Nanoscale Science and Engineering Center

SCIENCE OF NANOSCALE SYSTEMS AND THEIR DEVICE APPLICATIONS

Harvard, MIT, UC Santa Barbara and Museum of Science, Boston



Annual Report 2010-2011

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3. 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 including nanoparticles, nanowires, and heterostructures. 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 inside nanostructures using custom-made scanning probe microscopes, including cooled instruments. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing.

The Center for Nanoscale Systems (CNS) is a major investment by Harvard to provide shared facilities to conduct research in nanoscience and engineering. A new building, the Laboratory for Integrated Science and Engineering has been completed and outfitted with equipment. It houses CNS facilities for nanofabrication, imaging and materials growth. Harvard and UC Santa Barbara provide nanofabrication facilities to outside users through the National Nanotechnology Infrastructure Network (NNIN).

Connections with **Industry** are strengthened by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program**. Our Center is funded by the **Nanoelectronics Research Initiative (NRI)** of the **Semiconductor Research Corporation (SRC)** to develop new oxide materials for future logic switches. Many Center participants have collaborations with industry.

Our Center's educational program develops human resources at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities, including REU and RET programs, a introductory course *Applied Physics 298r* on nanoscience, and a series of workshops. The Museum of Science, Boston engages the public and introduces them to the big ideas in nanoscience in an entertaining and informative way, in collaboration with the researcher in our Center. The Museum is a core member of the new National Informal Science Education (NISE) Network.

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

4. LIST OF CENTER PARTICIPANTS AND ADVISORY BOARD

(a) Center Participants

Name	Field of Research	Institution
Joanna Aizenberg	Chemical Biology Materials	Harvard
Carol Lynn Alpert	Education and Outreach	Museum of Science
Raymond Ashoori	Physics	MIT
Debra T. Auguste	Chemical Engineering	Harvard
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
Cvnthia 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
Evelyn Hu	Electrical Engineering	Harvard
Marc A. Kastner	Physics	MIT
Efthimios Kaxiras	Physics & Applied Physics	Harvard
Charles M. Lieber	Chemistry & Applied Physics	Harvard
Marko Loncar	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 Stopa	Computational Materials	Harvard
Michael Tinkham	Physics	Harvard
David Weitz	Materials	Harvard
Robert M. Westervelt	Applied Physics & Physics	Harvard
George M. Whitesides	Chemistry	Harvard
Amir Yacoby	Physics	Harvard
Xiaowei Zhuang	Chemistry & Physics	Harvard

International Collaborators

Yasuhiko Arakawa
Fabio Beltram
Piotr Garstecki
Andre Geim
Koji Ishibashi
Makai Kawai
Leo Kouwenhoven
Eugenia Kumacheva
Daniel Loss
Hideo Ohno

- Nanoelectronics Physics Chemistry Physics Advance Device Engineering Physical Chemistry Physics Chemistry Physics Spintronics
- U Tokyo, Japan NEST, Pisa, Italy Polish Academy of Sciences University of Manchester, UK RIKEN, Japan RIKEN, Japan Delft University of Technology University of Toronto U Basel Tohoku University, Japan

Maria-Anita Rampi
Carsten Ronning
Hiroyuki Sakaki
Lars Samuelson
Seigo Tarucha
Yohinori Tokura
Hiroyuki Yamaguchi

Domestic Collaborators

Sangeeta Bhatia Donald Eigler Giannoula Klement Dale Larson Chinh Pham Richard Rogers Chemistry Solid State Physics Inst. of Industrial Science Physics Physics Materials Research Physical Sciences

HST Physics Biomedicine Biophysics NanoTech & Business Forum Bioimaging University of Ferrara, Italy University of Jena, Germany U Tokyo Lund University U Tokyo U Tokyo, RIKEN, Japan NTT Basic Research Lab., Japan

MIT IBM, Almaden Children's Hospital Harvard Medical School Greenberg Traurig, LLP Harvard School of Public Health

National Laboratories

Julia Phillips	Physical Sciences	Sandia, CINT

Public Outreach and Education

Carol Lynn Alpert	Museum of Science, Boston
Karine Thate	Museum of Science, Boston
Alex Florentino	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

(c) Academic Participating Institutions

1. Domestic

Boston College California Institute of Technology Columbia University CCNE (MIT, MGH, Harvard Medical School) City College of New York Columbia University Cornell University Florida State University Georgia Technical Institute Harvard University (CNS, FAS, SEAS) Harvard Medical School Harvard School of Public Health Harvard University NSEC Prime Massachusetts Institute of Technology National Nanotechnology Infrastructure Network Northwestern University Pennsylvania State University Princeton University **Rutgers** University Stanford University State University of New York, Albany Texas A&M **Tulane** University **Tufts University** University of California, Davis University of California, Los Angeles University of California, Santa Barbara University of California, Santa Cruz University of Illinois, Urbana-Champaign University of Maryland University of Massachusetts University of New Mexico University of Oregon University of Texas, Austin University of Washington University of Wisconsin, Madison Worcester Polytechnic Institute (WPI) Wyss Institute (Harvard)

2. International

Augsburg University, Augsburg, Germany Delft University of Technology, The Netherlands ESPCI, Paris, France ETH Zürich, Switzerland Heriot Watt University, UK Kaust, Saudi Arabia Koc University, Istanbul, Turkey Ludwig Maximilian University, Munich, Germany Luft University, Uppsala University, Sweden Lund University, Sweden Polish Academy of Sciences, Warsaw, Poland Stuttgart University, Stuttgart, Germany Technical University of Denmark, Denmark Technion, Haifa, Israel Tohoku University, Japan Twente, The Netherland Universidad de La Laguna, Tenerife, Spain University of Basel, Switzerland

University of Bern, Switzerland University of Brussel, Belgium University of Ferrara, Italy University of Jena, Germany University of Manchester, UK University of Marseille, France University of Montpellier, France University of Paris, France University of Regensburg, Germany University of Regensburg, Germany University of Rennes, France University of Salzburg, Austria University of Tokyo, Japan University of Toronto, Canada University of Vienna, Austria Weizmann Institute of Science, Rehovot, Israel

(d) Non-academic Participating Institutions

1. Domestic

Advanced Diamond Technologies Advanced Energy Consortium **Agilent Technologies** Alcatel-Lucent, Bell Labs. American Chemical Society Petroleum Research Fund Appollo Diamond Bill and Melinda Gates Foundation Children Hospital CINT Sandia National Laboratory **Davis Foundation** Draper Laboratory **Dreyfus Foundation** Element Six GlaxoSmithKline Grace Construction Products Greenberg Traurig, LLP HRL Laboratories, Malibu California Human Frontiers Science Program IBM Almaden Intel iRobot Lawrence Berkeley National Laboratory Lincoln Laboratory Massachusetts General Hospital Microsoft Corporation Museum of Science, Boston Multimedia Research Nanoscale Informal Science Education Network (NISE) Network of Museums New England Cable News Network National Enterprise for nanoScience and nanoTechnology (NEST), Pisa, Italy NIST Boulder Laboratory

Northrup-Grumman Physical Sciences, Inc. (PSI) Pranalytica, Inc., Los Angeles Sandia National Laboratories Sharp Laboratories of America Schlumberger Doll Research Center, Boston Semiconductor Research Corporation Siemens Corporate Research, Inc. Sloan Foundation Spencer Foundation Unilever, Trumble, CT Vertex Pharmaceutical Zena Technologies Center

2. International

BASF, Germany Eni S.p.A. Genomics Research Center, Taiwan Hamamatsu Photonics, Japan Institute for High Performance Computing, Singapore Institute of Industrial Sciences, Japan Institute for Solid State Physics, Chiba, Japan NTT Basic Research Laboratory, Japan Max Planck Institute, Munich, Germany Philips Research, The Netherlands Riken, Japan Saint Gobain Research, Paris, France US-Israel Bi-National Science Foundation

5. MISSION, SIGNIFCANT ACHIEVEMENTS, 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 7 describes how the three Research Clusters below address important applications, and how our investigators work together to reach these goals.

5a. Mission Statement

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Faculty in our Center have built strong connections with Industry to transfer advances in research into real products, working with Harvard's Office of Technology Development and by the Industrial Outreach Program of the Harvard School of Engineering and Applied Sciences. Over ten years of funding, Center faculty members have founded over 23 startup companies, which created over 484 high technology jobs. Thirty outside companies have purchased over 180 licenses of Center faculty intellectual property for a total of \$6.8M in licensing fees. In addition, the Center has formed 43 industrial collaborations.

Our Center's Educational Program develops human resources at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities, including Research Experience for Undergraduates (REU) and Research Experience for Teachers (RET) programs carried out each summer, an introductory course *Applied Physics 298r* in which Center faculty present tutorial lectures on nanoscience and technology, and the annual Frontiers in Nanoscale Science and Technology International Workshops. The Museum of Science, Boston engages the public and introduces them to the big ideas in nanoscience in an entertaining and informative way, in collaboration with researchers in our Center. The Museum is a core member of the NSF supported Nanoscale Informal Science Education (NISE) Network.

Our Center increases **Diversity** in the research community by: recruiting a more diverse group of graduate students and postdocs, increasing the diversity of participating faculty, recruiting members of underrepresented groups, in part through the REU program, introducing public school students to science and engineering through the RET program, and developing long-term partnerships with predominantly female and minority-serving institutions. Professor **Gary Harris**, **Director of the Nanoscale Science and Engineering Facility of Howard University** is spending the Spring 2011 on sabbatical leave at Harvard in <u>Westervelt</u>'s laboratory, hosted by our NSEC.

5b. Advances in Fundamental Knowledge and Technology

Cluster 1: Tools for Integrated Nanobiology

This Cluster develops new technology for lab-on-a-chip devices and systems. This year we feature Joanna Aizenberg's development of the new technique named STEPS (Structural Transformation by Electro-deposition on Patterned Substrates) to reshape high-aspect ratio (HAR) arrays of nano- and microstructures for applications in optics, bionano-interfaces, MEMS, and microfluidics.

In collaboration with the Wyss Institute and <u>Whitesides'</u> group, <u>Aizenberg</u> developed a low-cost, high-throughput benchtop method that enables a HAR array, or any other topographically patterned surface, to be reshaped with nanoscale precision by electrodeposition of conductive polymers. The method, named STEPS (Structural Transformation by Electro-deposition on Patterned Substrates), makes it possible to create a wide variety of tapered, anisotropic, or re-entrant geometries from a simple parent HAR array by controlling the deposition conditions as schematically shown in Figure 5.1. Each STEPS method created libraries of various patterns from a single master structure with the option of creating substrates with continuous or discrete gradients of nanostructure features. STEPS enables a wide range of systematic and combinatorial studies of the effect of substrate topography on surface properties leading to optimization



Figure 5.1. (a) Schematics showing the step-by-step structural transformation using sputter coated metal electrode (STEPS I), evaporated metal electrodes from the top (STEPS II), and evaporated metal electrodes at an angle (STEPS III). Green: parent substrate, yellow: metal coating, blue: polypyrrole. (b) Photographs of a parent high-aspect-ratio nanopillar array (left) and a gradient nanopillar array modified by PPy deposition (right). (c) SEM image of an array of conical structures transformed from the original cylindrical nanopillar array produced using STEPS II process. (d) SEM image of an array of uni-directionally bent conical structures transformed from the original cylindrical nanopillar array using STEPS III process.

of the structures for specific applications such as low cost plasmonic nanostructure array, combinatorial substrates for bacterial patterning, and mechanically reinforced high-aspect-ratio nanostructures as shown in Figure 5.1. STEPS method identifies solution-based deposition of conductive polymers as a new tool in nanofabrication and allows access to complex 3-D architectures that were previously difficult to fabricate.

Cluster 2: Nanoscale Building Blocks

This cluster synthesizes nanoscale building blocks of different geometries from new materials, and finds ways to couple them to the outside world. We feature work by Pierre Petroff to pattern the position of InAs quantum dots grown in a GaAs/InAs heterostructure. Conventional growth techniques produce InAs QDs at random positions, making it more difficult to fabricate a photonic system. Accurately positioning QDs during growth would have important consequences.

The ultimate goal of <u>Petroff's</u> project is the realization of **interacting** quantum dots (QDs) self-ordered in 2-D or 3-D lattices. Controlling nucleation sites and size uniformity of self-assembled QDs should permit this, as well as the positioning of a single QD or group of QDs into a cavity in a photonic crystal, making possible the exploitation of cavity QED effects recently observed by <u>Hu</u>.

Petroff has started the investigation of controlled nucleation and self-ordering of InAs QDs on GaAs, as illustrated in Figure 5.2. E-beam lithography defines small dips in a GaAs surface. After cleaning and GaAs buffer growth, an InAs QD is grown in each pit, followed by a GaAs cap layer. The bottom panels show that this technique works, and that it produces single QDs with sharp photoluminescence spectra.



Figure 5.2. Schematic of the method for positioning self-assembled quantum dots in a square 2D lattice (period 4 μ m) of patterned holes for site selected quantum dots nucleation (the value of r/w \approx 0.02). The AFM picture shows 4 single QDs in the holes. Two representative micro-PL spectra are also shown for a similar sample, which was capped with a 50 nm GaAs layer.

Cluster 3: Imaging at the Nanoscale

This cluster develops custom-made scanning probe microscopes, and new imaging techniques to visualize electrons and photons inside nanoscale systems. We feature research by <u>Jennifer Hoffman</u> and <u>Shriram Ramanathan</u> to image an electric-field induced metal-insulator transition in VO₂ thin films.

The goal of this project is to understand the metal-insulator transition (MIT) in VO_2 thin films at the nanoscale. The MIT in VO_2 can be induced by temperature, electric field, strain, and optical excitation. Because the transition occurs near 60°C, slightly above room temperature, VO_2 is attractive for potential applications including bolometers, tunable metamaterials, mem-

ristors and data storage devices. For VO_2 thin films, <u>Ramanathan</u> has found that an applied electric field gates the transition, creating a switch. Some propose that the structural transition is responsible for the MIT, while others argue that electron-electron interactions drive the transition.

<u>Hoffman's</u> lab is using conducting atomic force microscopy (CAFM) to simultaneously measure the topography and current in polycrystalline VO₂ films, as shown in Fig. 5.3. They use a CAFM tip to apply a local bias voltage and measure the resulting current flow with sub-grain resolution. From the measured *IV* curves, they can extract the local properties of VO₂ thin films including the resistance, and transition voltage. These images will increase our understanding of the MIT in VO₂ on the nanoscale for potential applications.



Figure 5.3. (a) Schematic of the microscope tip and sample geometry. (b) Topography of the VO₂ surface. (c) Current map at constant voltage (~ 2 V). (d) Typical *IV* curve at one location on the VO₂ surface. (e) Map of metal-insulator transition voltage for the forward direction.

5c. Advances in Education

Education and knowledge transfer to the public essential parts of our Center. <u>Kathryn</u> <u>Hollar</u>, Director of Education in the Harvard School of Engineering and Applied Sciences, has done an outstanding job organizing our Center's activities in education, outreach and diversity. A description of the activities she supervises, including Research Exchange lunches and the REU and RET summer programs is presented in Section 5e below.

Our Center informs the public about advances in nanoscience and technology, and engages there interest in the important society issues through a partnership with the **Museum of Science, Boston** led by <u>Carol Lynn Alpert</u>, Director of Strategic Projects. Activities at the Museum range from lobby presentations on nanoscience by Museum staff and Center faculty members, to interactively displays, to public forums on related topics such as the influence of information processing and storage on privacy. A more detailed description is given in Section 6e below.

The Museum of Science, Boston is a core member of the NSF supported Nanoscale Informal Science Education (NISE) Network that links together museums and research institutions across the US. Larry Bell leads the NISE Network at the Museum of Science, Boston. By partnering with the NISE Network, our Center can reach a large, nation-wide audience through entertaining presentations, informative exhibits, and an excellent website. The Scientific Advisory Board of the NISE Network includes a number of NSEC faculty members - Eric Mazur, George Whitesides, and Robert Westervelt. We enjoy working closely with the NISE Network to bring the excitement of nanoscience to the public.

The Harvard course *Applied Physics 298r* provides an introduction in nanoscience and technology to undergraduates and graduate students through a series of tutorial lectures by Center faculty about their field of research. To make the material widely available, the lecture slides and an audio recording of each lecture are available on the course's website. AP298r is currently being conducted, in the Spring 2011 semester. It gets excellent reviews.

Section 9 *Center Diversity*, Section 10 *Education*, and Section 11 *Outreach*, present the Center's programs in these areas.

5d. Advances in Industrial Collaborations

Harvard is developing new ways to transfer advances in research to industrial products. The **Office of Technology Development** (OTD) manages the intellectual property for our academic research, and works to transition new technologies to industry. The Office conducts activities ranging from filing patent applications, to connecting faculty with industrial executives and venture capital firms.

Over ten years of funding, Center faculty members have an impressive record of moving their academic research into industrial applications. They have founded over 23 startup companies, which created over 484 high technology jobs. Thirty outside companies have purchased over 180 licenses of Center faculty intellectual property for a

total of **\$6.8M in licensing fees**. In addition, the Center has formed 43 industrial collaborations.

Our Center has been awarded a supplement from the Nanoelectronic Research Initiative (NRI) of the Semiconductor Research Corporation (SRC). The semiconductor industry recognizes that 'beyond CMOS' technology will be needed for logic switches in the future, and it is supporting academic research to discover the right approach. Our Center is closely related to industry goals, with our emphasis on the growth of nanoscale building blocks, and on the development of new quantum devices for nanoelectronics and nanophotonics. The Center's NRI supplement supports Ramanathan's work on metal-insulator-transition switches made from thin film oxide materials.

The Harvard School of Engineering and Applied Sciences (SEAS), holds a yearly **Industrial Outreach Program** workshop in collaboration with our NSEC. The goal is to connect industrial researchers and venture capital firms with current research at Harvard and local institutions, through a series of presentations and poster sessions. These workshops have been very effective in the past.

The Center's international **Frontiers in Nanoscale Science and Technology (FNST)** workshops focus on nanoelectronics, nanophotonics, and quantum information processing. The workshops are held every year, and their location cycles between the US, Japan and Europe. The last Frontiers workshop was held in January 2011 at RIKEN in Tokyo, Japan — the speakers included Konstantin Novoselov 2010 Nobel Laureate for his research on graphene.

Harvard recently signed a Memo of Understanding (MOU) with RIKEN and with Tohoku University in Japan. The goal of each MOU is to promote collaborative research between the two institutions. The RIKEN 'Frontiers' workshop will help build connections between individual researchers on both sides of the Pacific. Our Center will offer travel scholarships to students and postdocs to allow them to attend the workshop.

These workshops have proven to be a very effective way for investigators from industry and academia to discuss the future of nanoelectronics and nanophotonics. We look forward to expanding our interactions with NRI and the semiconductor industry in the future.

5e. Current and Potential Impact of NSEC on Education, Workforce Development, Diversity, and Society

Our Center carries out a wide range of activities to advance public understanding of nanoscience and engineering, to encourage the participation of underrepresented groups at all levels of education, and to enhance the infrastructure for education and research at all levels, in Cambridge and other parts of the US, and internationally.

<u>Kathryn</u> <u>Hollar</u> coordiates activities for undergraduate and graduate students at Harvard and MIT and high school students in the local public schools. Our Center long-standing partnership with the Cambridge Public Schools, a school-system in which most

students are from the minority population of the US. Each year, we introduce over 300 7th grade students to scientific research at Harvard. Community activities at the Cambridge Public Schools impacted another 250 students and their families. The **Research Experiences for Teachers (RET)** program allows us to develop sustained and close relationships with teachers in the Cambridge Public Schools and in nearby school systems. Educational modules developed through the RET program have been disseminated to over 150 teachers through teacher workshops, and we expect to impact a wider audience through dissemination locally and nationally. In all of our K12 outreach efforts, we strive to partner with school systems and programs that have a significant population of underserved students.

The Center actively involves college undergraduates in its activities. **Research Experience for Undergraduates (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 to 40% of our participants each year are from underrepresented groups. Through professional development activities, including presentation and writing skills, we not only prepare the participants scientifically, but help them develop skills that will enhance their careers in science and engineering.

The partnership between our NSEC and the **Museum of Science, Boston** through <u>Carol Lynn Alpert</u> has become a model for the interaction between museum staff with scientific investigators. This relationship has informed thousands of people about the risks and benefits of nanoscale science and engineering, 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. These activities will engage young students with high technology and encourage them to prepare for a career this growing area.

The Center helps to coordinate a range of local and international workshops and meetings to discuss new directions in nanoscale science and engineering that have brought together over 500 practicing scientists and engineers, and leaders in business and government. The workshops include the annual **Industry Outreach Program** at Harvard, and the **Frontiers in Nanoscale Science and Technology** international workshops describe above. These annual events provide opportunities for our faculty, graduate students and postdoctoral researchers to share research results with a wide array of investigators and institutions.

8. HIGHLIGHTS

Frontiers in Nanoscale Science and Technology (FNST) Workshop — Harvard NanoDays 2010 — Museum of Science, Boston The Amazing Nano Brothers Juggling Show — Museum of Science, Boston Special Black History Month Presentation — Museum of Science, Boston

Nanofabrication Using Conducting Polymers — **Joanna Aizenberg** Strain Dependent Molecular Changes in Protein nanoFabrics — **Kevin (Kit) Parker** Patterning the Tips of Optical Fibers with Metallic Nanostructures Using

Nanoskiving — George M. Whitesides

Core-shell Nanoparticle Clusters — Federico Capasso Slot-waveguide Based On-chip Polarization Splitter and Passive Particle Sorting — Kenneth B. Crozier Imaging of Molecules for Electronic Switching— Cynthia M. Friend

Nanowire Arrays Grown within a Semiconductor Matrix — Arthur C. Gossard Plasmonic Optical Cavities— Evelyn Hu

A Diamond Nanowire Single Photon Source — Marco Lončar Self-positioning of Self-assembled Quantum Dots — Pierre Petroff

Anomalous Magnetotransport in a Graphene Device — **Bertrand I. Halperin** Nanoscale Imaging and Control of Resistance Switching in VO₂— **Jennifer**

Hoffman

Towards In-vivo Imaging of Hyperpolarized Silicon Nanoparticle Magnetic Resonance Imaging Agents — Charles Marcus

Local Investigation of Grain Boundary Defects in ZnO:Al Using a Scanning Tunneling Microscope — Venkatesh Narayanamurti

MBE Laboratory — University of California, Santa Barbara

Laboratory for Integrated Science and Engineering and Center for Nanoscale Systems — Harvard University

Frontiers in Nanoscale Science and Technology (FNST) Workshop



The Frontiers in Nanoscale Science and Technology (FNST) Workshop was held in January 2011 at RIKEN in Saitama, Japan. Konstantin Novoselov, the 2010 Nobel Laureate in Physics, was one of the keynote speakers at the workshop that drew over 150 attendees to learn about recent developments in nanoelectronic and photonic materials. This was the eighth FNST workshop that the NSEC helped organize to promote international collaboration through scholarship support for graduate students and postdoctoral fellows from our Center and other NSECs. It was gratifying to see many new junior faculty members, who participated in the early FNST workshops as students, attend with their graduate students presenting during the poster sessions and gaining their own valuable international experience.

NanoDays 2010

Museum of Science.

5,000 museum visitors

Four NSEC faculty members addressing public audiences 15 NSEC faculty and students leading hands-on demos Lots of fun for all!



The Amazing Nano Brothers Juggling Show

Museum of Science.

Seen by more than 14,000 visitors at MoS in 2010. Featured at the 2010 USA Science and Engineering Festival in Washington, DC.



A study by the Goodman Research Group confirms that the show is very successful educationally—as well as delighting both school and family audiences.

Special Black History Month Presentation

Museum of Science.



While serving as a Harvard NSEC visiting faculty member, and in conjunction with the traveling museum exhibit "Race: Are We So Different?" Professor Gary Harris of Howard University (above) discussed the history of black contributions to science and engineering with a large February school vacation week audience at the Museum of Science, Boston. Dr. Harris also returned for NanoDays at the Museum of Science in March 2011.

Nanofabrication Using Conducting Polymers

Philseok Kim^{†§}, Alex K Epstein[†], Mughees Khan[§], Sung H. Kang[†], Lauren D. Zarzar[‡], Darren Lipomi[‡], Mikhail Kats[†], Federico Capasso[†], George M. Whitesides^{§‡}, and Joanna Aizenberg^{†§‡}

Structural Transformation by Electrodeposition On Patterned Substrate



Arrays of high-aspect-ratio (HAR) nanostructures are useful in many emerging applications for their unique morphology-derived properties. However, fabrication of various HAR nanostructures is not an easy task by using conventional approaches. A rapid and high precision reshaping method to

generate an inexpensive library of modified HAR nanostructures from a single master structure was developed.



Meeting of STEPS and Nanoskiving = Exquisite Plasmonic Nanostructures

STEPS method can transform nanopost arrays into 4-layered nanopost arrays: Core epoxy/inner material layer/polypyrrole spacer layer/outer material layer. **Nanoskiving** (cross-sectioning by ultramicrotome) STEPS-modified HAR nanostructures generated multiple copies of identical plasmonic nanostructures.

^{*}School of Engineering and Applied Sciences, *Department of Chemistry and Chemical Biology, \$Wyss Institute for Biologically Inspired Engineering, Harvard University

Strain-Dependent Molecular Changes in Protein nanoFabrics Leila Deravi and Kevin Kit Parker



Forming arrays of FN nanofibers. A) Schematic of fiber release over time. FN lines are patterned onto PIPAAm substrates. B) Raman spectra of FN lines before and after they are released as nanofibers from the PIPAAm substrate. C) FN grid lines before and after release D. E) AFM and SEM, respectively of FN weave post-release.

The structural integrity of living tissues is maintained by an insoluble, cell-generated protein scaffold, known as the extracellular matrix (ECM). How protein fibers respond to strain within the extracellular space is a subject of debate, as the mechanism by which cells potentiate fibrillogenesis is poorly understood. An example of this is the protein extracellular matrix Fibronectin (FN). The assembly of FN into matrix fibers is dependent on the interplay between all three of its domains (I, II, or III). We hypothesized that if FN is undergoing a conformational change from a conformation compact in relaxed fibrils to an extended conformation under strain, then

its secondary structure will be altered. To test this hypothesis, we used Raman Spectroscopy and fluorescence resonance energy transfer (FRET) to demonstrate that FN within fully relaxed nanoFabrics is in a compact conformation. When relaxed FN nanoFabrics are mechanically strained, they exhibit a 6-fold extension without failure, likely due to protein extension under strain.

Patterning the Tips of Optical Fibers with Metallic Nanostructures using Nanoskiving

Joanna Aizenberg, Federico Capasso, and George Whitesides



NSEC researchers have developed a method to generate and transfer arrays of metallic nanostructures to the cleaved facets of optical fibers. The process relies on nanoskiving, in which an ultramicrotome, equipped with a diamond knife, sections epoxy nanostructures coated with thin metallic films and embedded in a block of epoxy. Sectioning produces arrays of nanostructures embedded in thin epoxy slabs, which can be transferred manually to the tips of optical fibers. They have successfully transferred gold nanocrescents, nanorings, high-aspect-ratio concentric nanocylinders, and gratings of parallel nanowires. These nanostructures could be used in biological sensors based on surface-enhanced Raman scattering (SERS) or localized surface plasmon resonances (LSPRs).

Core-shell Nanoparticle Clusters

Federico Capasso



The self-assembly of colloids is an alternative to top-down processing that enables the fabrication of nanostructures. We have shown that self-assembled clusters of metaldielectric spheres are the basis for nanophotonic structures. By tailoring the number and position of spheres in closepacked clusters, plasmon modes exhibiting strong magnetic and Fano-like resonances emerge. The use of identical spheres simplifies cluster assembly and facilitates the fabrication of highly symmetric structures. Dielectric spacers are used to tailor the interparticle spacing in these clusters to be approximately 2 nanometers. These types of chemically synthesized nanoparticle clusters can be generalized to other two- and three-dimensional structures and can serve as building blocks for new metamaterials

Slot-waveguide Based On-chip Polarization Splitter and Passive Particle Sorting

Shiyun Lin, Juejun Hu, and Kenneth Crozier



We have demonstrated an ultra-compact polarization splitter (a) leveraging the giant birefringence of silicon-oninsulator slot waveguides. The fabricated splitter device shows average polarization extinction ratios of 21 dB and 17 dB for the TE and TM polarizations, respectively over the entire C-band. Using a modified 3-dB TM mode optical splitter, we have achieved on-chip microparticle passive sorting. (b) In our demonstration, small (320 nm diameter) and large (2 μ m diameter) particles are separated into the slot and channel waveguides, respectively. The automated nature, along with the low-guided power employed makes this a promising approach for sorting sub-micron particles.

Imaging of Molecules for Electronic Switching

Cynthia Friend and Efthimios Kaxiras



Molecular interactions of molecules containing benzene rings with semiconductor surfaces are potentially important for development of molecular electronics, including graphene. Stilbene is a molecule with two phenyl rings connected by a C = C bond that has two different configurations-trans and cis-that can be switched with photons. We have separately imaged these two deposited (top images). molecules on titanium dioxide Simulations of the images confirm that the configurations shown are for the deposited molecules (lower images). Imaging can be used to study electron- and photon-induced switching.

Nanowire Arrays Grown within a Semiconductor Matrix

Arthur C. Gossard





The **Gossard** group has used MBE as the synthesis method to grow functional semimetal/semiconductor nanocomposites with a variety of nanostructures, including highly ordered ErSb nanowire arrays within a GaSb matrix. The unique structural, thermal and electrical properties give these materials potential in applications such as thermoelectrics and THz technology.

Plasmonic Optical Cavities Kasey Russell and Evelyn Hu



Schematic of the Nanowire Plasmonic Cavity

The cavity is defined between the Ag nanowire and the flat Ag substrate. The quantum dots comprise the optical medium.

Fluorescence spectra versus polarization angle shows emission highly polarized along cavity axis (dotted line).



700 750 800 850 900 950 100c Wavelength (nm) Fluorescence spectra of cavities depends systematically on cavity length (l_W) .



Optical cavities are strategically engineered environments that can profoundly change the optical behavior of light-emitting materials, such as their optical efficiency. Cavities made from metals are generally considered too 'lossy' to work at visible wavelengths, but at the nanoscale metals provide the unique opportunity to couple photons to collective excitations of electrons known as plasmons. We have formed plasmonic cavities from silver nanowires, coupled to quantum dots, and we have shown that these cavities can greatly modify the emission spectrum of the quantum dots. Ultimately, such cavities can make possible ultra-dense electronic/optical circuits and information processing.

A Diamond Nanowire Single Photon Source Marko Lončar



References

T.M. Babinec, B.J.M. Hausmann, M. Khan, Y. Zhang, J. Maze, P.R. Hemmer, and M. Lončar, "A diamond nanowire single photon source," *Nature Nano.* **5**, 195–199 (2010).

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M. Lončar, T. Babinec, and B.J.M. Hausmann, "Diamond Nanotechnology," *SPIE Newsroom* (2010). (Invited)

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Self-positioning of Self-assembled Quantum Dots

Pierre Petroff



Schematic of the method for positioning self-assembled quantum dots in a square 2-D lattice (period 4 μ m) of patterned holes for site-selected quantum dots nucleation (the value of r/w \approx 0.02). The AFM picture shows 4 single QDs in the holes. Two representative micro-PL spectra are also shown for a similar sample, which was capped with a 50 nm GaAs layer.

 10^{16} atoms/(cm².s) In and As are deposited by molecular beam epitaxy. They self-organize into InAs quantum dots, which are positioned in a pattern, which was lithographically defined on the GaAs substrate.

Anomalous Magnetotransport in a Graphene Device

Bertrand I. Halperin



Theory behind anomalous magnetoresistance in a graphene device, with a barrier of width 50 nm induced by a top gate. (a) Schematic showing variations of orbit size in the estimated potential U(x), for various values of the magnetic field, with transverse momentum $p_y = 0$. Long trajectories that extend outside the gated region do not contribute to Shubnikov-de Haas magnetoresistance oscillations. (c) Trajectories for the potential $U(x) = -ax^2$ and $p_y = 0$. Three types of trajectories are shown in momentum space (b) and position space (c): subcritical (red), critical (black), and super-critical (blue). [From N. Gu *et al.*, *Phys. Rev. Lett.* **106**, 066601 (2011).]

Mark Rudner, a postdoctoral fellow with NSEC salary support, in the group of **B. I. Halperin**, has collaborated with theorists at MIT and experimentalists at Columbia in a work that proposed and demonstrated a new regime of magnetotransport in a graphene device with a 50 nm potential barrier created by a top gate [1]. Landau levels, which are confined to the barrier region in a strong magnetic field, can undergo a deconfinement transition as the field is lowered, resulting in an abrupt disappearance of the Shubnikov-de Haas resistance oscillations. The behavior, observed by experiments, could be explained by a semiclassical analysis.

^[1] Nan Gu (MIT), Mark Rudner (Harvard), Andrea Young (Columbia), Philip Kim (Columbia), and Leonid Levitov (MIT), "Collapse of Landau Levels in Gated Graphene Structures," *Phys. Rev. Lett.* **106**, 066601 (2011).

Nanoscale Imaging and Control of Resistance Switching in VO₂

Jennifer Hoffman and Shriram Ramanathan Jeehoon Kim, Changhyun Ko, Alex Frenzel, Adam Pivonka, Kevin O'Connor



Vanadium dioxide exhibits a sharp metal-insulator phase transition at 60°C, near room temperature. It therefore has high potential for applications that could be easily integrated into existing technology. Ideas include bolometers, memristors, tunable frequency metamaterials, and data storage.

We have demonstrated simultaneous nanoscale imaging of current and topography through the metal-insulator transition in VO₂ at room temperature using conducting atomic force microscopy (CAFM). We have extracted and characterized local *IV* curves with sub-grain resolution. Using these curves, we have created maps of the local properties, such as transition voltage or conducting state resistance, of the VO₂ thin film. Correlating these properties of the film will lead to a greater understanding of the MIT in VO₂.

Jeehoon Kim, Changhyun Ko, Alex Frenzel, Shriram Ramanathan, and Jennifer E. Hoffman, *Appl. Phys. Lett.* **96**, 213106 (2010).

Towards In-vivo Imaging of Hyperpolarized Silicon Nanoparticle Magnetic Resonance Imaging Agents

Charles Marcus





Silicon nanoparticles offer promise as a new platform for targeted medical imaging and drug delivery due to their excellent nuclear properties, biocompatibility and ease of surface functionalization. Using the system we have developed for low temperature dynamic nuclear polarization, we can generate nuclear polarizations in silicon nanoparticles of ~ four orders of magnitude over the room temperature nuclear Boltzmann polarization. Much of this polarization is preserved as the sample is transferred to the imager, and can be observed in vitro with a decay time constant of almost one hour.

Local Investigation of Grain Boundary Defects in ZnO:Al Using a Scanning Tunneling Microscope

Edward Likovich, Rafael Jaramillo, Kasey Russell, Shriram Ramanathan, and Venkatesh Narayanamurti



We present an investigation of the local density of states (LDOS) in sputtered Al-doped ZnO using a scanning tunneling microscope. We observe a pronounced difference in the tunneling conductivity recorded on- and off-grain, with the grain boundary LDOS peaked ~600 meV below the Fermi level (~100 meV below the conduction band). These trap states are broadly distributed in energy, suggesting the existence of both shallow and deep traps that affect electron transport properties in this important transparent conducting oxide.
New in-situ Growth and Characterization System

University of California at Santa Barbara



A new state-of-the-art, *in-situ* growth and characterization system is now operational at the Molecule Beam Epitaxy (MBE) Shared Facility at the University of California at Santa Barbara. The system consists of five interconnected MBE/CBE areas that can be used to deposit III-V semiconductors, metals, metallic compounds and oxide materials. Determination of structure and chemistry at the atomic level at different stages of growth may be characterized using STM/AFM, Auger, XPS, LEED, or RHEED analysis. Atomic level electronic and magnetic properties can be studied via STM/STS, BEEM (VTSTM 50-800K), or Cryo-SFM (~4-300K) probe stations.

Laboratory for Integrated Science and Engineering and Center for Nanoscale Systems

Harvard University



The Laboratory for Integrated Science and Engineering at Harvard houses world-class, centralized experimental facilities with technical staff support for research groups working in nanoscale research as well as the larger community of external users from academia and industry. The shared facilities are managed by the Center for Nanoscale Systems which foster leading-edge, multidisciplinary research and education in the areas of imaging and nanoscale systems, bridging the disciplines of chemistry, physics, engineering, materials science, geology, biology, and medicine. This creates environment for collaborative research and meeting places conducive to productive scientific interactions.

7. STRATEGIC RESEARCH PLAN

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 including nanoparticles, nanowires, and heterostructures. 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 inside nanostructures using custom-made scanning probe microscopes, including cooled instruments. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing.

The desired outcomes for our Center's research are outlined in Figure 7.1. They are in two areas: Biology and medicine are addressed by the *Tools for Integrated Nanobiology* and *Nanoscale Building Blocks* research clusters. The outcomes are in the fields: *Microfluidic and Hybrid BioChips*, and *BioProbes*. Electronic and optical systems are





addressed by the *Nanoscale Building Blocks* and *Imaging at the Nanoscale* Clusters. The outcomes are in the fields of *Nanoelectronics*, *Nanophotonics*, and *Quantum Information Processing*. These applications will benefit society, and they are an important product of the Center's research program.

A list of the Center's participants is shown in Figure 7.2. New additions are <u>Evelyn</u> <u>Hu</u>, a widely respected expert in the fabrication and testing of photonic and electronic systems who is now at Harvard University, and <u>Chris Palmstrom</u>, an outstanding materials scientist at UC Santa Barbara. All of the Center's researchers currently work in more than one cluster, as shown in Figure 7.2. This overlap has increased substantially since our Center was created in 2001, and it is clear evidence of the benefits of collaborative research. The overlap between different research specialties creates exciting new topics, described in *Section 8 – Research Program*.

In the paragraphs below we show how the Center's participants work together to address potential outcomes of their research:

Microfluidic and Hybrid BioChips

Joanna Aizenberg (SEAS	Efthimios Kaxiras (Physics &	Robert Westervelt (SEAS &
	SEAS)	Physics)
Federico Capasso (SEAS)	Kit Parker (SEAS)	George Whitesides
- · ·		(Chemistry)
Donhee Ham (SEAS)		Xiaowei Zhuang (Chemistry
		& Physics)

The investigators in this area create new microfluidic and hybrid electronic/ microfluidic chips for applications in Biology and Medicine. <u>George Whitesides</u> is a pioneer in microfluidics and soft lithography. Microfluidic systems create biocompatible environments for the study of cells and can be used to create lab-on-a-chip systems for medical analysis. <u>Whitesides</u> works closely with Joanna Aizenberg, Federico Capasso, <u>Robert Westervelt</u> and other members of this group. Joanna Aizenberg is an expert in biomaterials and microfluidics. <u>Kit Parker</u> studies the behavior of cells in a microfluidic system using optical and scanning probe microscopy. <u>Xiaowei</u> Zhuang develops techniques for imaging viruses and proteins inside biological systems. Hybrid CMOS/microfluidic chips that combine biocompatible microfluidics with integrated circuits and optoelectronics have been created by <u>Donhee Ham</u> and <u>Robert Westervelt</u>, and <u>Federico Capasso</u> makes hybrid optical/microfluidic systems for sensing.

BioProbes

Joanna Aizenberg (SEAS)	Hongkun Park (Chemistry &	George Whitesides
	Physics)	(Chemistry)
Moungi Bawendi (Chemistry,	Kit Parker (SEAS)	Xiaowei Zhuang (Chemistry
MIT)		& Physics)

A group of Center investigators uses probes based on nanoscale objects of different types to sense and image biological systems. Joanna Aizenberg, Moungi Bawendi, Hongkun Park and Xiaowei Zhuang develop nanoparticles and nanowires that can be biologically functionalized. George Whitesides is functionalizing interior surfaces of microfludic systems with biologically active materials. Kit Parker has developed an atomic force microscope tip that can selectively bind certain proteins and act as a scalpel for nanosurgury on biological cells.

Nanoelectronics

Raymond Ashoori (Physics, MIT)	Jennifer Hoffman (Physics)	Chris Palmstrom (Materials, UCSB)
Moungi Bawendi (Chemistry, MIT)	Evelyn Hu (SEAS)	Pierre Petroff (Materials, UCSB)
Cynthia Friend (Chemistry)	Marc Kastner (Physics, MIT)	Michael Stopa (NNIN)
Arthur Gossard (Materials, UCSB)	Charles Marcus (Physics)	Shriram Ramanathan (SEAS)
Bertrand I. Halperin (Physics)	Venkatesh Narayanamurti (SEAS & Physics)	Robert Westervelt (SEAS & Physics)
Eric Heller (Chemistry & Physics)	Hongkun Park (Chemistry & Physics)	Amir Yacoby (Physics)

This group of investigators is developing new approaches in nanoelectronics. They combine the nanoscale building block synthesis and MBE growth with nanofabrication and theory to make, study, image, and understand new types of nanoscale devices. <u>Moungi Bawendi, Hongkun Park</u> and our international collaborator <u>Lars Samuelson</u> are experts in the synthesis of nanocrystals and nanowires from new materials and their assembly into electronic devices; <u>Cynthia Friend</u> grows and studies two-dimensional materials with only one atomic layer on a surface. <u>Shriram Ramanathan</u> has developed new oxide semiconductors for nanoscale logic switches. <u>Arthur Gossard, Pierre Petroff</u>

and <u>Chris Palmstrom</u> use the MBE Laboratory at UC Santa Barbara to make new types of semiconductor heterostructures and self-assembled quantum dots. Using the nanofabrication facilities in Harvard's Center for Nanoscale Systems (CNS) and at MIT, <u>Raymond Ashoori, Evelyn Hu</u>, <u>Marc Kastner, Charles Marcus, Venkatesh Narayanamurti, Robert Westervelt</u>, and <u>Amir Yacoby</u> use e-beam and optical lithography to make a wide variety of nanoscale electronic devices. The nanoelectronic devices studied by this group range from transistors made from nanowires and self-assembled dots, to few-electron quantum dots, to open two-dimensional electron gas devices for studies in strong magnetic fields. Scanning-probe imaging techniques developed by <u>Raymond Ashoori, Eric Heller, Jennifer Hoffman, Venkatesh Narayanamurti, Hongkun Park, Robert Westervelt</u>, and <u>Amir Yacoby</u> provide powerful tools to investigate how electrons move through these nanoscale devices. Collaborations with theorists <u>Bertrand Halperin, Eric Heller</u> and <u>Michael Stopa</u> allow the group to understand what the transport measurements and images mean.

Nanophotonics

Moungi Bawendi (Chemistry,	Evelyn Hu (SEAS)	Pierre Petroff (Materials,
MIT)		UCSB)
Federico Capasso (SEAS)	Marco Lončar (SEAS)	Xiaowei Zhuang (Chemistry & Physics)
Kenneth Crozier (SEAS)	Eric Mazur (SEAS & Physics)	5 /

The Nanophotonics group of investigators develops new approaches to photonics using nanoparticles, nanowires, nanofibers and imaging techniques. <u>Moungi Bawendi</u> is developing optoelectronic devices based on nanocrystal quantum dots. Using MBE growth, <u>Pierre Petroff</u> is making self-assembled InAs/GaInAs quantum dot and posts inside semiconductor heterostructures as photonic devices. <u>Marco Lončar is developing</u> photonic systems with embedded nanoparticles and nanowires. By placing a plasmonic grating on the end of a semiconductor laser chip, <u>Federico Capasso</u> is controlling the angular beam shape and it's spectral character. <u>Eric Mazur</u> is developing sub-wavelength diameter optical fiber devices. <u>Kenneth Crozier</u> is making optical traps for use in microfluidic systems based on miniature Fresnel lenses.

Quantum Information Processing

Bertrand I. Halperin (Physics)	Charles Marcus (Physics)	Robert Westervelt (SEAS & Physics)
Marc Kastner (Physics, MIT)	Michael Stopa (NNIN)	Amir Yacoby (Physics)

These investigators work closely with a group of international collaborators to implement and study systems for quantum information processing. <u>Marc Kastner, Charles Marcus</u>, and <u>Robert Westervelt</u> have developed one-electron quantum dots to implement qubits, and are developing ways to manipulate individual spins. Theoretical understanding and simulations are provided by <u>Bertrand I. Halperin</u> and <u>Michael Stopa</u>. This group has strong international collaborations with Leo Kouwenhoven, <u>Daniel Loss Lars Samuelson</u>, and <u>Seigo Tarucha</u> (see *International Collaborators* below).

Custom Scanning Probe Microscopes

Raymond Ashoori (Physics,	Eric Heller (Chemistry &	Robert Westervelt (SEAS &
MIT)	Physics)	Physics)
Federico Capasso (SEAS)	Jennifer Hoffman (Physics)	Amir Yacoby (Physics)
Kenneth Crozier (SEAS)	Venkatesh Naryanamurti	
	(SEAS & Physics)	

This group of investigators is well-known for developing new imaging techniques to study of electrons and photons inside nanoscale systems, and for building their own scanning probe microscopes. These tools will be extremely useful for visualizing and understanding nanoscale devices and systems. <u>Raymond Ashoori, Eric Heller, Robert Westervelt</u>, and <u>Amir Yacoby</u> use capacitive coupling between the tip of a cooled scanning probe microscope and the electrons to image their motion inside nanostructures. <u>Jennifer Hoffman</u> has constructed liquid-He cooled STM and a cooled high-spatial-resolution AFM to study high T_c superconductors and other materials. <u>Venkatesh Narayanamurti</u> has developed Ballistic Electron Emission Microscopy (BEEM) and Ballistic Electron Emission Luminescence (BEEL) Microscopy to study electron states inside nanostructures. <u>Kenneth Crozier</u> and <u>Federico Capasso</u> are developing a Near-field Scanning Optical Microscope with a robust microlens tip that is equipped with a plasmonic metal resonator to more tightly focus the electromagnetic field.

International Collaborators

Yasuhiko Arakawa	Koji Ishibashi (RIKEN, Japan)	Lars Samuelson (Lund
(University Tokyo, Japan)		University, Sweden)
Fabio Beltram (NEST, Italy)	Daniel Loss (University Basel)	Hiroyuki Sakaki (Toyota Tech
		Inst, Japan)
Leo Kouwenhoven (TU Delft)	Hideo Ohno (Tohoku	Seigo Tarucha (University
	University, Japan)	Tokyo, NTT, Japan)

Our Center has close collaborations with a strong group of investigators located overseas. Students and postdocs travel back and forth to carry out the research. <u>Hiroyuki</u> <u>Sakaki</u> is one of the founders of modern semiconductor physics through his development of superlattices and heterostructures. <u>Yasuhiko Arakawa</u> is a leader in photonics and heterostructure growth. <u>Koji Ishibashi</u> is an expert in carbon nanotube and semiconductor nanowire electronics. <u>Hideo Ohno</u> is an original developer of spintronics. <u>Leo Kouwenhoven, Daniel Loss, and Seigo Tarucha</u> are very well-known for their activity in quantum information processing. <u>Lars Samuelson</u> is a leader in nanowire synthesis and growth, and <u>Fabio Beltram</u> heads an impressive group at NEST.

Frontiers in Nanoscale Science and Technology Workshops

Our Center holds international *Frontiers in Nanoscale Science and Technology* (*FNST*) *Workshops* focused on nanoelectronics, nanophotonics, spintronics and quantum information processing. The workshops have attracted outstanding speakers, and they promote interesting and exciting discussions with the audience. Our Center provides scholarships to students and postdocs so that they can attend. The workshops they have proven to be a very effective way to connect students and postdocs with the newest ideas in nanoscience and technology.

Our seventh *Frontiers in Nanoscale Science and Technology Workshop* was held on January 5-7, at RIKEN in Tokyo, Japan, organized by <u>Koji</u> <u>Ishibashi</u> of RIKEN and <u>Robert Westervelt</u>. The Workshop is part of a Memo of Understanding between Harvard and RIKEN, to promote collaborate research between the two institutions. An impressive group of speakers participated, with leading investigators from academic and industry in Japan, Europe and the US, including the Konstantin Novoselov, the 2011 Nobel Laureate in Physics, as shown in Figure 7.3.

The eighth *Frontiers in Nanoscale Science and Technology Workshop* will be held in 2012 at Lund University in Sweden, hosted by <u>Lars Samuelson</u>.



Frontiers in Nanoscale Science & Technology

Nanoelectronics & Nanophotonics Spintronics & Quantum Information

Nanoscale Science and Engineering Center (NSEC) Harvard, MIT, UC Santa Barbara, Museum of Science, Boston Univ of Basel, TU Delft, Lund Univ, RIKEN, Univ of Tokyo



Speakers:

Tsuneya Ando (Tokyo Inst Tech) Hendric Bluhm (Harvard) Jonathan Fan (Harvard) Christian Glattli (CEA Saclay) Tetsuro Hanaguri (RIKEN) Pablo Jarillo-Herrero (MIT) Gijs de Lange (TU Delft) Heiner Linke (Lund Univ) Daniel Loss (U Basel) Fumihiro Matsukura (Tohoku Univ) Masahiro Nomura (Univ Tokyo) Konstantin Novoselov (Manchester) Hajime Okamoto (NTT) Hongkun Park (Harvard) Lars Samuelson (Lund) Axel Scherer (Caltech) Paul Sheehan (Naval Research Lab) Charles Smith (Cambridge) Kota Tateno (NTT) Robert Westervelt (Harvard) Hongqi Xu (Lund Univ) Michihisa Yamamoto (Univ Tokyo)

Figure 7.3. Poster for the 2011 Frontiers in Nanoscale Science and Engineering Workshop held in RIKEN, Tokyo, Japan and organized by <u>Koji Ishibashi</u> and <u>Robert Westervelt</u>.

8. RESEARCH PROGRAM, ACCOMPLISHMENTS, AND PLANS

Period: March 15, 2010 to March 14, 2011

RESEARCH PROGRAM

Overview:

Our Center develops tools to study nanoscale systems.

For electronics and photonics, would like to synthesize new types of nanostructures, and visualize the motion of electrons and photons inside, using custom imaging techniques based on scanning probe microscopy.

For biology and medicine, we would like to understand how interacting cells behave as a system, and investigate the interior workings of cells, by developing powerful tools based on microfluidics and semiconductor technology.

Three Research Clusters address these goals:

Cluster I: Tools for Integrated Nanobiology builds bridges between the physical sciences, biology, and medicine. The physical sciences offer powerful new tools for manipulating and testing biological cells and tissues based on microfluidic systems, soft lithography, and semiconductor technology. In turn, 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 II: Nanoscale Building Blocks addresses the synthesis of new classes of nanostructures that exhibit size-dependent properties. An emphasis is placed on zero, one-and two-dimensional nanostructures, including nanoparticles, nanowires and heterostructures. Techniques to synthesize nanostructures from new materials are being developed, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks provide new approaches for nanoelectronics and nanophotonics as well as sensors for biological systems.

Cluster III: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons in nanostructures using custom-made scanning probe microscopes (SPMs). These instruments include cooled SPMs for the capacitive probing of electrons inside nanostructures, cooled scanning tunneling microscopes (STMs), an STM equipped for Ballistic Electron Emission Microscopy (BEEM), and nearfield scanning optical microscopes (NSOMs). These tools are used to develop and understand the behavior of nanoelectronic and nanophotonic devices.

CLUSTER 1: Tools for Integrated Nanobiology

Period: March 15, 2010 to March 14, 2011

Coordinator: George M. Whitesides

Joanna Aizenberg (SEAS, Harvard)Kevin (Kit) Parker (SEAS, Harvard)Donhee Ham (SEAS, Harvard)Robert M. Westervelt (SEAS & Physics, Harvard)Efthimios Kaxiras (Physics & SEAS,
Harvard)George M. Whitesides (Chemistry, Harvard)

- *Collaborators*: Ilhan Aksay (Princeton University); Carol Lynn Alpert (Museum of Science, Boston); David Bell, Federico Capasso, L. Mahadevan, David Nelson, Arvi Samuel (Harvard University); Nader Engheta (University of Pennsylvania); Walter Fontana, Olga Futer (Ventex Pharmaceuticals); Bartosz Grzybowski (Northwestern University); Donald Ingber (WYSS Institute for Biologially Inspired Engineering at Harvard University); Chris Jones (iRobot); Tom Krupenkin (University of Wisconsin, Madison); Shawn Lockery (University of Oregon); Gabriel Lopez (University of New Mexico); Ralph Nuzzo (University of Illinois, Urbana-Champaign); David Walt (Tufts University); Ralph Weissleder (Mass. Gen. Hospital); Younan Xia (University of Washington);
- International Collaborators: Masahiro Kubo (NEC Corp. Japan); Maria-Anita Rampi (University of Ferrara, Italy); Jens Rieger (BASF, Germany and Harvard)

Number of postdoctoral fellows: 4 Number of graduate students: 3 Number of undergraduate students: 3

Introduction

As biology begins to ask more quantitative and analytical questions about the nature of the cell, it needs new tools to study subcellular structures that have nanoscale dimensions. An important task is to build bridges between the physical and biological sciences. The physical sciences offer to biology new measurement tools and new procedures for analyzing the information obtained. In turn, biology offers to the physical sciences an enormous range of engaging problems, and stimulating examples of very sophisticated, functional biological systems. It also offers the opportunity to think about "hybrid" systems that combine biological and non-biological components.

The interface between the biological and physical sciences is one with enormous promise for fundamentally new science and, ultimately, technology. By supporting collaborations between investigators in the School of Engineering and Applied Sciences (SEAS), the Department of Chemistry and Chemical Biology, the Harvard Medical School and the Harvard School of Public Health, Cluster 1 will catalyze and expand a series of very effective collaborations across the physical-biological interface.

We expect three outcomes:

Tools for Cellular Biology and Tissue Culture: One of the major contributions that the physical sciences can offer to biology are new physical tools that can provide new kinds of information about cells and tissues.

The Science and Engineering of Interfaces between Animate and Inanimate Systems: This research will contribute to studies of cells in cell cultures, and to the assembly of groups of cells of the same or different types. In society, it will contribute to engineering the interface between patients and prostheses.

Tools for the Development of Drugs: The control over cells afforded by new microfluidic tools will be the basis for entirely new types of bioassay that will be important as the pharmaceutical industry moves away from information-poor animal assays in preclinical studies toward more informative studies based on primary human cells.

Localized Materials Deposition on a Superhydrophobic Nanowire Array

Joanna Aizenberg

Chemical Engineering, Harvard University

Collaborators: David Nelson, George M. Whitesides (Harvard University); Carol Lynn Alpert (Museum of Science, Boston); Donald Ingber (WYSS Institute for Biologially Inspired Engineering at Harvard University); Tom Krupenkin (University of Wisconsin, Madison); Gabriel Lopez (University of New Mexico)

Structural Transformation by Electrodeposition on Patterned Substrates

Arrays of high-aspect-ratio (HAR) nano- and microstructures are of great interest for designing surfaces for applications in optics, bionano-interfaces, MEMS, microfluidics, but the difficulty of systematically varying their geometric parameters significantly limits their design and optimization for a specific function. In collaboration with the Wyss Institute and <u>Whitesides</u> group, we developed a low-cost, high-throughput benchtop



Figure 1.1. (a) Schematics showing the step-by-step structural transformation using sputter coated metal electrode (STEPS I), evaporated metal electrodes from the top (STEPS II), and evaporated metal electrodes at an angle (STEPS III). Green: parent substrate, yellow: metal coating, blue: polypyrrole. (b) Photographs of a parent high-aspect-ratio nanopillar array (left) and a gradient nanopillar array modified by PPy deposition (right). (c) SEM image of an array of conical structures transformed from the original cylindrical nanopillar array produced using STEPS II process. (d) SEM image of an array of unidirectionally bent conical structures transformed from the original cylindrical nanopillar array using STEPS III process.

method that enables a HAR array, or any other topographically patterned surface, to be reshaped with nanoscale precision by electrodeposition of conductive polymers. The method, we named STEPS (Structural Transformation by Electro-deposition on Patterned Substrates), makes it possible to create a wide variety of tapered, anisotropic, or reentrant geometries from a simple parent HAR array by controlling the deposition conditions as schematically shown in Figure 1.1. Each STEPS method created libraries of various patterns from a single master structure with the option of creating substrates with continuous or discrete gradients of features. **STEPS** nanostructure enables a wide range of systematic and combinatorial studies of the effect of substrate topography on surface properties leading to optimization of the structures for specific applications such as low cost plasmonic nano-

structure array, combinatorial substrates for bacterial patterning, and mechanically reinforced high-aspect-ratio nanostructures as shown in Figure 1.2. STEPS method identifies solution-based deposition of conductive polymers as a new tool in

nanofabrication and allows access to complex 3-D architectures that were previously difficult to fabricate.



Figure 1.2. (a-c): SEM images showing various modes of STEPS transforming original HAR nanostructures into various new structures. Images were taken from replicated samples from gradient-STEPS-modified HAR arrays. (d): SEM images of an example array of plasmonic nanostructures fabricated using STEPS method. Inset: A high magnification SEM image of a double-ring structure from the array. (e-f): Fluorescence microscopy images of spontaneous bacterial patterning on a HAR nanopillar array modified by gradient-STEPS. Continuously varying interstitial spaces created by STEPS affected the biologically-driven bacterial insertion. (e) No bacterial patterning on unmodified nanopillar array with wide interpillar spacings relative to bacteria scale; (f) robust patterning occurs on widened pillars as the interstitial space decreases.

Synthesis of Polygonal Rings and Wires of CuS on Structured Surfaces

Copper sulfides have been studied for many years because of the potential applications in optoelectronic devices and photovoltaics. However, traditional synthesis of these materials lacks the synthetic control over the stoichiometry, the crystallinity, and morphology which significantly influence properties such as the bandgap. **The purpose of this research is to use structured surfaces to control the crystallization of inorganic materials, especially CuS.** By using the limited surface area provided by the structured surface to grow inorganic materials, we hypothesize that we can obtain better control over the morphology and size of copper sulfide crystals. Crystallization experiments of CuS are carried out on micro-pillar arrays functionalized with self-assembled monolayers (SAMS) to render the micro-structured surfaces super-hydrophobic. These nano- and micron-scale pillars are made from commercially available epoxies using a double replication technique in which the pillars are molded



Figure 1.3. Timed studies of the growth of CuS rings. SEM image of: (A) formation of spherical particles on pillars (30 min), (B) petal like structures of CuS (1h), hexagonal ring formed by oriented attachment of spherical aggregates (2h), and (D) smooth rings with shape conforming to underlying structure; (E) schematic depicting the formation of rings with petal-like intermediate.

of CuS rings begins with nucleation of spherical particles on the tips, which then form chain-like assemblies that can detach. The resulting rings can also conform to the underlying substrates (Figure 1.3). These results suggest that it is possible to stabilize morphologies of inorganic materials by controlling the geometry of the underlying substrate. We will continue to study the crystallization of inorganic materials such as PbS, CdS, and CaCO₃.

from a PDMS negative mold of a Si master. The pillars are sputter-coated with a thin film of Pt/Pd and a self-assembled monolayer of 1-heptanethiol is grown on the metalized pillars via vapor phase deposition. The super-hydrophobic nature of these substrates allows for only the tips of the posts to be exposed to an aqueous chemical bath containing inorganic copper sulfate and sodium thiosulfate that react (50°C) and deposit copper sulfide on these micron and nanoscale nucleation sites.

Using the structured surfaces we successfully synthesized rings and ultralong wires of of CuS. We pinpointed the reaction conditions necessary to access the ring structures, a morphology not typically observed in CuS. At reaction times of 3h (Figure 1.3), we predominately formed rings and formed nanowires at long reaction times (12h) (Figure 1.4). We also proposed a reaction mechanism for the formation of the ring structures by doing a timed study of the growth.

Interestingly, the formation



Figure 1.4. SEM images of nanowires of CuS grown on micropillars (12h).

Miniaturized NMR System

Donhee Ham

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Collaborator: Ralph Weissleder (Massachusetts General Hospital)

Research Goal, Approach, and Accomplishments

In this work belonging to *Cluster 1: Tools for Integrated Nanobiology*, we seek to develop an interface between electronic solid-state systems (especially silicon CMOS chips) and biological samples for electronic biomolecular sensing aimed at disease screening. The advantage of using the electronic solid-state system would be the low-cost and small system size. In particular, we have focused on nuclear magnetic resonance (NMR) as a physical modality for the solid-state and biological systems interface. It combines the physics of NMR with high-performance radio-frequency (RF) silicon integrated circuits.

Traditional NMR systems are large and heavy, because of the large magnets used to produce strong NMR signals. In our work, we took an approach opposite to the convention, and used far smaller magnets to substantially reduce the size (hence the cost as well) of NMR systems. The small magnets inevitably lower the strength of NMR signal, which we were able to still retrieve by building a high-performing silicon RF transceiver IC.



Palm NMR system (0.1 kg)

- 20x lighter, 30x smaller, 2.5x more spin mass sensitive than our prior work ISSCC'08 & JSSC'09 [1, 2]
- 1200x lighter, 1200x smaller, 150x more spin mass sensitive than state-of-the-art commercial benchtop system [3]



Figure 1.5 shows the smallest NMR prototype we developed. It uses a ping-pong ballsized magnet, and the resulting weak NMR signal is retrieved by a silicon CMOS RF transceiver IC. This 0.1-kg NMR system is 1200 times lighter, 1100 times smaller, yet 150 times more spin mass sensitive than a 120-kg state-of-the-art commercial benchtom NMR system, and can be held at the palm of the hand.

With a 2 mL water sample placed in the solenoidal coil (not shown in the previous figure, as the coil is inside the magnet) of the palm NMR system, a spin-spin relaxation time (T_2) of water (protons of hydrogen atoms in water molecules) was measured.

Antibody-coated magnetic nanoparticles can bind to specific antigens in water to form magnetic particle clusters. These clusters perturb the water proton precessions, reducing the spin-spin relaxation time. This provides a biosensing modality (this technique was proposed by Ralph Weissleder of Massachusetts General Hospital, who is our bio side collaborator). By using this technique, we were able to detect avidin molecules with the palm NMR system.

The NMR work above relies on low-signal low-noise magnetic dipole coupling between the solid-state and biological systems. We are currently developing a massively parallel field-effect sensor array using silicon CMOS integrated circuits to pursue highsignal high-noise electric monopole (charge) coupling. This is an effort to develop an all electronic DNA microarray as well as protein chips, to provide an alternative to the standard optical method.

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Theory and Experimental Investigations of Nanomaterials and Devices

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Collaborators: Robert M. Westervelt, David Bell (Harvard University)

Research Goal, Approach and Accomplishments

Our two related lines of research, theory/experiments on graphene nanomaterials and devices, as described in the following, both involve highly resolution fabrication and characterization of graphene in molecular scale. Our research goal is to physically and/or chemically manipulated graphene in molecular scale to produce nanomaterials and devices that exibit novel electron, spin or ionic transport properties.

1. Transport Properties of Graphene Nano/Molecular Devices

Graphene, a 2-D material, has excellent structure integrity and unique pi-band electronic structure. In addition, because of the mono-atomic layer nature and strong carbon-carbon bond, graphene is particularly suited for forming molecular devices that have well-defined atomic configuration. When reduced to molecular size, even more intriguing properties would show up such as quantum confinement and spin polarization. We have shown using first principle calculation that nanometer-sized graphene flakes, can be classified as Class I and II, depending on the topological frustration of pi-band in the nanoflakes. Such frustration could lead to both ferromagnetic and anti-ferromagnetic coupling, which can be used as logic gate to process information [1-2]. In our experimental investigation of these graphene nanoflakes, transmission electron microscope (TEM) is especially useful because of the thin film nature of graphene, the atomic resolution of TEM as well as the capability of focused electron beam to interact and modify the graphene sheets. We have employed state-of-the-art TEM with spherical aberration correct and a monochrometer that was newly installed at the Center of Nanoscale Systems of Harvard.

We have already demonstrated imaging/modifying graphene with atomic resolution. To incorporate such sample in devices we have developed a procedure to deposit single layer of graphene suspended on the electrodes that are in turn patterned on suspended silicon nitride membrane. Such device makes it possible for us to make secure electric contact all the way to the nano-atomic features that we may fabricate with TEM, from a double quantum point contact, to single carbon chain, or a complex pattern made of graphene nanoflakes.

2. Chemically-Derived Graphene and Properties

Chemically-derived decorated graphene with various functional groups form new 2-D materials with novel properties, which might be dramatically different from that of graphene. We have focused on a special class of chemically-derived graphene material, where function groups of opposite nature are chemi-absorbed on different sides of graphene. In particular, we predicted [3], using first-principles calculation that when

graphene is put in water and subject to a potential difference across the membrane, a 2-D carbonhydrate can be formed directly from water and carbon. Such new 2-D crystalline structure is energetically favorable and remains stable at room temperature as observed in first-principles MD simulation. The hydration also dramatically changes the conducting properties of graphene, from a semi-metal to an insulator.

We have fabricated samples and a microfluidic device where the two sides of suspended graphene are subjected to different ionic potential. We use Raman spectroscopy to monitor the hydration process in real time. Our preliminary test shows that different ionic species, namely the proton and hydroxy group can be assembled to the surface of multiple layer of graphene with the assistance of an applied electric field. The immediate next step is to investigate the direct chemical bond interaction of these species through single layer graphene.

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Engineering Biologically Inspired Protein NanoFabrics

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Research Goal, Approach and Accomplishments

The structural integrity of tissues is dependent on the secondary protein structure of its extracellular matrix (ECM). The shear topology of FN III domains within the ECM protein Fibronectin (FN) elicits the mechanical stability and the internal elasticity of the ECM. To evaluate the molecular mechanism that accounts for FN elasticity *in vitro*, we followed how mechanical strain affects the secondary structure in protein nanoFabrics.

The goal of our research is identify the strain-dependent molecular mechanism of FN assembly during fibrillogenesis. Understanding how protein structure dictates fiber formation may offer a unique perspective for designing a range of new, tough biomaterials with programmable chemical properties that allow them to withstand large strains without breaking.

In our study of FN fibrillogenesis *in vitro*, we hypothesized that mechanical strain affects FN structure, as it transforms from an extended to a



Figure 1.6. Forming arrays of FN nanofibers. A) Schematic of fiber release over time. FN lines are patterned onto PIPAAm substrates. B) Raman spectra of FN lines before and after they are released as nanofibers from the PIPAAm substrate. C) FN grid lines before and after release D,E) AFM and SEM, respectively of FN weave post-release.

compact conformation during fibrillogenesis. To test this hypothesis, Raman spectroscopy and fluorescence resonance energy transfer (FRET) were used to identify the change in secondary structure of the aligned FN protein before and after they are released from their substrate.

We synthesized protein nanoFabrics composed of FN according to previously reported protocols [1]. Briefly, a monolayer of FN is microcontact printed onto a thermosensitive polymer (PIPAAm) coated substrate as lines with geometries ranging from 20 to 100 μ m lines over a 25 mm² area. In the presence of a low temperature (< 32°C) aqueous environment, the underlying PIPAAm dissolves, thereby releasing the lines as free-standing fibrillar networks (Figure 1.6). The structural properties of microcontact printed (unreleased) FN are contingent on the surface properties of its underlying substrate. For this reason, it was important to identify the macromolecular physical changes associated

with the nanoFabric formation. Still images, captured before and after the fibers were released from their substrate were taken using epifluorescent, atomic force, and scanning electron microscopes (Figure 1.6C-D). As the PIPAAM substrate slowly dissolved, the lines collapsed in a mechanism that is observed to begin at the edges of the line (t = 300 sec), fully contracting up to 65% their original width to form insoluble fibrils by 480 sec (Figure 1.6A). The dissolution of the underlying PIPAAm substrate relieves tension along the immobilized FN lines and initiates protein contraction. As they contract, we hypothesized that FN nanofibers form through a water mediated repulsion between non-polar, hydrophobic domains and the charged side groups with FN, through a phase transfer reaction [2,3]. This phase transfer occurs at the interface of both hydrophilic and hydrophobic media. As the PIPAAm slowly dissolves into solution at low temperatures, it forces segregation of the hydrophobic amino



Figure 1.7. Confocal images of dual-labeled FN nanoFabrics before and after release. A,B) nanoFabrics are excited at donor excitation wavelength were captured at donor emission wavelength (left) and acceptor emission wavelength (right). A) Minimal FRET is due to the extended conformation of FN within the lines. B) FRET fluorescence is induced by compacted conformation of FN within fibers. Scale bar $50 \mu m$.

acids into the protein core and causes the hydrophilic residues of FN to ascend to the surface, producing stable, water insoluble nanofibers.

To investigate whether this water mediated repulsion induces a chemical rearrangement of the nanoFabrics, we used Raman Spectroscopy, a technique based on the energy-dependent inelastic scattering of light by molecules [4-6], to identify the change in molecular structure of FN (Figure 1.6B). Raman spectra, collected separately for 12 nanofiber samples before and after they were released from the substrate, were analyzed for secondary structure composition (Figure 1.6B). Spectra of the lines were compared against the spectra for the released fibers. In both cases, the presence of an amide I peak at 1670 cm⁻¹ was observed; however, this peak for the released sample is slightly shifted from the unreleased sample, indicating a structural change along its molecular backbone (Figure 1.6B). Similar secondary structure shifts have been reported FN, as it is transferred from the bulk to adsorbed phase [6]. The 1450 cm⁻¹ multiplet is still present in the spectra; however, the amide III and amide II peaks were no longer evident. These changes in the spectra indicate that the secondary structure of FN may have become randomly oriented within the fibril.

To support the strain-dependent conformational changes observed within nanoFabrics using Raman Spectroscopy, FN was labeled for FRET to optically follow the change in protein structure as a function of fibrillogenesis. Briefly, acceptor fluorophores were bound to the cryptic cysteines of FN, and donor fluorophores were bound randomly to free amines, according to previously established protocols [7-9]. A solution of FRET FN was microcontact printed onto PIPAAm substrates, where the fluorescence intensity profiles within the nanofibers were monitored before, during, and after their release using confocal microscopy (Figure 1.7). The unreleased FN lines demonstrated negligible FRET signal when compared to the donor (AF 488) signal. FN is extended under tension as stamped lines, and the FN donor and acceptor molecules are too far apart to induce FRET. On the other hand, when the nanofibers were released, FRET fluorescence increased by 90%, indicating that FN within fibrils are in a compact or contracted conformational state. Our results indicate conformational changes in FN under low strains induce enhanced FRET signals. Utilizing the dynamic properties of FN during fibrillogenesis, we can now observe how FN nanoFabrics can be optically functionalized to show change in conformation state under strain. In this respect, we have designed a physiologically relevant *in vitro* model to study the structural reorganization of FN, once tension is released.

Incorporating the flexibility of the nanoFabrics technology, we have identified how mechanical strain affects the secondary structure of FN during fibrillogenesis. We believe that the conformational changes in FN are dependent on both the shear topology of FN and the chemical properties of the sacrificial substrate. Both enhanced FRET signal and a change in Raman spectra post-release supported that FN is contracting into a compact conformation during this molecular transition, as it relaxes its molecular conformation during fiber formation. Having used FN as a model system, programmable nanomaterials with similar strain dependent molecular responses can now be designed with enhanced mechanical stability to be translated beyond systems in Biology to bio-integrated soft materials.

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Simple Methods for Nanofabrication

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Research Goal, Approach, and Accomplishments

The research of our laboratory, as part of the NSEC center, has continued to offer new results over the last funding period. We have focused on developing nanoskiving, an unconventional method to fabricate and replicate nanostructures by mechanical sectioning with an ultramicrotome. The results of this research should enable application in optics, plasmonics, and medicine. There are three peer-reviewed publications in 2010, and two more that will be submitted by mid-2011. The following sections describe: (i) the fabrication and replication of arrays of complex, multi-material, high-aspect-ratio nanostructures by mechanical sectioning (collaboration with J. <u>Aizenberg</u> and <u>F</u>.



Figure 1.8 (*Left*) Example of the procedure used to fabricate arrays of metallic nanostructures by embedding and sectioning a metallized array of epoxy nanoposts using an ultramicrotome. This procedure produces manipulable slabs of epoxy containing arrays of metallic nanostructures.

<u>Capasso</u>); (ii) the transfer of these nanostructures to the tip of optical fibers; and (iii) the comparison of transmission spectra of arrays of gold nanostructures produced by nanoskiving, and FDTD simulations of the nanostructures with idealized geometries (collaboration with <u>F.</u> <u>Capasso</u>).

1.1. Fabrication and Replication of Complex, Multi-material, Highaspect-ratio Nanostructures by Nanoskiving (with <u>J. Aizenberg</u> and F. Capasso)

Nanoskiving is a simple method of nanofabrication whose key step is sectioning a planar or topographically patterned thin film, encapsulated in epoxy, with an ultramicrotome equipped with a diamond knife (Figure 1.8). After sectioning, the structures remain embedded in thin epoxy slabs. The slabs are macroscopic objects that preserve the orientations of the nanostructures within the arrays and also provide physical handles by which the user can transfer the nanostructures to substrates. After being deposited on a substrate, the epoxy slab can be removed by etching with an oxygen plasma. This action leaves free-standing nanostructures on the substrate.

1.2. Transfer the Metallic Nanostructures to the Tip of Optical Fibers

We chose five types of nanostructures to transfer to optical fibers: Crescents, rings, split rings, double rings, coaxial cylinders, and a grating of nanowires. These structures are interesting for their optical and plasmonic properties. Figure 1.9 summarizes the procedures used to produce closed rings by coating conformally the epoxy posts with gold, but structures bearing open loops, concentric rings, or other line segments can be made as well. Open-loop structures can be fabricated by placing the substrate at an angle to a collimated source of evaporating metal. "Shadow evaporation" can thus be used to coat only the sidewalls of the epoxy features in the path of the evaporated atoms. Upon embedding and sectioning these structures, we have obtained crescents and split rings.



Figure 1.9. (*Left*) Summary of the procedure used to fabricate and transfer arrays of metallic nanostructures to the facets of optical fibers. (*Right*) (a) An optical fiber bearing an array of gold crescents (shown in the inset). (b) A close-up of the facet. The inset is a single gold crescent. (c) A facet bearing a grating of gold nanowires. (d) The core of a fiber bearing an array of gold split rings. (Lipomi, D.J. *et al., Nano Lett.* **11**, 632–636, 2011).

1.3. Characterization and Simulation of Transmission Spectra of Gold Nanostructures Produced by Nanoskiving (with <u>F. Capasso</u>)

In order to demonstrate that the arrays of nanostructures produced by nanoskiving are of sufficient quality for optical applications, we obtained transmission spectra of an array of single rings and double, concentric rings (Figure 1.10) on a ZnSe substrate. The dimensions of the single rings were as follows: $d = 335 \pm 26$ nm, thickness = 34 ± 5 nm, and $h = 114 \pm 19$ nm. The dimensions of the double rings were as follows: $d_{\text{inner ring}} = 330 \pm 19$ nm, thickness_{inner ring} = 40 ± 5 nm, $d_{\text{outer ring}} = 725 \pm 48$ nm, thickness_{outer ring} = 38 ± 8 nm, and $h = 137 \pm 10$ nm. The source of irradiation was polarized perpendicular to the

direction of cutting. We placed the sample at the beam waist to approximate excitation by a planewave. The transmission spectrum of the single rings displayed one dip in transmission, while the spectrum of the double rings exhibited two (Figure 1.10a). These features in the spectra corresponded to the dipole resonances of the rings. As expected, the smaller ring produced a higher energy resonance ($\lambda \sim 2.5 \,\mu$ m) than did the larger ring (λ \sim 5 μ m). The positions of the resonances in the results of the FDTD simulations approximately matched those of the measured spectra (Figure Figure 1.10c shows the simulated 1.10b). intensities of the electric field in the near-field for each of the dipolar resonances of the rings.



Figure 1.10. (*Left*) Comparison of transmission spectra of arrays of gold nanostructures produced by nanoskiving, and FDTD simulations of the nanostructures with idealized geometries. (Lipomi, D.J. *et al.*, *ACS Nano* **4**, 4017-26, 2010)

CLUSTER 2: Nanoscale Building Blocks

Period: March 16, 2010 to March 15, 2011

Coordinators: Moungi Bawendi and Hongkun Park

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Seed Funding: Evelyn Hu (SEAS, Harvard)

Number of postdoctoral fellows: 2 Number of graduate students: 6 Number of undergraduate students: 3

Introduction

Tremendous progress has been made in the synthesis of nanoscale structures – nanocrystals, nanowires and nanotubes – that serve as building blocks for new devices and applications. However many challenges remain. They include the synthesis of nanostructures with well-defined sizes and shapes, the synthesis of new classes of materials, the in-depth characterization of newly developed nanostructures, the rational organization of these nanostructures into complex functional structures, and the fusion of nanoscale building blocks with state-of-the-art processing techniques, including e-beam lithography and focused-ion-beam sculpting, to build novel devices.

The *Nanoscale Building Blocks* cluster conducts a broad multidisciplinary, multiinvestigator research program that is designed to address these challenges. The proposed research is built upon the participants' expertise in the synthesis and characterization (both experimental and theoretical) of nanostructured materials. At the core of the program is the *rational synthesis of new classes of nanostructures that exhibit new sizedependent properties* that are distinct from bulk materials, with an emphasis on heterostructures and nanostructures with unconventional shape, as well as on zero-, oneand two-dimensional nanostructures made from new materials, including metal chalcogenides. The *incorporation of nanostructures into novel device geometries* constitutes another important part. These new devices will be tested to characterize the physical and chemical properties of the building blocks and to evaluate their technological applicability. *Understanding the behavior of these nanoscale building blocks* through theoretical investigations is an important part of the effort, because it is essential to advance the scientific and technological frontiers.

Magnetic and Semiconducting Nanoparticle Systems: Properties and Devices

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Collaborators: Rakesh Jain (Harvard Medical School); Seth Coe-Sullivan (QDVision)

Research Goal, Approach and Accomplishments

We report on two projects: (1) J-aggregate/nanocrystal quantum dot hybrid structures, and (2) Extracting single nanocrystal quantum dot spectral and dynamic information from solution.

J-Aggregate/Nanocrystal Quantum Dot Hybrid Structures

J-aggregates are ordered clusters of coherently-coupled molecular dyes, and they have been used as light sensitizers in film photography due to their intense absorptions. Hybrid structures containing J-aggregates may also have applications in device that require spectral specificity, such as color imaging or optical signaling. However, the use of J-aggregates in optoelectronic devices has posed a long-standing challenge, due to the difficulty of controlling aggregate formation and the low charge carrier mobility of many J-aggregates in solid state. We demonstrate a modular method to assemble three different cyanine J-aggregates onto CdSe nanowires, resulting in a photodetector that is colorsensitized in three specific, narrow absorption bands, with a fourth J-aggregate used as a control.



Figure 2.1. (a) Overview diagram depicting the interdigitated electrodes used to grow and characterize devices. (b) Optical micrograph, showing interdigitated electrodes used to grow and test devices. Faint brown shading between electrodes is the sparse network of CdSe nanowires. (c) Detail of the J-aggregate-templated CdSe nanowires. The structure of the three J-aggregating dyes 1, 2, 3, 4 are shown.



Figure 2.2.AFM images of a Jaggregate-nanowire device. (a) CdSe nanowires alone, before deposition of J-aggregates. (b) Same area as in a, following Jaggregate deposition.

Sample fabrication including optical lithography, physical vapor deposition and bonding, was performed using NSEC shared user facilities at MIT and Harvard (CNS) and the shared NSF-MRSEC user facilities at MIT.

Extracting Single Nanocrystal Quantum Dot Spectral and Dynamic Information from Solution

Conventional single-molecule fluorescence spectroscopy is limited in temporal resolution by the need to collect enough photons to measure a spectrum, in frequency resolution by the dispersing power of the spectrometer, and by environmental conditions by the need to immobilize the chromophore on a substrate. In this thesis, we use the

recently developed technique of photoncorrelation Fourier spectroscopy (PCFS) to circumvent each of these limitations and learn new insights about the spectral dynamics of single colloidal quantum dots (QDs).

Fluorescence spectroscopy of single quantum dots (QDs) has provided much fundamental insight, yet previous such experiments have previously been limited by the temporal and environmental requirements described above. On the slower timescales of conventional measurements, nanocrystals show significant dynamics both at room temperature and at liquid helium temperatures (see Figure



highly dynamic, both at room temperature (*left*) and low temperature (*right*).

2.3). We have applied PCFS to both single QDs at room temperature in solution and at low temperature. We have learned that the spectrum of single, room temperature QDs in



solution is surprisingly static for nearly 6 orders of magnitude in time, between 34 ns and 10 ms. At low temperature, the spectrum becomes significantly narrower and more dynamic.

PCFS combines the high temporal resolution of photon correlation measurements with the high frequency resolution of Fourier spectroscopy. The experimental setup consists of a Michelson interferometer where the two outputs are detected with avalanche photodiodes and cross-correlated with a hardware autocorrelator card (see Figure 2.4). The interferometer maps spectral changes into intensity changes, which can be measured with high temporal resolution by the autocorrelator. The distribution of spectral changes between photons with a given temporal separation determines the degree of correlation in the interferogram. By measuring the intensity correlation at different interferometer positions while dithering one mirror, a time-dependent spectral correlation function is obtained.





When observing single chromophores in solution, we combine our technique with Fluorescence Correlation Spectroscopy (FCS). Spectral correlations originating with the same chromophore are statistically enhanced and separable from the ensemble using intensity fluctuations from diffusion [2, 3]. Similar to the way FCS uses many particles diffusing through the focal volume to determine the average single particle diffusion coefficient, we use spectral correlations from many diffusing chromophores to determine the average single chromophore spectral correlation.



For our initial solution-phase experiment, we constructed an exceptionally polydisperse ensemble by mixing eight different sizes of CdSe QDs together. Each of the single QDs in this ensemble is expected to have roughly the same spectral width despite vastly different center frequencies. The significant difference in linewidth for the single particle and ensemble spectra allowed for the clear distinction in the spectral correlations. After demonstrating the technique, we switched to a more uniform sample and extract detailed quantitative information about the spectral dynamics for a nearly monodisperse sample of QDs (Figure 2.5).

We then applied PCFS to low temperature QDs. There, we found the spectrum of single CdSe/CdZnS QDs to be highly dynamic on microsecond timescales – a timescale too fast to be able to measure with conventional methods (Figure 2.6).

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Core-shell Nanoparticle Clusters as New Metamaterial Building Blocks

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Research Goal, Approach and Accomplishments

During the last year, <u>Capasso</u> and his group, have pursued a program with the goal of creating by self-assembly clusters of metallo-dielectric plasmonic nanoparticles and characterizing them optically. The self-assembly of metallic colloids provides a versatile and low-cost route to the construction of complex two- and three-dimensional optical materials. They showed that self-assembled clusters of spherical nanoshells have optical properties that can be controlled by varying the number and position of particles in the cluster. As such, a hierarchy of tunable plasmonic structures that exhibit strong electric, magnetic, and Fano-like resonances is formed. The resonances in these structures arise from the strong electromagnetic coupling between closely-spaced particles. Clusters are assembled in a relatively straightforward manner using a capillary-driven method, and their interparticle spacing is controlled using polymer spacers to be approximately 2 nm, surpassing the spatial resolution of conventional lithography.

The trimer, consisting of three nanoshells of equilateral spacing, is amongst the simplest cluster geometries to display interesting resonances; it supports a magnetic dipole mode. The scattering spectra and TEM image of an individual trimer consisting of three gold nanoshells are shown in Figure 2.7A.

Heptamers, which are symmetric clusters comprising seven equivalent elements, support complex plasmon mode interactions that lead to Fano-like interference. The Fano-like resonance is displayed in the calculated extinction spectrum of a heptamer (Figure 2.8A). The interfering bright and dark modes of the cluster can be characterized by surface charge density plots at their resonances. The charge density plot of the bright mode at its peak at 1160 nm shows the charge oscillations in each nanoshell oriented in the same direction, resulting in strong scattering due to the constructive interference of their radiated fields. The charge density plot at the bright mode is suppressed and that energy is stored in the dark mode. Here, the charge oscillations in the individual nanoshells are oriented in different directions, resulting in the destructive interference of their radiated fields. Calculations in the quasistatic limit show that the dipole moment of the outer hexagon is similar in magnitude but opposite in sign compared to the dipole moment of the central particle, leading to strong destructive interference of their radiating fields.



Figure 2.7. Magnetic dipole response in trimer clusters. (A) Experimental and theoretical s- and ppolarized scattering spectra for an individual trimer shown in the inset. These spectra are dominated by the scattered electric dipole radiation from the cluster. The incidence angle of the white light source is 78 degrees, and its polarization orientation relative to the trimer is shown in the inset. The simulations use nanoshells with [r1, r2] = [62, 102] nm and gap separations of 2.5 nm; r1 is the silica core radius and r2 is the nanoshell radius. (B) Experimental and theoretical s-polarized scattering spectra for the same trimer and orientation in (A), but with insertion of a cross-polarizer to cut out the electric dipole radiation. Both spectra now exhibit a clearly visible magnetic dipole peak that match in peak position and linewidth. The inset shows the calculated magnitude of the trimer magnetic dipole moment out of the trimer plane, confirming the nature of the spectral peak near 1400 nm.

We observe a strong Fano-like resonance in the experimental spectra. The TEM image of a single heptamer and its spectra for three different orientations are shown in Figure 2.8B. The scattering spectrum at each orientation shows a strong Fano minimum at 1450 nm. This isotropy is consistent with the symmetry of the heptamer. The peaks between 800 nm and 1300 nm are higher order modes that arise due to retardation effects created by the large incidence angle. The calculated scattering spectra of a heptamer for different polarization angles are shown in Figure 2.8C, where the cluster geometry is identical to that used in Figure 2.8A. These display Fano minima at 1450 nm with asymmetric lineshapes that match the experimental spectra.



Figure 2.8. Fano-resonant behavior of a plasmonic heptamer. (A) Calculated extinction spectrum and charge density plots for a heptamer excited at normal incidence with a 0 degree orientation angle. The nanoshells have dimensions [r1, r2] = [62.5, 85] nm, and the cluster has 1.6 nm gap. The charge density plot of the bright mode, whose peak resonance is denoted by the pink dashed line at 1160 nm, shows a total dipole moment that is large. The charge density plot of the heptamer at 1490 nm, denoted by the black dashed line, shows a total dipole moment that is nearly zero. (B) TEM image and spectra of a heptamer at three different incident electric field orientation angles. The nanoshells are measured to have average dimensions [r1, r2] = [62.5, 85] nm. A pronounced Fano minimum near 1450 nm wavelengths is clearly observed. (C) Calculated scattering spectra for a heptamer with a geometry matching that in (A), for the three orientation angles in (B).

The work described in this report has been published in *Science* (J. A. Fan, C. Wu, K. Bao, J. Bao, R. Bardhan, N. J. Halas, V.N. Manoharan, P. Nordlander, G. Shvets, and <u>F</u>. Capasso, "Self-assembled plasmonic nanoparticle clusters," *Science* **328**, 1135 (2010)).

Spring Constant Modulation of a Microfabricated Optical Tweezer

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Research Goal, Approach and Accomplishments

Goal. The dependence of device characteristics on polarization presents a major challenge to photonic circuit design and operation. On-chip optical polarization splitting is a key function for realizing polarization-transparent operation in integrated photonic circuits. Our goal is to develop a compact, integrated polarization splitter comprised of a channel waveguide (CWG) and a slot waveguide (SWG). The large birefringence introduced by the strong optical confinement in the low refractive index nano-slot for TE mode could be used to circumvent the challenge imposed by intrinsic material properties of silicon.

Besides the performance benefits and design flexibility of this slot-waveguide based platform, we would like to use the different optical mode profile of the two output ports (a SWG and a CWG) to achieve a passive size-selective opto-mechanical particle sorting which would not be possible in conventional splitters. In addition to its non-invasive and automated nature, our waveguide based sorting platform could provide several advantages over other particle sorting approaches including smaller-sized particles sorting, smaller optical power consumption, integration of different operations on-chip in a massively parallel manner.

Approach. Figure 2.9a shows a schematic diagram of our passive particle-sorting device. The bottom part without the microfluidic channel and particles shows the design of our on-chip polarization splitter. We introduce a new design degree of freedom by etching a vertical nano-slot in the waveguides. A giant birefringence (polarization-dependent group index difference $\Delta n_g > 1.5$) can be leveraged for polarization-independent directional coupling. The effective index difference creates large phase mismatch that prevents power transfer of the TE mode from the channel waveguide input port to the slot waveguide output port. On the other hand, the TM mode can evanescently couples into the slot waveguide. In this way, efficient polarization splitting is realized.



Figure 2.9a. Microparticle sorting device: Schematic diagram. **b**. Trans-mission spectra of the splitter device from both TE and TM ports

The microparticle-sorting device illustrated in Figure 2.9a is fabricated by bonding a microfluidic channel on top of a 3-dB TM mode optical splitter. Incident light from the CWG is split equally into two exit ports. Microparticles are delivered to the structure through a PDMS microfluidic channel. Particles in the vicinity of the waveguide are drawn onto its surface by the optical gradient force associated with its evanescent field. The trapped particles are then pushed along the waveguide by the scattering force. In the coupling region, smaller particles are switched to the SWG with the help of an obstacle. Meanwhile, larger particles remain on the CWG because they experience a trapping potential well with a different shape according to numerical simulations.

Accomplishments. We analytically modeled the birefringence properties in slot waveguides using coupled mode theory, which yields excellent agreement with eigenmode expansion simulation results. The theory predicts that low insertion loss (< 0.8 dB) and high extinction ratios (25 dB and 60 dB for TM and TE polarizations, respectively) can be achieved over the 1520 – 1570 nm wavelength range. The experimental results in Figure 2.9b shows that the fabricated splitter device, with a coupling length of only 13.6 μ m, has polarization extinction ratios of 21 dB and 17 dB for the TE and TM polarizations respectively over the entire C-band. The slot waveguide polarization splitter device can be applied for constructing polarization-transparent circuits.



Figure 2.10. CCD image of the sorting with a guided power of 20 mW. The waveguides are indicated by the gray lines in the first frame. The trapped particles are marked by white arrows with the indicators S and L for 320 nm and 2 μ m particles, respectively. The obstacle particle is marked in the second frame.

Figure 2.10 shows CCD images of the particle sorting using proposed structure illustrated in Figure 2.9a. After injecting DI water containing particles with diameters of 2 μ m and 320 nm to the microfluidic channel, the 2 μ m particles continue to be propelled along the CWG after leaving the coupling region, while the 320 nm particles are transferred to the SWG. The small displacement needed to switch particles enables low power operations by reducing the guided power by one to two orders-of-magnitude, compared to the laser powers employed in some previous reports. This low power-sorting approach can be used to sort sub-micron particles, which has proven to be difficult in other optical force based particle-sorting mechanisms. Given its passive nature and low power operation, we believe that the all-optical sorting mechanism we introduce could lead to a variety of lab-on-a-chip applications in life sciences, medical diagnosis and environmental sciences.
Novel Methods for the Synthesis of Electronic Materials

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Research Goal, Approach and Accomplishments

Our overall goal was to develop novel methods for the synthesis of electronic materials that have the potential to create the next generation of electronic devices. Our approach is to implement methods based on our understanding of surface chemistry to direct the controlled synthesis of key 2-D electronic materials. During the past year, we have been investigating the interaction of organic layers with TiO₂ using both computational and experimental tools. This project has the potential for high impact because of interest in using organic layers in molecular electronics and also as a means of growing graphene and other 2-D materials on semiconductors without the need for transfer from another substrate.

Our recent work has focused on the investigation of organic molecules containing phenyl rings that have the potential for switching behavior upon irradiation with electrons or with light. Stilbene, for example, has two geometric forms—*cis* and *trans*—that can be switched with ultraviolet light (Figure 2.11) [1].

We have used these molecules to probe the interactions of phenyl rings with titania. Our objectives are: (1)



Figure 2.11. Schematic of isomerization of cis stilben to the transform induced by light. (Taken from http://www.rsc.org/chemistryworld/News/2008/Nov em ber/13110801.asp)

To test for both electron-stimulated (via STM) and photon-induced isomerization; (2) to determine if the energy for switching is altered by interaction with the surface; and, (3) to probe the fundamental aspects of aromatic rings with semiconductors to probe the extent of perturbation or the electronic structure of these building blocks of graphene. The first step is to image the two isomers on the titania surface in order to determine if we can use imaging

We have demonstrated that we can distinguish the two different isomers of stilbene using molecular-scale imaging (Figure 2.12). Electrospray was used to introduce these molecules to the surface because of their low volatility. This method can be used for molecules or particles up to the tens of nanometer size scale. Density functional theory in collaboration with <u>Kaxiras</u> was used to model the stilbene-titania interactions. These studies demonstrate that we can use the combination of electrospray and STM to investigate molecular switching.



Figure 2.12. Scanning tunneling microscope (STM) images of cis and trans stilbene bound to $TiO_2(110)$ distinguish between the two forms of the molecules in the top images. Simulations of the STM images using density functional theory is depicted in the lower images that also have a schematic of the two different isomers.

We are currently investigating the switching behavior of stilbene on $TiO_2(110)$ using both uv irradiation and electron-induced processes. The electron-induced switching will be investigated on a single-molecule basis by using the STM tip as the electron source. Our demonstrated ability to image nanomaterials on an atomic scale, in combination with spectroscopic characterization of these materials will be used to determine if there are significant changes in the switching behavior of stilbene on the semiconductor.

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Semiconductor Heterostructures for Nanoscale Devices

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Research Goal, Approach and Accomplishments

In NSEC work in the <u>Gossard</u> group at UCSB during 2010, we used molecular beam epitaxy to grow semiconductor heterostructures containing two-dimensional electron gases for research by our NSEC Harvard collaborators on 1) probing semiconductor band structures and heterojunction interfaces, 2) study of electron tunneling through heterostructure potential barriers and 3) formation of gate-defined near-surface quantum dots and coupled quantum dots. The results on the Harvard NSEC measurements were fed back in turn to our growers at UCSB and provide useful information both for characterization of the grown material and the development of successive generations of structures.

In work on semiconductor band structures and heterojunction interfaces, systematic groups of gallium arsenide structures containing barriers with varying aluminum gallium arsenide compositions and layer thicknesses allowed Yi and <u>Narayanamurti</u> to self-consistently probe direct-gap band offset ratios and to probe directly semiconductor X and L valleys.

Growths of a series of indium gallium arsenide and indium aluminum arsenide structures with varying tunnel barriers, compositions, widths and doping profiles were used by Russell, <u>Capasso</u> and <u>Narayanamurti</u> to measure quasi-bound state lifetimes and to probe the energy dependence of electron tunneling and to identify scattering assisted tunneling processes. Work is continuing in collaboration with Harvard graduate student Edward M. Likovich.

Materials grown at UCSB with gallium arsenide quantum wells in close proximity to semiconductor surfaces were used by Laird and <u>Marcus</u> to demonstrate coherent manipulation and readout of three-spin qubits, using few-electron triple quantum dots.

In related work at UCSB, the direct formation of epitaxial embedded nanoparticles in heterogeneous semiconductor materials was studied. The materials were formed by self-organization of co-deposited semiconductor and semi-metallic materials. Composites containing nanometer-size ordered nanoparticles and nanorods of embedded rare earth semi-metallic compounds have now been formed. The work is benefiting from the newly expanded UCSB capability in the Palmstrom laboratory for *in-situ* ultra high vacuum microscopy and spectroscopy of pristine, freshly grown semiconductor structures and surfaces.

Single-Photon Photonic Devices

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Research Goal, Approach and Accomplishments

Optically active defects (color centers) in diamond — and in particular the Nitrogen-Vacancy (NV) center — have recently emerged as a solid-state platform for a wide variety of applications, ranging from the development of a quantum communication and information processing systems to nanoscale magnetometers for chemistry and biology. The focus of our research program is to develop high-quality diamond nanofabrication techniques that allow us to engineer the optical properties of single NV centers. Several groups at Harvard (Lukin, <u>Yacoby</u>, and Walsworth laboratories) have performed pioneering studies using NV defects in unstructured, bulk diamond samples, and our photonic devices are integrable with, and naturally complement, many of these existing applications. Beyond this, our goal is to *demonstrate novel quantum optical phenomena enabled by nanostructured diamond*. Towards this end, our research program has two main thrusts described below.

Bulk Diamond Nanofabrication: High-Performance Single Photon Sources

One major practical challenge to implementing systems based on the NV center in bulk diamond samples is that total internal reflection at the air-diamond interface dramatically reduces the possible single photon collection efficiency (~3-4%). Recently, we have demonstrated that top-down nanostructuring the surface of a bulk diamond with arrays of nanowires generated broadband waveguide modes that allow for an order of magnitude higher single photon collection (~30-40%) [1]. Our original nanowire devices used a top-down etching process [2] to mechanical isolate single "natural" NV centers from the defect-rich diamond substrate (~200 ppm nitrogen). In follow-up work, we have also demonstrated that it is possible to use ion-implantation and annealing to activate NV centers within pre-fabricated ultrapure diamond (~5 ppb nitrogen) nanowire devices [3]. The advantage of this approach is that we combine the high single photon flux offered by the nanowire geometry with the low intrinsic background fluorescence of a pure diamond to realize a nanowire single photon source with ~5X reduced multiphoton probability. In the future, this novel technique will be important for examining other important quantum parameters of single NV centers (e.g., spin coherence time, inhomogeneous broadening among NVs at low-temperature) in diamond nanostructures. In addition, we hope to develop an *in-situ* diamond lithography system in our confocal microscope to deterministically register our nanostructures to targeted NVs.

The other major limitation of the NV center in a bulk diamond sample is that its radiative rate is fixed ($\tau \sim 12$ ns). In order to engineer the fluorescence lifetime via the Purcell effect, we have recently proposed a novel platform based on a single NV center in a hybrid diamond-plasmon aperture cavity (Figure 2.13, left and center) [4]. The device, which consists of diamond nanopillars (height ~ 200 nm, diameter ~ 100 nm) etched on the top surface of a bulk diamond and embedded in a silver metallic film, theoretically



Figure 2.13. (*Left*) Cartoon of a plasmon aperture cavity in diamond designed to engineer the radiative rate of a single NV center [4]. Devices are optically addressed through the diamond crystal (green pump and red fluorescence). (*Center*) SEM image of bare nanopillars (before silver deposition) fabricated in pure diamond implanted with NV centers [3]. (*Right*) Fluorescence decay of a single NV center in a diamond nanopillar before (blue) and after (black) silver deposition for one representative device [5]. The silver capping layer generates a cavity effect, which is manifested in a reduction in the NV center fluorescence lifetime ($F_P = \tau_{Bare NP} / \tau_{Cavity} \sim 6$).

strong Purcell factor $(F_P = \tau_{Bulk} /$ $\tau_{Cavity} \sim 20$ 40). Moreover, FDTD calculations indicate that a significant fraction of single photons (~50%) couple to

surface plasmon channels, and this effect could either be suppressed with a grating to enhance light emission off-chip, or used as a resource for distributing quantum information on-chip in quantum plasmonic systems. To show that it is possible to position an NV center inside these small mode volume cavities (V ~ 0.01 (λ /n)³), we have recently used our implantation routine to realize a high yield (~10%) of bare nanopillar devices containing a single NV center [3]. After capping with silver, we have observed a cavity effect that reduces the fluorescence lifetime F_P = $\tau_{Bulk} / \tau_{Cavity} \sim 2$ relative to bulk diamond and F'_P = $\tau_{Bare NP} / \tau_{Cavity} \sim 6$ relative to a bare nanopillar (Figure 2.13, right) [5]. These enhancements are potentially limited by reduced overlap of NV center with cavity mode due to implant straggle, and we are exploring this issue further in the future.

Thin Diamond Nanofabrication: Planar Diamond Nanophotonic Devices

An even larger class of devices can envisioned in thin (~200 nm) diamond films on low-refractive index substrates. Index contrast between the high refractive index diamond layer (n ~ 2.4) and the glass substrate (n ~ 1.4) allows for vertical light confinement and the realization of planar nanophotonic devices. In the context of quantum photonics in diamond, this may allow for radically new phenomena such as single photon beam splitters and waveguides on-chip linear quantum optical computing, and strong lightmatter interactions between NV centers and resonators for cavity quantum electrodynamics (cQED). Fabricating these devices, however, has been an outstanding problem in the field for over a decade. Other approaches based on devices in nanocrystalline diamond films (lossy material, background fluorescence), ion-beam assisted lift-off (damaged diamond device layer reduces film quality), and focused ion beam machining (slow technique, gallium implantation) [6] have been largely unsuccessful. Indeed, we are not even aware of reports of single NV centers in these systems.



Figure 2.14. (Top left) Confocal microscope image of a diamond nanobeam waveguide (~200 nm thick, ~500 nm wide, and ~10 μ m long). White spots are NV centers in the thin diamond film, black area is glass substrate, and red asterisk are locations of scattering centers at the ends of the nanobeam. (Top right) Confocal microscope scan of the same chip with pump beam fixed on an NV center. Central spot (1) corresponds to fluorescence uncoupled to the nanobeam waveguide mode, and the distal ends (2, 3)correspond to far-field scattering after propagation along the nanobeam waveguide (red arrows). (Bottom row) Intensity auto-correlation measurements of 1 vs. 2 (bottom left) and 1 vs. 3 (bottom right) fluorescence show strong photon anti-bunching, which confirms a single photon generated from the waveguide center (1) is coupled to the nanobeam waveguide mode.

Our approach is to take high quality, ~ 5 µm thick single crystal diamond films and reduce them to ~ 200 nm thickness with our diamond etch recipe. These films can then be patterned with waveguides (Figure 2.14), photonic crystals, ring resonators, and potentially other integrated photonic systems. Preliminary measurements on some of these devices already show exciting results. For example, we have observed single NV centers in these diamond films. Moreover, by pumping a single NV center in an on-chip diamond nanobeam waveguide and monitoring far-field scattering in a two-collection channel confocal microscope, we are able to see fluorescence at the distal ends of the nanobeam [7]. Most exciting for applications in quantum photonics on a diamond chip, intensity auto-correlation measurements confirm the photon anti-bunching in the fluorescence at the ends of the nanobeam waveguide, which confirms that it is generated by a single NV center at the waveguide center.

We have fabricated diamond ring resonators in a similar film and are characterizing its resonances [8]. High quality factor resonances (Q \sim 10,000) have been observed at telecommunications wavelengths with a tapered-fiber probe, and this is an encouraging result that suggests that resonances should likewise be observed

at visible wavelengths corresponding to the NV spectrum. Moreover, single NV centers can be observed in the diamond ring resonators with a confocal microscope, but accessing scattered photons circulating in the whispering gallery modes of the ring resonator is a challenge with this system. In order to efficiently extract single photons coupled to the whispering gallery modes and observe resonances and pursue cQED phenomena, we will likely have to integrate a visible tapered-fiber probe into one of our confocal microscopes. In 2010 we demonstrated the first quantum photonic device in bulk diamond [1, 2], further refined this device [3], and expanded the scope of the project to new arenas of quantum photonics in diamond [4,5,7,8]. Moreover, our work has received significant recognition in the broader photonics community [9-10]. Further support of this program will allow us to continue to push the frontiers of high-quality nanofabrication and continue to observe novel quantum optical phenomena in diamond.

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Silica Nanowires for Microphotonic Devices

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Research Goal, Approach and Accomplishments

Our research focuses on fabrication and characterization of heavily doped silicon using femtosecond laser techniques. During the past year, we designed experiments to study laser-material interaction and effects of post-doping processes as well as extending the laser doping technique to nitrogen doping of TiO_2 . Accomplishments listed as below:

**Controlling sulfur concentration by changing SF6 pressure in the fabrication chamber* Preliminary results suggest that by changing the ambient pressure, we can change the dose of the desired dopant by 2 orders of magnitude. Furthermore, the dopant concentration profile can be used to understand the mechanism of dopant incorporation.

*Studied how post-doping processes changes the material properties

Annealing temperature, cooling rate and annealing environment affect the optical and electronic property of sulfur and selenium doped sample.

**Characterized below band-gap absorption using mid-infrared techniques* (collaboration with Professor Asenbaum, University of Salzburg, Austria)

*Studied laser interaction with wide band-gap semiconductor such as TiO_2 and possibility of nitrogen doping (collaboration with <u>Cynthia Friend</u>)



Figure 2.15. (*Left*) sulfur concentration as a function of SF_6 pressure. (*Right*) sulfur dose as a function of SF_6 pressure.



Figure 2.16 shows the infuence of post-doping annealing by measuring average infrared absorption (from 1.25 to 2.5 μ m) of sulfur or selenium doped silicon *via* fs-laser irradiation. Measureable increases in subbandgap absorptance occur at temperatures above 1350 K, which is not observed in previous studies. The curve is similar to a time-temperature-transformation diagram describing the precipitation of supersaturated point defects at heterogeneous nucleation sites.



Figure 2.17 shows the absorptance of fs-laser doped silicon with non-equilibrium concentrations of sulfur, selenium and tellurium. The samples doped with sulfur, selenium, or tellurium all have similar absorption curves. Above 1.1 eV, the absorptance is larger than 90%, compared to 70% absorptance of a 300- μ m thick silicon wafer. Below 1.1 eV, pure silicon is transparent, but black silicon samples exhibit an absorptance of 0.8 up to photon energies of 0.25 eV. Below 0.25 eV, the black silicon absorptance decreases as energy decreases.

Electrically Driven Surface Plasmon Circuit

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Research Goal, Approach and Accomplishments

Surface plasmon polaritons (SPPs) are propagating charge oscillations at metaldielectric interfaces that can be guided at the smooth interfaces of freestanding metal nanowires (NWs) and air, or dielectric NWs and metals. Unlike photons in conventional waveguides, SPPs can be confined far below the free-space diffraction limit. The tight confinement results in strong electric field, enhancing light-matter interactions and nonlinear effects. However, highly localized SPP modes have a large wave vector mismatch to far-field light and can be very difficult to optically couple into and out of.

Near-field electrical SPP coupling has been shown to be an efficient method for both excitation and measurement of SPPs. Moreover, the enhanced light-matter interactions in

the near-field of SPP waveguides have been used to efficiently capture the photoluminescence from single-photon emitters such as quantum dots and nitrogenvacancy centers in diamond. However, all electrical SPP circuit demonstrations to date have relied on far-field optical coupling for either SPP generation or detection.

Electron/hole pairs can covert to SPPs efficiently at the metalsemiconductor interface, and vice versa. An electrical circuit with an Ag NW crossing two parallel GaAs NWs serves as a simple experimental system to probe the SPP generation and detection at this interface (Figure 2.18). Electrical SPP generation is based on coupling electroluminescence (EL) from semiconductors to SPP modes in the near field. We used finite-difference time-domain (FDTD) simulations to calculate



Figure 2.18. (a) An illustration of a NW-based electrical plasmonic circuit where SPPs are generated and detected electrically. The right panel shows the mode profile in both the GaAs and Ag NWs calculated via FDTD simulation. (b) SEM image of a three-NW device where SPPs are both electrically generated and detected. (c) Upper panel: A sawtooth voltage pattern is applied to the SPP source of Device (V_b) and the resulting current pattern (I_{drive}) . Lower panel: The corresponding detection current (I_{detect}) recorded at the SPP detector.

the coupling of emission into SPPs. The SPP coupling efficiency of a dipole excited in air near the Ag NW can approach unity for small NW diameter. When the dipole is located

in a dielectric material, however, its emission rate into the far field will increase, thus decreasing the fraction coupled into SPPs down to ~20%. We also simulated the detection efficiency for Ag/GaAs NW crossbar structures with relevant dimensions. The detection efficiency increases with decreasing Ag NW diameter, and can be greater than 90% for Ag NWs with 50-nm diameters. Both the plasmon excitation and detection efficiencies are significantly higher than for far-field coupling, which is typically ~1-5%, and more importantly, these efficiencies increase with greater confinement.

To demonstrate this concept experimentally, we realized a prototype plasmonic circuit by fabricating electrodes on an assembly of three NWs: two GaAs NWs lying perpendicular to and underneath an Ag NW (Figure 2.18(b)). Applying V_b to one GaAs NW while grounding the Ag NW produces I_{drive} , the current through the junction. When $V_b > 2 V$, this junction produces SPP-coupled EL. This EL signal can be detected using both far-field optics and the current signal (I_{detect}) flowing through the second GaAs NW.

Our prototype devices show that SPPs can be both electrically generated and detected in optical circuits assembled from nanowire multi-junctions. There are several possible routes to improving these devices, such as increasing the EL efficiency with p-i-n heterostructures, tailoring the NW diameter and EL spectra to match, or fabricating gratings around the junction to direct EL into SPP modes. Electrical SPP sources could also be utilized to excite fluorescent molecules in the near field, a step towards completely electrically coupled active SPP circuits and electrical driven plasmonic lasers.

Referene

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Self-Assembled Quantum Nanostructures

Pierre M. Petroff Materials, University of California at Santa Barbara

International Collaborators: David Gershoni (Technion, Haifa, Israel); Richard Warburton (Heriot Watt University, Edinburgh, UK); K. Unterrainer (University of Vienna)

Research Goals and Accomplishments

Our goal is the realization of **interacting** quantum dots (QDs) self-ordered in 2-D or 3-D lattices. We want to achieve this by controlling the QDs nucleation. Controlling nucleation and size uniformity of self-assembled QDs should also permit the positioning of a single QD or group of QDs into a microcavity or the defect cavity of a photonic crystal thus making possible the exploitation of cavity QED effects.

Experimentally, we have started the investigation of controlled nucleation and selfordering on the bound states energy variations in self-assembled InAs/GaAs quantum dots (QDs). For the theoretical part of this study, we use a Monte Carlo simulation of the QDs nucleation to compare the size fluctuations in a QDs lattice and compare it to that of a random QDs distribution. The MC simulation shows a factor of \approx 20 reduction in the variation of the ground state exciton energy for the ordered QDs lattice.



Figure 2.19. MC simulations show atom and nucleation center borders (blue crosses and lines) after deposition and diffusion for: (a) a square unit cell of nucleation sites (r/w = 0.25) after 500 atoms are deposited and (b) a random arrangement of nucleation sites (surface area = $80 \times 80 \text{ nm}^2$) and a 2000 atoms deposition. The atoms, which have diffused show up at the border of the nucleation sites and their diffusion induced motions are stopped. Atoms inside the nucleation site have been directly and randomly deposited and do not diffuse. (c) The calculated standard deviation in the number of atoms per nucleation site for the square lattice as a function of r/w after 50,000 atoms have been deposited. The error bars correspond to the results of 10 MC simulations for each value of r/w.

For these simulations, we use a low indium deposition rate (0.001 ML/s), which produces a small indium concentration on the surface and a MC time $\Delta t = 10$ ms during which the diffusing indium atoms on the GaAs surface follow Fick's first and second laws. As usual, atoms are randomly deposited on the surface and periodic boundary conditions are applied. The nucleation lattice has a period w and the radius of the nucleation centers forming the lattice is r. Figure 2.19a shows a MC simulation for a square lattice of nucleation sites after deposition and diffusion of 500 atoms. Figure 2.19b shows the MC simulation for a random arrangement of nucleation sites after deposition and diffusion of 2000 atoms. In Figure 2.19b, the surface coverage by the nucleation centers is identical to that of a square lattice with r/w = 0.2. The atoms, which have diffused to the nucleation sites have been stopped at the edge of the circular trap

The other atoms showing up within the trap have directly fallen in the nucleation center and are not allowed to diffuse. Figure 2.19c shows the standard deviation, σ , in the number of atoms per nucleation site as a function of the dimensionless parameter r/w. As anticipated, a minimum in σ is observed as a function of r/w. Results of the MC simulation are summarized in the Table 2.1 below for a square lattice and a random distribution of nucleation sites. The value r/w ≈ 0.25 corresponds to the smallest standard deviation for the square lattice and a random arrangement of nucleation sites after deposition of 5.10⁴ atoms. To compare these results with experiments, we are assuming a truncated cone island shape, which contains 50,000 atoms. The size difference between islands is converted into an emission energy variation, ΔE , between the various QDs. The calculation assumes that the island diameter remains constant and variations in σ are reflected by changes in the height of the islands. The simulation results presented in Table 2.1, indicate the advantages of growing the self-assembled QDs into a very short period lattice to insure an improved size uniformity.

Nucleation site	QD density (cm ⁻²)	< σ >: number of atoms	$\Delta E (meV)$ computed
Random	6 10 ¹⁰	7810	≈ 20
Square lattice	6 10 ¹⁰	150	≈ 1

Table 2.1. Standard deviation in the number of atoms/nucleation site for various nucleation sites arrangements. For the lattice, the computed s value corresponds to the MC simulation giving the smallest s for which $r/w \approx 0.25$ (Figure 2.19c).

Experimentally, we have also demonstrated site-controlled QDs nucleation in a lattice using electron beam lithography and molecular beam epitaxy regrowth method (see Figure 2.20). The measured micro-photoluminescence of single QDs arranged in a lattice shows a narrower energy spread than the QDs grown without controlling the nucleation sites.

In the next phase of this study we will attempt to experimentally reach the nucleation regime, which is predicted to be optimal by the MC simulation.



Figure 2.20. Schematic of the method for positioning self-assembled quantum dots in a square 2-D lattice (period 4 μ m) of patterned holes for site selected quantum dots nucleation (the value of r/w \approx 0.02). The AFM picture shows 4 single QDs in the holes. Two representative micro-PL spectra are also shown for a similar sample, which was capped with a 50 nm GaAs layer.

Electronic and Structural Properties of High-Quality VO₂ Thin Films

Shriram Ramanathan Chemistry, Physics, Harvard University

Collaborators: Carol Lynn Alpert (Museum of Science, Boston); Gloria Hoefler (Agilent Technologies)

Research Goal, Approach and Accomplishments

The goal of our project is to explore mechanisms governing metal-insulator transition in vanadium oxide through combination of materials synthesis, device fabrication and electron transport studies. We have been able to successfully grow high-quality VO_2 films on a variety of substrates including silicon and demonstrated electrically driven phase transitions. This could be of significant relevance in designing new oxide-based devices.

CLUSTER 3: Imaging Electrons at the Nanoscale

Coordinator: Raymond Ashoori

Raymond Ashoori (Physics, MIT)	Charles M. Marcus (Physics, Harvard)
Bertrand I. Halperin (Physics, Harvard)	Venky Narayanamurti (SEAS & Physics, Harvard)
Eric Heller (Chemistry&Physics, Harvard)	Michael Stopa (NNIN, Harvard)
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Number of postdoctoral fellows: 2 Number of graduate students: 6 Number of undergraduate students: 3

Introduction

Electrons inside nanoscale structures display striking behavior that arises from the confinement of quantum waves. By visualizing how electrons move through nanoscale systems, we can understand the fundamental science and develop new quantum devices. These devices can direct electron flow, or control the motion of electron charges and spins for nanoelectronics, spintronics, or quantum information processing.

The goal of the *Imaging at the Nanoscale* cluster is to develop new ways to image electrons inside nanoscale systems, including their quantum behavior. This is difficult for electrons, because they are buried inside the structure, and because low temperatures are necessary. This Cluster brings together a group of investigators who have designed and

built scanning probe microscopes and developed new imaging techniques to image electrons inside nanoscale systems. Close collaborations with theorists allow us to understand what the images mean.

Expected outcomes of this research are:

New Approaches to Imaging Electrons in Nanoscale Systems — Custom-made scanning probe microscopes coupled with theoretical analysis allow us to understand the quantum behavior of electrons and photons inside nanoscale systems. These techniques are based on cooled Scanning Probe Microscopes (SPMs) capacitively coupled to the electrons below, Magnetic Force Microscopes (MFMs), Scanning Tunneling Microscopes (STMs), Ballistic Electron Emission Microscopy (BEEM), and Electron Emission Luminescence (BEEL) Microscopy. The investigators are experts in the design and fabrication of scanning probe microscopes.

Quantum Electronic and Photonic Devices — Visualizing the motion of electrons in nanostructures allows us to develop new types of nanoelectronic and photonic devices and systems based on quantum mechanics, that use nanocrystals, nanowires and semiconductor heterostructures from the Nanoscale Building Blocks Cluster and graphene, an exciting new material consisting of single atomic layers of carbon. Imaging and theoretical simulations will allow us to design new devices and understand how they work.

Physics of Graphene Sheets

Raymond Ashoori Physics, Massachusetts Institute of Technology

 Collaborators: Ivan Bozovic (Brookhaven National Lab); Walt de Heer (Georgia Tech); Pablo Jarillo-Herrero (Massachusets Institute of Technology); Loren Pfeiffer (Princeton University)
 International Collaborator: Jochen Mannhart (Augsburg University, Germany)

Research Goal, Approach and Accomplishments



Magnetization and Capacitance Studies of Novel Oxide Electronic Systems

Figure 3.1 (*Left panel*) A schematic diagram of the LAO/STO oxide samples. (*Center panel*) Top schematic view of capacitance pad layout on our samples. (*Right panel*) Photograph of our actual samples. Notice that, owing to the large bandgaps in these Perovskite materials, the material is fully transparent to visible light.

Several years ago, Ohtomo and Hwang discovered [1] an electronic system that forms, remarkably, at the interface between the two wide bandgap insulators lanthanum aluminate (LAO) on strontium titanate (STO). While this system has been probed in by numerous transport methods, the exact nature of the electronic system has remained unclear. Amazingly, the system is seen to superconduct at temperatures below 300 mK. As of yet, there are no clear published reports of the quantum Hall effect, and the dimensionality of the electron gas is unknown.

We have been performing magnetization, capacitance, and field penetration measurements on this system, collaborating with the group of Prof. Jochen Mannhart at Augsberg University who is growing the material for us. Figure 3.1 displays the basic sample structure that is grown using pulsed laser deposition. Niobium contacts are made to the interface through ion milling and evaporation, and the structure is capped with a layer of high-T_c superconductor YBCO. The YBCO is nearly lattice matched with the LAO and STO. So, it is a good material to use as an electrode for capacitance measurements.

Using a very small and light cantilever, we have completed a detailed study of the magnetization of this system over a wide range of magnetic fields and temperatures. The magnetization of this system is interesting because the system superconducts at low temperatures while first principles calculations suggest that the interfacial electrons should form a magnetic state. If true, superconductivity and magnetism may coexist, meaning that the superconducting state would not be a simple s-wave superconductor.

Our capacitance results demonstrate that we can gate the electronic system using a top gate. Moreover, we observe signatures in the capacitance that suggest that the electronic system is likely two-dimensional. Using temperature-dependent studies, we are working to observe the effect of the superconducting transition on the system capacitance.

Graphene–Boron Nitride Tunnel Junctions

We have been collaborating with Prof. Pablo Jarillo-Herrero (MIT) to produce thin layers of boron nitride on top of graphene. Ultimately, we would like to use these structures for tunneling experiments on the graphene. There a number of reasons why such tunneling measurements should yield more understandable spectra than found in STM measurements of grapheme. Most notably, tunneling in a planar geometry avoids large spatial potential distortions created by the work function difference between the tip and sample.

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Theory of Electron and Spin Transport in Nanostructures

Bertrand I. Halperin

Physics, Harvard University

- *Collaborators*: Nicholas d'Ambrumenil (University of Warwick), Leonid Levitov (MIT); Gil Refael (California Institute of Technology)
- International Collaborators: Rudolf Morf (Paul Scherrer Institute, Switzerland), Bernd Rosenow (Max Planck Institute); Ady Stern (Weizmann Institute, Israel)

Research Goal, Approach and Accomplishments

The overall goal of this work is to gain a better understanding of the electronic structure of nanoscale building blocks, and of the operations of nanoscale devices, in order to improve our ability to design and construct such devices. A crucial aspect of the development of new structures and devices are measurements to characterize these structures. Theoretical efforts are necessary to understand the results of such measurements as well as to suggest new types of measurements as well as possible improved structures. Our projects have been motivated by NSEC-supported experiments including particularly measurements of transport and imaging of electron flow and electronic states in structures made from nanowires or two-dimensional electron systems, including graphene and GaAs systems. Goals include development of theoretical and calculational techniques, as well as applications to specific systems.

Graphene Nanostructures. The peculiar electronic, optical, and mechanical properties of graphene sheets have attracted enormous interest for potential applications as well as for their intrinsic scientific interest. Because of the atomic scale thickness and the exposed surface of graphene films, it has been possible to produce large local changes in carrier concentration with local gates, and thereby to modulate the transport properties on a length scale of 10 nm [1-4]. However, the absence of backscattering in single-layer graphene, due to the Klein-Paradox effect, means that one cannot produce an insulating barrier, or produce a transistor with near-vanishing off-current by standard gate techniques. Possible ways to introduce an energy gap, and thus to suppress conductivity, include use of nano-width ribbons, or use of applied magnetic fields. Other possibilities arise in bilayer graphene films.

Mark Rudner, a postdoctoral fellow in <u>B.I. Halperin</u>'s group, joined forces with two theorists at MIT and experimentalists at Columbia, in a work that proposed and demonstrated a new regime of magnetotransport in a nanoscale device, which exploits the unique properties of graphene. They considered a device with a narrow potential barrier, and showed that Landau levels, which are confined to the barrier region in a strong magnetic field, can undergo a deconfinement transition as the field is lowered.

In transport measurements on a top-gated graphene device of this type, Shubnikov-de Haas oscillations were observed at high magnetic fields in the unipolar regime, but disappeared abruptly when the magnetic field was reduced below a critical value. The behavior was explained by a semi-classical analysis based on the transformation of closed cyclotron orbits into open deconfined trajectories, which was further supported by a quantum mechanical calculation of the local density of states in the barrier region.

This work, completed in 2010, was published in February 2011 in *Physical Review Letters*, where it was highlighted as an Editors' Suggestion [5].



Figure 3.2. Theory behind anomalous magnetoresistance in a graphene device with a barrier of width 50 nm, induced by a top gate. (a) Schematic showing variations of orbit size in the estimated potential U(x), for various values of the magnetic field, with transverse momentum $p_y=0$. Long trajectories that extend outside the gated region do not contribute to Shubnikov-de Haas magnetoresistance oscillations. (c) Trajectories for the potential $U(x) = -ax^2$ and $p_y=0$. Three types of trajectories are shown in momentum space (b) and position space (c): subcritical (red), critical (black), and supercritical (blue). Figure taken from Ref. [5].

Bilayer Graphene. Experiments at Harvard in the laboratory of <u>A</u>. <u>Yacoby</u> have suggested that high-quality bilayer graphene can develop an energy gap at low temperatures due to effects of electron-electron interactions [6,7]. Moreover, the phase diagram in the presence of applied magnetic field and/or an electric field perpendicular to the sample suggests that the gapped phase should have a spontaneously broken time reversal symmetry, and that it might be expected to show a quantized Hall effect in zero magnetic field [8]. However, no such Hall effect has been observed. Although in principle a sample with many domains of opposite sign could show a vanishing Hall resistance, it is not clear that such a cancellation would occur in practice. We have been exploring a variety of multi-domain models to investigate this question.

Spin, Spin-Orbit, and Hyperfine Effects in Nanowires, Nanotubes and GaAs Quantum Dots. In the past year, we have been exploring a number of phenomena involving the interaction of electron spins with nuclear spins and with the lattice, via spin orbit coupling, which can modify the transport properties of nanoscale devices. In work that was partially supported by NSEC, postdoctoral fellows Mark Rudner and Izhar Neder, together with <u>B.I. Halperin</u> and Leonid Levitov of MIT, were able to make progress in understanding some very puzzling experimental results in two-electron GaAs

double dot systems. In these experiments, nuclear polarization was achieved by using a gate voltage to shuttle one electron back and forth between the two dots in a carefully controlled repeated protocol [9]. The direction of nuclear polarization was found to be opposite from what one would expect in a simple analysis, where nuclei spins are flipped one at a time, as the electron system makes repeated transitions from an initial singlet state to a spin-aligned triplet state. Moreover, it was found that the magnitude of the polarization was an oscillatory function of the delay time between electron sweeps, showing a maximum when the delay time was an integral multiple of the Larmor period for one of the nuclear species. This was particularly surprising because in the absence of spin orbit effects (which have generally been estimated to be weak in these systems) the rate of longitudinal polarization should be independent of the orientation of the transverse component of the nuclear spins, and therefore should not be affected by the overall Larmor precession.

Our theoretical analysis showed that spin-orbit effects could be much enhanced if the gate voltage is held for a relatively long time at a place where the splitting between the singlet and the spin-aligned triplet state is small but non-zero. Furthermore, the net induced polarization in this situation would have a component that is a periodic function of the ratio between the repetition period and the Larmor period, and the sign could be reversed from the normal one. A first paper, describing the general framework for this combined effect of nuclear Larmor precession, hyperfine interactions, and electron spin-orbit coupling was published in 2010 [10], but work is continuing to more accurately apply the theory to the particular protocols used in the experiments.

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Theory of Electron Imaging in 2DEGS

Eric Heller

Chemistry and Physics, Harvard University

Collaborators: Don Eigler (IBM Almaden); Lev Kaplan (Tulane University); Hari Manohoran (Stanford University); Valerie Stempler (National Geographic)

International Collaborators: Antonia Ruiz Garcia (Universidad de La Laguna, Tenerife, Spain); Tobias Kramer (University of Regensburg, Germany)

Our accomplishments/goals for last year and this year fall into two categories:

1. Two-dimensional Electrons in Strong Magnetic Fields:

Collaboration with Tobias Kramer, Viktor Krueckl, and Robert Parrot

(A) We will continue our work with time-dependent FFT wavepackets, which makes expicit calculations on a given background potential, impurity field, electric field gradient, and magnetic field under thermal averaging possible.

(B) *Classical and semi-classical simulations of few electron problems*, with an eye to looking into conserved symmetries, the robustness of topological protection, and possible control of small groups of electrons.

(C) *Many electron simulations of quantum Hall devices,* classical molecular dynamics simulations treating thousands of interacting electrons have been performed. We hope to extend this type of GPU-based calculation to treat the charges semi-classically.

2. Graphene Conductance Fluctuations:

Collaboration with Jesse Bezerovsky, Mario Borunda, and Robert Westervelt

The joint theoretical and experimental efforts of the <u>Heller</u> and <u>Westervelt</u> groups aim at understanding coherent transport in realistic graphene devices. From the conductance scanning probe microscopy (SPM) images of graphene devices, our team studied universal conductance fluctuations (UCF). Although UCF have been measured by standard conductance measurements, our team managed for the first time to image UCF. Our simulations verified that the measurements are indeed imaging UCF caused by the motion of a single scatterer.

We have calculated the zero temperature CFs for quasi-particles obeying the massless 2D Dirac equation in the presence of disorder, assuming elastic scattering by fixed scatterers and with no sources of inelastic scattering. The motivation for the study of this system is threefold:

(A) The massless Dirac Hamiltonian model is of relevance to transport in graphene and the surface states of topological insulators.

(B) We probe the sensitivity of the conductance to changes in the impurity strengths over a range of carrier densities and system sizes that are accessible by current experiments.

(C) We calculate the CFs due to the motion of a single scatter.

Our results demonstrate the sensitivity of CFs to the motion of an ionized charged impurity and shows a dependence on the carrier density that applies to all but the most disordered graphene devices.

Our extensive numerical study addressed the challenge of understanding the implications of how changing the position of charge puddles (experimentally done using the charged tip of a scanning probe microscope) can affect the universal conductance fluctuations. We are developing theoretical and numerical approaches to understand several graphene transport problems.

High Spatial Resolution Magnetic and Electrostatic Force Microscope

Jennifer Hoffman

Physics, Harvard University

Research Goal, Approach and Accomplishments

The goal of this project is to understand and apply the metal-insulator transition (MIT) in vanadium dioxide (VO₂) at the nanoscale. The MIT in VO₂ can be induced by temperature, electric field, strain, and optical excitation. A structural transition is associated with the electronic MIT. Some propose that the structural transition is responsible for the MIT, while others argue that electron-electron interactions drive the transition. VO₂ is therefore a model system for studying the interplay of Mott and Peierls transitions. Since the temperature-induced transition occurs at 60°C, near room temperature, VO₂ has significant potential for application in devices that can be easily integrated into existing technology. Some proposed applications include bolometers, tunable metamaterials, memristors, and data storage devices.

We have used conducting atomic force microscopy (CAFM) to simultaneously measure the topography and current in a polycrystalline VO₂ film on a conducting Si substrate (grown by RF sputtering in the laboratory of <u>Shriram Ramanathan</u>). We have used a CAFM tip to apply a local bias voltage and to measure the resulting current flow with sub-grain resolution. From the measured IV curves, we have extracted local properties of the VO₂ film such as resistance, transition voltage, and film capacitance. Since we can induce the MIT in VO₂ through the application of a bias voltage, these curves provide information in both the metallic and insulating states with sub-grain resolution. Understanding the properties of the MIT in structures of this size is necessary for the use of VO₂ in technology such as nanosenors or memory.

In addition to the current measurement, we simultaneously measured the deflection of the cantilever. This independent measurement provides local information about the structural transition accompanying the MIT in VO₂. By characterizing the *IV* behavior and structural changes of VO₂ on the single-grain level, we have preliminary evidence that we may be able to tease apart and individually characterize the electronic and structural transitions. Previous bulk investigations of these two associated transitions have been unable to achieve conclusive separation due to nanoscale inhomogeneity.

Future work will be directed toward understanding the relationship between the structural and electronic phase transitions. We seek to determine repeatable parameters for which the electronic transition can take place in the absence of the structural one. This would be an important step toward incorporating VO₂ into technological applications, as material degradation after repeated structural transitions may limit the useful lifetime of VO₂ devices. Another future direction will be the fabrication of VO₂ devices such as a MottFET or memristor. We have a preliminary demonstration of nanoscale "writing" of the metallic state into the VO₂ film, although further work is needed to determine whether this observed effect is a surface change or a manifestation of the MIT throughout the film thickness.



Figure 3.3. (a) Schematic of the microscope tip and sample geometry. (b) Topography of the VO₂ surface. (c) Current map at constant voltage (~ 2 V). (d) Typical *IV* curve at one location on the VO₂ surface. (e) Map of metal-insulator transition voltage for the forward direction.



Figure 3.4. "Write" high conductance regions into the sample using a 13V tip bias; subsequently "read" the local conductance using a 3V tip bias.

Imaging Spins in Quantum Dots

Marc A. Kastner

Physics, Massachusetts Institute of Technology

Collaborators: Charles M. Marcus (Harvard University); Loren Pfeiffer (Princeton); Ya-Hong Xie (University of California at Los Angeles) *International Collaborator*: Muhammad Mustafa Hussain (KAUST, Saudi Arabia)

Research Goal, Approach and Accomplishments

The long-range goal of our NSEC work is to image electron spins in quantum dots. Semiconductor quantum dots or single-electron transistors (SETs) provide highly tunable structures for trapping and manipulating individual electrons. Applying a magnetic field to a SET splits the spin-up and spin-down states by the Zeeman energy. This provides a two-level quantum system that can be used as a qubit for quantum computation. <u>Robert M. Westervelt</u>'s group has made great advances in imaging electron charge density. Imaging the spin density of electrons in nanostructures will give additional information about electronic wavefunctions and may be useful in characterizing devices.

Our work has focused on the fabrication of quantum dots in Si quantum wells. Silicon-based quantum dots have the benefit of potentially very long spin decoherence times (T_2), because of their smaller nuclear magnetic moment, lower concentration of magnetic nuclei and lower overlap between nuclear and electronic wave functions. In principle, the silicon quantum well, in which the dot is created, could be grown from isotopically pure Si²⁸, which would further improve the spin decoherence time.

However, to achieve well-controlled quantum dots in Si/SiGe heterostructures, one must overcome complications that do not arise in GaAs/AlGaAs heterostructures. As reported last year, we discovered a very large noise level, which would make the detection of single-electron charging impossible. We inferred that a major problem with Si quantum wells in SiGe is motion of electrons among the donors in the doping layer. We are preparing to submit results showing that such a parallel conduction path is, indeed, what limits our ability to make controlled quantum dots. We have measured the conductance as a function of gate voltage for constrictions that are very wide—up to 30 μ m. We find (Figure 3.5) that a voltage of ~-6V on a gate depletes the entire mesa, making the formation of gate voltage, which confirms the presence of a parallel conduction channel.

As discussed last year, we are preparing double-gated structures, so that no doping will be necessary. The two gates are isolated by a layer of Al_2O_3 , prepared by atomic layer deposition. We have succeeded in making ohmic contacts and have deposited Al_2O_3 layers, which have negligible leakeage. However, at this time there appears to be a high density of defects that trap electrons and prevent the creation of a 2DEG with the gate voltage. We expect to identify the origin of these defects soon.



Figure 3.5. Differential conductance and capacitance of Sample A as a function of voltage applied to only Gate_1 at 4 K. The inset shows a false-color micrograph and a sketch of the active region of the device. The blue area in the sketch is the mesa nearby the gates; the four corners of the mesa extend beyond the sketch by ~ 1 mm, where there are four 0.08 mm² ohmic contacts near the edges of the corners. The unmarked gate is not used for measurement but it is bonded and grounded through the measurements of this study. Each pair of top gates (purple color) forms a QPC; the QPC separation between Gate_1 and Gate_2 is 3 mm; between Gate_2 and Gate_4 is 5 mm; between Gate_3 and Gate_4 is 10 mm. All the gates shown in the inset extend outside the mesa and are bonded to a chip carrier.

Nanoparticle-based Molecular Imaging via MRI

Charles M. Marcus

Physics, and Center for Nanoscale Systems, Harvard University

Collaborators: Pratip Bhattacharya (Huntington Medical Ressearch Institutes); David Cory (MIT); Susan Kauzlarich (University of California, Davis); Chandrasasekhar Ramanathan (Dartmouth College); Matthew Rosen (Massachusetts General Hospital)

Research Goal, Approach and Accomplishments

Reseach Goal. The broad objective of this research is to develop a molecular imaging probe based on magnetic resonance imaging (MRI) of hyperpolarized silicon nanoparticles, providing a novel tool for measuring and imaging biological processes in health and disease. Iron-oxide nanoparticle-based contrast agents have been used extensively in MRI to detect specific molecular targets as well as to label cells for cell tracking. However, traditional methods used for detecting iron-oxide nanoparticles suffer from several problems, including difficulty quantifying concentrations, and difficulty detecting the contrast agent in regions that undergo motion or have low native signal-tonoise ratio. Contrast agents containing hyperpolarized nuclei such as ¹³C, ¹²⁹Xe and ³He have been shown to provide a novel method to overcome many of these problems, but have short relaxation (T1) times. The ²⁹Si nuclei in silicon nanoparticles has been shown to exhibit long nuclear relaxation (DNP). Such ²⁹Si-based imaging agents will provide powerful and much needed new tools for targeted molecular imaging agents will tracking and the detection of tumors.

Approach. We have investigated a range of silicon nanoparticles fabricated by a variety of methods both at the Harvard CNS and through a collaboration with the Kauzlarich group at UC Davis. The nanoparticles are hyperpolarized at low temperatures and high magnetic fields by microwave induced DNP. A recently commissioned cryostat allows for the study of the DNP process across a range of temperatures. Microwaves are generated at room temperature using a Gunn diode source, and coupled to the sample via a mm waveguide and slot antenna. The cryostat has been designed so that the hyperpolarized sample can be removed in under 1 s and transferred to a nearby MRI machine for imaging. Imaging studies of hyperpolarized silicon nanoparticles will be carried out

Accomplishments - Enhancing Dynamic Nuclear Polarization through Microwave Frequency Modulation

We have developed a modulation technique that results in up to a 5-fold increase in the efficiency of microwave induced dynamic nuclear polarization at low temperatures. This results in faster polarization times, and allows us to



reach total nuclear polarizations of several percent, almost 4 orders of magnitude increase in the nuclear polarization compared to the Boltzmann polarization at room temperature.

Installation of 29Si DNP Polarizer Coupled to an Animal Imager

We have successfully installed a second DNP polarizer at Huntington Medical Research Institutes in Pasadena, CA. This is located in the same lab area as a 4.7 T animal imaging system, which will allow us to hyperpolarize silicon nanoparticles and transfer them to an animal within a short time period. Preliminary 1H imaging studies have been carried out on the interperotoneal cavity and gastrointestinal tracts of mice.

Development of Dual Tuned 29Si/1H Animal Imaging Coils and Pulse Sequences for Short T2 Hyperpolarized Imaging

A set of dual tuned 1 H/29 Si surfaces and volume imaging coils have been designed and constructed for imaging rodents of different sizes. These coils have been designed to allow full body 1 H imaging of the animal together



with 29 Si imaging of the hyperpolarized particles without the animal having to be adjusted in the coil. Current work is focused on developing fast low flip-angle gradient echo imaging sequences for hyperpolarized 29 Si imaging that are suitable for the HMRI scanner.

In-vivo Toxicity Studies of Silicon Nanoparticles

We have performed multi-week studies of the toxicity of silicon nanoparticles suspended in saline and injected into the interperotoneal cavity of healthy mice. Animals were able to survive a dose of 8000 mg/kg of silicon nanoparticles (200 mg of silicon for a standard mouse body weight of 25 g) with no adverse affects observed after 48 hours.

Spectroscopy of Hyperpolarized Silicon Nanoparticles in vitro

Spectroscopy of hyperpolarized 29 Si particles in solution phantoms has been performed in the animal scanner demonstrating that the particles can be successfully

transferred from the DNP-polarizer to the scanner and the 29 Si signal can be observed in physiologically relevant concentrations (~50 mg in 5 ml of solution) over a period of tens of minutes. We have observed changes in the hyperpolarized 29 Si lineshape in solution over time that indicates a measure of particle settling, a technique which may have potential applications in the detection of binding of functionalized particles to *in-vivo* targets.





Photonic Devices Based on GaN Nanowires

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Applied Physics and Physics, Harvard University

Collaborators: M. Bawendi, V. Bulovich (Massachusetts of Technology); R.D. Dupuis (Georgia Tech.); Arthur Gossard (University of California, Santa Barbara); S. Guha (IBM); L.R. Ram Mohan (Worcester Polytech Institute); A. Shakouri (University of California, Santa Cruz); L. Sumney (Semiconductor Research Corporation)

Research Goal, Approach and Accomplishments

Aluminum-doped Zinc Oxide (AZO) is an important material for incorporation into optoelectronic devices and has found application as transparent electrodes in thin film solar cells, ultraviolet photodetectors, and ultraviolet light emitters. AZO is fabricated by doping ZnO with Al, which increases the electrical conductivity by several orders of magnitude. The resulting material is called a transparent conducting oxide (TCO). AZO is second only to indium tin oxide (ITO) in present-day utilization.

Significant efforts have been undertaken to understand and control the formation of grains in AZO films, since grain boundaries are known to host imperfections such as segregated Al. A recent study of temperature dependent electronic transport in AZO films confirms that grain boundary scattering can have a significant effect on electron transport. We have studied local electron spectroscopy in sputtered AZO films using a scanning tunneling microscope (STM). STM operation is based on vacuum tunneling, which allows us to probe bias-dependent differential conductivity as a function of spatial position.

Figure 3.9 shows a typical STM tip-sample separation scan taken at -0.1 V sample bias. The relative contrast between grains and grain boundaries changes slightly with bias, suggesting that the relative density of states varies in energy. We are most interested

in the dependence of density of states on film granularity. To probe this, we pause the tip such that it is positioned over either a grain or a grain boundary, and sweep the bias while recording tunneling current.

Figure 3.9 shows data recorded on grains and grain boundaries. In both cases the plotted curves are the average of data measured at multiple locations on the sample. The on-grain conductivity is typical for tunneling between two metals and is nearly featureless. In contrast, the grain-boundary data are non-monotonic with prominent local maxima. The comparison between grain and grain-boundary data clearly implies a peak in



Figure 3.9. STM tip-sample separation scan showing contrast between grains and grain boundaries (denoted by black arrows).

the grain boundary local density of states located 0.6 eV below the Fermi level. This broad peak is naturally associated with the electron trap states that significantly affect electron transport in AZO. The grain boundaries therefore harbor a broad spectrum of electron traps, from shallow states within kT of the conduction band edge that may limit electron mobility, to deeper states that may deplete carriers from the conduction band.

The next steps in this investigation are to optically probe the defect levels in AZO using the STM to inject hot carriers that recombine with trapped electrons. To do so, we have modified the STM to incorporate a collecting lens directly on the backside of the sample, which couples



Figure 3.10. Differential conductivity spectra taken on grain (red) and on grain boundary (black). Note the feature at -0.6 V bias, which is attributed to trap states at grain boundaries.

light into a spectrometer for photon detection. Figure 3.11 shows the detected luminescence for a variety of applied biases. The sharp peaks are the result of surface defect states and the scaling of intensity is consistent with known theory of inelastic mean free path of hot carriers.



Figure 3.11. STM cathodoluminescence probed for various biases. These peaks are the result of optically active defects at the AZO surface.

Imaging Electrons inside InAs/InP Nanowires

Robert M. Westervelt

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- *Collaborators:* Larry Bell, Carol Lynn Alpert (NISE Network of Museums); George Bourianoff (Intel); Don Eigler (IBM); Barbara Herr Hawthorn (University of California, Santa Barbara); Robert Hwang (CINT Sandia National Lab); Rick Rogers (Harvard School of Public Health); Ralph Weissleder (CCNE: MIT, MGH, Harvard Medical School)
- International Collaborators: Erik Bakker (Phillips Research, The Netherland); Koji Ishibashi, Koji Kaya, Maki Kawai, Yoshinori Tokura (RIKEN); Leo Kouwenhoven (Delft University of Technology); Daniel Loss (University of Basel), Lars Samuelson (Lund University); Hideo Ohno (Tohoku University); Seigo Tarucha (University of Tokyo)

Research Goal, Approach and Accomplishments

The goal of this research is to image electrons inside ultrathin InAs/InP nanowires that act as quantum mechanically one-dimensional (1-D) systems. Lars Samuelson's group at Lund University can grow InAs nanowires with widths ~20 nm that are narrower than the Bohr radius. In these nanowires, it is relatively easy to form a 1-D electron gas, where motion transverse to the wire direction is frozen out at low temperatures. Novel physical properties are expected, including the formation of a Wigner crystal at low electron density, and a Luttinger liquid at higher densities. To define the geometry,

Samuelson's group grows a long (~200 nm) InAs quantum dot, defined by two thin InP barriers. In the Coulomb blockade regime at low temperatures, an integer number of electrons sit inside the dot, and the energy of quantum states can be measured from the conductance peak positions.

Westervelt's group tunes the charge on ultrathin InAs/InAs nanowire quantum dots with the conducting tip of a cooled scanning probe microscope (SPM), used as a movable gate. An image is obtained by displaying the conductance of the dot as the tip is scanned in a plane slightly above the sample. Coulomb blockade peaks appear as bright rings in the conductance image; from the position of these rings, one can determine the relative number of electrons on the dot, and the energy of the electron state, via Coulomb blockade spectroscopy [1].



Figure 3.12. Proposed technique for imaging the electron density profile in a long quantum dot inside an ultrathin InAs/InP nanowire. The tip perturbs the electron wavefunction, shifting its energy and the position of the corresponding Coulomb blockade conductance peak, as shown.

Figure 3.12 shows how this information could be used to extract the electron density profile for states inside the long dot. The charged tip slightly dents the wavefunction of an electron, shifting its energy, via first-order perturbation theory. The resulting energy shift can be imaged by the SPM tip, as illustrated in Figure 3.12. From the measured energy shift, one can determine the original electron density profile. We plan to pursue this approach in future experiments.

In addition to the nanowire dot experiments, <u>Westervelt</u>'s group is assembling two custom-made cooled scanning probe microscopes for future work. The SPM imaging heads are fabricated in Harvard's machine shop, and the custom control electronics is designed and built in our electronics shop.

Reference

 Erin E. Boyd, Kristian Storm, Lars Samuelson, and Robert M. Westervelt, "Scanning gate imaging of quantum dots in 1D ultra-thin InAs/InP nanowires," *Nanotechnology* 22, 185201 (2011).

Scanning SET Imaging of Graphene

Amir Yacoby Physics, Harvard University

Collaborator: Zhifen Ren (Boston College)

Research Goal, Approach and Accomplishments

The research objective of this proposal is to investigate novel quantum correlated phenomena in single and bilayer graphene. Our research focuses both on isotropic phases as well as spatially varying phenomena where geometry and boundary conditions play an important role. Our investigation explores both naturally occurring inhomogeneities due to intrinsic disorder as well as spatially dependent phenomena arising from patterning graphene into nanostructures, introducing nonuniform charge densities using local electrostatic gating, and through contacting graphene with novel materials. Our experimental approach consists of both conventional transport methods as well as sophisticated local probe techniques capable of imaging the local thermodynamic and transport properties of these quantum phenomena.

Progress. The unique energy spectrum of single and bilayer graphene are expected to lead to novel collective phenomena when interactions among charge carriers become important. The non-interacting energy spectrum of graphene and its bilayer counterpart consists of multiple degeneracies owing to the inherent spin, valley and layer symmetries. Interactions among charge carriers are expected to spontaneously break these symmetries, leading to gapped ordered states. In the quantum Hall regime these states are predicted to



Figure 3.13 Suspended bilayer graphene device.

be ferromagnetic in nature whereby the system becomes spin-polarized, layer polarized or both. In bilayer graphene, due to its parabolic dispersion, interaction-induced symmetry breaking is already expected at zero magnetic field. In this work, the underlying order of the various broken-symmetry states is investigated in bilayer graphene that is suspended between top and bottom gate electrodes. By controllably breaking the spin and sublattice symmetries we are able to deduce the order parameter of the various quantum Hall ferromagnetic states. At small carrier densities, we identify for the first time three distinct broken symmetry states, one of which is consistent with either spontaneously broken time-reversal symmetry or spontaneously broken rotational symmetry. These conclusions are further supported by local inverse compressibility measurements of suspended bilayer graphene using a scanning single electron transistor.

SEED: Plasmonic Optical Cavities

Evelyn Hu SEAS, Harvard University

Number of postdoctoral fellows:0Number of graduate students:1Number of undergraduate students:0

Research Goal, Approach and Accomplishments

The field of plasmonics holds great potential for manipulating and generating optical signals at deep sub-wavelength scale. One particularly interesting application is the coupling of nanoscale optical emitters, such as colloidal quantum dots, with resonant plasmonic structures. Such effects underlie plasmon-enhanced molecular fluorescence [1], and some theoretical estimates suggest that such coupling could lead to an enhancement of the spontaneous emission rate by up to 8 orders of magnitude. Thus far, however, optical emitters have only been coupled to antenna-type structures [1,2,3], principally silver nanowires. While these structures have the benefit of being broadband, they have very low quality factors [2,3], which limits their ability to enhance luminescence via the Purcell effect.

We would like to fabricate a plasmonic cavity system that has both smaller mode volume and larger quality factor than a simple silver nanowire. Such a cavity should modify the emission spectrum of optical emitters confined within the cavity.

Our cavity is comprised of a silver nanowire coupled with a planar silver film, as shown in Figure S1. The sides and ends of the



Figure S1. Schematic diagram of plasmonic nanocavity with coupled nanocrystal optical emitters (not to scale).

nanowire determine the effective boundaries of the cavity, concentrating the majority of the electromagnetic energy in the region between the nanowire and the planar silver. The nanowire and planar silver film are separated by a stack of dielectric spacers and monolayers of colloidal quantum dots, which function as optical emitters confined within the cavity.

The planar silver film is fabricated using template stripping [4] and has a typical rms roughness of 0.5 nm immediately after stripping, as shown in Figure S2a. A thin dielectric layer is then deposited onto the silver. Next, a monolayer of colloidal quantum dots is deposited on the sample, yielding coverage similar to that shown in Figure S2b.
The monolayer is formed through evaporation of solvent containing the quantum dots onto a water meniscus [5]. A PDMS stamp is then used to transfer the monolayer from the water meniscus to the sample [5]. Additional dielectric is deposited on top of the quantum dots, and finally silver nanowires are deposited onto the sample in a droplet of ethanol that is allowed to dry.





quantum dots stamped onto a carbon TEM grid and imaged using an SEM with a scanning transmission electron microscopy (STEM) detector at 30 kV acceleration voltage. The coverage is not close-packed, but the gaps (typically tens of nm) are small on the scale of the nanowire length (typically ~1 µm). This monolayer can extend over hundreds of microns, which should be sufficient for our investigation.





Figure S3. (a) Typical normalized microphotoluminescence spectra from four Ag nanowire cavities of varying length lw (black). Within the cavity are dielectric spacers of ~4 nm SiN above and below one monolayer of PbS quantum dots, for a total cavity thickness (i.e., nanowire-plane spacing) of ~15 nm. Also shown for comparison is the luminescence not

coupled to cavity modes (gray, 0.94 mm cavity). Filled blue and red curves show odd and even mode profiles for the given cavity length as calculated with Finite Difference Time-Domain simulations. (b) Polarization analysis of cavity fluorescence from a 0.93 mm cavity. Emission from the mode is highly polarized along the cavity axis (dotted line).

These plasmonic cavities form a critical building block in the rapidly growing field of plasmonics: Although these metal-based cavities have low absolute quality factors, the very small modal volumes of these cavities lead to high

ratios, Q/V, which is the parameter that governs the influence of the cavity over optical emitters. The composition of such cavities makes accessible a broad range of both semiconductor and organic emitter materials, and the nanowire-based geometry may naturally lend itself to impedance-matched connection to electrical circuits.

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9. CENTER DIVERSITY — PROGRESS AND PLANS

The NSEC based at Harvard University is committed to increasing the diversity of the science and engineering workforce, and to making science and engineering accessible to a broad audience. NSEC faculty participants are dedicated to increasing participation by members of underrepresented groups and to giving these scientists and engineers the resources and guidance needed to succeed in each stage of their careers so as to become leaders in both education and research. Our strategic plan for increasing diversity builds on connections we have made through various programs, and seeks to increase our impact by developing new partnerships, both internally and externally.

We have identified five broad goals that will be accomplished through a variety of initiatives: (1) to intensify the recruiting, support and professional development of a more diverse group of graduate students and postdoctoral researchers; (2) to increase the diversity of faculty participating in the NSEC; (3) to strengthen recruiting and mentoring of members of underrepresented groups through our joint REU programs; (4) to mentor pre-college students as they consider careers in science and engineering; and (5) to develop long-term partnerships with predominantly female and minority-serving institutions.

Goal 1: Recruiting, Professional Development and Support of a Diverse Group of Graduate Students and Postdoctoral Researchers

Graduate students and postdoctoral researchers are at crucial stages in their careers. Their experiences in terms of professional development, mentoring, and access to facilities and other opportunities have a significant impact on their career choices. Our goal is to leverage NSF and University support to recruit graduate students and postdoctoral researchers from underrepresented groups in science and engineering, and to provide resources to the students that will empower them to become educational and research leaders.

Strategy 1: Recruiting. Many of the strategies in place in the REU program to recruit highly qualified undergraduates to the summer program have been shared in recruiting of graduate students and postdoctoral researchers, including publicizing the graduate program and postdoctoral positions at conferences and on websites that reach a large population of underrepresented minorities. The Director of Educational Programs <u>Kathryn Hollar</u> coordinates with the Minority Recruitment Officer for the Harvard Graduate School of Arts and Sciences and the Graduate Program Administrator in Physics to share resources in these efforts.

More directly, we are fortunate to have recruited several talented students to graduate programs at Harvard via the REU. Since 2002, at least 26 former REU students have been recruited to graduate programs at Harvard, including 9 students from underrepresented groups and 15 women. In general, greater than 50% of past REU participants report that they are currently in a graduate program in science or engineering.

Strategy 2: Professional Development and Mentoring. The NSEC has developed a program of professional development for NSEC-affiliated graduate students and postdoctoral researchers through the research exchange seminar and the AP298r course. Postdoctoral researchers and graduate students also have the opportunity to participate in our educational programs, including developing mentoring and project management skills through our REU program and experience in presenting to K-12 classrooms through connections with the Cambridge Public Schools and our RET programs, and engaging the public at the Museum of Science, Boston.

The NSEC will also work in concert with the School of Engineering and Applied Sciences, the Chemistry and Chemical Biology Department, and the Physics Department and the University administration to leverage support for more professional development opportunities for graduate students and postdoctoral researchers. We will use some of our funding to support these professional development activities and for travel support.

Strategy 3: Support. We have established Center fellowships to encourage the participation of women and minority groups in science and engineering. Fellows are integrated into the research and educational community of the NSEC, and connections with faculty and institutes across the university are facilitated through this program. Access to research facilities and educational and professional development opportunities helps develop a strong pool of well-prepared researchers for faculty positions and the scientific community. In 2010–2011, these Postdoctoral Fellows include:

- Dr. Leila Deravi (Advisor: Parker)
- Dr Lyuba Kuznetsova (Advisor: <u>Capasso</u>)
- Dr. Martin Mwangi Tho (Advisor: <u>Whitesides</u>)
- Dr. Yolanda Vasquez (Advisor: <u>Aizenberg</u>)
- Dr. Miao Yu (Advisor: <u>Friend</u>)

Strategy 4: Diversity Working Group. For the past two years, we have invited graduate students, postdoctoral fellows, and undergraduates to attend the joint annual meeting of the National Society of Black Physicists and National Society of Hispanic Physicists. Out of these meetings, a core group of minority graduate students and postdoctoral fellows have started meeting regularly to discuss strategies for recruitment, retention and professional development of minority scientists and engineers. One initiative that this group has undertaken is to informally mentor minority students in our REU program. We will continue to meet with these students and postdoctoral fellows to follow-up on several suggested initiatives, including increased participation by Harvard undergraduates in national conferences, working with our undergraduate and graduate admissions office to recruit talented minority students to Harvard, developing a speakers bureau of faculty and postdoctoral fellows who are interesting in recruiting at Minority Serving Institutions, and developing metrics for tracking achievement and movement of minority students through Harvard.

Goal 2: Increase Diversity of *faculty* Participating in NSEC

One of the major challenges facing the science and engineering community is to increase the diversity of the faculty ranks. The collaborative and interdisciplinary nature of the research of the NSEC provides a supportive environment that effectively integrates young scientists and engineers into a vibrant scientific community at the beginning of their academic careers. The NSEC also provides access to cutting-edge instrumentation facilities, which are a valuable resource at an early career stage.

Strategy 1: Partnership with Radcliffe Institute. As discussed in Section 11, we partnered with the Radcliffe Institute this past year. Radcliffe Fellows continue to collaborate with NSEC faculty; recent examples include Dr. Tayhas Palmore, 2006–2007 Radcliffe Fellow and Paula T. Hammond, 2003–2004 Radcliffe Fellow. Joanna Aizenberg has a joint appointment at the Radcliffe Institute.

Strategy 2: Leadership and Focus in Faculty Hiring. The sciences and engineering at Harvard are experiencing a period of rapid growth, and faculty in the NSEC are in leadership roles at Harvard that can influence the recruitment and support of new faculty. The highly collaborative environment of the NSEC and the availability of world-class instrumentation also provide an ideal opportunity to develop the careers of new faculty. Junior faculty at Harvard contributes significantly to each research cluster within the NSEC. Close interaction with senior faculty helps new faculty to develop stronger individual research and educational programs.

Since 2002, we have increased the number of junior faculty supported by the NSEC from 1 in 2002 to 8 in 2010; the number of women faculty supported has increased from 1 in 2002 to 6 in 2010. In 2007, Joanna Aizenberg was hired as a senior faculty in SEAS and CCB, and has assumed leadership roles as a member of the Executive Committee for the NSEC. In 2009, Evelyn Hu was also hired as a senior faculty in SEAS, and plays a key role in our NSEC.

Goal 3: Strengthen Recruiting and Mentoring of Underrepresented Groups through REU Program

NSF support for the REU programs of the NSEC and allied programs in Materials Research provides core funding for a growing undergraduate research program that includes substantial funding from Harvard. These joint programs, which now support over 50 students each summer, share a common infrastructure for recruiting, providing community and professional development activities during the program, intensive mentoring during the summer and post-program, and program evaluation and tracking. Connections made through our REU program's focus on diversity also serve as critical building blocks for our strategic diversity plan.

Strategy 1: Recruiting. We have an active recruitment strategy that involves visits to minority serving institutions and conferences such as those held by the Society for Advancement of Chicano and Native Americans and the Annual Biomedical Research

Conference for Minority Students. This recruiting effort also includes universities with predominantly Hispanic enrollments, and primarily undergraduate institutions that serve women. Since 2002, faculty and staff have visited Morgan State University, Howard University, Morehouse College, Spelman College, Florida Agricultural and Mechanical University, the University of Puerto Rico (Rio Piedras, Humacao and Mayagüez campuses), Sweetbriar College, Texas Prairie View Agricultural and Mechanical University, and North Carolina Agricultural and Technical State University. At these recruiting visits, we discuss not only the opportunities available at Harvard, but also the characteristics of a strong application for a research experience program. Former REU students at these institutions often lead discussions on the summer research experience. Additionally, faculty and staff recruit at professional and research conferences and career fairs for underrepresented groups, including the joint annual conference of the National Society of Black Physicists and the National Society of Hispanic Physicists. To reach a wider audience of applicants for our REU program, we partner with the Graduate Admissions Offices of various departments, including SEAS and Physics, to distribute materials advertising our program at these conferences and career fairs. Attendance at these conferences aids us in recruiting students and in following-up with past REU alumni. In 2009, we recruited 3 very talented students from these conferences to our REU program. In 2010, we expanded our recruiting efforts to the annual Society for the Advancement of Chicanos and Native Americans in Science and the Annual Biomedical Research Conference for Minority Students.

In addition to these recruiting visits, we also advertise on many websites and listservs that are resources for underrepresented groups. REU participants report that the Internet is an important resource for finding summer programs; therefore, we also advertise on websites and listservs that target underrepresented groups in engineering. These efforts resulted in an increase in applicants to the joint programs from 247 in 2004 to over 800 in 2010. Applications for the 2011 REU program are projected to be in excess of 850. Of the 4 students funded through NSEC REU, 1 was from an underrepresented racial or ethnic group in science and engineering, and 3 were female. Of the 4 participants, 3 were freshmen, and 1 was a junior. Two students were from primarily undergraduate institutions. Two of the students had no prior research experience.

Strategy 2: Mentoring and Professional Development. The summer REU program includes many community-building and professional development activities for both REU participants and mentors, including a workshop on presentation skills, a seminar on career planning and applying to graduate school, and weekly presentations by faculty on research and ethics.

Strategy 3: Post-program Mentoring and Long-term Tracking. The relationships developed during the program extend past the summer: mentors provide guidance and support as students apply to graduate school, and also include students in the process of writing and submitting papers that are based on their summer work. Students are encouraged to present their work at local and national conferences, and funds are available through the REU/RET Site in Materials Research to support travel for mentors and REU participants to national conferences.

Goal 4: Introduce *Pre-college Students* to Science and Engineering Programs through Summer Opportunities or Year-round Programs

We continue to expand our repertoire of activities for pre-college students and teachers, focusing on collaborations that effectively impact schools and students that have high need or significant achievement gaps between student groups. We continued collaboration with a relatively new public school in Boston, The Engineering School at the Hyde Park Educational Program, and strengthened our relationship with the Cambridge Public Schools. Both of these schools have significant populations of students who have historically been underrepresented in science and engineering careers. The Cambridge Public School District is an urban district that is over 60% minority, with 37% of students enrolled in a free or reduced lunch program. The Engineering School, one of the small schools that are a result of the recent reorganization of several large Boston Public Schools into smaller learning communities, is comprised of 56% Black and 34% Hispanic students, with 65% of the students enrolled in a free or reduced lunch program. In both partnerships, we focus on supporting students in school-based scientific research or engineering design projects, rather than formal curriculum development. Both of these relationships were forged through our RET program, with the intent to develop long-term programs that include students directly in the research enterprise. This strategy capitalizes on our strengths as a highly disciplinary research institution, and allows us to meet critical student and teacher needs in terms of mentorship and professional development skills that are not explicitly covered in science curricula.

Strategy 1: Increase Collaboration with Cambridge and Boston Public Schools at the High School Level. A partnership with The Engineering School (TES) at the Hyde Park Educational Complex supports student internships and dual enrollment in college courses. The NSEC has supported the goal that TES has to increase student engagement in science and engineering competitions by providing expertise and feedback on student-defined science and engineering fair projects via email, class and student visits to Harvard, and visits to TES. Our graduate students and postdoctoral fellows have worked with TES students on poster presentation skills, experimental design, and finding resources for projects. As discussed in *Section 10—Education*, we were also successful in securing a grant from the Boston Public Schools to continue this science fair support, and add research internship opportunities for TES students. In 2010, we expanded this program to include students from Cambridge Rindge and Latin School. In 2011, we will work with other schools in the Boston Public Schools to offer similar opportunities.

Strategy 2: Continue Collaborations with Cambridge Middle Schools, Parents, and the Community. As discussed below in *Section 10—Education*, NSEC faculty participate in Project TEACH (The Educational Activities of Cambridge-Harvard), which brings each 7th grade class from CPSD to Harvard for a college awareness and science presentation day.

Strategy 3: Develop Connections with Urban Schools through RET. Our RET program recruits teachers from local urban schools to participate in the Center's research and educational activities for 6–8 weeks during the summer. We encourage many follow

up activities with teachers, including classroom visits and field trips to Harvard. As we continue to build research and educational programs in close partnership with CPSD and Boston Public Schools, we will integrate our RET teachers and their students into these activities. For example, we continue to include middle and high school teachers from CPSD and Boston Public Schools (BPS) in our joint RET programs, with the intent to build long-term partnerships that impact students directly (see discussion in *Section 10—Education*).

Strategy 4: Pursue Internal Partnerships. A partnership with the Office of Community Affairs at Harvard introduces middle school students in Cambridge to college and the possibility of science careers, as discussed in *Section 10—Education*. In 2011, through the Office of Community Affairs we will also participate in the Boston StepUp collaborative, which links schools in the Boston Public Schools with area universities to decrease the achievement gap in selected schools in Boston.

These four initiatives, natural extensions of established relationships, are examples of how we will continue to develop science education partnerships that engage students, teachers, and parents.

Goal 5: Develop Long-term Research and Educational Collaborations with Predominantly Female or Minority-serving Institutions

Each year, a group of Morehouse and Spelman College students visit Harvard and other colleges in the Northeast during their spring break to investigate graduate program options. The NSEC hosts a group of students from these colleges and introduces them to NSEC-related research. Additionally, <u>Eric Mazur</u> recently made a recruiting visit to the University of Puerto Rico Rio Piedras and Humacao campuses in February 2010 and 2011. As a result, we anticipate we will recruit 2–3 students from each group for our REU program.

Our goal over the course of NSF support is to formalize these research and educational partnerships with predominantly female and minority-serving institutions by facilitating the exchange of educational strategies and developing research collaborations.

10. EDUCATION AND HUMAN RESOURCES

Center participants continue to be actively involved in programs that engage the public, teachers, students, and young scientists and engineers in the excitement of scientific discovery and increase awareness of the impact of scientific research on their daily lives. Our broad goals are to increase public engagement in and awareness of advances in nanoscale science and engineering, and to promote career advancement for a diverse group of young scientists who represent the future of science and engineering. Our educational initiatives at the pre-college, undergraduate, graduate, and postdoctoral levels include embedded diversity initiatives and strategic collaborations whenever possible to encourage individuals from underrepresented groups to pursue careers in science and engineering. In addition to increasing public understanding of nanoscale science, Boston enhances the university-based activities such as our REU and RET programs, as well as professional development of postdoctoral fellows and graduate students.

10.1 Public Engagement

10.1.1 Holiday Science Lecture for Children and Families

Current Activities. For the eighth year, Professor Howard Stone, along with Daniel Rosenberg (Harvard Science Center demonstration staff), and Educational Programs Director <u>Kathryn Hollar</u> developed and presented our annual interactive Holiday Lecture.

This year's lecture, "Good Vibrations: How We Communicate," was held December 11 at Harvard and December 18. 2010 at Princeton University (Figure 10.1). This childrenand family-friendly science presentation is modeled after the Christmas Lectures first presented by Michael Faraday at the Royal Institution. Over 1000 attendees learned about the physics of waves and vibrations, as well as the physics of how animals and humans communicate.



Figure 10.1. Howard Stone enlists young audience members to help the difference between transverse and longitudinal waves.

Outcomes. The Holiday Lecture reaches now over 1000 people each year, and is designed to encourage families to continue explorations and discussions of science postlecture. Comment cards collected after each lecture indicate and informal feedback via email from returning families each year indicates that the lecture has impacts beyond the 1-hour Saturday celebration of science.

10.2. Pre-College Activities

10.2.1. Project TEACH

Current Activities. Through a continuing program, NSEC researchers share their enthusiasm for science through Project TEACH (The Educational Activities of Cambridge and Harvard). This early college awareness program is a joint effort of the MRSEC, the NSEC based at Harvard, and the Harvard Office of Community Affairs. Coordinated with the Cambridge Public Schools, Project TEACH brings each 7th grade class from the Cambridge Public School District to Harvard University throughout the school year. During the visit, students receive information about college admissions, and learn about college life from Harvard undergraduates. The class visit culminates in an interactive science presentation by a NSEC researcher on his or her research.

Outcomes. In 2010–2011, this program reached over 300 students.

Future plans. Beginning in 2009, participants in the NSEC-Museum of Science Public Communications Internship have used Project TEACH to test and refine talks they have developed through the internship. We will continue this model in order to help graduate students and postdoctoral fellows develop skills in engaging young audiences. In 2011, the program was extended to several Boston elementary schools.

10.2.2. Research Experiences for Teachers (RET) Program

Current Activities. The NSEC, in conjunction with an REU/RET Site in Materials Research and Engineering and an RET Site of the National Nanotechnology Infrastructure Network, hosted 6 teachers in 2010. Teachers work with faculty, postdoctoral researchers, graduate students, and REU participants on research or science curriculum projects. Teachers commit to 6–8 weeks during the summer, and are invited for a second summer to refine educational modules that are developed.

In addition to a research/educational project, RET participants also attend weekly seminars on educational and research topics and on research ethics. The integrated nature of RET and REU activities, particularly the faculty seminars during the summer, provide opportunities for teachers to explore development of small classroom modules based on seminar content. RET participants also met weekly over lunch to discuss informally their research projects and how to best relate their summer research project to their curricula. The summer research experience for teachers culminates in a poster session. Teachers take these posters back to their classrooms to give students an introduction to scientific research, and to emphasize that science and engineering careers are accessible, interesting, and that science and engineering profoundly affect everyday life. These posters have also served as the basis for talks at regional and national conferences for teachers and faculty. Materials developed by teachers can be accessed at our website, <u>www.eduprograms.seas.harvard.edu/RET.htm</u>. NSEC-supported participant and project information can be found in Table 10.1.

RET Participant, Subject/School	Project Title(s)
Joan Abrams	Controlled release of protein encapsulated in
Biotechnology	alginate: An engineering design activity for
(Cambridge Rindge and Latin School, MA)	high school
Joshua Bridger	Interactive NMR: Fundamentals to application
Physics	
(Dover Sherborn High School, MA)	
Joseph Childs	Developing low-cost soft lithography
Physics	techniques for high school laboratories
(Cambridge Rindge and Latin School, MA)	
Lisa Walker	Microbial fuel cells: Introducing elementary
2 nd grade	school students to energy in the soil
(Dallin School, Arlington, MA)	
Ernest Coakley	Investigating traumatic brain injury
Biology	
(The Engineering School at Hyde Park, MA)	
Rebekah Ravgiala	Cellular response to nanotopography - From
(Tyngsborough High School, MA)	High-Tech to High School

Table 10.1: NSEC RET Participants, 2010

Outcomes. This summer's work by NSEC RETs resulted in 5 classroom-tested modules. Josh Bridger presented the completed NMR module at the American Association of Physics Teachers in January 2011.

Planned Activities. RET participants will attend the National Science Teacher Association (NSTA) Annual Meeting in March 2011 to share modules with other RET participants across the nation through the NNIN RET program, and through the RET Networking meeting at NSTA. RETs Rebekah Ravgiala and Joseph Childs will present a workshop at NSTA on *Drug delivery* and *low-cost microfluidic laboratories*. Several "mentor teachers" will return next summer to continue professional development, and help less seasoned teachers bridge the gap between the research environment and the classroom. Next summer, returning teachers will also focus on writing papers on tested modules for publication in peer-reviewed educational journals and for presentation at national conferences.

10.2.3. Engineering Pathways for Success

Current Activities. In this initiative, co-sponsored by the NSEC, MRSEC, and Boston Public Schools, we have partnered with The Engineering School (TES) at the Hyde Park Educational Complex (http://www.bostonpublicschools.org/node/434), to implement orientation activities for incoming 9th grade students, science and engineering fair support, summer research internships for TES students, and dual enrollment opportunities. TES is a public high school, with >90% minority students, and has an explicit focus on S&E training; many students will be the first generation in their family to attend college. In Summer 2010, the NSEC hosted 3 TES students who worked in the on designing microbial fuel cells. Based on the initial success of this program, we

expanded the program to Cambridge Rindge and Latin School (CRLS), the public high school in Cambridge, MA. Using funds from the Cambridge Mayor's program, we worked with CRLS teacher Joseph Childs to place 12 students in NSEC and SEAS laboratories in Summer 2010; students continued their projects via a course at CRLS in the fall.

Outcomes. All eight of the student participants in the 2009 program graduated from TES this spring, and have been accepted to colleges on the East Coast, including NJIT, Spelman College, Wentworth Institute of Technology, UMass Amherst, and Worcester Polytechnic Institute. All of the participants plan to pursue STEM majors.

Planned Activities. Unfortunately, The Engineering School at Hyde Park will close this spring due to budget cuts in the Boston Public Schools. We will continue the program with Cambridge Rindge and Latin, and have received several inquiries from other Boston Public Schools.

10.2.4. Science, Engineering and Technology in the City

Current Activities. For the second year, the NSEC at Harvard co-hosted a Science, Engineering and Technology in the City (SET in the City) technology career awareness day for high school girls. SET in the City. First offered in June 2009, this event is coorganized by the Boston Area Girls STEM Collaborative, an organization founded in 2009 by outreach professionals at Boston area colleges (including <u>Kathryn Hollar</u>), Science Club for Girls, the Museum of Science, Boston, and area technology companies. The July 2010 SET in the City served over 200 girls, and featured NSEC faculty <u>Evelyn Hu</u> as the opening speaker. Also in 2010, Harvard worked with the Collaborative and WGBH to host 25 middle school girls for one day at Harvard as part of a week-long STEM summer day camp for Boston-area girls. In both of these events, girls participated in modified RET-developed classroom activities on drug delivery and diagnostics.

Planned Activities. We plan to continue these collaborative activities, with help from RET participants. A SET in the City event is planned for April 30, 2011, and the Collaborative is working to offer another Tech Savvy camp in Summer 2011.

10.3. Undergraduate Activities—REU Program

Current Activities. The NSEC has increased the number of REU participants through substantial supplemental funding from the School of Engineering and Applied Sciences (SEAS), Harvard College, the Wyss Institute for Biologically Inspired Engineering, and the Rowland Institute at Harvard (<u>Frans Spaepen</u>, Director). An NSF-funded REU/RET Site in Materials Research (PI <u>Eric Mazur</u>) has also allowed us to expand our professional development opportunities for participants. NSEC funded REU participants and projects are shown in Table 10.2.

REU Participant/Institution	Project Title
Michelle Barber/MIT	Self-assembly of metamaterials
Rachel Carey/Le Moyne College	Gold nano-electrodes templated by biodegradable polymers
Carina Fish/Harvard University	Soft robotics
Michael O'Brien/Eastern Nazarene College	Paper-based MEMS sensors

Table 10.2: REU Participants, 2010

The infrastructure provided by the REU/RET Site Program has allowed us to expand the program of professional development workshops, faculty seminars, and social and cultural activities that are designed to create community among participants and research advisors. These activities continue to include mentor training prior to the program start; weekly faculty-led research and ethics seminars; professional development workshops, including written and oral presentation skills workshops; large and small group discussions on applying to graduate school; and various athletic and social events during the summer.

One goal of our REU program is to develop essential skills in communicating effectively with scientists and the public. In collaboration with the Museum of Science, Boston, we hold a presentation skills workshop for REU students. During this workshop, students engaged in discussions with <u>Carol Lynn Alpert</u> and Karine Thate and other education associates from the Museum of Science, Boston, on how to present complex scientific concepts. This format is very effective in increasing the confidence of these young scientists and engineers in discussing science with their peers and mentors. The workshop is followed by evening practice sessions in the week prior to the final symposium. A new component of our REU program is a weekly meeting to help students learn to read and write scientific papers. Students rated this component very highly, and we plan to continue this workshop in future years.

In addition to the end-of-summer research symposium, mentors are encouraged to seek out opportunities for students to participate in professional meetings. This early exposure to the professional life of an academic is important in encouraging young scientists and engineers to continue in academia. For example, Mr. Kristopher Eric Martin presented his work at the Fall meeting of the California American Physical Society Division of Fluid Dynamics; several students will present at upcoming regional and national conferences.

Mentoring an REU student is a valuable professional development opportunity for a graduate student or postdoctoral researcher, allowing this population to explore effective models for project management. To enhance this experience for mentors, we have implemented a series of preparation sessions with REU mentors. New mentors participate in a series of luncheons in which faculty and other experienced mentors share strategies for mentoring undergraduate students, including planning a realistic project, modifying project goals, effectively managing time, and motivating students to work independently and as part of a team.

Outcomes. Since 2003, the NSEC has fully or partially funded 72 REU students. To date, 35% of these students are enrolled in MS/PhD programs in S&E, 36% are currently enrolled in undergraduate S&E programs, 11% are employed in S&E companies, while 8% are pursuing medical or law degrees, and the remaining 11% are teaching in K12, consulting or pursuing non-S&E careers.

Planned Activities. We plan to continue our program of activities for REU students and mentors, and will modify the program each year in response to formative evaluations.

10.4 Postdoctoral and Graduate Student Professional Development Activities

The NSEC based at Harvard has been involved in professional development of postdoctoral fellows since its inception. Sections 10.4.1-10.4.2 discuss ongoing opportunities for postdoctoral fellow and graduate student involvement in educational and professional development opportunities. In addition to the current NSEC-based activities describe below, graduate students and postdoctoral fellows are encouraged to participate in the professional development seminar series offered in spring of each year by SEAS (http://seas.harvard.edu/profdev), which addresses topics such as mentoring and project management, writing proposals and papers, and handling implicit biases. University-wide, postdoctoral fellows also have access to the professional development programs offered by the Office for Postdoctoral Fellows (http://postdoc.harvard.edu). Resources available include workshops on networking, academic interviewing, and responsible conduct in research. Additionally, postdoctoral fellows and graduate students who are REU mentors are also asked to participate in a series of mentoring and project management workshops in the spring.

10.4.1. Course and Seminar Development

Current Activities. In addition to the mentoring and professional development activities embedded in our other educational programs, graduate and advanced undergraduate students participate in AP298r, *Interdisciplinary Chemistry, Engineering and Physics*, an interdisciplinary graduate survey course of ongoing research at the Center. These activities are further discussed in **11. Outreach and Knowledge Transfer**.

10.4.2 *Public Communication Internships at Museum of Science*

Current Activities. In 2007, we instituted a Public Communications Internship (PCI) for graduate students and postdoctoral fellows, now led by education associate Karine Thate at the Museum of Science, Boston. In January 2010, 6 graduate students and postdoctoral fellows participated in the week-long internship. The workshop is designed to give participants an in-depth perspective on how museum personnel approach informal science education; participants then develop a "product," which can be a tabletop demonstration, a 20-minute talk for the Museum floor, or a video on their research.

Outcomes. To date, 4 videos, 5 presentations for the Museum of Science, and 3 tabletop demonstrations have been developed by graduate students or postdoctoral fellows.

Videos are posted to YouTubeTM, and will be linked to our website. Additionally, former participants will help with upcoming NanoDays events at the Museum of Science.

Planned Activities. We plan to continue the PCI, and will offer a session in June for graduate students and postdoctoral fellows. Participants in the PCI have and will continue to give talks in other venues, including through Project TEACH activities (see above), Science Cafes (www.sciencecafes.org), and Science in the News (https://sitn.hms. harvard.edu/podcasting/)

10.5 Museum of Science, Boston (subawardee)

Public Engagement and Professional Development in Nanoscale Informal Science Education and Science Communication

10.5.1 Research Accomplishments and Plans

The Museum of Science subaward is focused on producing robust and effective public engagement experiences in nanoscale science and engineering, as well as on building the capacity of educators and researchers to engage public audiences in nanoscale science and engineering. We seek to expose a broad and diverse audience to the research work of the NSEC and to nanoscale science and engineering generally, and to develop best practices in outreach and education that can be shared among the larger research and informal science education communities, through the NSF Nanoscale Informal Science Education Network, the NSF Nanoscale Science and Engineering Education initiative, the Association of Science-Technology Centers, the Materials Research Society, and other professional organizations. Over the past year we have deepened and expanded our pursuit of successful strategies pioneered in previous years, while also focusing on disseminating our educational products, professional development programs, and knowledge gleaned from evaluation efforts.

Public Engagement Activities and Impact

With NSEC support, MoS Education Associate Karine Thate developed live presentations related to nanoscale science and engineering in the Museum's popular Gordon Current Science & Technology Center, and delivered them three to four times a week. Karine's presentations, "Tiny Solutions to our BIG Energy Problem" and "The Future of Computing," were delivered a total of 127 times in 2010, to a combined audience of over 5,000 museum visitors. Karine also hosted Tom Babinec, an NSEC graduate student, as a guest researcher who came to the museum to teach visitors about Diamond Nanotechnology in June. In February 2011, Karine also hosted Gary Harris, an NSEC visiting faculty member from Howard University, who spoke on Black Scientists and Engineers: Ancient and Modern in Commemoration of Black History Month.

Karine Thate and Alex Fiorentino organized our biggest NanoDays event to date, held March 26 and 27, 2010. Attended by more than five-thousand museum visitors, this event included: two days of hands-on nano demonstrations with museum visitors led by more than 60 faculty and student volunteers (including 15 NSEC-affiliated volunteers); displays of nano-enhanced products from industry; seven guest researcher presentations

including four Harvard NSEC faculty members, collaborators, and students (<u>George</u> <u>Whitesides</u>, Donald Ingber, <u>Jennifer</u> <u>Hoffman</u>, and Raoul Correa); the building of a giant balloon model of a carbon nanotube in the Museum lobby; and four performances of *The Amazing Nano Brothers Juggling Show*. To help prepare Harvard volunteers for leading hands-on demos at NanoDays, a "Sharing Nanoscience with Hands-On Demos" workshop was held at Harvard on March 2.

MoS invited NSEC to be part of its local coalition producing public outreach for the Public Broadcasting System special series NOVA's *Making Stuff*. Using the same successful model as NanoDays, Karine Thate organized two more outreach events – NOVA's *Making Stuff* Days: Explorations in Materials Science and Engineering – on November 28, 2010 and January 23, 2011, which engaged public audiences in this emerging field of science and highlighted NOVA's 4-part documentary series on materials science, including an episode on nanotechnology. These events were attended by more 7,000 museum visitors and included the help of five Harvard volunteers.

Karine and NSEC student Lauren Zarzar, also participated in another outreach event April 29 – May 1, "Inspiring Minds: Meet Women in Science", by leading hands-on nanoscience demos with hundreds of museum visitors and students to help encourage girls to pursue science education and careers.

In early 2010, Karine delivered two *Sci-Tech Today* news stories featuring nano research and applications to the six-state television viewership of New England Cable News, reaching 8,000-22,000 viewers in the Boston market alone with each segment. A journal article about the successful 2009 Multimedia Research naturalistic, double-blind investigation that revealed the significant educational impact of these TV news segments was published in the *ASTC Dimensions* Journal in early 2011.

The Museum also shared nano research and applications with the public via 13 podcast interviews, which reach 5,000 subscribers and other browsers on iTunes. Five of these interviews featured Harvard NSEC affiliated faculty, students, and collaborators — <u>George Whitesides</u>, Donald Ingber, Jennifer Hoffman, Tom Babinec and Jacy Bird.

The Amazing Nano Brothers Juggling Show, partially supported by the Harvard NSEC, continued its very popular run at the Museum, with 72 live performances in 2010, to audiences totalling 14,370 people. This 40-minute stage production, written and directed by <u>Carol Lynn Alpert</u>, in collaboration with performers Joel Harris and Dan Foley, explores the structure of matter, nanoscale size and properties, and scanning probe microscopy. The show was invited to perform three times for packed audiences at the USA Science Festival on the National Mall in Washington, D.C. in October 2010, reaching another 1,300 people. In the spring of 2010, Goodman Research Group conducted an evaluation of learning outcomes for this highly-engaging and entertaining show. The evaluation confirmed that the drama of live performance and the medium of juggling were successful not only in captivating and engaging audiences, but also in teaching them. Results showed that both children and adults were learning new information about the field of nanotechnology – and even when the audience members

were already familiar with concepts, the performance provided excellent reinforcement and clarity for deeper understanding.

Talking Nano, the 6-DVD edited collection (partially supported by the Harvard NSEC) of presentations on nanotech research and societal implications, has continued to prove popular, with an additional 350 copies distributed in 2010. Talks by Harvard NSEC researchers George Whitesides, Eric Mazur, Don Eigler, and by former Education Associate Tim Miller, are included in the set, as well as a video of a performance of *The* Amazing Nano Brothers Juggling Show. The DVD set received a "two-thumbs-up" review by Sir Harry Kroto in the Jan/Feb 2009 edition of Materials Today, and is being widely distributed through the NISE Net and talkingnano.net for school, classroom, professional development and home use. The DVD set was distributed to over 200 science museums through the 2010 NanoDays kits. Project Lead The Way, which partners with middle and high schools to provide high quality STEM education, included Talking Nano as a curricular resource in one of its programs and many orders have been received from schools around the country. Each DVD has been tied to national and Massachusetts curricula framework standards. All income from the sales of *Talking Nano* sets is repaid to the supporting grant accounts and used to support ongoing reproduction and distribution of these resources

Lastly, the Museum expanded its nano-education reach in a few new ways – Karine developed an introductory "What is Nanotechnology?" classroom lesson for middle school students and presented it to eight science classes of 6th-grade students at Bigelow Middle School in Newton, MA; and hands-on nano activities were incorporated into one of the Museum's summer courses, "Environmental Extremes," for upper-elementary/middle school aged children. These activities formed the basis for a day exploring the smallest things in the universe.

Professional Development and Science Communication Training

The MoS NSEC team has been developing and delivering three types of science communication training programs for NSEC students and postdoctoral fellows.

Based on the success of several previous 4-day Public Communication Internships and using the feedback from past participants, the MoS NSEC team designed a more intensive 6-day Science Communication Internship that was held in January of 2010. This was attended by five NSEC graduate students who reported great satisfaction with the program and prototyped several successful nano outreach products that were tested with museum visitors. These students participated in subsequent outreach events and also assisted in our "Sharing Nanoscience with Hands-On Demos" training at Harvard on Mar. 2 to prepare other volunteers for NanoDays.

The MoS NSEC team also provided a workshop in science demonstration skills and inquiry-based learning for graduate students. This helped prepare students to volunteer at the Museum during the NanoDays events.

In addition to professional development workshops for NSEC students, the MoS NSEC team continues to regularly present professional development for museum professionals and K-12 teachers who are trying to incorporate more nanoscale science and engineering in their classrooms.

C.L. <u>Alpert</u> contributed to the Harvard NSEC's graduate seminar in Applied Physics with a seminar entitled: Nanotech and Society—Issues and Perspectives for Researchers.

10.5.2. Use of Shared Experimental Facilities

MoS concentrates on public engagement and thus makes little use of NSEC research facilities. One noteworthy exception is the aforementioned communication internship: students produced short films about their research work, filmed on location in their respective laboratories. Dragonfly TV also filmed at Harvard. The internship students make liberal use of MoS facilities while engaged in the internship.

10.5.3. Outreach and Knowledge Transfer

Harvard NSEC faculty and MoS collaborators provide active leadership in the activities of the NSF-funded Nanoscale Informal Science Education Network. PI Robert Westervelt continues to serve as chair of the Advisory Board; researchers George Whitesides and Eric Mazur continue to serve as advisors; NSEC Education Director Kathryn Hollar serves as a "Thinking Partner;" Carol Lynn Alpert serves as a Co-PI, and Tim Miller contributed significantly to the work of the NISE Net programs team and regional expansion team. Tim's live presentations, developed with Harvard NSEC support, are being packaged for distribution throughout the NISE Network, and program presenters at other museums and research centers will be able to adapt and present them for their own audiences. Carol Lynn Alpert wrote several articles and gave several talks on forming effective Research Center - Informal Science Education partnerships, at the Association of Science-Technology Centers, the Global Nanoscale Science and Engineering Education Workshop, and through a web and video conference seminar offered through the National Center for Teaching and Learning in Nanoscale Science and Engineering. <u>R.M.</u> Westervelt and <u>C.L.</u> Alpert shared the NSEC – MoS partnership experience at a meeting in Philadelphia organized by the American Physical Society and the Franklin Institute and at the annual December NSF NSE Grantees meeting. T. Miller participated in five NISE Net regional workshops and shared information with science museum staff about working with research centers and doing nano-public education and outreach.

11. OUTREACH AND KNOWLEDGE TRANSFER

The NSEC has strong partnerships with researchers from national laboratories, industry, and international institutions. During the past year, Center researchers worked closely with members of the Nanoelectronics Research Initiative (NRI) under a supplemental award to the NSEC aimed at ultra-small electronics. The NSEC co-sponsored a workshop at RIKEN in Japan on the Frontiers of Nanoscale Science and Technology (FNST) that brought together leading researchers from industry as well as many of our national and international collaborators. New international collaborators joined the NSEC and the successful visitor program continued that allows our postdoctoral fellows and graduate students to travel and work directly with our partners. These exchanges provide valuable educational and professional experiences. Several international delegations visited the Center and there were a number of talks given by industrial researchers. The NSEC also supported community-building endeavors through the postdoctoral fellow and graduate student coordinated research exchange seminars and courses. These activities are described in more detail below

NSF-NRI Supplement in Nanoelectronics

The NSEC maintains close ties with members of the Nanoelectronics Research Initiative (NRI). George Bourianoff, for example, has been a member of our External Advisory Committee. Meetings with members of the NRI during the past several years have identified areas of overlap between the NRI forward-looking 'research vectors' and ongoing research in the NSEC. When a supplement was announced by the NSF-SIA for graduate student and postdoctoral fellow to NSF Centers in nanoelectronics, a successful supplemental proposal was submitted to the NSF to synthesize and characterize oxide nanostructures. Assistant Professor <u>Shriram Ramanathan</u>, who came to Harvard from Intel, is one of the senior investigators involved in the research. The goal of the research effort is to understand mechanisms governing phase transitions in oxide thin films and how they are affected by temperature and electric fields. The effort has been jointly



Figure 11.1. Members of the Nanoelectronics Research Initiative (NRI) review committee with <u>Shriram Ramanathan</u> and his team (*left*); <u>Shriram Ramanathan</u>, Dmitry Ruzmetov, and Gokul Gopalkrishnan (*right*) giving an internet-based workshop on *Ultra-fast Semiconductor Switches* to the NRI community, May 2010.

funded by NSF at \$50k/yr and by the SIA/NRI through a gift award of \$50k/yr, extending over three years. Recent results by <u>Ramanathan</u> and his team have demonstrated electrically triggered metal-insulator transitions in vanadium oxide thin films at room temperature that is an important step in advancing new oxide electronics that incorporate phase transitions for use as ultra-fast switches. The ability to control the switching threshold could be the next stage in developing these nanostructures as novel solid-state sensors, as well. <u>Ramanathan</u> and his group have given an internet-based workshop on ultra-fast switches to the NRI community (Fig. 11.1) and he has organized recent MRS symposiums on Beyond CMOS – New Electronic Materials and Devices in conjunction with researchers participating in the NRI consortium.

International Technology Roadmap for Semiconductors (ITRS) — Emerging Research Devices (ERD) and Advances in Computational Nanoscience

The International Technology Roadmap for Semiconductors (ITRS) is the fifteenyear assessment of the semiconductor industry's future technology requirements. These future needs drive present-day strategies for worldwide research and development among manufacturers' research facilities, universities, and national laboratories.

The Emerging Research Devices (ERD) Section of the ITRS evaluates new approaches from academic and industrial labs that could lead to devices that go beyond the ultimate scaling of CMOS technology. <u>Robert Westervelt</u> participated in the Emerging Research Logic Devices meeting in Montreux, Switzerland. The technologies considered range from one-dimensional structures such as nanotube and nanowire FETs, to single-electron transistors, to spin transistors — all part of the research of our NSEC. A lively discussion between academic and industrial researchers during the meeting about the merits and limitations of different types of devices provided an important connection between our Center's research and future nanoelectronics for the semiconductor industry.

<u>Westervelt</u> was also invited by S. Shankar of Intel to serve as an expert panelist at the Spring MRS meeting Symposium on Advances in Computational Nanoscale, which has also been identified in the ITRS fifteen-year review as a key cross-cutting research area. The panel discussed the challenges in the development of carbon-based nanoelectronics and the role computational methods can play in guiding materials fabrication in tailoring device properties and performance.

Industrial Interaction and Technology Transfer

The NSEC continues to build partnerships between academic research and industry, often working with the respective institutional industrial liaison offices. At Harvard, for example, Center researchers work closely with the Office of Technology Development (OTD) led by Issac Kohlberg in forging new collaborations through company visits, such as meetings with scientists from Lockheed Martin (Fig. 11.2), and to manage intellectual property from the Center. Other industrial scientists visited the NSEC during the year to give talks on their company's research. At the same time, industrial support for NSEC-

related research not only leverages our NSF NSEC support, but also provides intellectual stimulus for important and relevant problems. Many of the industrial projects have an international component such as the fluid dynamics project studying the fundamental nature of the float-glass process with Saint-Gobain Research (Fig. 11.2). This project has been carried out at the Saint-Gobain Laboratory in Paris and will be continuing with



Figure 11.2. Joanna <u>Aizenberg</u> speaking to a delegation of scientists from Lockheed Martin (*left*); Dr. Michael Zimmerman from Saint-Gobain talking during a visit to the Center (*right*).

industrial scientists at their new, local laboratory in Northboro, MA. As another important example, Schlumberger recently relocated their research laboratory from Connecticut to Cambridge to be in closer proximity to MIT and Harvard. Several of the NSEC faculty members are working closely with Schlumberger researchers on new microfluidic sensor applications and multiphase flow problems in porous materials.

NSEC researchers also work closely with industry on technology development with patent applications filed in the fields of new porous film assembly processes, micromanipulator arrays, near-field laser antennas, novel nanostructured materials, oxide thin film switches, nanowire single photon source fabrication, and microfluidic devices. These are reported in 14. *Publications and Patents*. The best technology transfer continues to be in the form of Center students and postdoctoral fellows trained in this interdisciplinary fashion for positions in industry and as part of new start-up company formation.

Visitor Exchange Programs



Figure 11.3. (*Left*) Leo Kouwenhoven speaking with NSEC researchers; (*right*) Seigo Tararucha and Yasuhiko Arakawa talking with <u>Robert Westervelt</u> on a visit to the NSEC.

The NSEC has a visitor exchange program between Center universities and the national laboratories to share facilities and carry out collaborative research. The Visitors Program is managed by our Center coordinator to encourage collaborative research by supporting student travel. Leo Kouwenhoven (Fig. 11.3) oversees the student exchange with Delft, which has excellent facilities to make and test nanoscale structures as well as an outstanding graduate program. It is also possible for students to spend a few weeks or months visiting, to learn new skills and conduct research. Seigo Tarucha and Yasuhiko Arakawa (Fig. 11.3) look after similar visits with the University of Tokyo. Fabio Beltram from the National Enterprise for NanoScience and NanoTechnology (NEST) Pisa, Italy visited the NSEC to discuss ongoing collaborations with researchers in the Nanoscale Building Blocks and Imaging at the Nanoscale Clusters. Lars Samuelson and Andre Geim are also active collaborators with members of the NSEC. Samuelson is well known for his synthetic work in semiconductor nanostructures from Lund University in Sweden. Geim, from the University of Manchester, is a leading expert in graphene thin-film research for future electronic application with many ties to researchers in the Imaging Cluster.

There were a number of visits by Center faculty, postdoctoral fellows and graduate students to use facilities and collaborate on research with scientists at other Centers and National Laboratories. Erin Boyd and Halvar Trodahl traveled to Lund University where they worked with researchers to fabricate nanowire quantum dots of InAs and InAs/InP. Shaoyun Huang from RIKEN traveled to Harvard (Fig. 11.4), in turn, to learn and perform transport measurements of these nanostructures using the custom-built scanning probe microscope developed in the Center. Pablo Herrero from MIT visited Seigo Tarucha and his group at the University of Tokyo to learn about new methods in fabricating quantum dots. Thomas Balder from the Delft University of Technology visited Harvard to work with <u>Michael Stopa</u> who has developed simulations to guide experimentalists like Thomas with their work on transport in Nanoscale. Mark Jepson came from the University of Sheffield to talk about his new methods for secondary electron dopant imaging using scanning electron and the new He ion microscope systems. A symposium was held to explore the use of parallel computing in scientific problems



Figure 11.4. (*left*) Halvar Trodahl and Shaoyun Huang carrying out transport measurements on nanowire samples from Lund University; (*right*) <u>Michael Stopa</u> and Felice Frankel talking with members of the RIKEN delegation from Japan.

with NSEC researchers and scientists from RIKEN in Japan (Fig 11.4). A memorandum of understanding (MoU) was signed to continue these exchanges that are at the forefront of bringing parallel processing technology to scientific computation in the coming years; the NSEC also co-sponsored the Frontiers in Nanoscale Science and Technology workshop that was held at RIKEN in Japan in January 2011.

Yasuhiko Arakawa	University of Tokyo, Japan
Fabio Beltram	National Enterprise for nanoScience and nanoTechnology (NEST), Pisa, Italy
Piotr Garstecki	Institute of Physical Chemistry Polish Academy of Sciences, Warsaw, Poland
Andre Geim	University of Manchester, UK
Koji Ishibashi	RIKEN, Japan
Maki Kawai	RIKEN, Japan
Leo Kouwenhoven	Kavli Institute of Nanoscience Delft University of Technology, The Netherlands
Eugenia Kumacheva	University of Toronto, Canada
Daniel Loss	National Center of Competence in Research Nanoscale Science, University of Basel Switzerland
Hideo Ohno	Tohoku University, Japan
Maria-Anita Rampi	University of Ferrara, Italy
Carsten Ronning	University of Jena, Germany
Hiroyuki Sakaki	Institute of Industrial Science, Japan
Lars Samuelson	Nanometer Structure Consortium Lund University, Denmark
Seigo Tarucha	University of Tokyo, Japan
Yohinori Tokura	University of Tokyo, RIKEN, Japan
Hiroyuki Yamaguchi	NTT Basic Research Laboratory, Japan

Table 11.1 International Collaborators

The NSEC has fostered collaborations with a remarkable group of international partners who are not only outstanding scientists but also leaders of pre-eminent research institutes for nanoscale science worldwide (Table 11.1). This is an important outreach activity supported by the NSEC, since much of the best research is done in Japan or Europe. We have seen directly that our researchers learn from our collaborators how to make new structures and devices, how to conduct new experiments, and how to understand theoretically why a device or system works.

International Workshops

In January 2011, the NSEC co-sponsored the Frontiers in Nanoscale Science and Technology (FNST) workshop focusing on recent advances in nanowires, quantum dot, and graphene devices; quantum simulations; photonic and spintronic systems; and oxide



Figure 11.5 Frontiers of Nanoscale Science and Technology (FNST) Workshop at Harvard RIKEN (Japan) in January 2011.

semiconductor devices (Fig. 11.5) held on the RIKEN campus in Japan. The location of the FNST workshops rotates among our partners with invited speakers selected to draw both national and international from the United States, Japan, and Europe. Over 150 researchers from industry, national laboratories, and academe attended with large delegations from the United States, Asia, and Europe with our strong partnerships there. Keynote speakers were Kanstanin Novoselov, Nobel Laureate in Physics 2010, and Hido Ohno (Fig. 11.5, top left and right). The invited speakers included Hendric Bluhm (Harvard), Jonathan Fan (Harvard), Christian Glattli (CEA, Saclay), Tetsuro Hanaguri (RIKEN), Pablo Jarillo-Herrero (MIT), Jennifer Hoffman (Harvard), Leo Kouwenhoven (TU Delft), Gijs de Lange (TU Delft), Heiner Linke (Lund), Daniel Loss (Basel), Fumihiro Matsukura (Tohoku University), Masahiro Nomura (University of Tokyo), Hajime Okamoto (NTT), Hongkun Park (Harvard), Axel Scherer (Caltech), Paul Sheehan (Naval Research Laboratory), Charles Smith (Cambridge), Kota Tateno (NTT), Robert Westervelt (Harvard), Hongqi Xu (Lund), and Michihisa Yamamoto (University of Tokyo). Our NSEC provided student scholarships to graduate student researchers from the NSECs and other U.S. universities who applied and presented their work during poster sessions. Additional support for the workshop was provided by ICORP-JST, CINQIE-JST, RIKEN, and IT-MEXT [Japan]. The FNST workshop was the eighth international workshop since the beginning of the NSEC in 2001. Again this year, the workshop served to bring together the many postdoctoral fellows and graduate students who began collaborations through the visitor exchange program. The workshop is an opportunity to learn what progress has been made since those visits and explore new areas of exploration.

The Center also hosted several international groups during the past year including

England, delegations from France. Germany, Italy, Sweden, and Switzerland. In March, we hosted a delegation of Japanese students sponsored through the NSF/MEXT young scientist exchange program. Several graduate students, postdoctoral fellows, and junior faculty members from our Center, together with young scientists from Japan gave research talks 11.6). We had smaller (Fig. group discussions and tours of the shared experimental facilities during the afternoon. There will follow visits from a delegation of young U.S. scientists, including members from the NSEC that visited Japan in the fall.



Figure 11.6 Yasuo Azuma, a researcher from the MEXT-Japan group, presenting his work during their visit to the NSEC.

Industrial Partnership Workshop

In May 2010, NSEC members participated in the annual meeting of the Industrial Partnership Workshops (IPW) sponsored by Harvard's School of Engineering and Applied Sciences (HSEAS). The IPW is directed by Executive Dean Fawwaz Habbal and is aimed at strengthening external collaborations by facilitating mutually beneficial relationships between outside groups and HSEAS interdisciplinary research groups. The workshop last May on *Nanophotonics and Plasmonic Technologies* was heavily subscribed (www.seas.harvard.edu/partnerships/) with over 130 registrants. NSEC speakers at the IPW included Federico Capasso, Marko Lončar, Evelyn Hu (Fig. 11.7),



Figure 11.7. (*left*) <u>Evelyn Hu</u> speaking and (*right*) interactions during poster session at the Industrial Partnership Workshop, May 2010.

<u>Hongkun Park, Ken Crozier</u>, and <u>Eric Mazur</u>. Following the presentations and a networking activity, there was a poster session with NSEC postdoctoral fellows and graduate students to allow for more interaction between the NSEC researchers and attendees (Fig. 11.7).

Community Building

During the past year, the Center continued to host the Research Exchange seminar that was initiated and directed by NSEC postdoctoral fellows. The seminar is held bi-

weekly at lunchtime during academic the year to encourage NSEC postdoctoral fellows and graduate students to learn about each other's research (Fig. 11.8). The Exchange seminar has blossomed into a venue where graduate students can obtain the advice of the postdoctoral fellows on preparation for oral presentation and then give their talk at the Exchange. On occasion, outside speakers are invited and the seminar is held at Harvard University and MIT. emphasizing both locations



Figure 11.8. Thomas Babinec speaking on the development of nanowire single photon antennas at the Research Exchange luncheon in 2010.

of our NSEC activities in Cambridge.

With the realigned research activities, a major theme of new tool development has emerged. We also initiated a bi-monthly series of meetings for graduate students, postdoctoral fellows and faculty members involved in imaging and other new tool development. These meetings, often involving leading industrial scientists, helped to promote the exchange of best practices and technical expertise among members of the NSEC community.

In the Spring of 2011, the NSEC sponsored the academic course AP298r: Interdisciplinary Biology, Chemistry, Engineering, and Physics, which covered

fundamental concepts in nanoscale research as well as possible applications in a series of lectures by twenty-two NSEC faculty members (Fig. 11.9). Topics for the course were drawn from Tools for Integrated Nanobiology, NanoBuilding Blocks, and Imaging Electrons at the Nanoscale. The course included tutorial lectures on modeling at the nanoscale and the use of electron microscopy for image analysis. A paper and oral presentation on one of the topics were required and the lectures were being transcribed by the students at a level appropriate for secondary teachers as a further



Figure 11.9. <u>Cynthia</u> <u>Friend</u> giving her AP298r lecture.

extension of our outreach efforts. A dozen students took the course for credit and another twelve researchers and staff members regularly attended the class as auditors. The lectures are available on the Harvard website.

Research from the NSEC, particularly work from Cluster 1. Tools for Integrated Nanobiology, has lead to low-cost sensors that address needs in low-income populations of the U.S. and in the Developing World. <u>George Whitesides</u> was the keynote speaker at

a recent Innovations for Global Health Symposium (Fig. 11.10) organized by the Harvard Institute for Global Health (HIGH). The Symposium brought together academic researchers, prominent industrial scientists and, importantly, students who are now doing field work in Africa to meet the needs of this larger community. Whitesides is also initiating startup companies based on industrial applications of soft lithography for functional components and bioanalytical devices for use in developing economies and by first responder personnel of homeland security.



Figure 11.10. <u>George Whitesides</u> (*right*) answers a question following his presentation at a Harvard Initiative on Global Health (HIGH) workshop.

12. SHARED AND OTHER EXPERIMENTAL FACILITIES

The shared facilities are operated to encourage hands-on research by experienced and qualified users, and as educational tools for students and researchers from other disciplines who can benefit from their use. A broad range of facilities teaches students the skills of nanofabrication, imaging, and synthesis that they will need after graduation, and opens new avenues of investigations for all disciplines. The shared experimental facilities play a special role in fostering interdisciplinary exchanges. The facilities are the natural meeting places where students from all parts of the Center learn from one another and share technical expertise.



Figure 12.1. Recently opened Northwest building (*left*) and the new Laboratory for Integrated Science and Engineering (LISE) building (*right*) at Harvard University.

New Laboratory Construction

Harvard University supported the construction of the new, 470,000 sq. ft. Northwest building (Fig. 12.1) that was recently opened for occupancy. The building is, like other new science buildings built on campus, not dedicated to any particular science department but will be used to foster interdisciplinary research and teaching efforts with initial concentrations in the neurosciences, bioengineering and biophysics; the latter areas have strong overlap with ongoing NSEC cluster research. The new Northwest building joins the 135,000 sq. ft. Laboratory for Integrated Science and Engineering (LISE), which opened in the Summer of 2007 (Fig. 12.1), as another new interdisciplinary space in the North Yard. Both buildings create a research environment that centralizes major experimental facilities and fosters cross-disciplinary research. An important programmatic element in these new buildings is common space to promote collaborative exchanges. The LISE building includes extensive vibration-free space that houses major cleanroom and nanofabrication facilities, advanced imaging laboratories, and facilities for materials synthesis. In the past year, there has been substantial renovation for NSEC-associated faculty space as well as further build out for newly arriving imaging and fabrication instrumentation. These state-of-the-art facilities are available to all researchers in the NSEC institutions but also nationally through the NSF/National Nanotechnology Infrastructure Network (NNIN).



Figure 12.2. (*left*) Dr. Ning Wu working in Prof. Joanna Aizenberg'g laboratory; (*right*) Undergraduates working in the new Bioengineering Teaching Laboratory in Pierce Hall at Harvard University.

Harvard University also supported the construction of a new building in the North Yard at 60 Oxford Street. The top two floors, along with one floor in the adjacent Engineering Sciences Lab (ESL) at 58 Oxford Street are home to faculty in Bioengineering. Asst. Professor <u>Parker</u>'s laboratories, for example, are located in this new building where he carries out his collaborative work in the Tools for Integrated Nanobiology Cluster. The University has also made significant investments in new laboratory space for NSEC participants Joanna Aizenberg (Fig. 12.2), Evelyn Hu, and <u>Marko Lončar</u>. In addition, the University has recently completed major construction (\$2M) of new student training laboratories in bioengineering (Fig. 12.2), biophysics, computer aided design, and micropatterning. These recent buildings and teaching laboratories will continue to draw the science community together, across traditional departmental boundaries and be spaces where researchers can interact in new common experimental and training facilities.

Integrated Management of Facilities and Technical Staff

1999 Harvard In January announced the commitment to launch several new interdisciplinary research centers in the sciences. The faculty had identified a strong scientific and technological need for the understanding and development of mesoscale materials and structures. This challenge would new require sophisticated facilities (Fig. 12.3) for imaging, nanofabrication, synthesis, and growth. The Center for Imaging and Mesoscale Structures (CIMS) was born from this vision. Halperin, Co-PI of NSEC, was the first Scientific



Figure 12.3. Training class for researchers on the new Zeiss Libra 200 MC TEM.



Director of CIMS. Harvard University supports the Center for Imaging and Mesoscale Structures (CIMS) to support research and education in the area of nanotechnology and mesoscale science. A main mission of CIMS was the provision, operation and maintenance of complex facilities for imaging and fabrication. CIMS began to purchase equipment and hire technical staff as well as construct a second cleanroom in the basement of the Gordon McKay Laboratory. The management of the shared facilities at

Harvard from CIMS, MRSEC and NSEC were integrated in 2002; the management boards of these Centers work closely together. Importantly, instrumentation for new CIMS facilities are open to all students, research associates, staff and faculty of the NSEC (regardless of institution), and to all NSEC collaborators. This integration made CIMS the main source for centralized user facilities in the Oxford Street science campus. In Marcus September 2004, became the Scientific Director of CIMS. In April 2005, CIMS was renamed to the Center for Nanoscale Systems and they launched their new website (www.cns.fas.harvard.edu). In July 2010, Roy Gordon, a physical chemist,



Figure 12.4. Roy Gordon, CNS Scientific Director.

became the CNS Scientific Director (Fig. 12.4). CNS currently has nineteen full-time technical staff members and the available instrumentation is organized in three thematic areas: Imaging and Analysis; Nanofabrication (including cleanroom operation); and Materials Synthesis. The complete list of CNS shared facilities and instrumentation are given at: (www.cns.fas.harvard.edu/facilities/).

Recently a Zeiss Libra 200KV monochromated, aberration corrected Scanning Transmission Electron Micoscope (STEM) arrived and was installed in the LISE imaging suites. The new Libra 200 STEM has a resolution of 0.09 nm with analytical capability of energy- filtered spectroscopy and energy dispersive X-ray analysis (EDS). The new Libra 200 MC TEM (Fig. 12.3) has a demonstrated resolution down to 0.074 nm. The STEM and TEM are the only aberration corrected electron microscopes operating in the New England area and Zeiss co-sponsored a workshop on Aberration Corrected Electron Microscopy to introduce these new tools to area researchers. Angus Kirland, a leader in the field of aberration corrected electron microscopy from Oxford University, was a featured speaker during the workshop.

Two new field emission scanning electron microscopes have also been installed: a Zeiss Ultra, with ultimate imaging resolution of 1 nm and a Zeiss Supra for imaging and analytical work equipped with electron beam diffraction analysis (EBSD) and EDS. CNS also has a new Elionix STS-7000 E-beam system for nanometer electron-beam lithography. The Elionix system is complemented by a Raith 150 E-beam instrumentation as well as a JEOL JSM-7000F beam writer for high-current lithographic work. A new multi-beam FIB system, a Zeiss NVision 40, has also been installed that can be used for microfabrication, patterning and sample preparation.

CNS makes a direct, cost-sharing contribution to the NSEC through annual equipment acquisitions. The support and operation of the shared experimental facilities are the responsibility of CNS, with the only recharge to CNS from the NSEC in the form of user fees. The CNS annual budget for the technical staff and operating costs of the shared facilities (\$3 M/yr.) represents substantial leveraging of the NSF/NSEC support.

National Nanotechnology Infrastructure Network (NNIN)

UC Santa Barbara and Harvard University are two of the fourteen members of the National Nanotechnology



Infrastructure Network (NNIN) that began in March 2004 and was renewed in 2009. CNS is also responsible for managing the Harvard portion of the NNIN activity (www.nnin.org) that further reaches out to a national user base. The areas of focus at Harvard are soft lithography and the assembly of nanoparticle and molecular electronics; theoretical simulations of electron states and transport in nanoscale systems. These areas have significant overlap with research in the NSEC.

<u>Michael Stopa</u> leads the coordination of the computational initiative in NNIN (Fig. 12.5). <u>Stopa</u> was previously at NTT in Japan and gave several seminars as part of the



Figure 12.5. <u>Michael Stopa</u> providing theoretical guidance to REU students Daphne Paparis (Haverford) and Beatrice Perez (Univ. of Puerto Rico) along with Alan Aspuru-Guzik (*left*); <u>George Whitesides</u> speaking at the NNIN/C workshop (*right*).

international exchange programs of the NSEC. Like the NNIN experimental program, NNIN/C is a multi-university initiative, the object of which is to establish a national computing resource that provides hardware resources and simulation tools dedicated to nanoscience research for the academic and industrial research communities. The software tools include commercial software packages for design and analysis, of nanometer scale devices as well as some of the latest academic advances in nanoscale modeling and simulation software. A workshop *Synergy Between Experiment and Computation in Nanoscale Science* was recently held that attracted over 90 participants, from other NNIN computational sites, across the nation, and from 12 countries. NSEC speakers at the workshop included <u>Heller, Kaxiras, Marcus</u>, and <u>Whitesides</u> (Fig. 12.5).

Fettah Kosar (Fig. 12.6) oversees the operation of the Soft Lithography Foundary (SLF), which supports academic and industrial researchers and trains users on master fabrication and soft lithography. Before joining CNS, Kosar was a senior fellow in Paul Yager's group at UW, working on the design and development of a microfluidic point-of-care system for the rapid and on-the-field diagnosis of life-threatening infectious diseases in third-world countries. The University of Washington is another of the NNIN nodes that specializes in soft lithographic work. CNS organizes soft lithography



Figure 12.6. Fettah Kosar (*left, middle*) supervising students in the materials preparation facility; Jiangdong Deng (*right, middle*) assisting graduate student, Elaine Yee, and CNS staff member, Jason Tresback, with a surface characterization study in LISE.

technical forums with other members of the network to disseminate and share technical knowledge and practical information on soft lithography across NNIN sites. The nanofabrication facilities are managed by Jiangdong Deng (Fig. 12.6) who came to Harvard from Nanoptics, where he worked on the development of specialty optical fiber materials, after completing his doctoral studies at Virginia Tech.

User Statistics

The shared facilities are heavily subscribed with more than 1165 users from March 2010 through February 2011. Users came from many different institutions and varied technical fields. Below (Fig. 12.7) is statistical information of the shared facility users. Note that the Other category in the Institution Type chart includes small and large

corporations, state and federal agencies, and international institutions. Most projects cut across many technical fields. In fact, it is part of the mission of CNS and NNIN to promote such interdisciplinary research. However, for the sake of tracking trends, users must select only one technical field when applying to the CNS/NNIN User Program.



Figure 12.7. Shared Facilities user statistics from March 2010 to February 2011.

Student Training and Safety

Equally important to the acquisition of state-of-the-art instrumentation in the pursuit of our research program, is the availability of talented technical staff that provides training through regularly scheduled courses and hands-on laboratory instruction. The technical staff ensures that environmental health and safety procedures are followed and guidance is provided until researchers are certified as self-users. The staff also helps researchers develop new fabrication processes and measurements techniques, and upgrade equipment in response to changing research needs.

These cutting-edge instruments also are used in many of the Research Experience for Undergraduate (REU) and Teacher (RET) projects (Fig. 12.8) and, in many cases, are resources that are not available to participants in these summer research programs back at their home institutions. This is an important illustration how the NSEC brings together talented researchers, who serve as mentors for undergraduates and teachers, technical staff with expertise, and essential (and often sophisticated) experimental facilities. Several REU students have returned to Harvard after finishing their undergraduate degrees as graduate students demonstrating the importance this activity has on their career choices.



Figure 12.8. (*Left*) Sarah Kostinski (REU, Univ. of Michigan) working with her mentor, David Woolf on her project investigating forces from coupled surface plasmons; (*right*) Sarah, David, Arthur Spector (REU, Harvard) and Prof. <u>Federico Capasso</u> following an afternoon research meeting.

Other Facilities

Center participants have access to other imaging, cleanroom, and synthesis facilities at MIT and UC Santa Barbara. The molecular beam epitaxy (MBE) facilities at UC Santa Barbara, for example, have long been among the premier facilities available worldwide. Under the direction of Chris Palmstrom, UCSB recently completed installation of a new, interconnected 5-MBE chamber facility (Fig. 12.9) featuring: (1) A modified VG V80H MBE station for As- and Sb-based III-V semiconductors and As-and Ga-based metallic compounds, (2) a VG V80 for metal oxide growth, (3) a modified Gen-II EMOF MBE for metallic compound growth with atomic absorption and X-ray energy dispersive spectrometry for composition control, (4) a VG V80 MBE system for Ti-based metallic compounds, and (5) a VG V80H chemical beam epitaxy (CBE) growth system for As- and P-based III-Vs. These growth and deposition systems are complemented by a number of *in situ* surface characterization tools, including an Omicron variable temperature (50-750K) scanning probe microscope (STM and AFM),



Figure 12.9. The new interconnected 5 molecular beam expitaxy (MBE) growth and characterization facility at UC Santa Barbara (*left*); Chris Palmstrom (UCSB) giving a talk at our Center (*right*).

Auger and X-ray photoelectron spectroscopies, reflection high-energy and low-energy electron diffraction, and *in situ* current-voltage and capacitance-voltage measurements.

The NSEC has supported exchanges through the travel program by students who are experts in materials growth (UC Santa Barbara) to meet with students working in transport measurement (Cambridge). The National Laboratories also have excellent capabilities that help NSEC researchers, particularly those in micro-electromechanical structure (MEMS) fabrication facilities at Sandia (<u>www.cint.lanl.gov</u>). <u>Westervelt</u> serves on the Advisory Board of CINT.

Center participants benefit strongly from international collaborations with Delft University of Technology in The Netherlands, and the University of Tokyo, the Institute for Industrial Research and NTT in Japan. These institutions are world leaders in mesoscopic science and engineering. Leo Kouwenhoven has created a visiting program with Delft to exchange students and share facilities for collaborative research. Hiroyuki Sakaki and Seigo Tarucha are also coordinating visits with the University of Tokyo, the Institute for Industrial Research, and NTT for the design and fabrication, and testing of nanoscale structures (see also NSEC International Workshops in *11. Outreach and Knowledge Transfer*, above). Our international collaborators have contributed to the travel support for student exchanges and to support joint workshops.

13. PERSONNEL

Administrative Structure

The Nanoscale Science and Engineering Center consists of twenty-seven senior investigators at four institutions (Harvard University; Massachusetts Institute of Technology; Museum of Science, Boston; and the University of California at Santa Barbara) with important collaborations with researchers from national laboratories, industry and international institutions. The NSEC offers dynamic educational programs for students and teachers at all academic levels and pursues unique opportunities to bring this research to the public through innovative programs with the Museum of Science in Boston. Harvard University is the coordinating institution for the NSEC. The administrative structure of the NSEC is shown below (Fig. 13.1).



Figure 13.1. Administrative structure of the NSEC.

The Center is directed by the PI <u>Robert</u> <u>Westervelt</u>, who has a joint faculty appointment in the School of Engineering and Applied Sciences (SEAS) and the Department of Physics, and the Co-PI <u>Bertrand Halperin</u>, in the Department of Physics at Harvard. Decisions on research allocations and other major issues are made with the advice of the NSEC Executive Committee, shown in Table 13.1 (Fig. 13.2). Funding allocations are decided each year by the Executive Committee based on proposals for collaborative research and demonstrated progress in the previous year. New faculty members are added when their research overlaps with the goals of the Center and innovative projects, unrelated to the current program, may also be approved for funding


Figure 13.2. NSEC Executive Committee.

on a rapid and shorter-term basis as Seed Projects. The NSEC Executive Committee considers major capital equipment expenditures, evaluates staff appointments, and takes an active role concerning the allocation and budgeting process. In addition to the PI <u>Westervelt</u>, co-PI <u>Halperin</u>, and the cluster coordinators, members include <u>Friend</u>, <u>Graham</u>, <u>Habbal</u>, <u>Hollar</u>, and <u>Murray</u>. All of the *ex officio* and at large members play key roles in support of the NSEC.

Joanna Aizenberg	Cluster 1 (coordinator)	Harvard	SEAS, CCB, Radcliffe
Raymond Ashoori	Cluster 3 (coordinator)	M.I.T.	Physics
Moungi Bawendi	Cluster 2 (coordinator)	M.I.T.	Chemistry
Federico Capasso	At Large	Harvard	SEAS
Cynthia M. Friend	At Large, CCB Chair (04-07)	Harvard	CCB and SEAS
Robert Graham	NSEC Assistant Director	Harvard	SEAS
Fawwaz Habbal	Executive Dean, ex officio	Harvard	FAS and SEAS
Kathryn A. Hollar	Education Director, ex officio	Harvard	SEAS
Bertrand I. Halperin	NSEC co-PI	Harvard	Physics
Cherry Murray	Dean, ex officio	Harvard	SEAS
Hongkun Park	Cluster 2 (coordinator)	Harvard	CCB and SEAS
Robert M. Westervelt	NSEC PI, Director	Harvard	SEAS and Physics
George M. Whitesides	Cluster 1 (coordinator)	Harvard	ССВ

Table 13.1Executive Committee

SEAS: School of Engineering and Applied Sciences

CCB: Chemistry and Chemical Biology

FAS: Faculty of Arts and Sciences

<u>Cherry Murray</u> joined Harvard in July 2009 as the new Dean of the School of Engineering and Applied Sciences (SEAS). <u>Murray</u> came from Lawrence Livermore National Laboratory (LLNL) and recently served as President of the American Physical Society (APS). The NSEC is administered through Harvard's SEAS and benefits from the use of SEAS services (*i.e.*, purchasing and accounting) at no direct cost. <u>Fawwaz</u>

<u>Habbal</u> is Executive Dean for Research and Planning in SEAS. He came to Harvard from industry and oversees the annual Industry Partnership Workshop (IPW) each spring. The NSEC annual meeting and advisory board have been held in proximity to the Industry Partnership Workshop. This timing takes advantage of presentations that are of interest to current and potential industrial collaborators.

<u>Cynthia Friend</u> serves as Associate Director of the Harvard MRSEC and is also an Associate Dean of FAS. She was Chair of the Department of Chemistry and Chemical Biology (CCB) from 2004-07. She is also the PI of the NSF-REU Site award in

Materials Research that is jointly run with the NSEC, REU and RET programs. Friend plays a key role in advising the senior University administrators on issues of gender and of importance to members of underrepresented groups in science and engineering. She was Co-Chair of the national workshop, "Building Strong Academic Chemistry Departments through Gender Equity," which provided recommendations for academic institutions and federal agencies and continues to give invited talks on the subject at NSFsponsored workshops and other national meetings (Fig. 13.3).



Figure 13.3. <u>Cynthia</u> <u>Friend</u> meeting with women in physical sciences.

There is an important relationship with the Center for Nanoscale Systems that has responsibility for the integrated management of the shared facilities. Gordon, a well-known inorganic chemist, became Scientific Director of CNS in July 2010; <u>Marcus</u> and <u>Halperin</u>, served as the previous Scientific Directors. Costs of technical staff and major instrumentation, all available to NSEC researchers, are borne by the University. This represents substantial leveraging of the NSF/NSEC support. CNS is also the managing institution for activities of the National Nanotechnology Infrastructure Network (NNIN) at Harvard. UC Santa Barbara is also one of the thirteen partner institutions of NNIN.

The NSEC Assistant Director is the senior non-faculty person who is responsible for the Center's operation. They help supervise the staff, oversee programs and workshops, and manage the preparations of reports. A Center coordinator administers the NSEC's Visiting Program to help students, researchers, and faculty members from other institutions collaborate with our researchers through visits to carry out research and utilize the shared facilities, as needed. The Center staff members are also involved in developing new connections between our Center researchers and scientists in industry and national laboratories. <u>Kathryn Hollar</u> is the Director of Educational Programs in SEAS (Fig. 13.4). <u>Hollar</u> came from the Department of Chemical Engineering at Rowan University in Glassboro, NJ. She manages the Center programs in education at all levels, and promotes outreach

to public schools and the general public. <u>Hollar</u> works closely, for example, with the Museum of Science staff to adapt new laboratory results for the Current Science & Technology Center (MoS/CSTC) and as part of the NSF/Nanoscale Informal Science Education (NISE) Network. They work together to provide professional development tools through workshops for our undergraduates and K12 teachers. She is also coordinating the REU Site award with close partnerships to the Cambridge Public Schools, a majority minority school system. The NSEC makes an annual contribution for salary, but the largest portion of her support comes from the University.



Figure 13.4. <u>Kathryn Hollar</u> (*right*) assisting with interactive demonstration being developed with the Museum of Science as shown here with <u>B.I. Halperin</u>, RET participants, and NSEC researchers.

Advisory Committee

An Advisory Committee, shown in Table 13.2, consists of leading figures in business and industry and the national laboratories, provides guidance to the Executive Committee, particularly in its efforts to expand and intensify links between the NSEC and industry.

The Advisory Committee serves as an external board concerning the importance and relevance of the Center's research and educational programs. The Advisory Committee also meets with our NSEC postdoctoral fellows and graduate students, offering advice and assistance in career development. The industrial members of the Advisory Committee are also helpful in establishing visits between Center researchers and industrial executives and research scientists to explore collaboration as well as applications of the Center's research.

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
Paul L. McEuen	Cornell University
Carmichael Roberts	WMR Biomedical
John Rogers	University of Illinois
Richard Slusher	Lucent Technologies
Tom Theis	IBM, T. L. Watson Research Center
Richard Slusher	Lucent Technologies
Tom Theis	IBM, T.J. Watson Research Center
Ellen D. Williams	University of Maryland

Table 13	.2. 'Adv	isory Co	mmittee
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Selection Guidelines and Procedures

The following guidelines are used in evaluating potential new Research and Seed Projects, major equipment purchases for Shared Facilities, and in the decisions to fund educational or outreach programs.

- 1. High-quality research with clear and concise scientific goals
- 2. Interdisciplinary nature
- 3. Originality; high-risk research with high potential
- 4. Relevance to existing or planned research groups
- 5. Career development for younger faculty
- 6. Promotion of innovative teaching, training and learning in materials science

Director's Reserve

Because of the ever-changing and fast-paced nature of scientific research, unexpected occasions to fund an exciting research idea, a new faculty member, or new equipment will often arise. Reserved funding is allocated to the Director's Fund so that these opportunities may be fully exploited. Funding of students is emphasized to foster their career development.

Administration of Center Visiting Programs and Outreach Activities

The NSEC supports visiting programs to help graduate and undergraduate students do collaborative work at the academic institutions; at the national laboratories, with

researchers in industry; and with our international partners-the University of Technology at Delft, the University of Tokyo, NEST in Italy, the University of Basel, and Lund University (Sweden). The NSEC also supports activities such as the Research Exchange program that is organized NSEC postdoctoral by fellows and graduate students and meetings of NSEC cluster groups (Fig. 13.5) that promote a sense of community within the Center.



Figure 13.5. Bi-weekly meeting of the Research Exchange group, organized by NSEC postdoctoral fellows and graduate students.

14. NSEC PUBLICATIONS and PATENTS

- *Note*: ^{*a*} signifies research principally supported by the NSEC ^{*b*} signifies research partially supported by the NSEC ^{*c*} signifies research where NSEC Facilities were utilized
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- 15. Ferrigno, Rosaria; Jiang, Xingyu; Whitesides, George M., "Fluid Delivery System and Method;" Exclusive Licensed; Application #11/181,371; Filed: 7/14/2005; Patent #2564211; Issued: 8/3/2010 (USA).
- 16. Gracias, David H.; Tien, Joe; Whitesides, George M., "Assay Device and Method;" Licensed; Application #11/352,923; Filed: 2/13/2006; Patent #7736890; Issued: 6/15/2010 (USA).
- 17. Jacobs, Heiko O.; Whitesides, George M., "Fluidic Arrays and Method of Using;" Licensed; Application #10/316,997; Filed: 12/11/2002; Patent #7741130; Issued: 6/22/2010 (USA).

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- 1. **Mazur, Eric**; Shen, Mengyan; "*Femtosecond Laser-Induced Formation of Submicrometer Spikes on a Semiconductor Substrate*;" Licensed; Harvard Case 2536; Application #11/196,929; Filed: 8/4/05; Patent #7442629; Issued: 10/25/08.
- 2. **Mazur, Eric**; Winkler, Mark T.; "Engineering Flat Surfaces On Materials Doped Via Pulsed Laser Irradiation;" Licensed; Harvard Case 3121; Application #12/864,967; Filed: 7/28/10.
- 3. **Mazur, Eric**; Shen, Mengyan; "*Femtosecond Laser-Induced Formation of Submicrometer Spikes on a Semiconductor Substrate*;" Licensed; Harvard Case 2536; Application #12/235,086; Filed: 9/22/08; Patent #7884446; Issued: 2/8/11.
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- 10. Carrilho, Emanuel; Martinez, Andres W.; Mirica, Katherine A.; Phillips, Scott T.; Siegel, Adam C.; Whitesides, George M.; Wiley, Benjamin J.; "Three-

dimensional Microfluidic Devices;" Licensed; Application #12/934,499; Filed: 9/24/2010.

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- Dickey, Michael D.; Martinez, Andres W.; Phillips, Scott T.; Rozkiewicz, Dorota Idalia; Siegel, Adam C.; Whitesides, George M.; Wiley, Benjamin J.; "Paper-Based Microfluidic Systems;" Licensed; Application #2009228012; Filed: 9/23/2010 (AUSTRALIA).
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- 21. Duffy, David C.; Jackman, Rebecca J.; Jensen, Klavs F.; Vaeth, Kathleen; Whitesides, George M.; "Methods of Alteration of Surface Affinities Using

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- 23. Ferrigno, Rosaria; Jiang, Xingyu; Whitesides, George M., "Fluid Delivery System and Method;" Licensed; Application #11/181,371; Filed: 7/14/2005; Patent #2564211; Issued: 8/3/2010 (USA).
- 24. Gracias, David H.; Tien, Joe; Whitesides, George M., "Assay Device and Method;" Licensed; Application #11/352,923; Filed: 2/13/2006; Patent #7736890; Issued: 6/15/2010 (USA).
- 25. Jacobs, Heiko O.; Whitesides, George M., "Fluidic Arrays and Method of Using;" Licensed; Application #10/316,997; Filed: 12/11/2002; Patent #7741130; Issued: 6/22/2010 (USA).
- 26. Linder, Vincent; Sia, Samuel K.; Whitesides, George M., "Elastomeric Mask and Use in Fabrication of Devices, Including Pixelated Electroluminescent Displays;" Licensed; Application #2,564,211; Filed: 7/26/2006; Patent #2329412; Issued: 9/21/2010 (CANADA).
- 27. Whitesides, George M.; "Vertical Flow-through Devices for Multiplexed Elisa Driven by Wicking;" Licensed; Applications #61/416,453; Filed: 11/23/20.

15. HONORS AND AWARDS, 2010–2011

Joanna Aizenberg

- First Place in International Science and Engineering Visualization Challenge to a graduate student Sung Hoon Kang, February 2010
- NSF Graduate Research Fellowship awarded to graduate student Lauren Zarzar, April 2010
- National Defense Science and Engineering Graduate Fellowship awarded to graduate student Lauren Zarzar, April 2010
- Naff Award Lectureship, University of Kentucky, April 2010
- Jerome B. Cohen Distinguished Lectureship, Northwestern University, May 2010
- The Eastman Chemical Company Award Lectureship, Goodyear Polymer Center, October 2010
- Molecular Foundry Distinguished Lectureship, Lawrence Berkeley National Labs, October 2010
- W.J. Chute Distinguished Lectureship in Chemistry, Dalhousie University, October 2010

Raymond Ashoori

Fellow of the American Physical Society 2009, awarded in 2010

Moungi Bawendi

American Chemical Society Award in Colloid and Surface Science, American Chemical Society, 2010

Federic Capasso

- Berthold Leibinger Zukunftspreis Prize, Berthold Leibinger Stiftung, 2010
- An international award for excellent research on the application or generation of laser light
- Julius Springer Prize for Applied Physics, Springer, 2010
- For numerous pioneer achievements in the field of nanoscale physics and related materials applications.

Recognized as a Laser Luminary by SPIE, SPIE, 2010

As part of the Laserfest Celebrations for the 50th Anniversary of the first laser.

Cynthia M. Friend

American Chemical Society Fellow, 2010 Dawson Lectureship, University of Kentucky, 2010

Arthur C. Gossard

Fellow of the American Association for the Advancement of Science (AAAS), 2010

Jennifer Hoffman

Sloan Fellowship, Sloan Foundation, 2010

Marko Lončar

Silver Medal, Materials Research Society Conference Graduate Student Competition, Tom Babinec, 2010 Sloan Fellowship, 2010

Eric Mazur

Harvard-Australia Fellow, Harvard Club of Sydney, 2010 Konopinski Lecturer, University of Indiana, Bloomington, IN, 2010

Venkatesh Narayanamurti

- Member, Committee on International Security and Arms Control, the National Academies, 2008-2010
- Member, University Advisory Council, Semiconductor Research Corporation, 2008-
- Member, Dean's Advisory Board, College of Engineering, Boston University, 2008-
- Chair Elect, Panel on Public Affairs (POPA), American Physical Society, 2009-2012
- Member, Electronics Engineering Peer Committee, NAE, 2009-2012
- Member, Advisory Board, WPI-Advanced Institute for Materials Research, Tohoku University, Sendai, Japan, 2009-
- Chair, Search Committee for Director of Division Materials Research, NSF, 2009-2010
- Governing Board, Indo-US Science and Technology Forum, 2009-
- Brain Trust, US Department of Energy, ARPA-E, 2010-2013
- Committee on Science, Engineering and Public Policy (AAAS), 2010-2013
- Review Board, Center for High Technology Materials, University of New Mexico, 2010
- Advisory Board, Energy Frontier Research Center, University of Michigan, 2010-2013

Advisory Board, Energy Frontier Research Center, UCSB, 2010-2013

- Advisory Board, Energy Frontier Research Center, MIT, 2010-2013
- Chair, University of California review committee for Governor Gray Davis Institute (CITRIS), 2010

Elected to Council of the American Academy of Arts and Sciences, 2010-2013

Kevin (Kit) Parker

Lifetime Achievement Award, National Engineers Week, Boston Engineering Society, 2010

Robert M. Westervelt

Director, Board of Scientific Advisors, NISE Network, 2006-present Board of Advisors, CINT Sandia National Laboratory, CINT Sandia National Laborstory, 2003-present

George M. Whitesides

Othmer Gold Medal (Chemical Heritage Foundation), 2010 Honorary Doctor of Science, University of Windsor, Canada, 2010 Honorary Doctor of Science, McGill University, Canada, 2010 Admitted to Institut de France-Académie des Sciences, 2010

16. BUSINESS PLAN FOR CLASS OF 2001 NSECs

Our Center was one of the first six NSECs created by the NSF in 2001. By encouraging multidisciplinary research between researchers working in different, but related fields, our NSEC has had a strong positive effect. It has built collaborations between faculty in Applied Physics, Chemistry, Electrical Engineering, Materials Science, and Physics at Harvard, MIT and UC Santa Barbara, as described in this and earlier Annual Reports, as well as interchanges with our international collaborators in Europe and Japan. Working with the Museum of Science, Boston and the Nanoscale Informal Science Education (NISE) Network our Center has created a very strong and active outreach program.

The ten-year period of funding from the NSF will end in 2011, and it is appropriate to consider the effects that our Center has had on the support for nanoscience and technology at our institutions, as well as our plans for the future. Our Center is actively pursuing new sources of funding from the government and from industry to extend our work into the future. Promising areas include the development of portable biosensors to move diagnostic tests from hospital labs to the point of care. Each biosensor combines microfluidic sampling with photonic biosensors, and electronic control — areas that are covered very well in our Center. A promising way to use these sensors would be to tract the progress of an injured person in an ambulance as they are brought to the hospital. Another promising area is the development of wireless biosensors that use RFID technology to place a set of small biosensors inside the body, or on the body's surface, to track a patient's condition and to report dangerous events. A set of these sensors on a patient would form a wireless network to monitor their condition, with data that could be forwarded to medical personnel.

An important part of the business plan for our Center is the transfer of advances in nanoscience and engineering to industry, so the benefits will be available to the public. Over the past ten years, Center faculty members have started 23 new companies and 484 new, high-quality jobs. These recent startups will continue to grow in the future, providing a legacy for our Center. In addition, outside companies have purchased over 180 licenses for the Center faculty intellectual property for a total of \$6.8M in licensing fees. A description of the new companies and industrial connections for our NSEC is given below.

The following sections describe important advances in the infrastructure for research and education in Nanoscale Science and Engineering that were stimulated by our Center to benefit society: *Harvard University's Investments in Nanoscience and Engineering*, *Startup Companies associated with our NSEC*, *International Collaborations*, and *Education and Outreach with the Museum of Science, Boston*.

Harvard University's Investments in Nanoscience and Engineering

Over the past ten years, Harvard University has invested more than \$500M to construct new laboratories and new, shared facilities to support research nanoscience and technology. Dean Jeremy Knowles felt the University should use some of the money gained during the stock market boom in the 1990's to support multidisciplinary science



Figure 16.1. Photo showing the Laboratory for Integrated Science and Engineering (LISE) and Center for Nanoscale Systems (CNS) centered in between the School of Engineering and Applied Sciences (SEAS) laboratories, the Department of Chemistry and Chemical Biology (Chemistry) and the Department of Physics (Physics).

and engineering. One of the first areas identified and approved by the Corporation was Nanoscale Science and Technology, which joins Chemistry, Engineering, Materials Science and Physics, and also fosters greater collaboration between Biology and Medicine with the hard sciences.

Two new buildings were constructed: The Laboratory for Integrated Science and Engineering (LISE), finished in 2007, and the Northwest Building, finished in 2008. LISE houses the Center for Nanoscale Systems (CNS), which provides state-of-the-art experimental facilities for nanofabrication, imaging and surface analysis, and advanced material synthesis, described in Section 12 — Shared Experimental Facilities.

The new LISE building and new CNS shared facilities provide valuable tools which strongly promote multidisciplinary research. Their location, shown in Figure 16.1, is centered in between the School for Engineering and Applied Sciences (SEAS), which includes Applied Physics, Electrical Engineering and Materials Science, the Dept of Chemistry and Chemical Biology (Chemistry) and the Dept of Physics (Physics). CNS provides an excellent cleanroom equipped for e-beam, optical and soft lithography, an outstanding set of electron microscopes, and surface analysis tools including a high resolution, monochromated and aberration corrected STEM and TEM, and facilities for advanced material synthesis. This is an ideal arrangement for investigators in nanoscience and technology at Harvard, MIT and other schools, as well as industrial users.

In 2004 <u>Westervelt</u> and <u>Narayanamurti</u> joined PI <u>Sandip Tiwari</u> at Cornell and co-PIs from a consortium of schools in their successful proposal for a National Nanoscale Infrastructure Network (NNIN). The NNIN provides easy access, for researchers from all parts of the country to use CNS facilities, and it has been very effective, and popular.

The construction of the Northwest Building was a major undertaking by the University that was completed in 2008. The goal is to bring together investigators from departments in the Faculty of Arts and Sciences and Harvard Medical School who would like to connect research in medicine and biology with the physical sciences. The Northwest Building provides excellent new space that strongly promotes these collaborations.

In summary, our NSEC has been very effective in promoting multidisciplinary work in nanoscience and technology, and it has helped create the need for an integrated research environment that Harvard has met through it's generous investments in new research laboratories and new shared facilities. The number of researchers taking part continues to grow each year. These investments will benefit research for some time, and they create an important legacy of our Center.

Startup Companies Associated with our NSEC

An important role for research in the nanoscale field is to transfer advances in science and technology from academic laboratories to industry, through the creation of startup companies. The public can benefit from these advances, by using the new products that are made possible. In addition, startup companies create high-tech jobs and new income, as well as profit to the initial investors.

Creating new companies that are based on discoveries and advances in nanoscience has been an essential part of our NSEC's business plan. Over the past ten years our Center's faculty members have founded over 23 startup companies, which created over 484 high technology jobs. Thirty outside companies purchased 180 licenses of the intellectual property of Center faculty for a total of \$6.8M in licensing fees. In addition, the Center has formed 43 industrial collaborations.

These startup companies represent a strong record of achievement and provide an important legacy for our Center. Because they were created only a few years ago, their growth will continue well into the future, producing new types of products and services for the public, as well as high quality jobs. A number of examples are presented below:

<u>George Whitesides</u>, coordinator of Cluster 1, is a pioneer in the field of microfluidics. He developed much of the technology needed to assemble microfluidic systems using novel techniques for printing and assembly, and technology for soft lithography. He is also an excellent entrepreneur. He has created a number of startup companies based on advances in his academic laboratory, to transfer these advances to the public, through new products and devices.

Two companies, Nano Terra and Arsenal Medical, founded in the last decade by <u>Whitesides</u> with <u>Carmichael Roberts</u>, create products based on soft lithography, selfassembly and microfluidics. <u>Roberts</u> is an African American who previously worked with <u>Whitesides</u> as a postdoctoral associate; he currently works in Venture Capital. A short description of these companies follows:

Nano Terra (George Whitesides and Carmichael Roberts, founders) Nano Terra assembles structures and chemistries on all lengths scales and a great variety of surface geometries to make smart materials and surfaces, flexible electronics and displays, fuel cells, batteries and solar cells. The technology includes soft lithography, self-assembly, surface chemistry and microfluidics.

Arsenal Medical (George Whitesides and Carmichael Roberts, founders) Arsenal develops therapeutics based on "BioActive" composites that have mechanical and biochemical compatability with tissues, and are bioabsorbed over appropriate time scales. "ElastaCore" composites are elastic materials that take the place of biocompatible metals

to provide a structural strength. "AxioCore" composites can locally dose drugs and therapeutic molecules.

Recently <u>Whitesides</u> created new ways to do medical diagnostic tests inexpensively using portable systems. The first is paper microfluidics, with channels defined by wax or a similar substance. This provides a very inexpensive approach to testing bodily fluids, which is well suited to the developing world. The second is the POCKET technique, which allows one to do a test with molecular sensitivity in a portable system. He made these advances available to the public through two startup companies, Diagnostics for All, and Claros:

Diagnostics for All (George Whitesides, founder) Diagnostics for All is a nonprofit organization that is producing paper microfluidic systems to diagnose disease. One can dip the end of the paper in a bodily fluid and examine the test results as a change in color in one or more sensitive spots. The cost is extremely low, making paper microfluidics well suited for the developing world.

Claros (<u>George Whitesides</u>, founder) Claros builds portable instruments that move *in vitro* medical diagnostic tests from hospital laboratories to the point of care. A disposable cartridge the size of a credit card is used to test a finger stick of blood or another bodily fluid with molecular sensitivity.

While he was a Junior Fellow at Harvard, John Rogers worked with George <u>Whitesides</u> developing new techniques for creating structures through printing, assembly, and soft lithography. After moving to the University of Illinois at Urbana Champaign, <u>Rogers</u> extended these techniques to create flexible electronics — high quality semiconductor devices transferred from their original substrate to flexible materials. He made these advances available to the public through two startups:

Semprius (John Rogers, founder) Semprius produces concentrator photovoltaic modules for solar power generation, using micro-transfer printing and related techniques originally based in soft lithography. Using this approach, one can put high performance semiconductors on a wide variety of surfaces.

MC10 (John Rogers, founder) MC10 produces flexible electronics, in the form of conformal CMOS circuits that can bend and wrap around surfaces. They can be imbedded into paper, fabric, latex and leather, have novel geometries and experience extreme strain. The approach is an extension of soft lithography.

<u>Moungi</u> <u>Bawendi</u>, coordinator of Cluster 2, is a leader in the growth of nanoscale semiconductor quantum dots. He has refined his techniques, and can synthesize a wide variety of high quality quantum dots and dot heterostructures. Quantum dots are very useful for optical applications, because the color of their fluorescence is controlled by the dot size. Recently <u>Bawendi</u> helped create a startup to make these advances available to the public:

Qd Vision (Moungi Bawendi, founder) Qd Vision manufactures lighting and display products based on semiconductor quantum dots. These include solid-state lighting that uses quantum dots to produce true color matching, with high power efficiency and low cost, as well as digital displays with a color range that is enhanced by quantum dots.

<u>Lars Samuelson</u> is another leader in nanoscale synthesis, who is expert in the epitaxial growth of nanowire heterostructures, and using them to develop new types of devices. He transferred this knowledge to industry by creating a new company QuNano that is producing solid-state lighting based on nanowire LEDs:

QuNano (Lars Samuelson, founder) QuNano develops quantum nanoscale semiconductor materials and devices based on nanowire epitaxial growth and process technologies. Thee products include nanowire LED solid-state light sources, with high efficiency, long life, and low cost.

International Collaborations

Our Center has built strong international connections with institutions in Japan and Europe through research collaborations, including the exchange of students. We hold yearly Frontiers in Nanoscale Science and Technology (FNST) Workshops that join researchers from all areas to discuss nanoelectronics, nanophotonics and quantum information. The workshops attract an outstanding group of speakers and attendees, including many students, and the location rotates between the US, Japan and Europe. These bonds formed through these collaborations will continue in the future.

Several years ago, our Center strengthened our connections with investigators at RIKEN in Japan. A Memo of Understanding (MOU) has been signed by Harvard and RIKEN to promote collaborative research between the two institutions. We followed by organizing a number of international joint symposia to address nanoscale electronics and photonics, and advanced computer simulations of nanoscale systems. To build on this effort, this year's Frontiers in Nanoscale Science and Technology Workshop was held at RIKEN in Japan on January 5–7, 2011.

In addition, a Memo of Understanding between Harvard University and Tohoku University in Japan has been set up through Prof. Hideo Ohno. The Tohoku/Harvard MOU will promote collaborative research focused on spintronics, quantum information, and new materials for electronics. The MOUs with RIKEN and Tohoku University will promote the continued growth of collaborative research in the future.

Education and Outreach with the Museum of Science, Boston

An essential role for our Center is to educate young people in the multidisciplinary field of nanoscience and engineering. Our field is new, it bridges traditional disciplines, and it is not covered well in most textbooks. By learning more about nanoscience, public school students get a view of their future to help them figure out what topics they would like to pursue in college or in a profession. Undergraduates and graduate students get an education that is more modern and more directly useful for their future jobs in industry or academia. Industrial executives often say young scientists and engineers with a strong education in nanoscience and technology are the Center's most important product.

The Museum of Science, Boston has been a member of our NSEC since 2001, and has been a very effective partner with our academic institutions. <u>Carol Lynn Alpert</u> presented hot new topics in nanoscience to the public in a way they found engaging and enjoyable, ranging from public presentations in the Museum lobby to video pieces on

cable TV. This requires real skill, and the museum staff members are experts at pulling in an audience.

Our positive experience showed that close collaborations between science museums and academic institutions are a very effective way to inform the public about nanoscience and get them involved in important issues, and was appreciated at the NSF. In 2005, a call for proposals was initiated by the NSF to create a Nanoscale Informal Science Education (NISE) Network of science museums to connect the public with new developments in science and technology. The Museum of Science, Boston was part of the winning team, and helped led the effort. The Scientific Advisory committee includes participants in our NSEC, including <u>Robert Westervelt</u>, <u>George Whitesides</u>, <u>Eric Mazur</u> and <u>Carol Lynn Alpert</u>. The NISE Network has been a great success — the partner institutions are actively involved, and produce engaging presentations, displays and entertaining events such as NanoDays for the public nationwide. Over the last ten years, the \$100k/yr investment by our NSEC in the Museum of Science, Boston has grown into the \$4M/yr NISE Network that serves millions of people.

An important legacy of our NSEC will be the creation of programs to connect young people with hot new topics in nanoscience and technology, through active collaborations between museums and academic institutions. This will benefit us all.