1. PROJECT SUMMARY

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons inside nanostructures for new nanoelectronic and nanophotonic devices, and to investigate how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Research Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

Cluster 2: Nanoscale Building Blocks makes new classes of nanostructures that exhibit size-dependent properties. We synthesize structures with unconventional shapes, as well as zero, one- and two-dimensional nanostructures such as nanoparticles and nanowires. New materials are introduced, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks are promising for nanoelectronics and nanophotonics as well as for biosensors.

Cluster 3: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons in nanostructures using custom-made scanning probe microscopes. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing. New types of semiconductor heterostructures are grown for this work using Molecular Beam Epitaxy.

The **Center for Nanoscale Systems (CNS)** is a major investment by Harvard to provide the facilities needed for research in his area. A new building, the **Laboratory for Integrated Science and Engineering** is nearing completion — it will house **CNS** facilities for imaging, nanofabrication, and materials growth. Harvard and UC Santa Barbara in our Center provide nanofabrication facilities to outside users through the **National Nanotechnology Infrastructure Network** (NNIN).

Connections with **Industry** are built by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program**. This year our Center was funded by the **Nanoelectronics Research Initiative** of the **Semiconductor Industry Association** to develop new oxide materials for future logic switches. Many Center participants have collaborations with industry.

Our Center promotes **education** in nanoscale science and engineering and develops **human resources** at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities including REU and RET programs, a course *Applied Physics 298r – Interdisciplinary Chemistry, Engineering and Physics*, and a series of workshops.

The **Museum of Science, Boston** presents advances in nanoscience from our Center to the public in an entertaining and informative way. The Museum and the Exploratorium lead the new **National Informal Science Education (NISE) Network**.

Our Center plans to increase **Diversity** by: (1) recruiting a more diverse group of graduate students and postdocs, (2) increasing the diversity of participating faculty, (3) recruiting members of underrepresented groups by extending REU approaches, (4) introducing public school students to science and engineering, and (5) developing long-term partnerships with predominantly female and minority-serving institutions.

2. LIST OF CENTER PARTICIPANTS AND ADVISORY BOARD

(a) Center Participants

Name	Field of Research	Institution
Carol Lynn Alpert	Education and Outreach	Museum of Science
Raymond Ashoori	Physics	MIT
Michael Aziz	Physics & Applied Physics	Harvard
Moungi G. Bawendi	Chemistry	MIT
Federico Capasso	Applied Physics & Elect. Eng.	Harvard
Kenneth B. Crozier	Electrical Engineering	Harvard
Eugene Demler	Physics	Harvard
Daniel Fisher	Physics	Harvard
Cynthia M. Friend	Chemistry & Applied Physics	Harvard
Gerald Gabrielse	Physics	Harvard
Arthur C. Gossard	Materials	UCSB
Bertrand I. Halperin	Physics	Harvard
Donhee Ham	Electrical Engineering	Harvard
Eric J. Heller	Chemistry & Physics	Harvard
Jennifer E. Hoffman	Physics	Harvard
Marc A. Kastner	Physics	MIT
Efthimios Kaxiras	Physics & Applied Physics	Harvard
Charles M. Lieber	Chemistry & Applied Physics	Harvard
Mikhail Lukin	Physics	Harvard
Charles M. Marcus	Physics	Harvard
Eric Mazur	Applied Physics & Physics	Harvard
Joseph Mizgerd	Biology & Public Health	Harvard
Venkatesh Narayanamurti	Applied Physics & Physics	Harvard
Hongkun Park	Chemistry	Harvard
Mara Prentiss	Physics	Harvard
Kevin (Kit) Parker	Bioengineering	Harvard
Pierre Petroff	Materials	UCSB
Shriram Ramanathan	Materials	Harvard
Howard A. Stone	Materials & Fluid Mechanics	Harvard
Michael Tinkham	Physics	Harvard
David Weitz	Materials	Harvard
Robert M. Westervelt	Applied Physics & Physics	Harvard
George M. Whitesides	Chemistry	Harvard
Xiaowei Zhuang	Chemistry & Physics	Harvard

International Collaborators

Fabio Beltram	Physics	NEST, Pisa, Italy
Piotr Garstecki	Chemistry	Polish Academy of Sciences
Leo Kouwenhoven	Physics	Delft University of Technology
Eugenia Kumacheva	Physics	University of Toronto
Daniel Loss	Physics	U Basel
Maria-Anita Rampi	Physics	University of Ferrara, Italy
Lars Samuelson	Physics	Lund University
Hiroyuki Sakaki	Inst. of Industrial Science	U Tokyo
Seigo Tarucha	Physics	U Tokyo

Domestic Collaborators

Sangeeta Bhatia	HST	MIT
Giannoula Klement	Biomedicine	Children's Hospital
Dale Larson	Biophysics	Harvard Medical School
Chinh Pham	NanoTech & Business Forum	Greenberg Traurig, LLP
Richard Rogers	Bioimaging	Harvard School of Public Health

National Laboratories

Julia Phillips	Physical Sciences	Sandia, CINT

Public Outreach and Education

Carol Lynn Alpert	Museum of Science, Boston
Tim Miller	Museum of Science, Boston
Robert Graham	Harvard
Kathryn Hollar	Harvard

(b) Advisory Committee

Kenneth Babcock	Si Biosensors
George I. Bourianoff	Intel Corporation
Donald Eigler	IBM, Almaden Research Center
Steven Girvin	Yale University
Rachel Goldman	University of Michigan
Harald Hess	Howard Hughes Medical Institute
Evelyn Hu	University of California, Santa Barbara
Paul L. McEuen	Cornell University
Carmichael Roberts	WMR Biomedical, Inc.
John Rogers	University of Illinois
Richard Slusher	Lucent Technologies
Tom Theis	IBM, T.J. Watson Research Center
Ellen D. Williams	University of Maryland

3. MISSION AND BROADER IMPACT

In the following mission statement, taken from our **Project Summary**, we present the goal of our Center — to develop tools for the study of nanoscale systems — and describe its research, education and outreach programs. The **Strategic Research Plan** presented in Section 5 describes how the three Research Clusters below address important applications, and how our investigators work together to reach these goals.

3a. Mission Statement

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons in nanostructures for future electronics and photonics, and to understand how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

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The **Museum of Science, Boston** presents advances in nanoscience from our Center to the public in an entertaining and informative way. Larry Bell and **Carol Lynn Alpert** at the Museum are co-PIs of the new **National Informal Science Education (NISE)** network run with core partners: The Exploratorium and The Science Museum of Minnesota. The NISE network is designed to foster public awareness, engagement and understanding of nanoscale science, engineering and technology.

Our Center aims to increase **Diversity** by: (1) recruiting a more diverse group of graduate students and postdocs, (2) increasing the diversity of participating faculty, (3) recruiting members of underrepresented groups by extending REU approaches, (4) introducing public school students to science and engineering, and (5) developing long-term partnerships with predominantly female and minority-serving institutions.

3b. Advances in Fundamental Knowledge and Technology

Cluster 1: Tools for Integrated NanoBiology

This Cluster is based on the development of microfluidic and hybrid biochips and ways probe biological systems on the nanoscale. An essential tool for NanoBiology is the ability to image and manipulate the living cells. We feature two recent achievements by **Kit Parker** and **Donhee Ham**.

Parker is developing atomic force microscope (AFM) tips coated with a conductive polymer (polypyrrole) to modulate protein-protein interactions using the tip voltage (Fig. 3.1). By combining imaging with manipulation, these devices can be used conduct image-guided cell surgery to target, manipulate and extract items of interest.

In a demonstration of this technique, a conducting AFM tip coated with polypyrole can be used to pick up and move a fluorescent bead coated with fibronectin (FN) (Fig. 3.2). The polypyrole is doped with anti-fibronectin (αFN) and sulphate polyions. By applying a positive tip voltage, polypyrrole is oxidized and binding of FN proteins is facilitated,

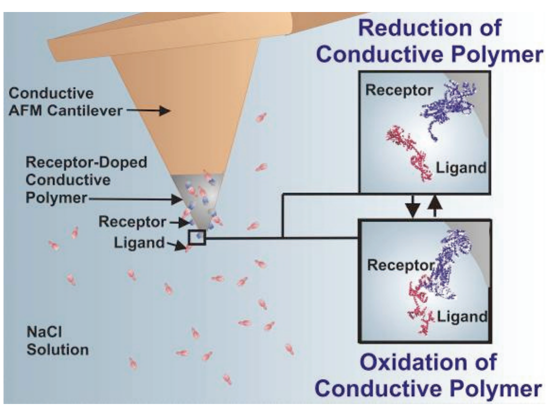

Figure 3.1. AFM cantilevers functionalized with receptor-doped conductive polymers can be used to dynamically modulate protein-protein interactions at the micro- and nanoscale by controlling the oxidation and reduction states of the polymer. (**Parker**)

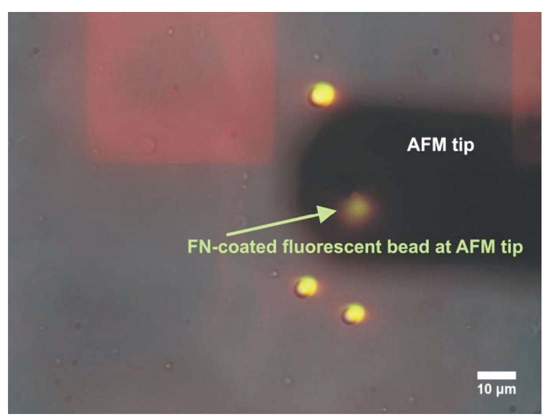

Figure 3.2. Movement of a fibronectin (FN)-coated fluorescent bead using an anti-fibronectin (αFN)-doped polypyrrole AFM tip. (**Parker**)

allowing the tip to pick up a FN-coated bead. Conversely, during reduction of polypyrrole by applying a negative tip voltage, binding of FN is not promoted and the bead remains free [Gooding *et al.,* 2004]. In this way, one can use the AFM to pick up and move FN coated objects.

Ham and **Westervelt** have developed hybrid CMOS/Microfluidic chips that combine a custom made integrated circuit (IC) with a microfludic system built on top [Lee *et al*., 2007]. The IC provides the power semiconductor technology, and the microfluidic system provides a biocompatible environment for cells. Cells tagged by magnetic beads could be individually trapped and moved through the fluid by a microcoil array below. **Westervelt'**s group has used a similar approach to manipulate objects in the microfluidic system via dielectrophoresis using an array of RF electrodes in fabricated in the IC below.

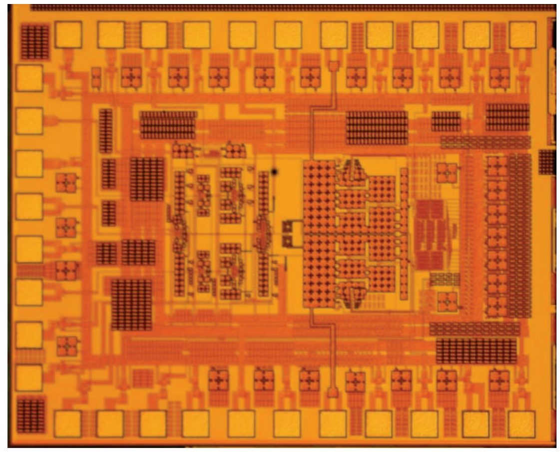

Figure 3.3. **Ham** and **Westervelt** have developed CMOS/Microfluidic hybrid chips that can manipulate individual biological cells tagged by magnetic beads: A microcoil array in a custom CMOS chip controls the motion of the bead-bound-cells in the microfluidic chamber above. They plan to extend this work to imaging. The figure shows a microcoil bridge circuit designed to detect cells tagged by magnetic beads in the microfluidic system above.

Ham has recently extended this work by designing a chip that can sense the presence of magnetic bead in the microfluidic system above. The magnetic bead is detected via its interaction with an RF magnetic field created by the IC. A chip containing an RF bridge circuit for bead detection is shown in Fig. 3.3. This approach is promising, because a single hybrid CMOS/Microfluidic chip can potentially sense and manipulate cells tagged with magnetic beads in the microfluidic chamber.

The application of semiconductor technology to biology and medicine is advancing rapidly. Lee, **Ham** and **Westervelt** [2007] have edited a book for Springer titled *CMOS Biotechnology* that contains chapters by groups from Electrical Engineering describing their development of medical tools.

Cluster 2: Nano Building Blocks

This cluster is developing new types of building blocks for nanoelectronics and nanophotonics, as well as probes for biological systems. **Bawendi** is developing nanocrystal heterostructures and hybrids, **Park** and **Lieber** are synthesizing nanowires and heterostructures from new materials in new geometries, **Capasso** and **Crozier** use nano building blocks to make nanophotonic devices, and **Friend** and **Ramanathan** are developing chalcogenides and oxide semiconductors for future nanoelectronics. Lars Samuelson (Lund University, Sweden) recently joined the Center as an international collaborator. In the highlights here we feature three new building blocks.

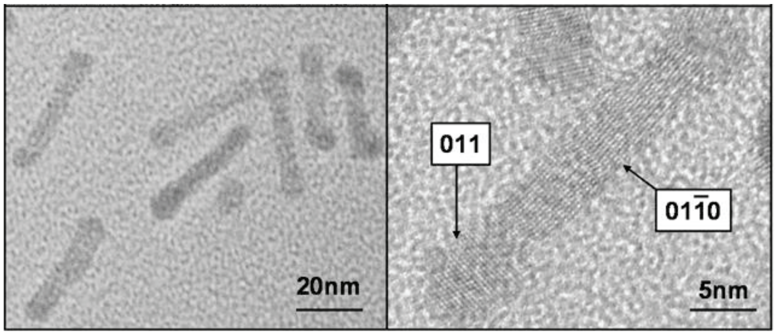

Figure 3.4. Electron microscope images of "nanobarbells" specifically made of two semiconductors specifically chosen because electrons are drawn into the "bar" (CdSe) while holes are drawn into the "tips" (CdTe). These could potentially be used in nanocrystal-based solar energy conversion. (**Bawendi**)

The transformation of light into current requires as a first step the rapid dissociation of electrons and holes so that they can be carried to opposite electrodes. This is accomplished in bulk structures by creating an interface between two semiconductor layers that promotes this dissociation. **Bawendi**'s group has designed and synthesized nano-interfaces in nanocrystals structures specifically to enable the rapid dissociation of electrons and holes at the nanoscale.

Figure 3.4 shows electron microscope images of "nanobarbells" composed of a CdSe "bar" with two CdSe "tips." When illuminated by light, the electrons are drawn into the "bar" and the holes into the "tips." These nano-heterostructures could potentially be used in nanocrystal-based solar energy conversion schemes.

A novel structure of a different type has been made by **Lieber**'s group. They have synthesized p-type/intrinsic/n-type (p-i-n) silicon core/shell/shell nanowires, shown in Fig. 3.5. The nanowires consist of a single crystalline p-Si core, surrounded by intrinsic, then n-Si shells of controlled thickless. Using a selective wet etch, they have separately contacted the p-Si core and the n-Si outer shell. Electrical transport measurements through these show well-defined diode behavior.

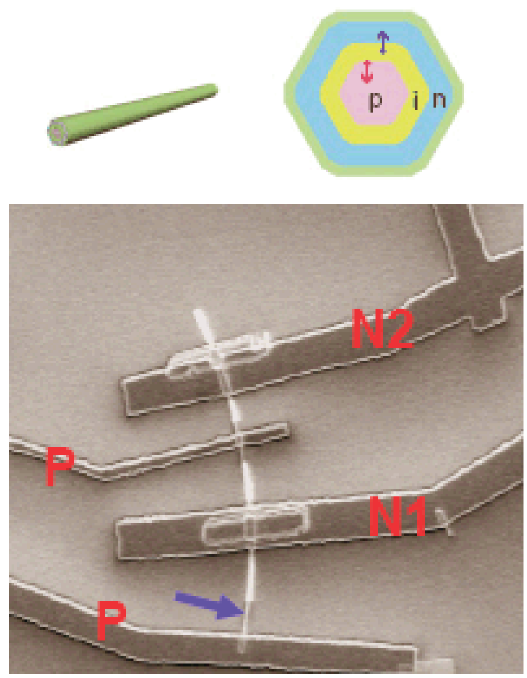

Figure 3.5. **Lieber** has designed, prepared and characterized the first *p-i-n* silicon core/ shell/shell nanowire structures. The nanowires consist of a single-crystalline p-Si nanowire core and conformal *i*- and *n*-shells. Devices with separate contacts to the *p*-type core and *n*-type outer shell demonstrate well-defined diode behavior.

These new *p-i-n* nanowire structures open up unique opportunities as building blocks for the creation of novel photovoltaics and integrated electronic logic gates.

The challenge of making truly nanoscale devices for future nanoelectronics has inspired research in new materials. **Park**, **Ramanathan** and **Friend** are investigating metal-oxide and chalcogenide materials. VO_2

undergoes a metal-insulator phase transition that could be used as the basis for a switch.

Park has synthesized and tested the properties of VO_2 nanobeams to understand their potential for nanoelectronics. A substrate leads to a coherent uniaxial strain on the nanobeam that causes spontaneous formation of alternating nanoscale metal-insulator domains along the nanobeam length as shown in Fig. 6.6, and thus produces nanoscale M-I heterostructures within a compositionally homogenous material [Wu *et al.*, 2006]. This study demonstrates that VO_2 and W-VO_2 nanobeams behave as a one-dimensional system for the M-I phase transition.

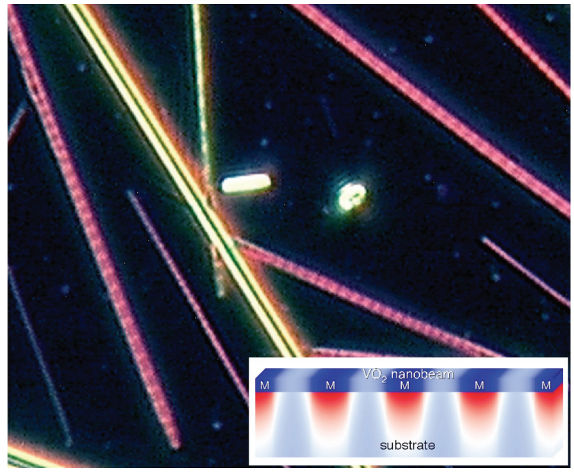

Figure 3.6. Dark-field optical images of VO_2 nanobeams on a SiO_2 surface at 100°C. *Inset*: schematic diagram showing the periodic domain pattern of a VO_2 nanobeam strained on a SiO_2 substrate. (**Park**)

Cluster 3: Imaging at the Nanoscale

This cluster is developing new approaches to visualizing the behavior of electrons and photons inside nanostructures using custom made scanning probe microscopes, and sophisticated theoretical simulations. The imagers collaborate closely with the MBE Lab at UC Santa Barbara, who grow III-V heterostructures for this research, as well as with investigators in the *Nano Building Blocks* research area. In these highlights we describe research by **Ashoori** and **Petroff** to image self assembled InAs quantum dot self assembled in heterostructures, and theoretical simulations by **Heller** to understand images of magnetic focusing in a two-dimensional electron gas by **Westervelt.**

Self-assembled InAs quantum dots are fascinating structures for nanoelectronics and nanophotonics. They can be so small that they hold only one or two electrons. Using a scanning probe microscope (SPM) to gate InAs dots is very attractive, because one can potentially add single electrons to an individual dot. **Ashoori** plans to do Coulomb blockade spectroscopy on individual InAs dots using a cooled SPM and structures grown by **Petroff**. He has succeeded in measuring single electrons in an individual dot.

Petroff is extending his growth techniques to make GaInAs quantum posts, shown in the TEM and STEM images in Figure 3.7.

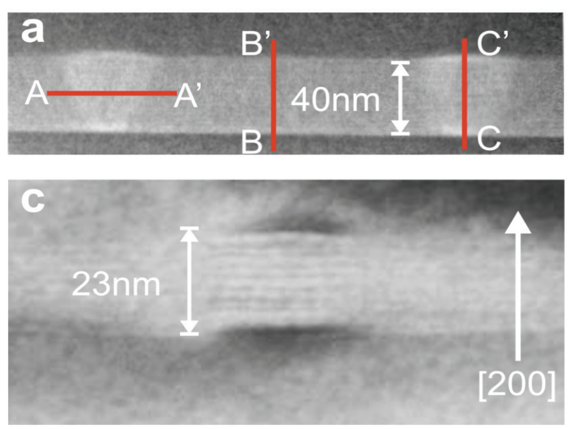

Figure 3.7. Cross-sectional images of GaInAs quantum posts grown from an InAs quantum dot seed, observed in TEM and STEM: (**a**) The In-rich regions in the quantum post show as bright areas; (**b**) is conventional contrast TEM images of a 23 nm high quantum post. (**Petroff**)

The quantum post is In-rich ($Ga_{0.55}In_{0.45}As$) compared with the surrounding matrix ($Ga_{0.9}In_{0.1}As$). Each quantum post starts from an InAs quantum dot seed. When illuminated, the quantum post has the useful property that it separates electrons and holes in a way analogous to the "nanobarbells" synthesized by **Bawendi** in Cluster 2: The electrons fill the post, while the holes are confined in the InAs seed. This separation of carriers into different materials is promising for new approaches to nanoscale electronic and photonic devices.

Heller is working with **Westervelt** to develop a new technique for imaging the flow of electron waves from one location to another in a two-dimensional electron gas. The technique uses a charged SPM tip to form a lens for electrons in the 2DEG below; the lens deflects electrons and changes the transmission.

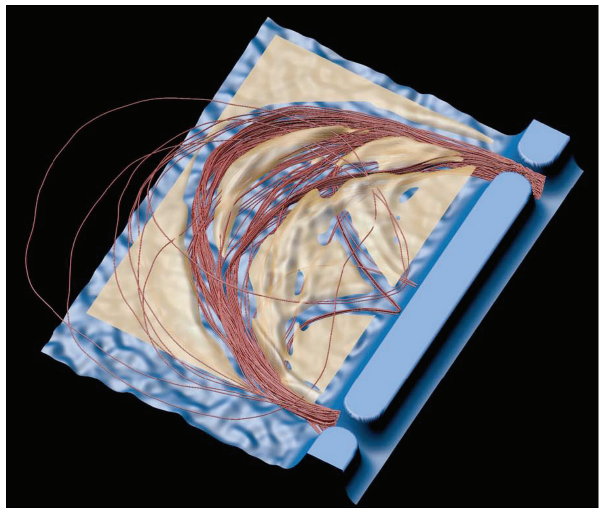

Figure 3.8. This layered figure shows simulations of the magnetic focusing of electrons flowing through a two-dimensional electron gas from one quantum point contact (QPC) to another. Classical trajectories are shown in red, while the tan layer shows the *change* in the flux into the second QPC as a function of the scanning probe microscope tip (not shown), which deflects electrons. If the deflecting tip is placed in "highways" of high nascent flux, it blocks the flow between the QPCs. (**Heller**)

Heller and **Westervelt** tested this approach by imaging magnetic focusing in a 2DEG using a cooled SPM; magnetic focusing occurs when the electrons travel along curved cyclotron orbits between two quantum point contacts (QPCs) [Aidala *et al.,* 2007]. **Heller**'s detailed simulations show how the deflecting tip images the original classical orbits, as shown in Fig. 3.8. This new imaging technique will be very useful in the study of open systems in a magnetic field for spintronics and quantum information processing.

References

Aidala, Katherine E., Robert E. Parrott, Tobias Kramer, R. M. Westervelt, Eric J. Heller, Micah P. Hanson, Arthur C. Gossard, "Imaging Magnetic Focusing of Coherent Electron Waves," *Nature Physics*, in press (2007).

Gooding, J.J. *et al.,* Electrochemical Modulation of Antigen-antibody Binding, *Biosensors and Bioelectronics* **20**, 260–268 (2004).

Lee, Hahko, Yong Liu, Donhee Ham, and Robert M. Westervelt, "Integrated Cell Manipulation System - CMOS/Microfluidic Hybrid," *Lab Chip* **7**, 331 (2007).

Lee, Hakho, Donhee Ham, and R.M. Westervelt, editors, *CMOS Biotechnology,* a book in the series *Integrated Circuits and Systems*, edited by Chandrakasan (Springer, 2007).

Wu, J., Q. Gu, B. S. Guiton, N.P. de Leon, L. Ouyang, and H. Park, *Nano Lett.* **6**, 2313 (2006).

3c. Advances in Education

Education is an important mission of our Center. As the coordinator, **Kathryn Hollar** has done an outstanding job organizing our programs for education, outreach and diversity. A description of our activities are presented below in Section 3e.

The NSF selected the Museum of Science, Boston, the Exploratorium in San Francisco, and the Science Museum of Minnesota to form a national **Nanoscale Informal Science Education (NISE) Network** of multiple science and research institutions. **Carol Lynn Alpert** and Larry Bell at the Museum of Science are coPI's. Our NSEC has collaborated with **Carol Lynn Alpert** since 2001 to bring ideas from nanoscience to the public, in which the Museum is expert. The NISE Network will allow us to reach a nation-wide audience through entertaining and informative exhibits and presentations. The Scientific Advisory Board of the NISE Network includes NSEC faculty **Eric Mazur**, **George Whitesides**, and **Robert Westervelt**, who is its Chair. We look forward to working closely with the NISE Network to bring the excitement of nanoscience to the public.

Applied Physics 298r is a course at Harvard that is run every other year by our NSEC. The aim is to provide an introduction to Nanoscale Science and Engineering to undergraduates and graduate students. The Center's faculty members present a series of tutorial lectures about their field of research, following an overview by the Director. The lecture slides are openly available on the course's website. AP298r being held in Spring 2007, this term. It gets excellent reviews. Section 7 *Center Diversity*, Section 8 *Education,* and Section 9 *Outreach,* present the Center's programs in these areas.

6d. Advances in Industrial Collaborations

Harvard is making important advancements in connecting academic research with industry. In May 2005 the University appointed Isaac Kohlberg as Associate Provost and chief technology development officer to oversee the development of new technologies based on discoveries at Harvard. The **Office of Technology Development** conducts a broad range of activities ranging from reporting inventions, to helping faculty connect with industry. The Center works with Alan Gordon of this office. He has become quite familiar with the research of our investigators, and learns about advances that may have industrial applications. Senior executives from major companies have been brought to Harvard to learn about new research and possible collaborations. The active approach promises to be very effective.

In Fall 2005 our Center was awarded a supplement from the **Nanoelectronic Research Initiative (NRI)** of the **Semiconductor Industry Association (SIA)**. The SIA recognizes that technology beyond CMOS will be needed for logic switches in the future, and it is supporting research at universities to help discover the right approach. Our Center is closely related to these goals, with our emphasis on nanowire devices, nanoelectronics and nanophotonics. The Center's most recent international *Frontiers in Nanoscale Science and Technology* workshop, held at the University of Tokyo on March 29–31, 2007, included talks by George Bourianoff (Intel) and Jun'ichi Sone (NEC) about the future of electronics, and researchers Tsuneya Ando (Tokyo Tech), Yasuhiko Arakawa (Univ. Tokyo), **Federico Capasso** (Harvard), Yu Ming Lin (IBM), Daniel Loss (Univ. Basel) Hiroyuki Sakaki (Univ. Tokyo), Friedrich Schaeffler (Linz), and Lieven Vandersypen (Delft) about nanoelectronics and nanophotonics. The mix was quite successful. We look forward to expanding our interactions with NRI and the semiconductor industry in the future.

6e. Current and Potential Impact of NSEC on Education, Workforce Development, Diversity, and Society

The NSEC based at Harvard University has a wide repertoire of activities that contribute to the public understanding of nanoscale science and engineering, encourage participation of underrepresented groups at all levels of education, enhance the infrastructure of research and education at all education levels both locally and internationally.

The collaboration between the NSEC based at Harvard and the Museum of Science, Boston, has been a model for interaction between an informal science organization and a research and higher education organization. This relationship has informed thousands of people of the risks and benefits of nanoscale science and engineering to society through multimedia, television, museum visits, and public presentations; it has also helped practicing scientists and engineers to engage the public in discussions of the *realistic* risks and benefits of this new technology. Participation in the NISE-Network will not only deepen this level of understanding by researchers of how to effectively listen and respond to public concerns regarding nanoscale science and engineering research, it will also allow us to disseminate these new communication models across a wide network of collaborators.

Through our long-standing relationship with the Cambridge Public Schools, a school system with a minority majority population, we introduce over 300 7^{th} grade students each year to scientific research being conducted at Harvard University. Community activities with Cambridge Public Schools impacted another 250 students and their families. The Research Experiences for Teachers program allows us to develop sustained and close relationships with teachers in the Cambridge Public Schools and surrounding school systems. Modules developed through the RET program have been disseminated to over 150 teachers through teacher workshops. As we continue to develop new modules through the RET program, we expect to impact a wider audience through continued dissemination locally and nationally. In all our K12 outreach efforts, we strive to partner with school systems and programs that have a significant population of underserved students.

The REU program is one of our flagship programs for preparing a diverse pool of future leaders in science and engineering. Through aggressive recruiting efforts, 30–40% of our participants each year are from underrepresented groups. Through professional development activities such as presentation and writing skills and mentor training, we not only prepare the participants and mentors scientifically, but help them develop skills that will enhance their careers in science and engineering.

In 2006–2007, local and international workshops and collaborations have brought together over 500 practicing scientists, engineers, as well as leaders in business and government, to discuss new directions in nanoscale science and engineering. For example, the *Frontiers in Nanoscale Science and Engineering* workshop and *Industry Partnership Program* at Harvard are annual events that continue to provide opportunities for our faculty, graduate students and postdoctoral researchers to share research results with a wide array of institutions.