1	F		Visual Impairment	9	Not Hispanic or Latino	3	Asian	1	Permanent Resident
		0	Stanford	1	Physics				Mobility/Orthopedic Impairment	1	Decline to State	1	Black or African American	3	Other non-US Citizen
		0	UTEP	0	Chemistry				Other	3	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		5	FIU	0	ME			10	None			5	White	3	Not Available
				0	Other			1	Decline to State			2	Decline to State		
								3	Not Available			3	Not Available		
2	Undergraduate Students	2	Berkeley	0	E.E.	0	M	0	Hearing Impairment	0	Hispanic	0	American Indian or Alaskan Native	2	US Citizens
		0	MIT	1	Mats Sci	2	F	0	Visual Impairment	0	Not Hispanic or Latino	0	Asian	0	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment	2	Decline to State	0	Black or African American	0	Other non-US Citizen
		0	UTEP	1	ChemE			0	Other	0	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	0	ME			1	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	
57	Pre-College Students	0	Berkeley	0	E.E.	34	M	0	Hearing Impairment	42	URM	1	American Indian or Alaskan Native	56	US Citizens
		0	MIT	0	Mats Sci	23	F	0	Visual Impairment	15	Non-URM	8	Asian	1	Permanent Resident
		0	Stanford	0	Physics			0	Mobility/Orthopedic Impairment			14	Black or African American	0	Other non-US Citizen
		0	UTEP	0	Other			0	Other			0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC	57	N/A			0	None			4	White	0	Not Available
		0	CCC					0	Decline to State			0	Decline to State		
		57	Other					57	Not Available			30	Not Available		
10	Staff	7	Berkeley	2	E3S	4	M	0	Hearing Impairment	1	Hispanic	0	American Indian or Alaskan Native	8	US Citizens
		3	MIT	2	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	2	Not Available	0	Native Hawaiian or Other Pacific Islander	0	Decline to State
		0	LATTC					9	None			4	White	2	Not Available
								1	Decline to State			0	Decline to State		
								0	Not Available			2	Not Available		
97	TOTAL AFFILIATES														

6. *Center Partners*

	Organization Name	Organization Type	Address	Contact Name	Type of Partner	160 hours or more?
1.	Intel	Company	Hillsboro, OR, CA	Ian Young	Knowledge Transfer	N
2.	IBM	Company	Yorktown Heights, NY	Ghavam Shahidi & Paul Solomon	Research, Knowledge Transfer	N
3.	IBM	Company	Zurich, Switzerland	Lukas Czornomaz	Research	N
4.	Lam Research	Company	Fremont, CA	David Hemker & N. Draeger	Research, Knowledge Transfer	N
5.	Hewlett-Packard Enterprise	Company	Palo Alto, CA	Stan Williams	Research, Knowledge Transfer	N
6.	Applied Materials	Company	Santa Clara, CA	Ellie Yieh & Nansung Kim	Research, Knowledge Transfer	N
7.	Northrup Grunman	Company	Sacramento, CA	Mike Wojtowicz	Research, Knowledge Transfer	N
8.	Lawrence Berkeley National Laboratory	National Laboratory	Berkeley, CA	Hans A. Bechtel & Michael C. Martin	Research	N
9.	Aerospace Corporation	Company	El Segundo, CA	Joel Schulman	Research	N

10.	Western Digital Corporation	Company	Fremont, CA	Rabee Ikkawi	Research	N
11.	MIT Lincoln Laboratory	FRDC	Lexington, MA	Jeff Chou	Research	Yes
12.	University of California, Berkeley, ME Dept.	University	Berkeley, CA	Xiang Zhang	Research	N
13.	CEA-LETI	French National Laboratory	Grenoble, France	Louis Hutin & Oliver Faynot	Education Knowledge Transfer	N
14.	MIT Office of Engineering Outreach Programs	University	Cambridge, MA	Shawna Young	Education & Diversity	N
15.	MIT Office of the Dean of Graduate Education	University	Cambridge, MA	Eboney Hearn	Education & Diversity	N
16.	MIT Office of Digital Learning	University	Washington DC	Elizabeth COE	Education	N
17.	UC Berkeley Transfer Alliance Project	University	Berkeley, CA	Merryl Owen	Education & Diversity	N
18.	UC Berkeley Summer Sessions	University	Berkeley, CA	Richard Russo	Education	N
19.	Berkeley Engineering Graduate Outreach	University	Berkeley, CA	Meltem Erol	Education & Diversity	N
20.	Synthetic Biology Engineering Research Center	University	Berkeley, CA	Shaila Kotadia	Education & Diversity	N
21.	The Team for Research in Ubiquitous Secure Technology	University	Berkeley, CA	Larry Rohrbough	Education & Diversity	N
22.	UC Berkeley, Center for Teaching & Learning	University	Berkeley, CA	Richard Freishtat	Education	N
23.	Lawrence Hall of Science	Museum	Berkeley, CA	Lynn Tran	Education	N
24.	UC Berkeley, School of Public Health	University	Berkeley, CA	Deborah Barnett	Education	N

25.	UC Berkeley Engineering Student Services	University	Berkeley, CA	Tiffany Reardon	Education & Diversity	N
26.	UC Berkeley, Berkeley Edge Conference	University	Berkeley, CA	Ira Young	Education & Diversity	N
27.	UC Berkeley, Science@Cal	University	Berkeley, CA	Rachel Winheld	Education & Diversity	N
28.	Mathematics Engineering Science Achievement	Non-Profit	Oakland, CA	Julian Martinez	Education & Diversity	N
29.	Center for Integrated Quantum Materials	University	Washington D.C.	Tina L. Brower-Thomas	Education & Diversity	N
30.	University of California Office of the President	University	Oakland, CA	Pamela Jenkins	Diversity	N
31.	Berkeley Engineering and Mentors	Non-Profit	Berkeley, CA	Siddarth Krishna	Education & Diversity	N
32.	Texas Instrument	Company	Santa Clara	Ajith Amerasekera	Knowledge Transfer	N
33.	UC Santa Barbara	University	Santa Barbara, CA	John Bowers	Knowledge Transfer	N
34.	Peking University	University	Beijing, China	Ru Huang	Knowledge Transfer	N
35.	Carnegie Mellon University	University	Pittsburgh, PA	Larry Pileggi	Knowledge Transfer	N
36.	Universität Kassel	University	Kassel, Germany	Johann Peter Reithmaier	Knowledge Transfer	N
37.	University of Bologna	University	Bologna, Italy	Enrico Sangiorgi	Knowledge Transfer	N
38.	University of Utah	University	Salt Lake City, UT	Massood Tabib-Azar	Knowledge Transfer	N
39.	UC Los Angeles	University	Los Angeles, CA	Kang Wang	Symposium Organizing Committee	N
40.	KAIST	University	Daejeon, South Korea	Jun-Bo Yoon	Knowledge Transfer	N
41.	UC Berkeley Space Science Laboratories	University	Berkeley, CA	Claire Raftery	Education & Diversity	N
42.	Program yoUr Future	Non-Profit	Berkeley, CA	Alankrita Dayal	Education & Diversity	N
43.	Louis Stokes Alliances for Minority Participation	Non-Profit	El Paso, TX	Ariana Arciero	Education & Diversity	N

44.	Georgia Institute of Technology	University	Atlanta, GA	Manu O. Platt	Diversity	N
45.	UC Berkeley Black Graduate Engineering and Science Students	University	Berkeley, CA	Benjamin Osoba	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).	6
2.	The number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center).	54
3.	The total leveraged support for the current year (sum of funding for the Center from all sources other than NSF-STC) [Leveraged funding should include both cash and in-kind support related to Center activities, but not funds awarded to individual PIs.]	$647, 899
4.	The number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF).	120

8. *Media Publicity of Center*

None.

IX. INDIRECT/OTHER IMPACTS

International Activities:

- A. Vindãna (*UTEP*), an undergraduate researcher (ETERN) at the Center, spent nine weeks at CEA-Leti, Grenoble France doing research in NEMS. He is a co-author with other scientists in the hosting laboratory on a paper that was accepted for oral presentation at IEDM in December 2015.
- E. Yablonovitch received the 2015 Isaac Newton Medal and Prize for “his visionary and foundational contributions to photonic nanostructures”, awarded by the Institute of Physics.
- E. Yablonovitch gave talks related to TFET, Optical Antennas, and Photonic Crystals at various locations outside the US: Belgium, Canada, Hong Kong, Israel, Italy, Japan, Korea, Sweden, and the UK. These topics relate to Theme I and III research of the Center.
- Work from C. Chang-Hasnain, M. Wu, and E. Yablonovitch was presented at International Nano-Optoelectronics Workshop (iNOW), Tokyo, Japan, August 3-7.
- J. A. del Alamo gave talks on III-V MOSFETs for CMOS at various locations outside the US: Belgium, Germany, and Japan. The talk includes research that was funded by E^3S as part of Theme I research. He received the Doctor *Honoris Causa* diploma from Universidad Politécnica de Madrid in November 2015.
- O. Faynot, from CEA-Leti in Grenoble, France presented remotely for one of the E^3S Seminars, attended by the Center’s students, postdocs, and faculty.

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

- In the knowledge transfer section of this report, we identified two device structures and a processing technology that resulted from the Center funding and are finding applications beyond low energy digital electronics. Efforts are underway with research partners to further develop the device approaches for other electronic applications, while the device processing technology has been under evaluation by several companies.

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^3S Transfer-to-Excellence REU program to community college students outside of disciplines affiliated with the Center from five to fifteen summer students annually. The Site was renewed in 2015, and will continue on until 2018. During the summer 2015 (period 6), the Center hosted nine community college students from science and engineering majors in six different labs on Berkeley’s campus, including labs at Lawrence Berkeley National Laboratory (LBNL). These students’ research focused on robotics and biotechnology. Over the Center’s lifespan, E^3S has hosted 60 community college students from 35 institutions from every region in the State of California. In total, 60 projects have been advised by 34 faculty mentors and supervised by graduate student and postdoc mentors. Among this group of students, 90% have transferred to a 4-year institution.
- Community College Faculty: Similar to the expansion of the summer research program for community college students, the Center expanded its E^3S Teacher Fellows Program from two to six community college faculty with a NSF Research Experience for Teachers (RET) Site award. Beginning in Period 5, curriculum development workshops on context-based learning were implemented. This is 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 6, five community college faculty from mathematics, physiology, electrical engineering, and chemistry departments in San Francisco Bay Area community colleges conducted a nine-week research experience in cyber security and energy. In addition to coordinating the logistics (i.e., application, selection, placement, and implementation) for the summer RET program, the Center hosted four curriculum development workshops, three on context-based learning pedagogy and one on digital/online education with UC Berkeley's Center for Teaching and Learning, the Berkeley Resource Center for Online Education, the 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 2015-2016 academic year.

- HBCU Students: In Period 5, the Center was awarded supplemental funding from the University of California, Office of the President in order to create the UCB-HBCU REU programs. This award funds students to conduct summer research with UC Berkeley EE Faculty that are associated with a research center on campus (CIAN, E^{3}S, NASCENT, TANMS). The students are then able to go back to their HBCU and conduct research during the semesters at their home institutes. All 4 centers have committed to hosting the students for a second summer in their respective REU programs, as long as the student maintains eligibility. In Period 6, four students took part in the inaugural year of this REU program. The Center hosted these students, and incorporated them into the E^{3}S REU workshops and activities.
- E. Alon, an E^{3}S faculty member at Berkeley, has been spending significant time re-engineering the freshmen electrical engineering curriculum. The time needed for the effort has resulted in a decrease in his participation in E^{3}S research. Nevertheless, as reported in the Education section, he shared his experience with one of the visiting community college faculty who spent time in Summer 2015 at UC Berkeley to develop new electrical engineering curriculum for his community college.

Additional other impacts include:

- An undergraduate physics major was a work-study student at the Center for more than one year. The summer after her graduation, she became the program assistant of the Center's community college program. As part of her responsibilities she developed teaching for the program's bootcamp that prepares the students for research. During this bootcamp, she taught the students data collection and analysis. She was also a mentor to the participants through the duration of the program. She recently decided to pursue graduate studies in science education particularly for the underserved populations. We believe that her experience working in the Center's undergraduate program has inspired her to pursue a career in science education.

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XI. APPENDICES

Appendix A: Biographical Information of New Faculty

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. Professor Fischer 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 in 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).

New Faculty in Period 7

Jing Kong is a Professor in the Electrical Engineering and Computer Science Department at MIT. The current research activity in her group involves CVD synthesis, characterization of graphene and related two dimensional materials, investigation of their electronic and optical properties and developing their applications. Professor Kong received her Ph.D. degree in Chemistry from Stanford University in 2002. Prior to joining the faculty at MIT in 2004, she was a research scientist at NASA Ames Research Center and a postdoctoral researcher at Delft University. She is member of the American Chemical Society, the American Physical Society, and the Materials Research Society. She received the 2001 Foresight Distinguished Student Award in Nanotechnology, the Stanford Annual Reviews Prize in Physical Chemistry (2002), and the MIT 3M Award (2005).

Steven G. Louie received his Ph.D. in physics from UC Berkeley in 1976. After having worked at the IBM Watson Research Center, Bell Laboratories, and University of Pennsylvania, he joined the UC Berkeley faculty in 1980. He is a member of the National Academy of Sciences (2005), fellow of the American Physical Society (1985), senior faculty scientist and Theory Facility Director of the Molecular Foundry at LBNL, and editor of the journal Solid State Communications. He has been awarded a Sloan Fellowship (1980), a Guggenheim Fellowship (1989), two Miller Professorships (1986, 1995), the U.S. Department of Energy Award for Sustained Outstanding Research in Solid State Physics (1993), the Lawrence Berkeley National Laboratory's Outstanding Performance Award (1995), the Aneesur Rahman Prize for Computational Physics of the American Physical Society (1996), the Davisson-Germer Prize in Surface Physics of the American Physical Society (1999), and shared with M. L. Cohen the Foresight Institute Richard P. Feynman Prize in Nanotechnology (2003). He is identified by the ISI as one of the most highly cited researchers in physics.

Appendix B: Biographical Information of New Staff

Dr. Michael H. Bartl joined the Center for Energy Efficient Electronics Science (E^3S) as Executive Director in November 2015. Previously, he was an associate professor of physical and materials chemistry, and an adjunct professor of physics at the University of Utah. He earned his doctorate degree in inorganic chemistry from Karl-Franzens University Graz, Austria, and conducted postdoctoral research at the University of California, Santa Barbara. Dr. Bartl is the scientific co-founder of Navillum Nanotechnologies, and a Deputy Editor for Scripta Materialia. He was the recipient of a "DuPont Young Professorship", and was named a "Brilliant 10" researcher by Popular Science magazine in 2010 and a Scialog Fellow by the Research Corporation for Science Advancement in 2013. Dr. Bartl has published more than 50 journal articles about his research activities in functional nanostructured materials for energy and information technology applications.

Fanny Li joined the Center for Energy Efficient Electronics Science (E^3S) as Program Coordinator in February 2016. Previously, she supported the Center as a student, where she focused on event planning and the education programs. While at UC Berkeley, she served as coordinator and mentor for Oakland Asian Student Educational Services (OASES), a non-profit organization providing services to underrepresented and less privileged youth. She also collaborated with colleagues across the Bay Area to organize Bay Area's largest education hackathon. She earned her bachelor of arts degree in Integrative Biology at the University of California, Berkeley in May 2015.

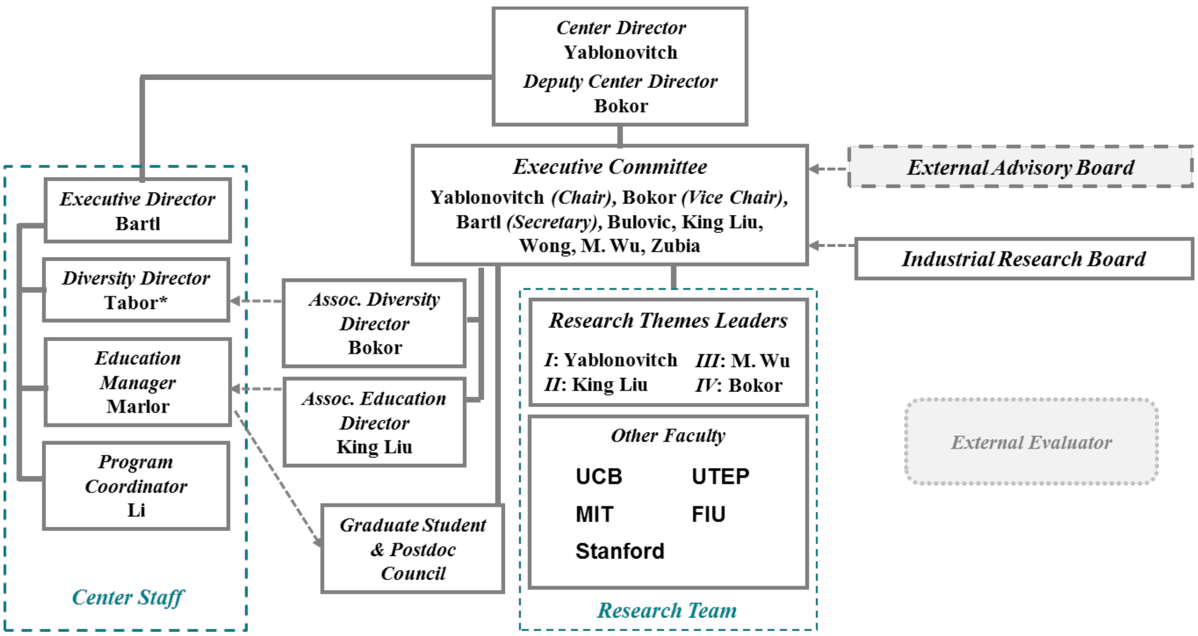
Dr. Aimee Tabor* joined the Center for Energy Efficient Electronics Science (E^3S) as Diversity & Outreach in December 2015. Previously, she was the Education Director for the TRUST Science & Technology Center. At TRUST, she had responsibility for strategic planning and program development to meet the Center's broader impact goal of increasing participation of women and underrepresented minorities in computer science. Additionally, she was also responsible for outreach and professional development for TRUST graduate students. Prior to TRUST, she worked as program evaluator for San Francisco Unified School District auditing the work and progress on consultants and school interventions. Dr. Tabor has an Ed.D. from the University of Pennsylvania and B.A. from the University of California, San Diego.

**We are saddened to report that Dr. Tabor passed away only nine days after she joined the Center.*

Appendix C: Organizational Chart

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

January 13, 2016



Tragically, Dr. Tabor passed away on December 9, 2015.

Appendix D: 2015 Research Seminars Attendance

Dates	Faculty	Postdocs	Graduate Students	Undergrad Students	Staff	Other
2015 Seminar Series						
February 11	3	6	13	0	4	3
February 25	0	6	6	0	2	2
March 11	3	4	12	0	3	2
April 8	3	5	9	1	4	1
April 15	3	9	8	1	4	1
April 29	3	6	10	1	3	2
June 18	4	8	13	11	4	3
July 2	5	7	11	11	4	9
July 16	4	5	7	10	4	6
July 30	3	10	6	8	4	2
October 15	5	18	4	1	3	0
October 29	2	4	4	1	3	1
November 12	2	5	7	0	2	0
December 3	4	5	7	0	5	0

Appendix E: E^3S Professional Development Program

Objective: Equip E3S graduate students and postdocs with the skills and experiences needed to maximize their potential and success in their professional careers.

Requirements: Formal, but flexible.

- One outreach **OR** mentoring training area required
  - Diversity training embedded into outreach and mentoring
- Three other areas required

Training Areas

- Outreach
  - Attend outreach training (1 hour)
  - Take lead in 1 outreach event **OR** supporting role in 3 events
- Mentoring
  - Attend mentor training (1-hour)
    Mentor an undergraduate or high school student
- Leadership
  - Complete online or in-person leadership training (1 hour)
  - Take lead in 1 leadership event **OR** supporting role in 3 events
- Science Communication
  - Attend a science communication workshop (1 hour)
  - Present research to center (1 hour)
  - Present research to non-center audience (1 hour)
- Proposal Writing
  - Attend a proposal writing workshop (1 hour)
  - Submit a proposal
- Teaching
  - Complete online or in-person teacher training
  - Practice teaching **OR** develop course curriculum at any academic level of your choice
- Entrepreneurship
  - Attend a entrepreneurship workshop (1 hour)
  - Develop and submit a business plan **OR** complete innovation and commercialization course

Honors/Award: Receive E^3S professional development certificate for completion for required training areas.

Student Name:

____

Professional Development Interests & Opportunities

LEADERSHIP	
_____	Graduate Student & Postdoc Council: Organize one meeting per term to discuss E3S students/postdocs activities, events, concerns (fall & spring/1-3 hours)
_____	Research Teleseminar Coordinator: Contact speakers and set up videoconference (fall & spring/bi-weekly)
_____	Journal Club Coordinator: Contact speakers and set up videoconference (summer/bi-weekly)
_____	Retreat Planning Committee: Help plan and host student/postdoc retreat (August/5-10 hours)
_____	Spring Research Review Committee: Help plan and host 1-day spring conference for E3S students/postdocs (Spring/5-10 hours)
_____	STC Directors Meeting: Serve as E3S students/postdocs student representative and participate in poster session (August or September/1-2 days)
_____	Institution Representative: Serve as point of contact to welcome new students/postdocs to center at your institution and relay student concerns to the student council and to bring up to the executive committee (1-year term)
TEACHING & CURRICULUM DEVELOPMENT	
_____	E3S Summer Research Workshop (E3S SRW): Instruct one-week course on introduction to electronics (1 week in summer/40 hours)
_____	Curriculum Development: Create tradition and online course modules for in energy efficient electronics topics for teachers and high school students (10-20 hours)
MENTORING	
_____	E3S Research Experience for Undergraduates (E3S REU): Mentor undergraduate students during summer (9-week internship/40 hours per week)
_____	E3S Internship (ETERN): Mentor undergraduate students during fall/spring terms (10-week internship/10 hours per week)
_____	MIT Online Science Technology Engineering Community (MOSTEC): Mentor high school students online. Provide information about being a scientist of engineer, discuss how to apply to college, provide guidance on research project (August – January/1-3 hours per week)
EVALUATION	
_____	REU Poster Evaluator: Review poster at summer research program end-of-year poster symposium (1 day/2 hours)

_____	REU Application Evaluator: Review applications for summer research programs (5-10 hours)
RESEARCH (Posters)	
_____	Site Visit Poster Session: Present your research at NSF Site Visit (1-2 days: January 8-9, 2013)
_____	BEARS Poster Session (UC Berkeley only): Present your research to industrial partners and potential donors (February 2013/2 hours)
_____	Graduate Student Visit Day – Poster Session: Present your research to admitted graduate students (March 2013/2 hours)
RESEARCH (Presentations)	
_____	Present at research seminar (fall or spring /1 hour)
_____	Present at journal club (summer /1 hour)
RESEARCH (Tours)	
_____	Cleanroom tour
_____	Lab tour
_____	Other, please specify: ________________________________
OUTREACH	
_____	Research presentation for non-scientists & engineers (e.g., teachers, middle and high school students (1 day/1-2 hours)
_____	Lead hands-on project for high school students (1 day/2 hours)
_____	Serve as judge at science fair (1 day/2-4 hours)
_____	Demonstrate research at science fair for middle and high school students (1 day/2-4 hours)
_____	Panel member: Talk about experience as scientist or engineer (1 day/1-2 hours)
_____	Present to summer research students on career development topics (e.g., creating posters, giving technical talks, applying for fellowships, writing scientific papers, applying to graduate school, etc.) (1 day/1-2 hours) Please specify topic(s) of interest: _________________________
OTHER *(must be approved by Education and Outreach Director)*	
_____	Please specify:
_____	Please specify:

Appendix F: E3S REU Joint Recruitment Calendar

2015 Joint Recruitment Calendar

for Summer Research Experiences for Undergraduates and Engineering Graduate Diversity

April 2015			
Women in Cyber Security	March 27-28	Atlanta, GA	Trust
October 2015			
Grace Hopper Conference	October 14-16	Houston, TX	COE
Society for Advancement of Chicanos and			
Native Americans in Science (SACNAS) Conference	October 29-31	Washington, D.C.	E3S
Society of Women Engineers	October 22- 24	Nashville, TN	E3S
November 2015			
Hampton University & Norfolk State University	November 4	Norfolk, VA	E3S
Morgan State University	November 12	Baltimore, MD	E3S
University of the District of Columbia	November 12	Washington, D.C.	E3S
Society of Hispanic Prof Engineers Annual Conf	November 13-14	Baltimore, MD	E3S
American Indian Science and Engineering Society	November19-21	Phoenix, AZ	COE
December 2015			
E3S Webinar: Program Overview and Q & A	December 2	Online	E3S
January 2016			
E3S Webinar: Program Overview and Q & A	January 19	Online	E3S
E3S Webinar: Program Overview and Q & A	January 25	Online	E3S

Appendix G: TTE REU Recruitment Calendar

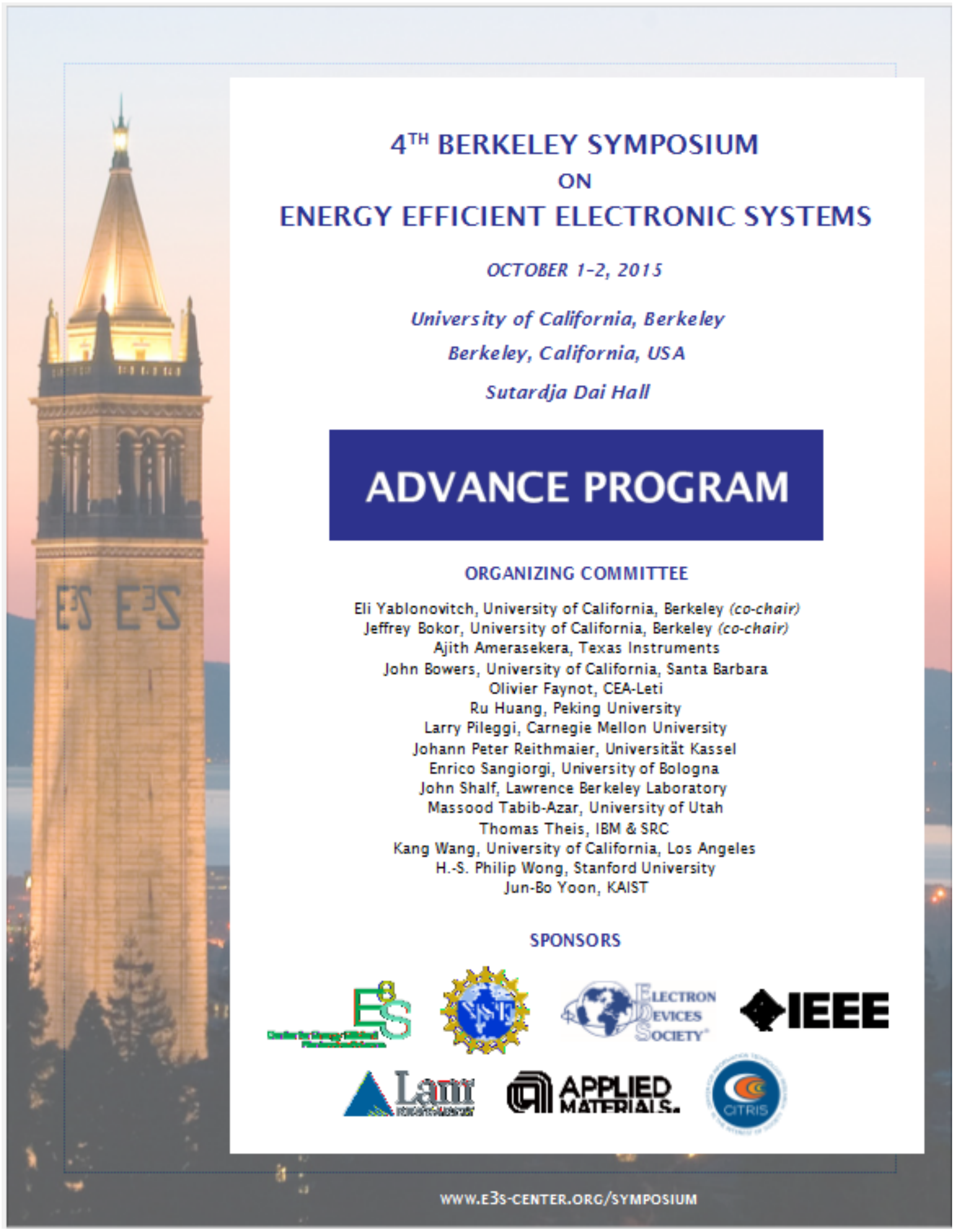
October 2015		
UC-Berkeley’s Community College Day	October 9	Berkeley, CA
Society for Advancement of Chicanos and Native Americans in Science (SACNAS) 2014 Conference	October 29-31	Washington, D.C.

November 2015		
Society of Hispanic Professionals Engineers Annual Conference	November 13-14	Baltimore, MD
Diablo Valley College	November 12	Walnut Creek, CA
East Lost Angeles College	November 13	Los Angeles, CA
Los Angeles Trade Technical College	November 13	Los Angeles, CA
El Camino College	November 13	Los Angeles, CA

December 2015		
Webinar- Topic: Program Overview, Q & A	December 2	Online
Sacramento City College	December 4	Sacramento, CA
Reedley College	December 10	Reedley, CA

January 2016		
Webinar- Topic: Program Overview, Q & A	January 19	Online
Webinar- Topic: Program Overview, Q & A	January 25	Online

Appendix H: 2015 Berkeley Symposium on Energy Efficient Electronic Systems



4TH BERKELEY SYMPOSIUM
ON
ENERGY EFFICIENT ELECTRONIC SYSTEMS

ADVANCE PROGRAM

THURSDAY, OCTOBER 1 — **Banatao Auditorium, Sutardja Dai Hall**

8:00 AM **Badge Pick-up & Breakfast**

8:45 AM ***Session I: Opening Session***
Moderator - E. Yablonovitch: University of California, Berkeley, USA

Opening Remarks
E. Yablonovitch and **J. Bokor**: University of California, Berkeley, USA

Specialization for Energy Efficiency Using Agile Development
B. Nikolic, J. Bachrach, E. Alon, K. Asanovic, and D. Patterson: University of California, Berkeley, USA **(Invited)**

Superconducting Computing: Lessons from an Emerging Technology
D. S. Holmes: IARPA, USA **(Invited)**

Millivolt Switches Will Support Better Energy-Reliability Tradeoffs
E. Debenedictis and H. Zima: Sandia National Laboratory, USA

SOTB Technology, which Enables Perpetually Reliable CPU for IoT Applications
K. Ishibashi, N. Sugii, K. Kobayashi, T. Koide, H. Nagatomi and S. Kamohara: University of Electro-Communications, Japan

10:20 AM **Break**

10:40 AM ***Session II: Spintronics***
Moderator - J. Bokor: University of California, Berkeley, USA

mLogic: All Spin Logic Device and Circuits
J.-G. Zhu, D. M. Bromberg, M. Moneck, V. Sokalski, and L. Pileggi: Carnegie Mellon, University, USA **(Invited)**

Electric-Field-Controlled MRAM based on Voltage Control of Magnetic Anisotropy (VCMA): Recent Progress and Perspectives
P. Khalili and K. Wang: University of California, Los Angeles, USA **(Invited)**

Magnonic Holographic Co-Processor: an Approach to Energy-Efficient Complementary Logic Circuitry
A. Khitun: University of California, Riverside, USA

Quantitative Comparison of Power-Gating Architectures for FinFET-based Nonvolatile SRAM using Spintronics Retention Technology
Y. Shuto, S. Yamamoto and S. Sugahara: Tokyo Institute of Technology, Japan

Anomalous Properties of Sub-10-nm Magnetic Tunneling Junctions
M. Stone, J. Hong, R. Cuduru, A. Hadjikhani, A. Manossaukis, E. Stimphil, P. Liang, J. Bokor and S. Khizroev: Florida International University, USA

Spintronics Panel

12:30 PM **Lunch**

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4TH BERKELEY SYMPOSIUM
ON
ENERGY EFFICIENT ELECTRONIC SYSTEMS

ADVANCE PROGRAM

THURSDAY, OCTOBER 1 | **Banatao Auditorium, Sutardja Dai Hall**

1:45 PM **_KEYNOTE PRESENTATION_**
Introduced by E. Yablonovitch: University of California, Berkeley, USA
What the Brain Tells Us about the Future of Silicon
J. Hawkins: Numenta, USA **(Invited)**

2:25 PM ***Session III: Nanomechanical Logic***
Moderator - N. Draeger: Lam Research, USA
From Microelectromechanical Switches to Nanoelectromechanical Switches: Lessons and Differences
J.-B. Yoon: KAIST, Korea **(Invited)**
Operating Micromechanical Logic Gates Below kBT: Physical vs Logical Reversibility
M. López-Suárez, I. Neri, and L. Gammaitno: University of Perugia, Italy **(Invited)**
Body-Biased Operation for Improved MEM Relay Energy Efficiency
A. Peschot, C. Qian, D. J. Connelly and T.-J. King Liu: University of California, Berkeley, USA
Tunneling Nanoelectromechanical Switches
F. Niroui, E. Sletten, Y. Song, A. Wang, W. J. Ong, Jing Kong, E. Yablonovitch, T. Swager, J. Lang and V. Bulovic: MIT, USA

3:45 PM **Break**

4:05 PM ***Session IV: Devices with Novel Materials***
Moderator - N. Kim, Applied Materials, USA
Van der Waals Heterostructures for Tunnel Transistors
T. Roy, M. Tosun, M. Amani, D.-H. Lien, D. Kiriya, P. Zhao, S. Desai, A. Sachid, S. R. Madhvapathy, and **A. Javey**: University of California, Berkeley, USA **(Invited)**
2D Tunnel Transistors for Ultra-Low Power Applications: Promises and Challenges
H. Ilatikhameneh, G. Klimeck and R. Rahman: Purdue University, USA
Understanding Negative Capacitance Dynamics in Ferroelectric Capacitors
A. Khan, K. Chatterjee, S. Salahuddin and R. Ramesh: University of California, Berkeley, USA

5:05 PM **Walk to the Gordon and Betty Moore Lobby, Hearst Memorial Mining Building**

5:25 PM *Poster Session and Reception*

7:15 PM **Close of Day 1**

3

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4TH BERKELEY SYMPOSIUM ON ENERGY EFFICIENT ELECTRONIC SYSTEMS

ADVANCE PROGRAM

THURSDAY, OCTOBER 1, 5:25 - 7:15 PM **Hearst Mining Memorial Building**

Poster Session and Reception

1. *Ambient Temperature Optimization for Enterprise Servers: Key to Large-Scale Energy Savings*
   K. Vaidyanathan, K. Gross and S. Sondur: Oracle Corp., USA
2. *Not Faster nor Slower Tasks, but Less Energy Hungry and Parallel: Simulation Results*
   S. Xavier-De-Souza, C. Barros, M. Jales and L. Silveira: Universidade Federal do Rio Grande do Norte, Brazil
3. *An Ultra-Low-Power Low-Noise Amplifier in 45nm SOI CMOS for Portable EEG Applications*
   P. Cadfort: US Army Research Laboratory, USA
4. *Mapping 1D-FFT on an Energy Efficient 3D FPGA-DRAM Architecture*
   P. Cadfort, A.Dasu and A. Akoglu: US Army Research Laboratory, USA
5. *Magneto-Electric Magnetic Tunnel Junction Logic Devices*
   N. Sharma, A. Marshall, J. Bird and P. Dowben: University of Texas, Dallas, USA
6. *The Energy Scaling Advantages of RRAM Crossbars*
   S. Agarwal, O. Parekh, T.-T. Quach, C. James, J. Aimone, and M. Marinella: Sandia National Laboratories, USA
7. *Spin-Orbit Torques: Direct Optical Characterization and Laser Assisted Magnetization Switching*
   Y. Yang, A. Pattabi, J. Gorchon, Z. Gu, R Wilson, J. Finley, O. J. Lee, H. Abdel-Raziq, D. Bhowmik, S. Salahuddin and J. Bokor: University of California, Berkeley, USA
8. *Ultrafast Spin Dynamics as Route to High Speed and Energy Efficient Information Technologies*
   T. Rasing: Radboud University, Netherlands
9. *Defect and Temperature Dependence of Tunneling in InGaAs/GaAsSb Heterojunctions with Varying Band Alignments*
   R. Iutzi, C. Heidelberger and E. Fitzgerald: MIT, USA
10. *Low-Noise Near-Ballistic BN-Graphene-BN Heterostructure Field-Effect Transistors for Energy Efficient Electronic Applications*
    M. Stolyarov, A. Balandin, M. Shur and S. Rumyantsev: University of California, Riverside, USA
11. *Regioregular Synthesis of Boron-Doped Graphene Nanoribbons*
    R. Cloke, T. Marangoni and F. Fischer: University of California, Berkeley, USA
12. *An Improved Unipolar CMOS with Elevated Body and Spacer for Low-Power Application*
    W.-H. Lee, J.-T. Lin, K.-C. Juang, T.-C. Chang, C.-K. Huang, C.-C. Lai, B.-C. Yan and Y.-H. Lin: National Sun Yat Sen University, Taiwan
13. *Monolayer Strain by NEMS for Low Power Application*
    S. Almeida and D. Zubia: University of Texas at El Paso, USA

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4TH BERKELEY SYMPOSIUM ON ENERGY EFFICIENT ELECTRONIC SYSTEMS

ADVANCE PROGRAM

THURSDAY, OCTOBER 1, 5:25 - 7:15 PM **Hearst Mining Memorial Building**

Poster Session and Reception (continued)

14. *Sub-5 nm Gap Formation for Low Power NEM Switches*
    J. Cao, L. Li, K. Kato, T.-J. King Liu and H.-S.P. Wong: Stanford University, USA
15. *MEM Diode for Energy-Efficient Power Conversion*
    B. Osoba, C. Qian, A. Peschot and T.-J. King Liu: University of California, Berkeley, USA
16. *Electromechanically Actuating Molecules*
    W. J. Ong, E. Sletten, F. Niroui, J. Lang, V. Bulović and T. Swager: MIT, USA
17. *Novel Device Functionalities Enabled by Substitutional Doping Against Native Propensity in 2D Semiconductors*
    J. Suh, B. Saha and J. Wu: University of California, Berkeley, USA
18. *Electrically Injected Nanoled with Large Spontaneous Emission Enhancement from an Optical Antenna*
    S. Fortuna, M. Eggleston, K. Messer, E. Yablonovitch and M. Wu: University of California, Berkeley, USA: University of California, Berkeley, USA
19. *Optical Slot Antennas for Enhancement of WSe_2 Spontaneous Emission Rate*
    K. Messer, M. Eggleston, S. Desai, S. Fortuna, S. Madhavapathy, P. Zhao, J. Xiao, X. Zhang, A. Javey, M. Wu and E. Yablonovitch: University of California, Berkeley, USA
20. *Optical Interposer for Large Multichip Modules*
    A. Michaels and E. Yablonovitch: University of California, Berkeley, USA

7:15 PM **End of Day 1**

4TH BERKELEY SYMPOSIUM ON ENERGY EFFICIENT ELECTRONIC SYSTEMS

ADVANCE PROGRAM

FRIDAY, OCTOBER 2 — **Banatao Auditorium, Sutardja Dai Hall**

8:30 AM **Badge Pick-up & Breakfast**

9:00 AM ***Session V: Reconvening Session***
Moderator - T. Theis: IBM and SRC, USA

From Nanodevices to Nanosystems: The N3XT Information Technology
S. Mitra: Stanford University, USA **(Invited)**

KEYNOTE PRESENTATION
Our Computer Systems Are Not Good Enough
R. Colwell: Formerly, DARPA: USA **(Invited)**

10:15 AM ***Session VI: Nanoelectronics – Tunneling FET-1***
Moderator - O. Faynot: CEA-Leti, France

Impact of Interface Defects on Tunneling FET Turn-on Steepness
T. Xiao, X. Zhao, S. Agarwal and E. Yablonovitch: University of California, Berkeley, USA

A Framework for Generation and Recombination in Tunneling Field-Effect Transistors
J. Teherani, W. Chern, S. Agarwal, J. Hoyt and D. Antoniadis: MIT, USA

10:50 AM **Break**

11:10 AM ***Session VII: Nanoelectronics – Tunneling FET-2***
Moderator - A. Seabaugh: University of Notre Dame, USA

Influence of Interface Traps on the Performance of Tunnel FETs
D. Esseni, M. Pala, E. Gnani and E. Sangiorgi: University of Udine, Italy **(Invited)**

Challenges of Fulfilling the Promise of Tunnel FETs
S. Datta and R. Pandey: Pennsylvania State University, USA **(Invited)**

Tunneling FET Device Technologies Using III-V and Ge Materials
S. Takagi, M.-S. Kim, M. Noguchi, K. Nishi and M. Takenaka: University of Tokyo, Japan **(Invited)**

Tunneling FET Panel

12:35 PM **Lunch**

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4TH BERKELEY SYMPOSIUM
ON
ENERGY EFFICIENT ELECTRONIC SYSTEMS

ADVANCE PROGRAM

FRIDAY, OCTOBER 2 — **Banatao Auditorium, Sutardja Dai Hall**

2:00 PM **_Session VIII: Optical Interconnects_**
Moderator - A. Krishnamoorthy: Oracle Corporation, USA

Optical Antenna-Enhanced Nano LED for Energy-Efficient Optical Interconnect
M. C. Wu, E. Yablonovitch, S. Fortuna, M. Eggleston, and K. Messer: University of California, Berkeley, USA **(Invited)**

Low Capacitance, High Speed Phototransistors With a Large Absorption Region
C. Lalau Keraly, R. Going, M. C. Wu and E. Yablonovitch: University of California, Berkeley, USA

High-density 3D Electronic-Photonic Integration
V. Stojanovic: UC Berkeley, USA **(Invited)**

Optoelectronic Integration for Reduced Power Dissipation
De Dobbelaere: Luxtera, Inc, USA **(Invited)**

Silicon Photonics Panel

3:45 PM **_Closing Remarks_**
E. Yablonovitch and **J. Bokor**: University of California, Berkeley, USA

4:00 PM **End of Symposium**

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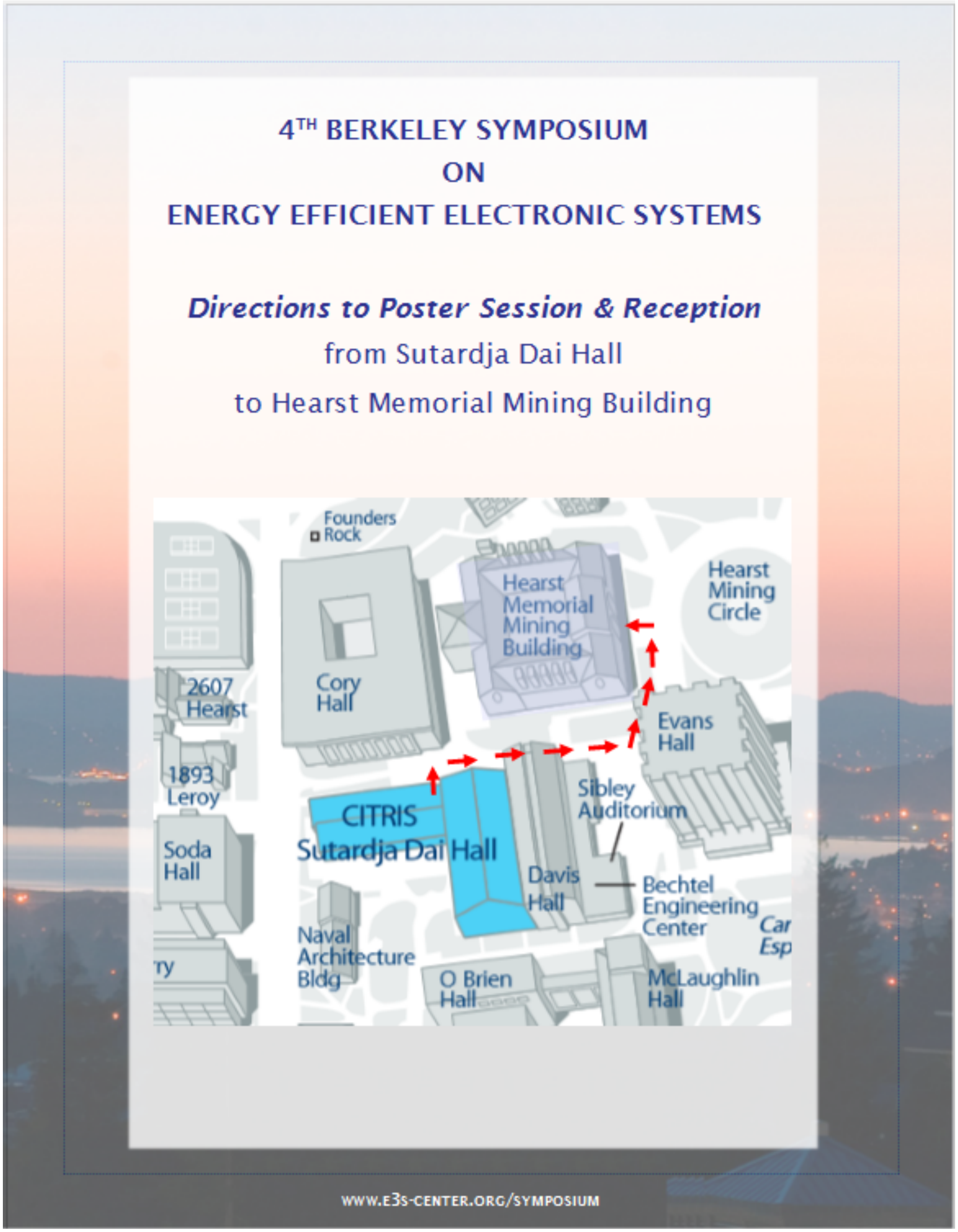
4TH BERKELEY SYMPOSIUM
ON
ENERGY EFFICIENT ELECTRONIC SYSTEMS
Directions to Poster Session & Reception
from Sutardja Dai Hall
to Hearst Memorial Mining Building
Founders Rock
Hearst Memorial Mining Building
Hearst Mining Circle
2607 Hearst
Cory Hall
Evans Hall
1893 Leroy
CITRIS
Sutardja Dai Hall
Sibley Auditorium
Soda Hall
Davis Hall
Bechtel Engineering Center
Naval Architecture Bldg
O Brien Hall
McLaughlin Hall
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6th Annual Retreat:
Toward A Legacy of Home Runs

September 13-14, 2015
50 Vassar Street
MIT, Cambridge, MA

ADVANCE AGENDA

Sunday, September 13, 2015

Grier Room (34-401 A&B)

Time	Duration	Activity / Topic	Speakers
9:30 AM	0:30	*Breakfast & Check-In*	
10:00 AM	0:10	**Welcome, Review of Agenda & Meeting Goals**	**Yablonovitch**
10:10 AM	0:55	**The Center in Context**	
	0:20	*Ultra-Low Energy Devices: What are the Home Runs?*	**Yablonovitch**
	0:15	*3D Integration of Logic and Memory - the N3XT 1000X in Energy Efficiency*	**Wong**
	0:20	*Open Discussion: Other Competing Emerging Technologies, including negative-capacitance MOSFET, analog neural nets, etc.*	*Discussion Leader:* **Alon**
11:05 AM	0:15	*Break*	
11:20 AM	1:30	***Theme I: Nanoelectronics***	
	0:20	*t-FET's as a: Dit versus dN/dE problem*	**Yablonovitch**
	0:20	*Research status of t-FET centers world-wide*	**Chern & Xiao**
	0:10	*Latest progress in monolayer chalcogenides*	**Javey**
	0:10	*Progress in molecular synthesized graphene nanoribbons*	**Fischer**
	0:10	*New results in conventional semiconductor t-FET's*	**Antoniadis**
	0:20	*Wide-ranging discussion regarding possible Home Runs*	*Discussion Leader:* **Yablonovitch**
1:30 PM	1:05	**Theme IV: Nanomagnetics**	
	0:20	*Nano-magnetics: What can be a Home Run?*	**Bokor**
	0:10	*Optimization of voltage/energy in magnetic logic*	**Stojanovic**
	0:10	*Hybrid CMOS/STTRAM architectures for low energy processing*	**Salahuddin**
	0:10	*Worldwide competitive analysis in magnetic switching*	**Stone**

	0:15	*Discussion: what can be promised for the 2nd 5yrs?*	*Discussion Leader:* **Bokor**
2:35 PM	0:55	**Theme II - Nanomechanics**	
	0:20	*Nano-Hydraulic communication for logic circuits*	**King Liu**
	0:10	*How many gates are needed for Internet of Things slow data compression?*	**Alon**
	0:10	*Can squitches go to low voltage?*	**Lang**
	0:15	*Discussion: what can be promised for the 2nd 5yrs?*	*Discussion Leader:* **King Liu**
3:30PM	0:15	*Break & Poster Setup*	
3:45PM	1:00	**Theme III: Nanophotonics**	
	0:15	*Can we promise a complete optical communications system?*	M. Wu
	0:10	*Electrically injected optical antenna LED*	Fortuna
	0:10	*Optical antenna spontaneous emission competitors*	Messer
	0:10	*What's the most sensitive nano-photodetector system?*	Keraly
	0:15	*What nano-photonic opportunities are being overlooked?*	*Discussion Leader:* **Bulović**
	0:15	*Break & Poster Setup*	
5:00 PM	1:00	*Poster Session*	
6:00 PM	1:15	*Dinner and Recognitions (Haus-Allen Rooms, 36-428 & 462)*	
7:15 PM		*End of Day 1*	

2015 E^{3}S Annual Retreat Posters

Title	Authors (*Poster Presenters)
Theme I	
1. Site-Specific Substitutional Boron-Doping of Semiconducting Armchair Graphene Nanoribbons	R. R. Cloke, T. Marangoni, G. D. Nguyen, T. Joshi, D. J. Rizzo, C. Bronner, T. Cao, S. G. Louie, M. F. Crommie, and **F. R. Fischer***
2. Tunneling in Band Alignment-Tunable InGaAs/GaAsSb Heterojunctions	**R. Iutzi*** and E. Fitzgerald
Theme II	
3. NEM Relays Using van der Waals Nanomaterials for Low Energy Contact with Tunable Tunneling Gap and Zero Leakage and Detailed Measurements of Tunneling Across Relay Gap	**J. Cao***, S. Lee, and H.-S. P. Wong
4. 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, V. Bulovic
5. Advanced Materials Engineering for NEM Relay	**B. Saha***, C. Ko, B. Osoba, T. J. King Liu, J. Wu
6. MoS_2 Strained by NEMS for Low Power Application	**S. Almeida***, S. Desai, C. Qian, T. J. King Liu, A. Javey, D. Zubia
Theme III	
7. Near-Unity Photoluminescence Quantum Yield in MoS_2	**M. Amani***, D.-H. Lien, D. Kiriya, S. R. Madhvapathy, E. Yablonovitch, and A. Javey
8. Large Spontaneous Emission Rate Enhancement in Electrically-Injected nanoLED Coupled to an Optical Antenna	**S. Fortuna***, M. Eggleston, K. Messer, E. Yablonovitch, M. C. Wu
9. III-V Nanopillar Phototransistor Directly Grown on Silicon	**I. Bhattacharya***, W. Ko, T. Tran, F. Lu, S. Deshpande, C. Chang-Hasnain, M. C. Wu, E. Yablonovitch, D. Zubia
10. Helium-Ion Milling of Gold Slot Antennas	**K. Han***, M. C. Wu
11. Limits to Efficient Enhancement of Spontaneous Emission Rates in Light Emitters	**K. Messer***, M. Eggleston, S. Fortuna, M. C. Wu, E. Yablonovitch
Theme IV	
12. Exploring Different Types of Nano Magnetic Tunneling Junction Devices	**J. Hong***, A. Hadjikhani, M. Stone, F. Allen, P. Liang, S. Khizroev, J. Bokor
13. Direct Optical Detection of Current Induced Spin Accumulation Through Magnetization Induced Second Harmonic Generation	**A. Pattabi***, Z. Gu, J. Gorchon, Y. Yang, J. Finley, H. A. Raziq, O. J. Lee
14. Ultrafast Non-Equilibrium Magnetic Switching	**Y. Yang***, J. Gorchon, R. Wilson, A. Pattabi, H. Abdel-Raziq, D. Bhowmik, O. Lee, J. Chen, L. He

ADVANCE AGENDA

Day 2 – Monday, September 14, 2015

Haus-Allen Rooms (36-428 & 462)

Time	Duration	Activity / Topic	Speaker/Facilitator
8:45 AM	0:30	*Breakfast*	
9:15 AM	1:15	**Education Legacy Discussion**	**King Liu**
10:30 AM	0:15	*Break*	
10:45 AM	1:00	**Diversity Talk & Discussions**	**Prof. Manu Platt, Georgia Tech & EBICS STC** *(invited speaker)*
11:45 AM	1:00	**Building Legacy & Tracking Successes**	**Yuen**
12:35 PM	0:10	**Closing Statement**	**Yablonovitch**

Parallel Sessions			
		Haus Room	*Allen Room*
12:45 PM	2:00	**Faculty Lunch & Dialog Session**	**Students & Postdocs Lunch & Proposal Writing Workshop** **Prof. Sheryl Sorby, OSU** *(trainer)*
2:45 PM	0:15	*Break*	
3:00 PM	1:15	**Executive Committee Meeting**	

4:15PM *Last Departure for Airport*

Center for Energy Efficient Electronics Science

Appendix J: 2015 Joint Meeting of the E3S External Advisory Board & E3S Industry Members

Agenda
University of California, Berkeley
Friday, November 20, 2015

Presentations: 210 McLaughlin Hall, Poster Session: 550 Sutardja Dai Hall
External Advisory Board Deliberations: 210 McLaughlin Hall
Industry Partners Meeting with Faculty: 552 Sutardja Dai Hall

Webex Meeting Number: 805 683 398
Meeting Link: https://e3s.webex.com/e3s/j.php?MTID=mfbac47ba01fdd43d1ae1d9ee070113e8
Audio Connection: 1-650-479-3208 Call-in toll number (US/Canada) Access Code: 805 683 398

Time	Topic	Speakers	Session Duration
8:30 AM	*Breakfast*		
9:00 AM	Welcome & Overview	Yablonovitch	*0.30*
9:30 AM	Education & Diversity; Q&A	Marlor	*0:45*
10:15 AM	Center Management & Knowledge Transfer; Q&A	Yuen	*0:30*
10:45 AM	*Break*		
11:00 AM	Research Overview; Q&A	Yablonovitch	*0:55*
11:55 AM	Theme I; Q&A	Yablonovitch, Xiao & Amani	*0:40*
12:35 PM	*Lunch*		*0:40*
1:15 PM	Theme II; Q&A	King Liu & Bulovic	*0:40*
1:55 PM	Theme III; Q&A	Yablonovitch, Messer & Keraly	*0:45*
2:40 PM	Theme IV; Q&A	Bokor & Bhowmik	*0:40*
3:20 PM	Wrap-up; Q&A	Yablonovitch	*0:30*
3:50 PM	*Break*		
4:05 PM	Poster Session		*0:40*
4:45 PM	External Advisory Board – Deliberations (Duration: 1:30)	Industry Partners Meeting with Faculty (Duration: 1:00)	
6:15 PM	Critical Feedback to E^{3}S		*0.30*
6:45 PM	*Conclusion*		

Appendix K: Annual Graduate Students & Postdocs Survey

Year to Year Comparison

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

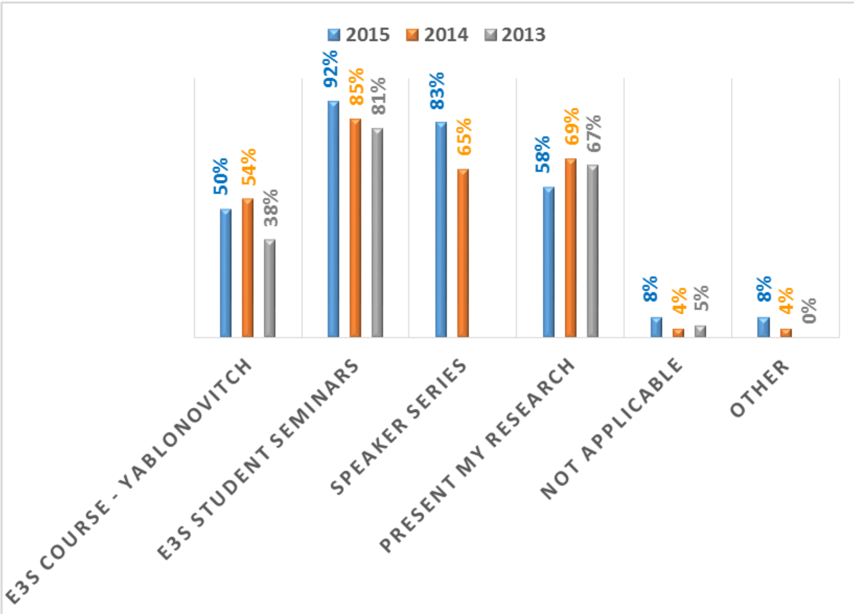
Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree

		2015	**2014**	**2013**	**2012**	**2011**
	Total Number of Respondents	29	26	21	20	15
	Survey Questions					
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.	4.4 ± 0.6	4.6 ± 0.6	4.4 ± 0.5	4.2 ± 0.7	4 ± 1
	The Center is making progress in its research program.	4.4 ± 0.7	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.	4.6 ± 0.5	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.	4.3 ± 0.9	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.	4.6 ± 0.6	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.	4.4 ± 0.8	4.5 ± 0.7			

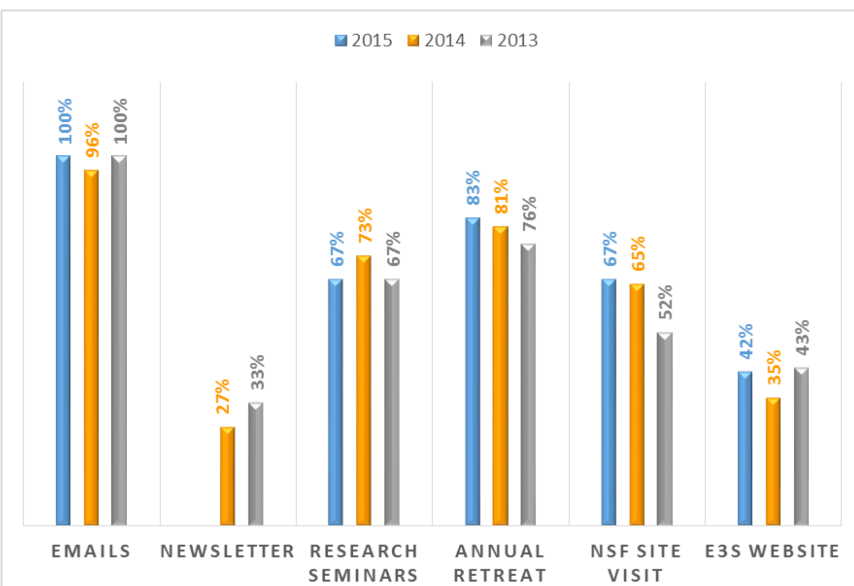
Communication	The Leadership Team keeps Center members well informed as there is a clear and timely communication on all Center activities.	4.2 ± 0.8	4.7 ± 0.6	4.2 ± 0.6	4.2 ± 0.5	4 ± 0.7
Collaboration	The Leadership Team provides a research environment that is collaborative.	4.3 ± 0.8		4.2 ± 0.7	4.2 ± 0.7	3.7 ± 0.7
	The Leadership Team is providing a work environment that values and encourages teamwork.	4.4 ± 0.8	4.6 ± 0.5	3.9 ± 0.8		
	The Leadership Team is providing opportunities to collaborate.	4.2 ± 1.0	4.8 ± 0.4	4.1 ± 0.9		
	The Leadership Team is providing tools that facilitate collaboration.	4.3 ± 1.1	4.4 ± 0.8	4.1 ± 0.7		
	Since joining the Center, I have developed a working relationship with someone in the Center who is not part of my home institution.	4 ± 1	4 ± 1	4 ± 1	3 ± 1	
Decision Making	The Leadership Team is effective in making decisions on behalf of the Center.	4.5 ± 0.6		4.2 ± 0.7	4.1 ± 0.6	4.1 ± 0.6
	The Leadership Team is agile in making decisions on behalf of the Center.	4.5 ± 0.6		4.1 ± 0.9	4.1 ± 0.7	3.9 ± 0.7
	The Leadership Team is making decisions that are in the best interest of the Center.	4.4 ± 0.6	4.5 ± 0.6			
Performance Focus	The Leadership Team promotes a culture permeating the Center's relationships, processes, and activities that recognize and values performance, and avoids possessiveness.	4.3 ± 1.0	4.5 ± 0.6	4.1 ± 0.7	3.9 ± 0.9	4 ± 1
	The Leadership Team is recognizing and evaluating me on my performance.	4.0 ± 1.0	4.4 ± 0.7	3.8 ± 1.0		

Part B: Effectiveness of the Center's Activities

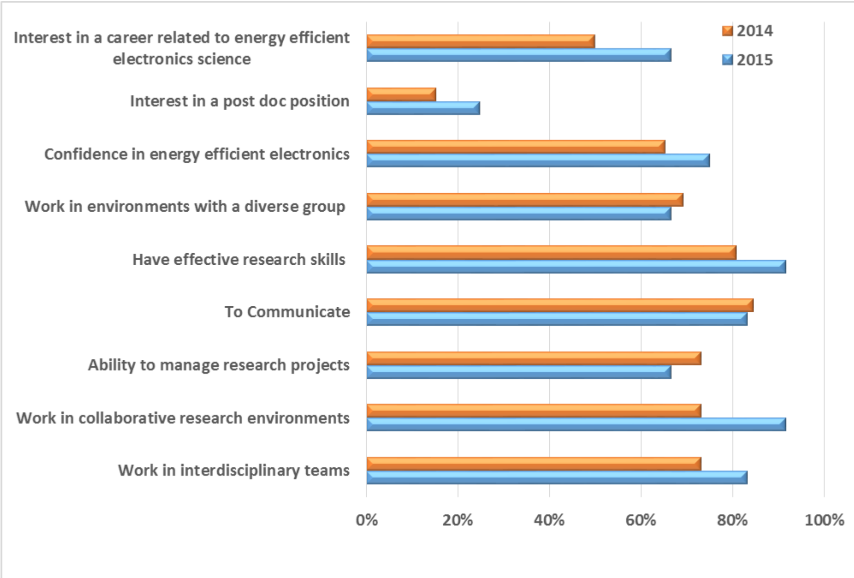
1. Respondents indicated the following activities are sharpening their understanding of low energy consumption device science and technology.



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

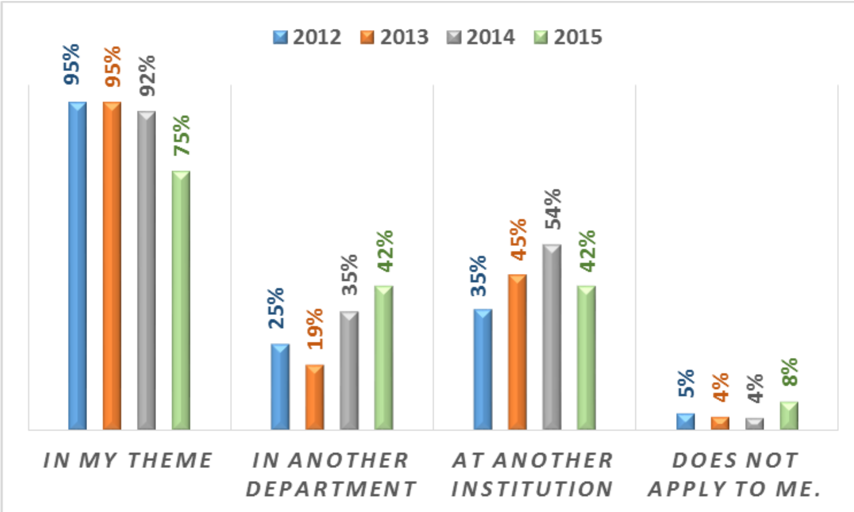


3. Respondentss identified the following areas were positively impacted as a result of their experience at E^3S.

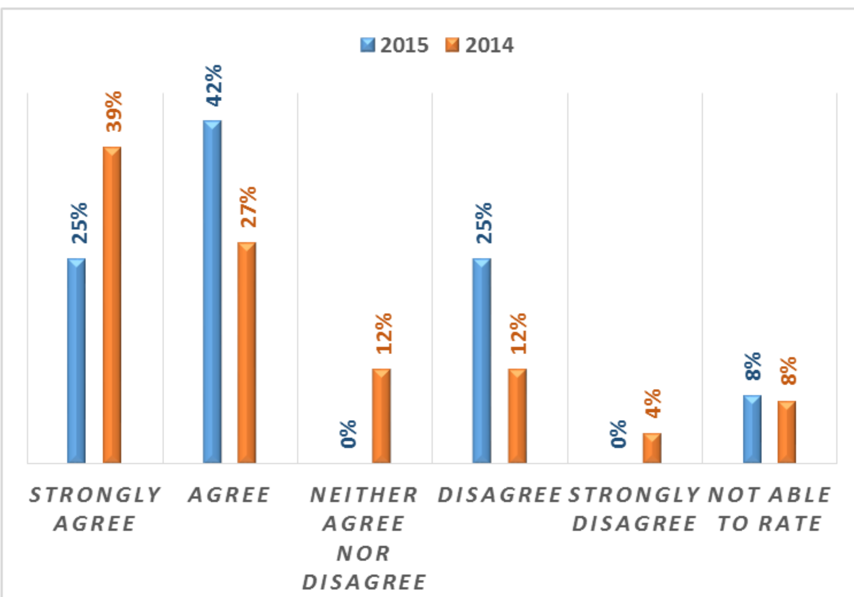


Part C: State of Collaborations

1. Respondents indicated that the following people helped with their E^{3}S research.

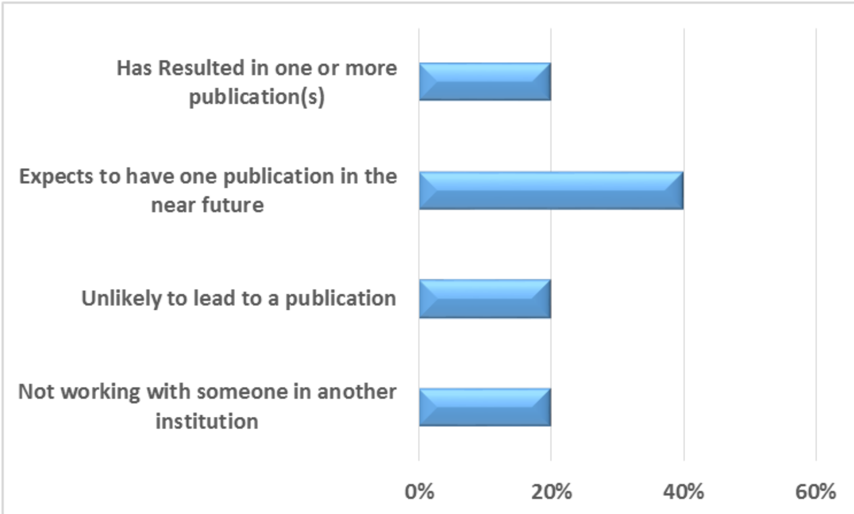


2. Respondents have developed a working relationship with someone in the Center who is not part of their home institution.



Center for Energy Efficient Electronics Science

3. Respondents' collaboration with someone in another institution has or will have the following results.



Part D: Ethics

100% of respondents felt that their E^3S colleagues acted in an ethical manner.

Appendix L: Annual Faculty Survey

Year to Year Comparison

Leadership Survey

Responses in Likert Scale: 5=Strongly Agree; 4=Agree; 3=Neutral; 2=Disagree; 1=Strongly Disagree

The E^{3}S leadership team is dedicated to:	2013	2014	2015
Creating an inclusive work environment.	4.8±0.4	5.0±0	4.9±0.2
Promoting a work environment that values and encourages teamwork.	4.8±0.4	5.0±0	4.9±0.3
Providing open and timely communication to me.	4.7±0.5	4.9±0.3	4.7±0.6
Recognizing and evaluating me on my performance.	4.3±0.8	4.7±0.7	4.7±0.6
Making decisions that are in the best interest of the Center.	4.8±0.4	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	4.9±0.3
Providing tools that facilitate collaboration.	4.5±0.7	4.7±0.6	4.6±0.6
Educating a diverse generation	4.8±0.4	4.9±0.5	4.9±0.3
Identifying fundamentally new concepts and scientific principles	4.9±0.3	4.9±0.2	4.9±0.2

In addition, all respondents answered the question "*I feel that my E^{3}S colleagues act in an ethical manner*" with **YES**.