Center for Energy Efficient Electronics Science

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First Annual Report

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

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I. GENERAL INFORMATION

1a. Center Information

Date submitted	December 22, 2010
Reporting period	September 15, 2010 – February 28, 2011
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.

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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	Tuskegee is a research, education, and outreach partner to encourage greater minority participation in engineering.

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Role of Institution at Center	Contra Costa College is an education and outreach partner to encourage greater minority participation in engineering.

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Role of Institution at Center	LATTC is an education and outreach partner to encourage greater minority participation in engineering.

1b. New Center Faculty

No new center faculty was added during this reporting period.

1c. Report Point of Contact

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

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2. *Context Statement*

Information processing equipment, including all personal computers, consumer electronics, telephony, office equipment, network equipment, data centers and servers, and supercomputers consume a significant fraction of electricity production. This aggregate energy is growing dramatically with time. Moreover, energy and power constraints loom over information processing technology, for both grid connected and portable applications, independent of supply constraints. Without fundamental and conceptual breakthroughs in the underlying physics, chemistry, and materials science that form the foundation of information processing technologies, the inexorable growth in the role of information in our society will require a decrease in the energy per digital function.

The Center for Energy Efficient Electronics Science (E^3S) was established in 2010 to respond to this challenge. The Center's focus is at the heart of information processing, the basic logic switch, and the short-to-medium range communication of information between logic elements. These elements represent the root of the energy dissipation in information processing systems. In large measure, we have become too dependent on the transistor. The transistor, which has defined the technology of our age, suffers from a serious drawback, in that it requires a powering voltage close to 1 Volt ($>>kT/q=26$ milli Volts) to operate well. On the other hand, the wires of an electronic circuit could operate, with tolerable signal-to-noise ratio, even at voltages as low as 1 milli-Volt. Indeed the energy per bit-function in digital electronics is currently $\sim 10^6$ times higher than it need be.

The Center for E^3S is a partnership of UC Berkeley, MIT, Stanford University and Tuskegee University to research revolutionary concepts and scientific principles that would result in the fundamentally new and different science that would enable a milli-Volt electronic switch. The potential improvement factor in digital electronics is 10^3 in voltage, V, or $\sim 10^6$ in power, which often goes as V^2. The team of multi-disciplinary and multi-institutional researchers has joined forces to accelerate new fundamental science that can lead to a radically lower power successor to conventional technology. The Center for E^3S' partnership also includes two community colleges, Contra Costa College (CCC) and Los Angeles Trade Technical College (LATTC), as the Center strives to deliver on its education and outreach mission to educate a diverse generation of scientists, engineers, and technicians to be the future leaders, researchers, educators, and workers in the new electronics science and technology; to foster understanding by society of the energy challenge faced in information technology; and to promote the application of the Center's research outcomes as the foundation for technological solutions in low energy consumption electronic systems.

The Center for E^3S was formally established when the Sponsored Research Office of the lead institution, the University of California, Berkeley, received the grant notification letter from the Division of Grants and Agreements of the National Science Foundation on September 30, 2010. This end of September version of the award letter is a revision of an earlier letter, amending certain inconsistencies and gaps found in the earlier letter. Upon receipt of the NSF grant, the University of California. Berkeley took over two months to prepare the paperwork for subaward agreements, because the receipt of the NSF award was coincidental with a planned physical move by the organization that has the responsibility for setting up the subaward accounts and a shortage in personnel in the Sponsored Research Office. The subaward agreements were finally sent to the three research partners, MIT, Stanford, and Tuskegee on December 10. Upon review, MIT requested changes in the terms of the IP Management Agreement, but the request came at the eve of Berkeley's winter recess. The Center now expects that all subaward accounts will be established at the research partner institutions by early January 2011. While the Center recognized that NSF allows pre-award spending up to May 3, 2010, only researchers of one subaward institution, MIT, were allowed by their institution to incur some pre-award spending. Nevertheless, with the following activities the Center's operations have begun:

- the Kickoff Meeting on November 7 and 8 that was attended by 63 attendees and speakers;
- the formulation of the Center's Strategic Plan that was shared with NSF on November 8;
- the initial release of the Center's website on December 13, 2010, which offers cyber presence as well as a collaborative work environment for the Center's participants;
- the establishment of the Center's Biweekly Student Seminar Series at the end of September, 2010, bringing together biweekly the students and faculty of the four participating research institutions via teleconferencing; and
- the initiation of a full-time administrative team with the hiring of the Center's Executive Director, who joined the Center at the end of September.

II. RESEARCH

1a. Goals and Objectives

The foundations of the thermodynamics of computation were established by Landauer and Bennett; a good review of this work was published by Bennett in 1982 [1]. An oft-quoted result is that a computer operating at temperature T must dissipate at least kTln{2} (about 18meV at room temperature) per logical operation. This is frequently referred to as the "Landauer limit". However, for reversible or adiabatic operations, the minimum dissipation can in fact be made much less than kT [1]. For reference, leading edge CMOS in 2009 dissipates a minimum of ~30,000eV per digital function when the energy required to charge the wires is included. The Roadmap [2] projects a goal for this value to be reduced to ~800eV/digital function in 2022, but this will require new technology. Can digital logic systems be constructed to approach or even break the Landauer limit? This is the overarching fundamental question that the researchers in the Center seek to address.

Conventional transistors are thermally activated, with an energy barrier to block the flow of electrons, whose height is modulated to allow current to flow. But the off-current of both field-effect and bipolar transistors is limited by thermally excited carriers that can leap over that barrier. The source/drain leakage current of a MOSFET drops exponentially with control voltage, V, in the form of the Boltzmann factor exp(-qV/kT). This thermal factor gives rise to the subthreshold swing, S=60mV/decade, which is ln{10}kT/q, where kT/q=26 mV is the thermal voltage at room temperature. A good ON/OFF current ratio requires a voltage swing many times greater than kT/q.

The new switch is targeted to have the following three specifications:

- Steepness (or sensitivity): ~1mV/decade, which would allow switches with a swing of only few milli-volts.
- On/Off ratio: 10^6 : 1; for example 10Ω : 10MΩ
- Current Density or Conductance Density (for miniaturization): 1 milli-mho/micron; i.e. a 1 micron device should conduct at 1KΩ in the on-state.

1b. Performance and Management Indicators

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

1c. Problems Encountered During Reporting Period

- UC Berkeley:
  - The process to establish subaward agreements with partner research institutions is continuing at the filing time of this report. Complexity of the agreements and an office relocation in one of the support organizations contributed to the delay.
  - Wafer-processing equipment is currently being moved to a new larger cleanroom facility. The move to the new lab is scheduled to be completed by December 31, 2010.
  - The process of setting up a combined laser MBE/ UHV sputtering system to support Theme IV has begun.
- Stanford University: The delay in setting up a subaward account has delayed the start of research on behalf of the Center. Stanford has not allowed pre-award expenditures to be incurred.
- Tuskegee University: The delay in setting up a subaward account has delayed the start of research on behalf of the Center. Tuskegee has likewise not allowed pre-award expenditures to be incurred.
- MIT: The need for device simulators in Theme I research could not be filled by commercially-available simulators, as they incorporate overly simplified tunneling models. Because of these limitations, the Theme I researchers at MIT have established a collaboration with Prof. Mathieu Luisier of Purdue to begin using the OMEN code to calculate quantum mechanical transport in TFET device structures.

2a. Research Thrusts

The work of the Center for E3S is initially organized into four distinct themes:

I. Nanoelectronics with a focus on solid state millivolt switching
II. Nanomechanics with a focus on zero-leakage switching
III. Nanophotonics focused on few-photon communication
IV. Nanomagnetics that has the potential of surpassing the Landauer Limit.

Themes I, II and IV each pursue a different approach to low-energy electronics, each with a different mix of characteristics. One objective is to perform the research needed to evaluate how closely these characteristics might be able to approach fundamental limits. Theme III addresses the challenge that is common to all digital systems, namely high bandwidth communications both intra-chip and chip-to-chip.

Over-arching these four themes is the systems integration research, whose outcomes will include a common set of metrics for each of the themes and a systems perspective that will enable future ultra-low energy information systems to be built and integrated using elements of each of these approaches.

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

In Theme I, the approach is to continue to use a solid-state switch, but to radically alter the switching principle, so that it can operate at a drastically lower voltage than CMOS. A main concept involves changing the fundamental switching mechanism from modulating thermionic emission current over a barrier, to modulating the tunneling current through a barrier. It might be thought that a sensitive switch, responding more steeply than kT/q, would violate some type of thermodynamic restriction, but this appears not to be the case.

There are two ways of achieving such sensitive switching; i.e. achieving steepness. One is by modulating the tunnel barrier, while the second is via a density of states switch.

The latter is similar to the “Backward Diode” concept. At small amounts of reverse voltage in a pn junction, the valence band density of states just begins to overlap the conduction band density of states. If the band edges are assumed to be step-function sharp, then the turn-on characteristic can be correspondingly steep. While “Backward Diodes” have been routinely made in Ge-homojunctions since the 1960’s, very little is known about how sharp a semiconductor band edge can really be, but it appears to be sharper than kT/q. The closest known electrical measurement is the I-V response curve of heavily doped “backward diodes”, in which switching action occurs near zero volts. In that case, a band-edge sharpness of ~0.5kT was been measured long ago [3] in a Germanium homojunction. Similar promising results were observed in a 3-terminal carbon nano-tube device [4].

Type III band alignment, as in the lattice-matched p-GaSb/n-InAs heterostructure system, permits a very thin tunnel barrier, allowing good on-state current at milli-Volt threshold voltages. The n-InAs layer can be a quantum well, with small enough quantum capacitance to allow good gate modulation efficiency in the 2d electron gas. Indeed the n-type layer is likely to be so thin that lattice mismatch would be acceptable, permitting a much wider choice of material combinations. The ability to operate at lower voltage depends upon the steepness of the band edges. The band-to-band optical absorption has been measured in Si and GaAs, whose band-edge sharpness is ~0.4kT and ~0.3kT, respectively.

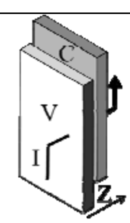
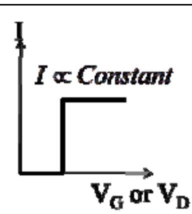
Nonetheless, the science of band-edge sharpness is poorly developed. The Center's synergistic, multi-faceted approach (with theoretical, computational, and experimental components) also involves the Co-PI's C. Hu (Berkeley), D. Antoniadis (MIT), J. Hoyt (MIT), J. del Alamo (MIT), E. Fitzgerald (MIT), and A. Javey (MIT). The team will develop reliable measurement methods for band-edge sharpness, in a variety of different materials. It is believed that the band-edge fuzziness arises from phonon lattice distortions operating through deformation potentials. Indeed the deformation potentials in Si and Ge sometimes have opposite signs, so that they can cancel. Novel superlattice structures will be investigated theoretically and experimentally in an effort to cancel the "effective" deformation potential (Deformation Potential Engineering) and thereby reduce or eliminate thermal broadening of band edges leading to ultra-sharp band-to-band tunneling characteristics.

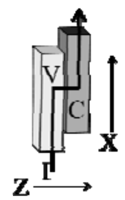
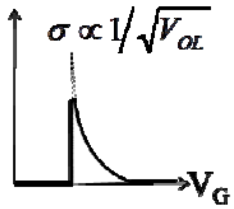
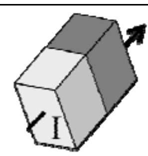
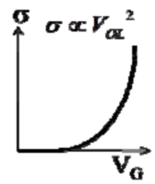
Low band-gap nanomaterials such as InAs and InSb nanowires will be explored as well as core-shall nanowire heterostructures such as InAs/AlSb. Theoretical efforts to improve on band alignments and edge steepness will be carried out in tandem with experimental measurements to help guide the selection of materials and design of structures.

We will also study a detailed energy landscape of ferroelectric insulators which provide "transformer" action as gate insulators boosting the voltage seen by a transistor channel. These tunneling and ferro-electric gate architectures, as a framework, provide new opportunities.

Described below is a list of activities that either were pursued or will be initiated in this 1st Reporting Period.

- Tunnel Field Effect Transistor (TFET):
  - The theoretical study on the effect of dimensionality on the performance of a density of state switch was initiated. Cases involving different combinations of 0d, 1d, 2d and 3d were analyzed. The conclusion is a density of states switch is explicitly affected by dimensionality and the program should concentrate on 2d/2d pn junctions.

2d-2d			• Good wave-function overlap above the band edges • Transverse Momentum is Conserved at High k

1d-1d			• The effect of the divergent 1d density of states will be averaged out by band-edge smearing
3d-3d			• The common 3d-3d pn junction has only a parabolic turn-on characteristic, even when the band edge is perfectly sharp.

- Building on the findings of the theoretical work at UC Berkeley comparing tunneling in systems of various dimensionalities, the MIT researchers will begin to explore tunneling experimentally in gated 2D-to-2D and 1D-to-1D electron gas systems during the latter half of the 1st Reporting Period.
  - Initial work has focused on tunneling in strained silicon/strained germanium Type II heterostructures. Strained Si/Strained Ge capacitors were fabricated on relaxed silicon-germanium alloy substrates using an Atomic Layer Deposition high-K Al_2O_3 dielectric as the gate insulator. The band alignments at the strained-silicon/strained-germanium heterointerface for various levels of strain will be extracted by fitting experimentally measured capacitance-voltage curves, obtained from these capacitors, to simulation results. The band-alignments for the strained-silicon/strained-germanium type-II heterointerface are poorly known, and this data will provide fundamental information pertinent to tunneling in this materials system, in particular the effective band gap at the heterointerface.
  - By the end of the 1st Reporting Period, we will have initiated the setup simulations of atomistic, full-band quantum transport simulations, using the OMEN simulator developed at Purdue. The simulations will be run in collaboration with Prof. Mathieu Luisier of the Birck Nanotechnology Center and the Network for Computational Nanotechnology (NCN) at Purdue. OMEN is the most sophisticated quantum mechanical device simulator available and the capability to utilize it will be important in guiding experiments and for understanding tunneling transport in various TFET device structures under investigation.
- The effect of defect-related trap states within the band-to-band tunneling region of a tunnel field effect transistor (TFET) is under investigation. Specifically, erbium (Er) ion implantation is being used to introduce trap states at the source junctions of TFETs as well as MOSFET control devices. Additionally, the benefit of back-gate biasing for enhancing thin-body TFET on/off current ratio is being investigated via two-dimensional device simulations.

- The design of n-channel and p-channel germanium-source TFETs is being investigated via two-dimensional device simulations, since Ge has a smaller band gap than Si and hence can provide for much larger on-state tunneling current.
- Investigations on the optimal designs of silicon tunneling transistors that will exhibit sub-60mV per decade switching behavior are being undertaken. Emphases are on two designs. The first employs a vertical PN junction in the transistor source to create a steep switching when the gate voltage creates an overlap of the valence and conduction band across the PN junction. Due to the existence of a large electric field, the band overlap triggers a sudden increase of tunneling current. The second design makes use of an ultra-thin SOI body about 5nm in thickness. Since the starting position of the tunneling path is a function of the gate voltage, deeper as gate voltage lowers, the tunneling current drops suddenly to zero when the gate voltage is low enough to push the starting point of tunneling out of the SOI film (into the buried oxide).
    - A thorough TCAD simulation study of complimentary TFETs using Si-Ge heterojunctions has been completed. It was shown that symmetrical P-type and N-type TFETs can be produce on the same substrate by engineering the strain or the strains in the Si and the Ge films. Specifically, relaxed SiGe substrates of 50% Ge and 83% Ge can produce symmetrical complimentary TFEs. By the end of this Reporting Period, The first experimental fabrication of nano-ribbon InAs on dielectric TFET will be completed.
- Before the end of this Reporting Period, the emphasis is expected to shift toward III-V compound semiconductor TFETs. III-V device fabrication difficulties will require us to experiment with several approaches. Both vertical and horizontal designs of TFETs will be investigated. A new project that uses thin InAs film on dielectric substrate will have commenced.

- Super-Steep Sub-threshold Devices: Project targets the realization of super-steep subthreshold devices based on impact ionization on narrow band-gap materials suitable for operation at very low voltage. Toward this end, we are studying impact ionization in a variety of InGaAs and InAs High Electron Mobility Transistors (HEMT) that have been fabricated in the last few years. Measurements will include DC I-V characteristics, pulsed characteristics, and RF characteristics at various temperatures. We will then build a model for impact ionization that explains all measurements. From this, we will synthesize device design guidelines to maximize subthreshold swing steepness. We will design and fabricate devices and will characterize their suitability for low voltage logic.
    - In this Reporting Period, studies to characterize impact ionization in low-InAs composition InGaAs HEMTs at various bias points and temperatures have been initiated. Results follow a simple model for impact ionization.
    - By the end of this Reporting Period, modeling for impact ionization in InGaAs and InAs HEMTs that includes dynamics and the role of temperature will be initiated. This will be done for channel materials of different compositions.
- Device Fabrication:

- III/V-on-insulator (XOI): Work to explore novel device concepts for low power InAs/InAsSb XOI MOSFET and III-V XOI TFETs has recently been initiated. The research is utilizing an epitaxial transfer method for the integration of ultrathin layers of single-crystalline InAs on Si/SiO2 substrates; a parallel to silicon-on-insulator (SOI) technology, thus the abbreviation "XOI" to represent this compound semiconductor-on-insulator platform. Through experiments and simulation, the electrical properties of InAs XOI transistors are explored, elucidating the critical role of quantum confinement in the transport properties of ultrathin XOI layers. Importantly, a high quality InAs/dielectric interface is obtained by the use of a novel thermally grown interfacial InAsOx layer (~1 nm thick). The fabricated FETs exhibit an impressive peak transconductance of ~1.6 mS/µm at VDS=0.5V with ON/OFF current ratio of greater than 10,000 and a subthreshold swing of 107-150 mV/decade for a channel length of ~0.5 µm. XOI presents a novel material platform for exploring various device concepts based on III-V compound semiconductors. By the end of the 1st Reporting Period, fabrication of III-V XOI TFETs is expected to be completed.
- Collaborations between some Theme I researchers at Berkeley and MIT has also been initiated. Two potential heterostructures that can be fabricated using the infrastructure at MIT have been defined; a lower risk and higher risk structure.

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

Theme II is investigating the science and technology of nanoscale electro-mechanical (NEM) switches (relays), to enable milli-Volt switching with ~1ns delay, low on-state resistance (<1kΩ), and zero off-state leakage current. Power gating of CMOS electronics (*i.e.* cutting off the connection to the power supply when the electronic circuitry is idle, in "sleep mode") is a near-term application for these switches. An analytical comparative analysis showed that NEM relays can provide energy-reduction benefits over MOSFETs as power gates, for off-periods greater than 1 ms [5]. Note that the switching speed requirement for power gates is considerably relaxed (on the order of 1ns), since one or more clock cycles are acceptable to switch a block into/out-of sleep mode.

A mechanical switch technology has many potential benefits: zero leakage current and hence zero static energy consumption; abrupt transitions between on and off states, which facilitate low-voltage operation so that the active energy can be <1 aJ per switch; immunity to noise due to hysteretic switching behavior; wide operating temperature range; and a low process thermal budget that allows for post-CMOS integration or fabrication on low-cost plastic substrates. To achieve energy efficiency superior to that of CMOS technology with comparable block-level performance, the dimensions of a relay must be scaled down into the nanoscale regime. Additional issues to be addressed by the research efforts under this Theme include reliability (endurance and stability of on-state resistance); minimization of surface adhesion forces (which will ultimately set the minimum energy for a relay); and process-induced variations.

The following research activities have been or will be initiated during the 1st Reporting Period:

- Device scaling study: An initial study of micro-relay design for ultra-low-voltage operation was performed. It was found that if surface adhesion force continues to scale down with the area of the contact dimple regions, then sub-10 mV operation should be feasible with a 5 nm actuation gap across a 1 square micron actuation area and 3 nm contact gaps across 16nm x 16nm contact dimple areas, assuming 3.5um-long x 83nm-wide x 40nm-thick flexures. Thermal vibrations and mechanical shock were determined to be non-issues, due to the very small mass of the relay structure.

- Low-voltage NEM relays: Integrated process flows for fabrication of energy-efficient relays will be investigated. This research will involve materials and process development. For example, carbon coating of electrodes for improved reliability (endurance) and reduced surface adhesion force (low-voltage operation) will be explored. A complementary relay design, in which mechanical energy is stored during an initialization operation and recycled to reduce the electrical energy needed for switching, will be studied.
- Contact physics study: Fundamental understanding of contact physics is critical to achieving reliable mechanical switches. Therefore, a theory will be developed for predictive modeling of contact behavior (resistance and endurance).
- Contactless switch: The long-term objective of this project is to develop a low-loss switch based upon metal-doped polymers that conduct through tunneling. The polymers will be embedded in a MEMS device that compresses them, thereby modulating the conduction process and effecting a switch. Research in this area for this Reporting Period has focused on developing necessary materials and fabrication processes.
  - Candidate polymer-metal composites have been identified, and measurements of their electrical and mechanical properties have begun. Development of a metal-film fabrication process with which the MEMS device can be fabricated has also been initiated. The outline of a candidate fabrication process for a complete switch has also been established.
  - Fabrication of the first switch is targeted for completion by the end of this Reporting Period, after which characterization of the electrical performance of the switch will commence.

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

Research in optical interconnects includes two optical emitter projects:

- The Nano LED project involves the design and fabrication of a semiconductor LED enclosed within a sub-wavelength cavity designed for high modulation bandwidths. Current designs use an optical antenna to achieve this cavity and work has been concentrated on developing fabrication techniques necessary to fabricate such a small device. Ongoing simulation work for this project has been focused on understanding the basic operation principles of a nano-cavity device and the effect of device structure on performance. The ultimate goal of this project is to create a nano device capable of modulation bandwidths greatly exceeding tens of gigahertz with room temperature electrical injection that can be integrated with silicon transistor technology.
  - One challenge is in in designing a device with power output adequate enough to detect with available instrumentation. Improvements of current testing equipment as well as extensive device modeling and redesign have opened up the avenue to address this challenge. A nano LED with mode volumes down to 0.03 cubic half-wavelengths has been simulated. Fabrication

techniques for this structure have also been developed that will allow for the fabrication and testing of this device in the near future. Within the next few months, enhanced spontaneous emission is expected to be seen from one of the newly fabricated nano LEDs. This will be accompanied by further low temperature testing and characterization.

- The Plasmonic Crystal Laser project is aimed at fabricating a small mode volume semiconductor laser using a one dimensional plasmonic crystal. This project's goal is toward creating a small mode volume laser that can be integrated with waveguides and other plasmonic devices in a single nanophotonic platform. Milestones on the way to this goal included integrating electrical injection and room temperature operation. The current plasmonic crystal laser design uses a metal-insulator plasmonic structure. This structure will also be easier to modify for use with electrical injection.
  - Etching of the semiconductor material has been studied. This has involved investigations into different etch recipes and processes as well as a partial redesign of the materials involved. This structure has been successfully fabricated and tested and shown to lase at low temperature with optical pumping. Near-future work will be toward adapting the design to a metal-insulator-metal structure that will have the added benefit of lower mode volumes and greater ability to engineer the different optical modes. Changes to the current design of the plasmonic crystal laser are expected to allow lasing in both the fundamental and second order modes. These modes have yet to be seen with only higher order modes obtaining lasing.
  - Work will also be done toward developing a wafer bonding technique that is compatible with our current process. This will be an important step toward showing silicon integration with our devices and will also help solve some of our current fabrication difficulties.
- Planning meetings are scheduled between MIT researchers and the Theme III leader on relevant device structures that the researchers of MIT and UC Berkeley can jointly work on.

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

The Center is pursuing nanomagnetics or spintronics for use in classical logic, as this approach offers the promise that the spin degree of freedom can exhibit very low energy dissipation, and thus, the possibility of approaching or even exceeding the Landauer limit [6]. Prior work of one of the Center's co-PI's, Salahuddin, and his collaborators has recently shown [7], in detail, how adiabatic switching is possible in nanomagnetic logic, leading to extremely low energy dissipation. There are spins systems, such as NV centers in diamond, [8] that are among the lowest dissipation [9] dynamical systems in nature. This could allow NML fabrics for reversible logic [10], the energy dissipation dropping below the Landauer limit. The goal of dropping below the Landauer limit makes Theme III the most futuristic and forward looking of the Center's initial themes.

Described below are the projects that either have been pursued or will be initiated in the 1st Reporting Period.

- Spin Logic Physics:
  - Investigation on the fundamental limits of nanomagnetic logic energy dissipation was undertaken. Micromagnetic simulations have been performed to explicitly confirm that exactly kTln2 of energy is dissipated in erasure of a single nanomagnetic bit (Landauer's limit), and the results have shown that the energy dissipated in a nanomagnetic majority logic gate can also be

made to be kTln2. The near-term goals and activities for this project are to perform experimental studies that test the results of our simulations. We are putting together a new magneto-optic Kerr effect (MOKE) apparatus with a special quadrupole electromagnet that will allow us to apply a DC magnetic field in the plane of the surface of a sample with arbitrary angular orientation of the field within the plane.

- All electrical readout and control of spin systems with superconducting circuitry is an attractive route for studying spin dynamics and relaxation times, with an eye toward high density information storage or magnetic logic. As well, this is an ideal setup for performing NMR or ESR studies on doped semiconductors and magnetic nanoparticles, and studying interactions between spins and their substrates. Species with a zero-field splitting (ZFS), such as bismuth doped silicon or NV centers in diamond, are particularly attractive, as the absence of a strong magnetic bias field facilitates compatibility with low loss superconducting circuitry.
  - We have observed interaction between a tunable superconducting resonator and an ensemble of Bi spins implanted in an epitaxial layer of 28Si. As the resonator tunes through the ZFS, we observed an avoided crossing indicative of collective strong coupling.
  - Before the end of this Reporting Period, we expect that we will have attempted to measure their relaxation times. Studies on NV centers in diamond using a dispersive nanoSQUID magnetometer will also be initiated, as well as study of coherence properties as a function of spin density.
  - The research of the 1st Reporting Period is benefiting from collaboration with Dr. Thomas Schenkel at Lawrence Berkeley National Laboratory. His student, Christoph Weis, implanted the Bismuth in the 28Si wafer, in which we have since observed a coupling between the spins and our device. One of Dr. Schenkel's students will also implant NV centers in diamond wafers when we reach that stage of the experiment.

- Communications for Spin Logic: To study and understand spin diffusion as a possible means of communication for spin based logic, we plan to fabricate magnetic multilayers that can be ultimately used to inject spins into metallic channels. Ultimate goal would be to fabricate structures where non local diffusion of spins can be probed and controlled. In this Reporting Period, the focus is to optimize the growth and characterize of magnetic multilayers.

- Switching Dynamics: The focus is to explore the science of ferromagnet-multiferroic interfaces to enable electric field control of spin transport. Prior work has shown that a BFO film stacked with a planar ferromagnetic island is capable of switching the ferromagnetic magnetization simply by the application of a small voltage across the BFO [11]. The emphasis in the 1st Reporting Period is to establish the thin film synthesis protocols that have been completed.

2av. System Integration *Project Leader: E. Alon (Berkeley)*

Although there is no doubt that new switching device concepts are fundamentally necessary in order to tackle the power crisis facing today's integrated circuits, circuit and system-level considerations also play a crucial role in determining the ability of a given device technology to realize its potential energy-

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efficiency benefits. In fact, the manner in which the devices are utilized to implement the functionality found in typical chips – and in particular, digital logic – will have direct implications on the characteristics required of any potential CMOS-replacement devices.

The principal goals of the system integration thrust are therefore threefold. First, by leveraging knowledge of the composition and construction of typical digital systems, we aim to derive a set of requirements that any new switching device technology must satisfy in order for it to be an attractive replacement for CMOS transistors. Although the circuit-level behavior of some of the proposed devices (e.g., tunneling FETs and NEM relays) is qualitatively similar to that of MOS transistors, almost all of them have unique characteristics (e.g., unidirectional current flow, large delays associated with mechanical motion, etc.) which will require re-thinking the manner in which circuits should be designed with these switches. Our second major goal will therefore be to develop circuit techniques for common building blocks like digital logic, clocking structures, memories, and interfaces that optimally leverage the new switching devices. Finally, based on our previous experiences, we have found that experimentally demonstrating the optimized circuit and system designs not only validates the proposed concepts, but can be extremely beneficial in exposing unexpected phenomena and/or opportunities in the new device. Therefore, as the device concepts mature to the stage where the co-PI's within the center and/or industrial collaborators are able to fabricate multiple such functioning devices, our third goal will be to demonstrate integrated circuit blocks utilizing the new devices.

Research into the circuit and system-implied requirements on new switching device technologies will be carried out in parallel with the exploration of the science and technology that will be used to realize the devices themselves. For example, a circuit-level energy-performance optimization/analysis will show why a certain I_{on}/I_{off} will be required by a new switch. Similarly, given the large number of devices in a modern IC (quickly approaching 10 billion/chip), limits on the tolerable levels of device variability (and how this variability will affect energy-efficiency) will be derived based on the characteristics of the circuit implemented out of the devices.

This framework, in addition to elucidating such requirements, will be extended to result in a methodology by which the energy, performance, and area (cost) tradeoffs of the new devices can be evaluated and compared against other candidates. While the devices will obviously evolve substantially over the life of the center, we will aim to complete this framework early on so that it can serve as a direct feedback mechanism to the device designers. This framework will also be used to ensure that the energy-efficiency of the entire system is considered. For example, if a new switching device were to successfully reduce the power consumed by the core digital logic by a factor of 100, the power consumed by the I/O's would quickly dominate the chip's total power. Our energy-performance-area framework will therefore also be expanded to include the potential impact of the devices developed in the Nanophotonics thrust (including the circuitry used to drive them) in order to quantify their ability to reduce the I/O power as well.

A generic framework for evaluating multiple new device concepts is important as a means for high-level device design feedback, but realistic estimates of a system's energy and/or performance can only be obtained by examining actual implementations. This is especially true in the context of new devices, which may have significantly different characteristics than CMOS transistors – which means that circuits utilizing these devices should be designed very differently than their CMOS-based counterparts. As the candidates for the most energy-efficient devices become clearer (through e.g. the previously mentioned evaluation framework), we will therefore proceed to develop circuit and system design techniques tailored to the individual device characteristics. For example, since the delay of NEM relays is dominated by their mechanical motion, the optimal topology for constructing digital logic gates out of these relays is to utilize a single large, complex gate with many inputs (rather than a cascade of many simpler gates with fewer inputs) in order to allow all of the mechanical motion to happen in parallel.

Beyond developing optimized circuit topologies, as the device fabrication techniques become available we will aim to experimentally demonstrate integrated circuits utilizing the devices proposed within the center. Initial efforts will focus on demonstrating the basic functionality of the circuits in order to prove their viability, but as the technologies mature we will aim to design and fabricate circuits of increasing complexity as well as characterize their energy and performance.

- By the end of the 1st Reporting Period, an initial mathematical analysis of the circuit-driven requirements on device level characteristics such as I_{on}/I_{off}, R_{on}, etc. is expected to be completed. Furthermore, we also plan to complete a preliminary analysis on the impact of variability on steep turn-on devices.

2b. *Performance with respect to the indicators/metrics*

It is too early in the life of the Center to present data associated with the performance metrics given in Section II.1b. However, in this section we will present the actions we have taken to support the performance metrics.

The Strategic Plan stated that the Integrative Research goal will be enabled by the following actions that are to be taken within the first several months after the founding of the Center:

- Convening a Kickoff Meeting to enable a discussion on research opportunities addressing the common problems across the different projects.
- Communicating a process for soliciting proposals of new projects at the Kickoff Meeting
- Communicating the Center's values at the Kickoff Meeting
- Establishing and sharing a dossier for each research theme and the associated system research, each containing descriptions of the different elements within each theme and the associated roster of co-PI's.
- Establishing and supporting a teleseminar series on the Center's research projects that will begin within three months after the Center's inception.

The Center held a Kickoff Meeting on November 7 and 8, 2010 in Cambridge, MA, bringing together co-PI's, students, administrative staff, as well as the Center's external collaborators and industrial partners. There were a total of 63 people from the Center's four research academic partners, two external collaborating academic institutions, three corporations and one research institute. The center-wide meeting served multiple purposes and supported many strategic objectives of the Center, but foremost, it was an opportunity for the Center's participants and affiliates to come to a common understanding of the Center's research goals, discuss research status, openly share technical ideas, deliberate on how to integrate the Center's research portfolio. During the meeting, E. Yablonovitch, Center Director, shared the Center's values and defined the Center's process for considering new research directions. The agenda of this two day Kickoff Meeting is given in Appendix I. Other aspects of the Kickoff Meeting will be discussed in the appropriate sections later in this Annual Report.

The Center's Biweekly Student Seminar Series held its inaugural video-conference on September 23, 2010, where it was established that student seminars will be presented via teleconference on every other Thursday when the participating academic institutions are in session. Since then, there have been four seminars, with student and faculty participation from all four research institutions at practically each one. By the end of the 1st Reporting Period, the Center will have hosted five additional seminars. Appendix II gives the seminar schedules for Fall and Spring semesters (4Q2010 and 1H2011) and summary information of past attendance.

The Center released the initial version of its website on December 13, 2010; the url is www.e3s-center.org. One key initial objective is to make available a collaboration environment to the Center's participants. Workgroups based on research themes and the Center's recurring activities have been set up. We expect that as the Center's intranet is widely used by the Center's participants, additional workgroups will be established to enhance collaboration. See Section VII – Management for more information about the capabilities of the website.

Establishing the dossiers of each research theme and making them available to the Center's community is progressing in conjunction with the build-out of the website. It is expected that by the end of January 2011, the dossier for each Theme will be available to all who have login privileges to the Center's website.

2c. Research Plans for the Next Reporting Period

During the 2nd Reporting Period, the Center's research team will continue to pursue the research projects that were initiated in the 1st Period.

2ci. Theme I:

In earlier work, Hoyt and Antoniadis have studied, by experiment and simulation, TFETs fabricated in the silicon/SiGe materials system. Although small effective band gaps at the heterointerface can be achieved with strained silicon/strained germanium, the indirect nature of the band structure is a limitation. In the 2nd reporting period, tunneling in direct band-gap III-V heterostructures will be studied. Various structures will be explored through modeling and simulation, using a combination of commercially available programs and specialized full band quantum transport simulation that uses the OMEN code. Once a suitable three-terminal test structure is designed, fabrication of the device structure will begin.

Continuing the research of the 1st Reporting Period, Ge-source TFET and defect-enhanced TFET devices will be electrically characterized and the results will be compared against theory and simulations. Simple circuits employing TFETs (logic gates, ring oscillators) will be demonstrated.

Activities to build a model for impact ionization in narrow bandgap InGaAs and InAs HEMTs that explains all measurements will continue. From this, del Alamo will synthesize device design guidelines to maximize sub-threshold swing steepness. Research on design and fabrication of devices and characterization of their suitability for low voltage logic will be pursued.

Research on various homo and heterojunction III-V XOI TFETs will continue. Javey and Hu will collaborate on material growth. Collaboration with materials growers at University of New Mexico will also be initiated.

2cii. Theme II:

The Center's researchers located at different institutions will collaborate in the investigation of contact-less mechanical switches, since these appear to be the most promising for achieving high endurance and reliability. Specifically, knowledge and learning for various tunneling materials, fabrication processes, and device designs will be shared between researchers at UC Berkeley, Stanford, and MIT. New materials (particularly polymer-metal composites) will continue to be explored for improved performance, and a compact actuation method will be developed. A secondary objective will be to simplify the switch fabrication process to facilitate its eventual miniaturization.

For contacting mechanical switch designs, approaches to reducing surface adhesion force will be investigated and research into the physics of mechanical contacts will continue.

Advancements in materials and process technology will be made to lower the operating voltage for the various switch designs. Through compact device modeling and circuit simulations, the energy efficiency of NEM relay technology will be investigated in a circuit and system context.

2ciii. Theme III:

The Nano LED Project will continue toward making a low temperature optically pumped device. During this time period the main focus will be toward modifying device structure and improving fabrication methods to increase the modulation speeds of the device. Consideration will also be given to designs that are more easily combined with electrical injection. Continued technical challenges will persist with the fabrication of nano LEDs, due to the small required device volumes. Knowledge will be drawn from the experience gained in similar projects at UC Berkeley, such as optical antenna and nano laser fabrication.

The Plasmonic Crystal Laser Project will begin to move away from low temperature measurements and optical pumping and toward room temperature electrical injection. The first step in this will be using electrical injection, which will require a partial redesign of the device as well as improvements in current measurement apparatus. Electrical injection will continue to present many new challenges, one of them being setup of proper testing equipment. This is currently being worked on for a related project, and much of the experience gained there can be transferred to this project. Moving toward a metal-insulator-metal structure will also significantly simplify the demands of electrical injection.

2civ. Theme IV

- Spin Logic Physics:
  - The plans for the 2nd Reporting Period are to continue the activities initiated in the 1st Reporting Period. We will use the newly developed MOKE apparatus to carefully measure

hysteresis loops for nanomagnets and extract energy dissipation from this data. We seek to experimentally confirm Landauer's limit in nanomagnetic bit erasure.

- Utilizing species with a zero-field splitting (ZFS), experiments will be designed to explore the link between the classical Landauer limit and the unitarity present in coherent quantum interactions. The Landauer principle loosely states that erasing one bit of information requires an energy of kTln2, which may impose a final limit on low power electronics. Spin based computation is one candidate for a technology that could reach the Landauer limit. When the principles of reversible computing are applied, coherently controlled spin systems might even surpass this limit.

2cv. System Integration: During the 2nd Reporting Period, research activities on applying the preliminary analysis to a number of the devices will be initiated within the center in order to begin understanding their circuit-level energy-performance-area implications. We then plan to begin actively collaborating with several of the device design groups in order to explore circuit designs for the most promising candidates.

III. EDUCATION

1a. Goals and Objectives

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

- To train in the graduate programs of the Center's participating institutions, a new generation of PhD and MS-level scientists and engineers who, on completion of undergraduate and graduate programs at Center universities, will
  - be facile with scientific approaches to low energy digital electronics systems;
  - understand that working in diverse teams optimizes creativity; and
  - understand the process of innovation, entrepreneurship and the transition of research results to commercially-viable products.
- To train an engaged, skilled and diverse technical workforce by providing a pipeline from secondary school to college.
- To develop methods to retain these individuals within the E^3S research areas.

The Center's leadership is making a concerted effort to collaborate with existing programs and similar initiatives to integrate education components into ongoing activities, thus augmenting and enhancing effective programs already in place and leveraging resources. In this Reporting Period, efforts to impact all levels have begun. The education activities being pursued in this Reporting Period have or will involve and/or impact post docs, graduate students, undergraduate students, and high school students.

1b. Performance and Management Indicators

Objective	Metrics	Frequency

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

1c. Problems Encountered During Reporting Period

- The Center has yet to fill the position of Education Director. This position has been approved by the Dean's Office of the College of Engineering in Berkeley, but because of the level, the scoring of this position is a slightly longer process and has yet to be completed. Recognizing that its Education activities must continue while the position is being filled, the strategy is to undertake these activities with the support of the Center's Executive Director, who will leverage the efforts and infrastructure of established high school and undergraduate programs. The Center's proposal had identified the established programs to be SEEDS and MITES at MIT and SHARP and SUBERB at Berkeley.
- The Center's proposal to NSF called for hosting Research Experiences for Undergraduates (REU) activities through the established Summer Undergraduate Program in Engineering Research at Berkeley (SUPERB). Unfortunately both REU grants, which have funded the SUPERB program, are up for renewal, and the outcome of the renewal process is not expected to be known until the latter half of 1Q2011. Given the need to start the recruiting process in the beginning of January 2011, the Center plans to advertise and recruit its own REU opportunities through the Center's website. During the recruitment process, it will collaborate with the NSF funded Center of Integrated Nanomechanical Systems (COINS), whose Education Director, M. Erol, is helping the Center for E^3S to develop recruitment and application materials, and will integrate E^3S' recruitment needs into the COINS' recruitment process by disseminating E^3S' information and seek students on E^3S' behalf. In the summer of 2011, the Center plans to support its REU students by using either the infrastructure of the SUPERB program or that of COINS; the selection will be made at the end of this Reporting Period. See COINS' letter of support in Appendix III.
- The development of the proposed new undergraduate education program, Transfer-To-Excellence (TTE), will not begin until the arrival of the Education Director. This program, which has the goal of enhancing the transfer rate of students from 2-year community colleges to 4 year college, will not begin until the 2nd Reporting Period. Nevertheless, we are hopeful that we will still be successful in implementing the program in the fall of 2011 to provide support to students from either of the Center's two community college partners, CCC and LATTC, as they enroll in engineering courses at a U of California campus as part of their 2 year community college education.

2a. Internal Education Activities

Activity Name	Kickoff Meeting
Led by	E. Yablonovitch (Berkeley)
Intended Audience	Faculty, Staff, Students and Post-Docs
Approx Number of Attendees (if appl.)	Center's Faculty: 9 Berkeley, 4 MIT, 1 Stanford, 1 Tuskegee Staff: 2 UC Berkeley; 1 Tuskegee Graduate Students – 16 Berkeley, 7 MIT, 2 Stanford, 1 Tuskegee Post-Docs: 4 Berkeley; 1 MIT, 2 Stanford External Attendees & Speakers: 2 foreign collaborators, 1 domestic collaborator, 3 industrial advisors, 1 Berkeley guest speaker, 3 MIT guest speakers

The Kickoff Meeting was also an Education Event for the faculty, graduate students and post-docs, and partners. E. Yablonovitch, Center Director, communicated the Center's values, while J. Yuen, Executive Director, presented a summary of the Center's Strategic Plan, including vision, mission, goals and metrics. The audience learned about the Center's research, through the many technical talks and panel discussions, and about the Center's Education and Outreach mission and the examples of programs that can help achieve the Center's Education and Outreach programs.

Activity Name	Student and Post Doc Council
Led by	J. Yuen (Berkeley)
Intended Audience	Students and Post-Docs
Approx Number of Attendees (if appl.)	Varies by meetings

On the second day of the Kickoff Meeting, there was a separate session for the students and post-docs (20 Berkeley, 8 MIT, 4 Stanford and 1 Tuskegee) to discuss their interest in having a Student and Post Doc Council. On the previous evening, the students and post-docs had the opportunity to meet each other through their own networking event. The intent was for the networking event to serve as an "ice-breaker" preparing the student and post-doc attendees to exchange ideas on a student council on the following day; 22 graduate students and 2 post-docs attended (14 Berkeley, 4 MIT, 3 Stanford, 1 Tuskegee). The Student Council discussion was led by 2 graduate students (1 Berkeley and 1 MIT) and was mentored by J. Yuen, Executive Director. The majority of the students and post-docs expressed interest in a networking forum. The first action item resulting from the discussion is the establishment of a directory of students and post-docs that will provide information on the individual's technical expertise and research. Two students from UC Berkeley agreed to facilitate the development of the directory. Also, it was agreed that there will be a standing monthly meeting of students and post-docs. A second meeting was convened via videoconferencing in late November that was attended by 8 students and 2 post-docs (7 from U. C. Berkeley, 3 from Stanford and 1 from MIT).

Activity Name	Poster Session at Kickoff Meeting
Led by	J. Yuen (Berkeley)
Intended Audience	All Attendees of Kickoff Meeting
Approx Number of Attendees (if appl.)	60

The Poster Session at the Kickoff Meeting was an opportunity for the graduate student and post-doc attendees to present their E3S related research. Public technical presentation and dialog contributes to the building of communication and leadership skills. This portion of the meeting was organized as part of the Center's objective to provide leadership experiences the Center's graduate student and post-docs.

Activity Name	E^3S course
Led by	E. Yablonovitch (Berkeley) and E. Fitzgerald (MIT)
Intended Audience	Graduate Students
Approx Number of Attendees (if appl.)	Varies by course offering

In the 1st Reporting Period, E. Yablonovitch taught an E^3S course the fall semester. The course, EE 290B, entitled "Advanced Topics in Solid State Devices", recognized the limit on energy efficiency for logic operations, memory operations, and communications that is dictated by the fact that the universal switch, the transistor, is thermally activated, and requires a high voltage >>kT/q~1Volt to operate well, while, the wires in a circuit would have tolerable signal-to-noise ratio operating even at 1 mVolt. This is manifested as a factor of $\sim 10^6$ inefficiency in current digital electronics. The goal of the course is to explore the technical options that could eventually eliminate this million-fold factor. The course covered the following topics:

a. Solid-state switching devices that operate in the milli-Volt regime;
b. Nano-transistor options with steeper sub-threshold slope;
c. Nano-optical links;
d. Novel nano-scale impedance matching transformers, including plasmonics;
e. New forms of amplification using giant magneto-resistance and other spintronic effects;
f. Nano-mechanical switching elements that are capable of very low voltage operation;
g. Low-temperature electronics; and
h. Electro-chemical switching elements.

The Berkeley course, which had two graduate student instructors, was attended by 15 Berkeley students who took the course for credit, and 9 other individuals from Berkeley who audited the course. In addition, 7 individuals from MIT, including 3 co-PI's of the Center, attended the course as guests. Other guests included 1 student from Tuskegee who is a participant in the Center, 2 external collaborators and a staff member from Intel, a company on the Center's Internal Industrial Advisory Board. The course offering fulfilled the goal in Center Strategic Plan.

Activity Name	Cal Science & Engineering Festival
Led by	Caryl Esteves (BNNI)
Intended Audience	Outreach to the general public
Approx Number of Attendees (if appl.)	TBD – rescheduled for January 23, 2011

The Center for E^3S contributed funding to Cal Science & Engineering Festival, which was originally schedule to be held on October, 2010 in conjunction with the inaugural USA Science & Engineering Festival in Washington D.C. However, the Berkeley event, which was first scheduled to be an outdoor event, was postponed due to inclement weather and has been rescheduled to be an indoor event that will not take place until January 2011.

Activity Name	E^3S Research Experiences for Undergraduates (E^3S REU)
Led by	J. Yuen (Berkeley)
Intended Audience	3rd and 4th year undergraduate students
Approx Number of Attendees (if appl.)	Goal of 5 REU positions in the summer 2011

The recruitment process of the E^3S REU program will begin in January 2011, even though the selection of the candidates for the targeted 5 positions will occur in the 2nd Reporting Period. For more information about this activity, see comments under Section III.1.c.

Activity Name	E^3S Research Experiences for High Schoolers (E^3S REHS)
Led by	J. Yuen (Berkeley), C. Chang-Hasnain (Berkeley) & Avi Rosenzweig (Berkeley Nanosciences & Nanoengineering Institute)
Intended Audience	3rd and 4th year highschool students
Approx Number of Attendees (if appl.)	Goal of 5 REHS positions in the summer 2011

The Center for E^3S has started to implement its plans to provide research opportunities for high school students by leveraging the activities of the Summer High-school Apprenticeship Research Program (SHARP) that has been part of the Nanoscale Science and Engineering (NSE) Graduate Group at Berkeley. SHARP was founded by C. Chang-Hasnain, the Center's co-PI and Associate Education

Director, and is managed by Avi Rosenzweig of BNNI. Agreements have been established with Avi Rosenzweig that the Center will fund 5 high school students and provide graduate students to mentor them as part of the summer 2011 program. The website of the Center is being prepared to advertise SHARP's 2011 recruitment that will begin in January 2011. The Center further agreed that it will fund and support the development and offering of lectures and educational materials for all SHARP graduate student mentors, (E^3S participants and students of other affiliations) to enhance mentoring skills. In the beginning of the 2nd Reporting Period, T. Farlough (Tuskegee), a staff participant of the Center for E3S who has significant experience organizing mentoring workshops, will advise on the development of the lecture topics and education materials for the graduate student mentors.

2b. *Professional Development Activities*

J. Yuen, Executive Director, served as a reviewer for a NSF panel on Advanced Technological Education.

2c. *External Educational Activities*

None to report

2d. *Integration of Research and Education*

In the short time since its founding, the Center has rigorously sought to use all opportunities to integrate its Research and Education activities.

Activity	Research	Education
Kickoff Meeting	Presentation of the research portfolio Open discussions of Research Directions	• Education for the entire Center - Communication of the Center's Values - Communication of the Strategic Plan - Communication of administrative requirements - External Speakers on topics relevant to E^3S • Education for Students & Post-Docs - Technical presentations and panel discussions by co-PI's - Poster Sessions by students & post-docs - Networking - Discussion of Student and Post-Doc Council
E^3S Course	E^3S research topics	• Education of Students & Post-Docs • Education of co-PI's on alternative E^3S research topics

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REU & REHS Programs	Research on E^3S topics	• Graduate student as mentors • Education to enhance mentoring skills of graduate students

2e. *Performance with respect to the indicators/metrics*

While it is premature to report on the effectiveness of the Center's Education programs, it must be recognized that the Center has well-defined plans of action to implement REU and REHS programs in time for the summer of 2011. The actions in the 1st Reporting Period will enable the Center to meet its goal of impacting the entire pipeline of students from high school through to graduate school.

The REHS and REU programs will be a venue for graduate students to exercise and enhance their leadership skills. Another venue is the newly initiated Student and Post-Doc Council. While the Center has not initiated specific programs for post-docs, this Council should offer an opportunity for post-docs to provide mentoring to graduate students.

One critical education milestone, graduate students, post-docs and faculty from 3 of the four research institutions of the Center participated in a credit granting E3S course training this Reporting Period; some for credit while others as guests.

2f. *Internal and External Education Activities for Next Reporting Period*

During its November 8, 2010 meeting in Cambridge, the Center's Executive Committee decided that E. Fitzgerald (MIT) will offer an E^3S course at MIT by using the material that was developed at Berkeley. It is expected that the E^3S course will be offered in the next Reporting Period.

In the 2nd Reporting Period, the Center will develop and offer the following training to its faculty, students, post-docs and staff:

- Ethical Conduct of Research; and
- A patent workshop

Both subjects will be part of the Center's training agenda in support of the goals of Knowledge Transfer and Management; see Sections IV & VII. While recognizing that the members may have prior exposure to these topics, the Center believes that training with a common set of material will enable the members, some of whom are from different institutions, to develop a common understanding, which is necessary to achieve an integrated approach to both issues throughout the Center. The challenge for the Center will be to develop effective course material for those who already have knowledge of the topics.

Under the direction of the new Education Director and D. Antoniadis, a new teaching module on energy efficient electronics will be developed and incorporated into the electronics course of MIT's Saturday Engineering Enrichment & Discovery (SEED) Academy. The target audience is 12th grade high school students who take an electronics course in the fall semester of the final year of the three year SEED program.

The Center recognizes the need to identify the methodology for assessing program effectiveness earlier in the life of the programs to ensure that the data needed for assessment will be collected in a timely and appropriate manner. Thus, the Education Director will work with independent assessment experts in this coming Period to establish the methodology and tools for data collection.

IV. KNOWLEDGE TRANSFER

1a. *Goals and Objectives*

Knowledge transfer is the conveying of research results from the Center's faculty and students to society. Knowledge transfer goals of the Center for E^3S are to establish industry/education partnerships as venues for introducing new and more efficient electronics technologies, and to prepare workers at all levels to participate in the new opportunities. Cross-fertilization would go in both directions, up and down the food chain, for device researchers at the leading electronics companies, circuit designers, CAD software writers, all the way to manufacturing workers in the semiconductor equipment industry. Thus opportunities will be created at all levels, from Community College students up to Ph.D. graduates from research Universities. Knowledge transfer is envisioned to be through the following channels:

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

1b. *Performance and Management Indicators*

Objective	***Metrics***	***Frequency***
Knowledge Transfer	Website Hits & Unique Visitors	Yearly
	Number of Contacts with Industry	Yearly
	Center publications: • Number of publications • Number of citations	Yearly
	Patent Disclosures	Yearly
	Students hired into relevant industries	Yearly
	Technology development attributable to Center's research	Yearly beginning in Year 4

1c. Problems Encountered During Reporting Period

None.

2a. Knowledge Transfer Activities

Being a new Center, the initial emphasis in Knowledge Transfer is to establish the recognition of the Center among the industrial, research and educational stakeholders in digital electronics field. This recognition starts with dissemination of information on the Center's activities and receiving input from others outside the Center who are engaged in synergistic activities. Toward that goal, the Center's activities in the 1st Reporting Period are as follows.

Kickoff Meeting – November 7&8 2010		
Led by	E. Yablonovitch (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	Intel Corporation	Santa Clara, California
2.	IBM	Hopewell Junction, New York
3.	Lam Research	Fremont, California
4.	Aerospace Corporation	El Segundo, California
5.	Oxford University	Oxford, United Kingdom
6.	Technische Universität Berlin	Berlin, Germany

The Kickoff Meeting was a venue for our industrial and academic partners to learn about the Center's. The Kickoff Meeting involved participation by representatives from three of the four companies that are members of the Industrial Research Board. See Section V – External Partnership and Section VII – Management.

Center for E^3S Open House – February 17, 2011		
Led by	J. Yuen (Berkeley)	
Organizations Involved - Bay Area high tech companies attending the 2011 Berkeley EECS Annual Research Symposium (BEARS)		
	Name	*Address*
	TBD	

Since 2004, the Industrial Relations Office of the EECS Department of Berkeley has been hosting BEARS, an annual Research Symposium. As in previous years, many centers and organizations associated with the EECS Department will follow the half day research symposium with open houses for additional interactions with the symposium attendees, who are typically from Bay Area high tech companies. The Center for E^3S will join this tradition and host a lunch and a 2 hour open house following the upcoming 2011 BEARS. This open house will be the Center's first opportunity, since its founding, to reach a broad audience from the information technology industry. The Center's goal for this event is to continue building the momentum with industry that resulted from the 2009 Symposium on Energy Efficient Electronics Systems that was hosted by Berkeley prior to the Center being awarded by NSF.

2b. Other Knowledge Transfer Activities and Outcomes

Nothing additional to report in this period

2c. Performance with respect to Metrics/Indicators

In this short Reporting Period, the Center initiated or planned activities to facilitate two way knowledge transfers from the Center and to the Center.

2d. Knowledge Transfer Plans for Next Reporting Period

In the next Reporting Period, the following will be initiated to support the Center's Knowledge Transfer goals:

- Talks by external speakers;
- A Journal Club; and
- Newsletters for industry.

In addition, the Center will develop and offer a Patent workshop in support of the performance metric, patent disclosures; see Section III.2f - Education.

V. EXTERNAL PARTNERSHIPS

1a. Goals and Objectives

External partnerships form the cornerstone in the execution of the E^3S' two way knowledge transfer strategy. The Center seeks partnerships with either industry or other academic/research institutions. Prior to the start of the 1st Reporting Period, the Center had already established external partnerships in both categories. In this Reporting Period, the Center has added new academic research partners.

- International Research Partners:

	Name	Affiliation	Primary Research Interest
1	Feliciano Giustino	Oxford University, U.K.	Band Edge Theory
2	Sajeev John	University of Toronto, Canada	Band Edge Theory
3	H. S. Kwok	Hong Kong University of Science & Technology, Hong Kong	Material growth & device fabrication
4	Schroeder Thomas	IHP Institute,	Nanoelectronics and

(New)		Frankfurt/Oder, Germany	Integration with Optics
5 *(New)*	Dieter Bimberg	Technische Universität Berlin, Berlin, Germany	Optical Interconnect

The academic research partners extend the Center's intellectual perspective and bandwidth. Since they are located globally, the academic research partnerships have the potential to offer international research opportunities, particularly for the Center's graduate student researchers, as well as be a source of engineering and scientific talents for the Center.

- Industrial Research Partners

  Four leaders in the electronics industry supported the proposal to NSF to fund the Center for E^3S. IBM, Intel, & HP are working toward the goal of energy efficient electronics science and have agreed to perform parallel research in their own laboratories and, in time, assign their staff to participate in the research as part of the Center. Lam Research has gifted two major process modules to Berkeley that will be used by E^3S researchers. These four corporate sponsors are working with the Center through an Industry Research Board; see Section VII – Management.

  Foremost in the Center's knowledge transfer goals is, as noted above, to use these industrial partnerships to make certain that the Center's academic technical directions will be practical, and lead to real successes. Thus, the commitment of parallel research and the eventual assignment of staff from the corporate partner companies to be resident at the Center will support this very important goal.

  In addition, the Center's goals in working with corporate partners include enhancing the education experience of the graduate students of the Center and the undergraduate students of the Center's community college partners through fellowships and internships.

  Besides maximizing the working relationship with the four sponsoring companies, the Center, as part of its knowledge transfer objective, will continuously seek to increase the number of corporate partnerships

1b. Performance and Management Indicators

Objective	***Metrics***	***Frequency***
Knowledge Transfer	Number of Contacts with Industry	Yearly

1c. Problems Encountered During Reporting Period

None

2a. Partnership Activities

Kickoff Meeting – November 7&8 2010

Led by	E. Yablonovitch (Berkeley)	
Organizations Involved		
	Name	*Address*
1.	IBM	Yorktown Heights, New York
2.	Aerospace Corporation	El Segundo, California
3.	Oxford University	Oxford, United Kingdom

The IBM representative, Dr. Paul Solomon, served as a member of the panel that discussed "How to Advance Theme 1, and What are the Realistic Prospects?" Also on the same panel was Dr. Joel Schulman, Aerospace Corporation, an external collaborator, who not only contributed to the discussions, but also gave a short review of TFET recent activities. A presentation on "Sharpness of Band Edges" was made by Feliciano Giustino, whose research is relevant to the Theme 1 research topic.

Biweekly Seminar – December 16, 2010		
Led by	J. Hoyt (MIT) & D. Antoniadis (MIT)	
Organizations Involved		
	Name	*Address*
	IBM	Yorktown Heights, New York

As previously mentioned, the Center's goal is a two-way transfer of information from the Center and to the Center. In that spirit, J. Hoyt and D. Antoniadis (both MIT) sponsored a talk where their graduate student, Jamie Teherani talked on "Imaginary Band Structure in Silicon Tunneling"; research that he previously pursued as an intern at IBM before becoming a participant of the Center. The seminar was attended by the IBM researcher, Dr. Paul Solomon. This seminar, which was attended by 10 faculty, 19 graduate students, 5 post-docs and 1 staff from MIT, Berkeley and Stanford, included a discussion with the Theme I co-PI's on further analysis of the presented IBM experimental data.

Research Partnership Development		
Led by	E. Yablonovitch (Berkeley)	
Organizations Involved		
	Name	*Address*
	IHP Institute	Frankfurt (Oder), Germany

A visit by E. Yablonovitch, Center Director, in June 2010 resulted in a MOU to facilitate research cooperation and exchanges between IHP Institute and the Center. The cooperation is focused on novel basic materials research approaches for low power silicon microelectronics and integration of photonics and electronics. The MOU covers exchange of information of equipment and facility; professional technical experience and in fields of interest; exchange of staff members; and joint development projects.

Research Partnership Development		
Led by	E. Yablonovitch (Berkeley)	
Organizations Involved		
	Name	*Address*
	Technische Universität Berlin	Berlin, Germany

A visit by E. Yablonovitch, Center Director, in June 2010 resulted in a verbal agreement to collaborate. Another outcome of the visit is that a Ph.D. graduate student of Technische Universität Berlin chose to join Berkeley and the Center for E^3S as a post-doc working in Theme I research under the guidance of E. Yablonovitch, Center Director. The new post-doc started his fellowship at Berkeley in November 2010.

2b. *Other Outcomes & Impacts*

None to report

2c. *Performance with respect to Metrics/Indicators*

The Center values external partnerships with both academia and industry. However, in its Strategic Plan, it has chosen to track progress to put more emphasis on the number of contacts with industry as these contacts are the enablers to extract value from established industrial partnerships as well as the pipeline for new partnerships. The rationale behind this choice is the recognition that industrial partnerships are the primary channels for Knowledge Transfer. In this Reporting Period, the Center has pursued activities with members of its industrial partners and its international academic partners.

2d. *Partnership Plans for Next Reporting Period*

Tracking of the number of contacts made industry will begin in the next Reporting Period. The Center will continue with the new contacts and develop new partnering opportunities.

VI. DIVERSITY

1a. *Goals and Objectives*

The diversity programs of the Center for E^3S seek to: 1) infuse the science and engineering pipeline with new, diverse and talented individuals; 2) develop methods to retain these individuals within the E3S research areas; 3) prepare these individuals for successful careers in research and education in the academic, public, and private sectors; and 4) devise appropriate metrics to assess the success of these efforts. However, the Center's Diversity goals and objectives are not standalone; they are integrated with Education and Research. The Center seeks to ensure that the composition of center participants reflects the diversity of the US, with a particular focus on underrepresented racial/ethnic backgrounds, women, and people with disabilities.

The Center will establish a baseline of the composition of its participants and affiliates after 12 months of operations. Then, it will set objectives to increase in URM participation upon completion of the baseline study.

1b. Performance and Management Indicators

Objective	Metrics	Frequency
Diversity	Increase in the number of Under-Represented Minorities associated with the Center	Year 1*: Baseline
		Every 2 years thereafter

1c. Problems Encountered During Reporting Period

None to report.

2a. Diversity Activities

<u>E^{3}S Research Experiences for Undergraduates (E^{3}S - REU):</u>

- The Center's own efforts to recruit applicants of under-represented minority groups will be led by Tanjula Farlough of Tuskegee, a staff participant of the Center. In the absence of a full-time Diversity Director, we look to T. Farlough's leadership to guide the Center's Diversity outreach activities. In particular, for the 2011 E^{3}S - REU program, the Center will leverage the outreach programs that T. Farlough has previously established at Tuskegee University to help with recruitment. Her efforts, which will begin in January 2011, will focus on outreach to URM students at Tuskegee, Cornell, U of Wisconsin - Madison, Alabama State and Auburn.
- The recruitment partnership with COINS (see Section III - Education) will include outreach to URM students. We will leverage COINS's recent efforts, which included presentations and workshops given at schools such as Florida International University, University of Maryland, Baltimore County's Meyerhoff Program, UC Riverside, and Smith College, and at national conferences such as the Society of Women Engineers and SACNAS, an organization committed to advancing Hispanics/Chicanos and Native Americans in Science. In January 2011 as the summer openings are posted on the E^{3}S website, M. Erol of COINS will send out information to those universities and professional societies alerting them of the Center for E^{3}S and its summer REU opportunities.

2b. Impact of Activities on the Center's Diversity

The Center has just been established and the activities described in this section have barely begun. We cannot report impact until the end of the next Reporting Period.

2c. Performance with respect to Metrics/Indicators

Section VIII gives a preliminary view of the demographic profile of the Center. However, since some of its programs will not begin until 2011, the baseline on URM participation is not scheduled to be reported in the Annual Report of the 2nd Reporting Period. The Center will strive to broaden participation in its 2011 Education programs.

2d. Diversity Plans for Next Reporting Period

- In Section III – Education, we shared that the Center plans to sponsor lectures and educational materials development to enhance the mentoring skills of graduate students in the SHARP program. These lectures and materials will emphasize the role of mentors in enabling diverse participation in science and engineering.
- The Center for E^3S has proposed to NSF that its Diversity program will include outreach to people with disabilities. In the 2nd Reporting Period, the Center will initiate efforts with one of its two community colleges partners, Los Angeles Trade Technical College and Contra County College, to develop a supplementary program to recruit and support students with disability to participate in the education programs of the Center.

VII. MANAGEMENT

1a. Center's organizational strategy and its underlying rationale

The organizational structure of the Center for E3S has been designed to provide leadership and support to the Center as the members pursue research, as well as to its programmatic goals of education, diversity, and knowledge transfer in an environment that must span disciplinary and institutional boundaries. See Appendix IV for an organizational chart.

At the heart of the Center is an Executive Committee (EC) that has multi-institutional and multi-disciplinary participation. The EC is responsible for the Center's Strategic Plan. As part of its leadership responsibility, the EC will conduct an annual review of the progress toward fulfilling the Center's goals, identify corrective actions, and revise the Plan, if deemed necessary. This leadership committee is led by the Center Director (and Principal Investigator), Professor E. Yablonovitch (Berkeley) and the Associate Center Director, J. Bokor (Berkeley). Other EC members are: D. Antoniadis (MIT), C. Chang-Hasnain (Berkeley), E. Fitzgerald (MIT), T.J. King Liu (Berkeley), P. Wong (Stanford), M. Wu (Berkeley), J. Yuen (Executive Director), the to be hired Education Director, and the to be hired Diversity Director.

The Center's Research is led by E. Yablonovitch, the PI who is also the Center's Director. As indicated in Section II – Research, the Research program of this Reporting Period is organized into four themes and an over-arching the systems integration research. The team leaders are members of the EC.

The Center has a management team that has full-time responsibility for the Center's operations and for facilitating the delivery of programmatic outcomes. This team is led by Dr. J. Yuen, Executive Director, and includes Janny Peng, Administrative Manager, and the two Education and Diversity Director positions. Several EC members have been assigned to provide timely and focused EC support to the management team. E. Yablonovitch, as the Center Director, provides oversight to the entire team, and in particular, he guides and supports the Executive Director. C. Chang-Hasnain, in the role of Associate Education Director, will guide and support the Education Director, and J. Bokor, in the role of Associate Diversity Director will guide and support the Diversity Director.

1b. Performance and Management Indicators

Objective	Metrics	Frequency
Strategic Plan	Assessment of goals, objectives, and outcomes	Yearly
Executive Committee Leadership	Perception of recognition Survey	Yearly
	Survey of co-PI's	Yearly
	External Advisory Board survey	Yearly
Ethical Conduct	Survey on fairness in authorship	Yearly
	Survey on Plagiarism	Yearly
	Spot checks on laboratory notebooks	Yearly

1c. Performance with respect to Metrics/Indicators

It is too early to have report results on the metrics given above; 1a. of this section.

1d. Problems Encountered During Reporting Period

The delay in the finalizing the NSF STC award agreement contributed to the late start by the Center in establishing its full-time management team and the Center's headquarter operations in Berkeley. In 4Q-2010, Dr. J. Yuen, Executive Director, has tactically focused on the time sensitive needs of the Center. The development of the Center's public identity, in the form of a new logo and the first release of a new website has been completed. The management team coordinated the release of the Strategic plan, organized the Kickoff Meeting and developed action plans for the Center's 2011 summer education programs that require the preparation for recruitment to begin in December 2010. Significant effort was expended on facilitating the implementation of the subawards, which has yet to be completed at the time of this annual report. Reasons for the delays were previously reported in Section II – Research. The outstanding issues preventing completion of the subawards have been identified and we expect the all agreements to be completed in the first week in January, 2011. Efforts to increase the bandwidth of the management team have been hampered by an unexpectedly longer than usual hiring approval process, in part due to staff shortage, a consequence of austerity measures at Berkeley. The job opening for the Education Director is approved, but job posting will not begin until January, 2011.

2. Management & Communications System

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

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

E. Yablonovitch, as the Center Director, shared the above set of values as part of the introductory talk that opened the Center's Kickoff Meeting. J. Yuen, Executive Director, presented a summary of the Strategic Plan, sharing the Center's vision, mission, goals and metrics to track progress and outcomes. NSF grant administrative requirements and the schedule of events were also communicated on the second day of the centerwide meeting.

The approach of this new Center is for a more formalized communication system to emerge, as its members and subgroups experiment with various communications venues. To date, the Center has communicated mainly through ad hoc meetings.

- Executive Committee Meetings – The EC met twice in October to adopt the agenda for the Kickoff Meeting and the Strategic Plan. Calls for both meetings were issued about 2 weeks before the meeting date. In each case, the presence of a simple majority was used in defining a quorum for decision making.
- Meeting with IRB Representatives – While the actual IRB members were not present at the Kickoff Meeting, the EC took the opportunity to meeting with the attendees of two IRB member companies as a group. The representatives from Intel and IBM attended the meeting.
- Theme Meetings – The theme leaders have called meetings of the co-PI's as needed. For example, the co-Po's of Theme IV, under the leadership of J. Bokor, held 4 ad hoc meetings at the beginning this Reporting Period to establish a strategy. Theme II, led by T.J. King Liu, held a meeting that included all co-PI's working on the Theme. Co-PI's and their students from Berkeley, Stanford and MIT involved in Theme II participated through teleconferencing.
- Center Planning – A capital planning meeting was attended by 8 of the 11 Berkeley PI/co-PI's. One co-PI, who could not attend, sent input in advance. The team identified the common capital needs for the next Reporting Period, developed a strategy for funding, and assigned owners to execute on the agreements.

Standing meetings are beginning to emerge.

- Theme Group Meetings – Theme IV has on-going weekly meetings
- Biweekly Student Seminars – The faculty, graduate students, and post-docs of the 4 partner institutions have been meeting regularly every other Thursday while the institutions are in session. The only exception resulted from the Kickoff Meeting. Each session of 1H 2011 has an assigned faculty sponsor and speakers and titles of talks for Q1 2011 have been communicated.

- Monthly Student and Post-Doc Council Meetings – E^{3}S graduate students and post-docs have agreed to a standing monthly meeting to develop the Student and Post-Doc Council and coordinate group activities.

In the next Reporting Period, the Center's management team will seek to formalize a schedule of key Center events and meetings based on the learnings and practices of the 1st Reporting Period. The Center's website will carry a calendar of events and meetings, promoting center wide communication.

In the 1st Reporting Period, the Center has been developing and/or implementing tools to foster communication among the partner institutions that spans across the country.

- Video conferencing: The Center has implemented the use of Webex. For example, the Biweekly Student Seminar Series used the video conferencing capability enabling slides to be presented to multiple locations and the attendees of different locations to see each other. The Student & Post-Doc Council has met using the same venue.
- Website: The Center has released the first version of its website that includes an intranet; www.e3s-center.org. The Center's new website leveraged the website capability of another Berkeley STC, TRUST, adopting its backend platform, but implementing a unique E^{3}S look and feel in its webpages. This site offers the Center's participants and affiliates individual accounts and membership in multiple workspaces via a secure login procedure. The website offers e-mail lists, collaborative workspaces, archiving and access for publications and presentations, news items, blogs, information on past and future events, and workshop/conference registration pages. The website can support workgroup web pages via participant supplied HTML and Wiki pages. The goal is for the new intranet to be the key collaborative and communication tool for the Center.

Open and timely communications are intended to enable the Center to be agile, particularly in its Research approaches. E. Yablonovitch communicated the Center's process for consideration of funding new research ideas at the Kickoff Meeting, fulfilling an action item identified in the Strategic Plan that will enhance the Center's ability to achieve its strategic goal of Integrative Research.

3. *Center's internal and external advisors or advisory bodies*

The primary sources of advice and guidance for the Center for E^{3}S are two groups:

- External Advisory Board (EAB): The E^{3}S EAB consists of a distinguished group of senior-level and other leaders from industry, academia, and government research laboratories. It offers perspectives from a broad range of focus and experience, and its guidance supplements the strategic planning by the management team and the E^{3}S Executive Committee. The primary goal of the EAB is to offer an independent assessment of the Center's Executive Committee, particularly in regard its leadership in research, education, outreach, and diversity goals, plans and accomplishments. EAB input plays a crucial role through its annual assessment of the Center.

  The EAB membership has also been chosen recognizing the skills of each member, so that the members will complement each other and the Center will have the benefit of the broad range of experience and perspectives necessary to support the breadth of the Center's mission. EAB members, their affiliations, and their primary expertise are listed in the table below.

	Name	Affiliation	Primary Expertise
1	Nick Alexopoulos	Broadcom	Industry liaison with universities
2	Katherine Dunphy-Guzman	Sandia	Diversity
3	Deborah Estrin	UCLA	Education
4	Vijay Gill	Google	Research
5	Mark Lundstrom	Purdue	Research & Education
6	Horst Simon	LBNL	Research

- Industrial Research Board (IRB): The Center for E3S is fortunate to have received strong support from four leaders in the semiconductor industry even before its inception. IBM, Intel, & HP are working toward the goal of energy efficient electronics science and, as noted above, have agreed to perform parallel research in their own laboratories and, in time, assign their staff to participate in the research as part of the Center. Lam Research has gifted two major process modules to Berkeley that will be used by E^3S researchers. The IRB will monitor, advise and participate in the Center's research, education and knowledge transfer goals.

  IRB members and their affiliations are listed in the table below.

	Name	Affiliation
1	Paolo Gargini	Intel
2	David Hemker	Lam Research
3	Ghavam Shahidi	IBM
4	Stan Williams	HP

4. *Changes in Strategic Plan*

The timelines laid out in the version of the Strategic Plan that was submitted to NSF assumed Year 1 to begin in September 2010 and end 12 months later. However, this and future Annual Reports follow a Reporting Period schedule that differs from what constitutes a "Year " or 12 months period in the Strategic Plan. Before the end of this Reporting Period, the Center will revise the schedule of milestones in the Strategic Plan to reflect NSF's Reporting Period schedule.

VIII. CENTER-WIDE OUTPUTS AND ISSUES

1. *Publications*

H. Ko, K. Takei, R. Kapadia, S. Chuang, H. Fang, P. W. Leu, K. Ganapathi, E. Plis, H. S. Kim, S.-Y. Chen, M. Madsen, A. C. Ford, Y.-L. Chueh, S. Krishna, S. Salahuddin, A. Javey. "Ultrathin compound semiconductor on insulator layers for high performance nanoscale transistors", *Nature*, 468, 286–289, 2010.

2. *Conferences Presentations*

E. Yablonovitch, "Energy Efficient Electronics; Searching for the Milli-Volt Switch", *International Nano-Optoelectronic Workshop*, Changchun, Jilin, Manchuria, China; August, 2010.

E. Yablonovitch, "Energy Efficient Electronics; Searching for the Milli-Volt Switch", Tutorial; *IEEE Nano Symposium*, Seoul Korea; August, 2010

A. Lakhani, M. K. Kim, E. K. Lau, and M. C. Wu, "Lasing in a One-Dimensional Plasmonic Crystal," *International Semiconductor Laser Conference,* Kyoto, Japan, September 2010.

C. Hu, "Paths to Energy Efficient ICs", plenary paper, *SOI Conference*, San Diego, CA, USA, October, 2010.

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

S. Oh, L. Wei, S. Chong, J. Luo, H.-S. P. Wong, "Device and Circuit Interactive Design and Optimization Beyond the Conventional Scaling Era," invited special session paper (paper 17.3), *IEEE International Electron Devices Meeting*, San Francisco, CA, USA, December, 2010.

3. *Other Dissemination Activities*

E. Yablonovitch, "Energy Efficient Electronics; Searching for the Milli-Volt Switch", IHP Institute, Frankfurt/Oder, Germany; June 24, 2010

E. Yablonovitch, "Energy Efficient Electronics; Searching for the Milli-Volt Switch", Technical University of Berlin, Berlin, Germany; June 25, 2010

E. Yablonovitch, "Energy Efficient Electronics; Searching for the Milli-Volt Switch", NSF Nanoscale Science and Engineering Grantees Conference, Arlington VA; December 6, 2010.

E. Yablonovitch, "Energy Efficient Electronics; Searching for the Milli-Volt Switch", Edison Lecture at the Naval Research Lab, Washington DC; December 7, 2010.

J. Teherani (Graduate Student, MIT) hosted a Saturday fabrication lab tour and gave a presentation about microelectronics research to 30 female middle school students in the Boston area to encourage interest in science and engineering, as part of an outreach event of the Society of Women Engineers, KEYs (keys to empowering youth) program.

4. *Awards and Other Honors*

Recipient	**Reason for Award**	**Award Name**	**Sponsor**	**Date**	**Award type**
Elad Alon	Teaching	Electrical Engineering Outstanding Teaching	UC Berkeley EECS Department	May, 2010	Education

		Award			
Eli Yablonovitch	Contribution to Industry, Technology & Education	Mountbatten Medal	Inst. of Eng'g. & Tech. UK	November, 2010	Research
Eli Yablonovitch	Sponsors' interest in energy questions	James and Katherine Lau Chair	James and Katherine Lau of NetApp Inc.	December, 2010	Distinguished Professorship Chair
Tsu-Jae King Liu	Contributions to nanoscale MOS transistors, memory devices, and MEMS devices	Kiyo Tomiyasu Award	IEEE	December 2010	Research
Natania Antler (Berkeley)	Merit	NSF GRFP	NSF	May 2010	Fellowship
James Teherani (MIT)	Merit	National Defense Science & Engineering Graduate Fellowship	Department of Defense	August, 2010	Fellowship
James Teherani (MIT)	Merit	NSF Graduate Fellowship	NSF	August, 2010	Fellowship

5. *Undergraduates, M.S. Ph.D. Students who have Graduated*

None to report

6. *General Outputs of Knowledge Transfer Activities*

Patents: none to report

Licenses: none to report

Startup companies: none to report

7. *Participants*

Category		Institutional Affiliation		Department		Gender		Disability Status	Ethnicity		Race		Citizenship	
19	Faculty	11	Berkeley	15	E.E.	16	M	All - Not Available	0	Hispanic	13	White	19	US citizens & US Permaent Residents
		6	MIT	3	Mats Sci	3	F		18	Not Hispanic	5	Asian		
		1	Stanford	1	Physics				1	Not Available	0	Black	0	Non US Citizen w Visa
		1	Tuskegee								1	Not Available	0	Not Available
9	Post-Docs	7	Berkeley	5	E.E.	9	M	All - Not Available	0	Hispanic	4	White	1	US citizens & US Permaent Residents
		0	MIT	2	Mats Sci		F		9	Not Hispanic	5	Asian		
		2	Stanford	2	Physics				0	Not Disclosed	0	Black	8	Non US Citizen w Visa
		0	Tuskegee									Not Available	0	Not Available
23	Graduate Students	13	Berkeley	18	E.E.	20	M	All - Not Available	21	Hispanic	10	White	5	US citizens & US Permaent Residents
		6	MIT	3	Mats Sci	3	F		0	Not Hispanic	10	Asian		
		3	Stanford	1	Physics				2	Not Available	1	Black	11	Non US Citizen w Visa
		1	Tuskegee	1	Other						2	Not Available	7	Not Available
3	Staff	2	Berkeley		E.E.	0	M	All - Not Available	3	Hispanic	0	White	3	US citizens & US Permaent Residents
		0	MIT		Mats Sci	3	F		0	Not Hispanic	2	Asian		
		0	Stanford		Physics				0	Not Available	1	Black	0	Non US Citizen w Visa
		1	Tuskegee	3	Other						0	Not Available	0	Not Available

8. *Affiliates*

Category		Institutional Affiliation		Department		Gender		Disability Status	Ethnicity		Race		Citizenship	
1	Faculty	7	Berkeley	7	EE	14	M	Not Available	0	Hispanic	9	White	10	US citizens & US Permaent Residents
4	Research Scientists	4	MIT	1	Mats. Sci	4	F		16	Not Hispanic	7	Asian		
5	Post-Docs	0	Stanford	4	Physics				0	Not Available	2	Black	4	Non US Citizen w Visa
4	Graduate Students	0	Tuskegee	2	Other						0	Not Available	2	Foreign Visitor
1	Undergraduates	2	Other Academic	4	Not Available								2	Not Available
3	Other	5	Other											

IX. INDIRECT/OTHER IMPACTS

None to report

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XI. APPENDICES

Appendix I: Kickoff Meeting Agenda

Center for Energy Efficient Electronics Science

A National Science Foundation Science & Technology Center

Kickoff Meeting - 1st Annual

November 7 & 8, 2010
Cambridge, MA

AGENDA

Sunday, November 7 - Boston Marriott Cambridge, 50 Broadway, Cambridge

10:30am	Check in – Pickup Name Badge	
11:00am	Welcome & Introductions	**Yablonovitch**
11:10am	Center's Strategic Plan	**Yablonovitch & Yuen**
12:15pm	Lunch	
1:15pm	*System Level Requirements for a new Switch*	**Alon**
1:45pm	Theme 1: *Scientific Alternatives for a new Semiconductor Switch*	**Yablonovitch**
2:15pm	Invited Talk: *Can Theory provide answers regarding band tails?*	**Giustino** *(Oxford)*
2:45pm	Panel Discussion - *How to Advance Theme 1, and What Are the Realistic Prospects?*	

Panelists: Yablonovitch, Antoniadis, Hoyt, J. Schulman *(Aerospace Corp.)*, ***P. Solomon*** *(IBM)*

3:15pm	Break	
3:45pm	Theme 2: *Scientific Alternatives for Low Voltage Nano-Mechanical Switching*	**King Liu**
4:15pm	Panel Discussion - *Nanomechanical Switching, What Performance is Possible and How Soon?*	

Panelists: King Liu, P. Wong, Bulovic

4:45pm	Theme 3: *Goals and Prospects for Efficient Optical Interconnect Systems*	**M. Wu**
5:15pm	Panel Discussion - *Ultra-sensitive photodetectors and ultra-speed datacomm approaches*	

Panelists: M. Wu, Chang-Hasnain, Yablonovitch

Sunday, November 7 - Boston Marriott Cambridge, 50 Broadway, Cambridge

5:45pm Poster Session

	Xin Zhao	*Devices with Steep Sub-Threshold Characteristics based on Impact Ionization on Narrow Bandgap Materials*	MIT
	Daesung Lee	*Scaled-Down Lateral Nanoelectromechanical Switches*	Stanford
	Frank Yaul Apoorva Murarka Sarah Paydavosi	*Nano Electromechanical Switch*	MIT
	Jamie Teherani	*Band-to-Band Tunneling in Silicon Diodes*	MIT
	Michael Eggleston Ryan Going	*Optical Antenna Based nanoLED*	UC Berkeley
	Peter Matheu	*Planar SOI TFET Enhancement via Back Bias*	UC Berkeley
	Natania Antler	*Spin Readout with Superconducting Circuits*	UC Berkeley
	Rehan Kapadia	*Ultra-thin III-V on Insulator (XOI) for Low Power Transistors*	UC Berkeley
	Brian Lambson	*Nanomagnetic Logic*	UC Berkeley
	Sapan Agarwal	*Effects of Dimensionality on TFET Turn On Characteristics*	UC Berkeley
	Jack Yaung	*Micro-Relay Technology and Scaling for mV Operation*	UC Berkeley

7:00pm Group Dinner

8:00pm Executive Committee Meeting

Sunday, November 7 - The Thirsty Ear Pub, 235 Albany Street, Cambridge

8pm to 10pm Students & Post Docs Social

Monday, November 8 - Research Building for Electronics, Haus & Allen Rooms, MIT;
50 Vasser Street, 4th Floor, Cambridge

8:00am	Continental Breakfast	
8:30am	**Theme 4**: *Strategy for Nano-Magnetism, and Surpassing the Landauer Limit*	**Bokor**
9:00am	Panel Discussion - *Developing practical new signaling concepts in spin magnetics* **Panelists: Bokor, Salahuddin, Yablonovitch**	
9:30am	Invited Talk: *VO_x Compounds as Metal-Insulator Switches*	**J. Wu** *(Berkeley)*
10:00am	Invited Talk: *Education & Outreach Opportunities at Tuskegee*	**Farlough** *(Tuskegee)*
10:30am	Break	
11:00am	Invited Talk: *Education and Outreach Programs at MIT*	**Young** *(MIT)*
11:30am	Invited Talk: *Emergent Behaviors of Integrated Cellular Systems, MIT STC*	**Kamm** *(Director)*
12noon	General Lunch	
12noon	Executive Committee Lunch	
1:00pm	Administrative Requirements	**Yuen & Peng**
1:30pm	Breakout Sessions	
	Breakout Session 1 (Students & Post-Docs): *Student Council*	**Agarwal, Teherani & Yuen**
	Breakout Session 2 (Faculty & Staff): *Integration of Research Approaches, Education & Outreach*	**Yablonovitch**
2:30pm	Plenary Session: *Reports from Breakout Sessions*	
3:30pm	Review of Action Items, Next Steps & Closing Comments	
4:00pm	Meeting Adjournment & Departure	

Appendix II: 2011 Seminar Series & 2011 Seminar Series

Dates *(see Note)*	**Seminars**	**Speakers**	**Sponsors**
2010			
October 7	**Tunneling Transistors and the Density of States Effects of Different Dimensionalities**	Sapan Agarwal	Professor Yablonovitch *(Berkeley)*
October 21	**Micro-Relay Technology and Scaling for mV Operation**	Jack Yaung	Professor King-Liu *(Berkeley)*
November 18	**Nano-LEDs for Optical Interconnects**	Erwin Lau	Professor Wu *(Berkeley)*
December 2	**Nanomagnetic Logic and the Thermodynamic Limits of Computation**	Brian Lambson	Professor Bokor *(Berkeley)*
December 16	**Tunneling in Si-based Heterostructures**	Jamie Teherani	Professors Antoniadis & Hoyt *(MIT)*
2011			
January 13	**Scaled Vertical and Lateral NEM Relays**	Daesung Lee	Professor Wong *(Stanford)*
January 27	**Recent simulation results on 1D and 2D tunnel FET structures: Transport, limitations on ON current, 'Ballistic Leakage' and Structural Characterization**	Kartik Ganapathi & Youngki Yoon	Professor Salahuddin *(Berkeley)*
February 10	**III/V-on-Insulator (XOI) Materials and Devices**	Rehan Kapadia	Professor Javey *(Berkeley)*
February 24	Theme III	Roger Chen	Professor Chang-Hasnain *(Berkeley)*
March 10	**The Squitch: Introduction and Initial Development Progress**	Sarah Paydavosi & Frank Yaul	Professor Bulovic & Lang *(MIT)*
April 7	**Devices with Steep Subthreshold Characteristics based on Impact Ionization on Narrow Bandgap Materials**	Xin Zhao	Professor del Alamo *(MIT)*
April 21	Theme IV	R. Vijay	Professor Siddiqi *(Berkeley)*
May 5	Themes I	Speaker TBD	Professor Yablonovitch *(Berkeley)*

Note: No Seminars on November 4, 2010, December 30, 2010, and March 24, 2011

Summary of Seminar Attendance	
October 7, 2010	5 faculty, 3 post-docs, 18 graduate students and 1 staff from Berkeley, MIT, Stanford and Tuskegee
October 21, 2010	6 faculty, 3 post-docs, 19 graduate students and 1 staff from Berkeley, MIT, Stanford and Tuskegee
November 18, 2010	4 faculty, 4 post-docs, 25 graduate students and 1 staff from Berkeley, MIT, and Stanford
December 2, 2010	5 faculty, 2 post-docs, 20 graduate students and 1 staff from Berkeley, MIT and Tuskegee
December 16, 2010	10 faculty, 5 post-docs, 19 graduate students and 1 staff from Berkeley, MIT, and Stanford, and 1 scientist from IBM

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Center of Integrated Nanomechanical Systems (COINS)
Berkeley Nanosciences and Nanoengineering Institute
548 Sutarjda Dai Hall MC 1726
BERKELEY, CALIFORNIA 94720
December 20, 2010

Dr. M. Josephine Yuen
Executive Director
Center for Energy Efficient Electronics Science (E3S)
University of California, Berkeley
Berkeley, CA 94720

Dear Dr. Yuen:

The Center of Integrated Nanomechanical Systems (COINS) is happy to collaborate with the Center for Energy Efficient Electronics Science regarding the positions you have for Research Experience for Undergraduates for Summer 2011. COINS has an established infrastructure in place for its summer research program and can help with developing your REU applications. In addition, we can also disseminate information about your Center and your REU openings to our contacts, and help with the selection and admission process.

COINS spent an extensive amount of time this past fall recruiting underrepresented minority students to our summer program. Presentations and workshops were given at schools such as Florida International University, University of Maryland, Baltimore County's Meyerhoff Program, UC Riverside, and Smith College. In addition, we recruited at national conferences such as the Society of Women Engineers and SACNAS, an organization committed to advancing Hispanics/Chicanos and Native Americans in Science. We will send your recruitment information to all of our contacts at these institutions.

I understand that E^3S originally intended to collaborate with one of UC Berkeley's SUPERB programs and that both SUPERB REU grants are currently under NSF review. Should the need arises, the E^3S summer REU students can participate in the COINS 2011 summer program.

The COINS Summer REU program has an established infrastructure that includes the following:

Logistics
- Securing travel and accommodations arrangements for participants
- Enrolling them in UCB summer session to ensure access to campus services
- Administering payment of stipend checks

Programmatic
- Orientation
- Weekly seminars on both academic and nanoscience topics
- Graduate school advising
- Field trips
- Social Activities
- Participation in poster session

If you have any questions or concerns, please do not hesitate to contact me.

Warm Regards,

Meltem Erol
Director
Education & Outreach
Center of Integrated Nanomechanical Systems (COINS)

Center for Energy Efficient
Electronics Science

Appendix IV: Organization Chart of the Center for E^3S