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 2003–2004
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Overview

The goal of this Nanoscale Science and Engineering Center is to study the fundamental properties of nanoscale structures with a view toward their possible use in novel electronic and magnetic devices. We concentrate on the movement of spins and charges including their quantum behavior. The following important questions are addressed at the same time: How can nanoscale structures be grown and assembled? How can they be imaged and probed? What are the fundamental behaviors of charge and spin? What could be the ultimate applications?

The Center addresses these questions through research that encompasses three areas: Synthesis and Growth of Nanoscale Structures uses chemical approaches to synthesize nanoscale structures composed of semiconductors, metals and polymers, and to make electronic devices and sensors from molecules and nanoparticles. Semiconductor heterostructures with novel electronic and magnetic properties are grown using Molecular Beam Epitaxy (MBE). Imaging Electrons inside Nanostructures explores new ways to image the behavior of electrons inside nanostructures using scanning probe microscopes (SPMs). Spins and Charges in Coherent Electronics investigates methods to use spins and charges in nanostructures for single-electronics, spintronics and quantum information processing. By combining advances in the three areas above, the Center hopes to discover and understand new types of electronic and magnetic devices.

Collaborations and Shared Facilities — The Center’s interdisciplinary research brings together participants from Harvard, MIT and UC Santa Barbara who are experts in Chemistry, Physics, Applied Physics and Materials Science. The Center maintains close collaborations with Sandia, Oak Ridge, and Brookhaven National Laboratories, and active international collaborations with Delft, U Basel and U Tokyo. A travel program encourages collaboration and sharing facilities.

Center for Imaging and Mesoscale Structures (CIMS) — The Center for Imaging and Mesoscale Structures (CIMS) is a major investment by Harvard to promote and aid interdisciplinary research by creating shared facilities operated with the assistance of technical staff. Harvard is constructing the new Laboratory for Integrated Science and Engineering (LISE) that will house CIMS facilities including a new Imaging Laboratory for electron, scanning-probe, and optical microscopy, a Cleanroom for nanofabrication and soft lithography, and an Advanced Materials Science Laboratory. CIMS and LISE provide valuable new capabilities for NSEC research, and bring students from different fields together to promote interdisciplinary research.

Workshops and International Collaboration — A workshop Frontiers in Materials and Nanoscience Research is held annually by the Industrial Outreach Program to introduce industrial researchers to research at Harvard and promote collaborations. The NSEC supports international events: A joint US/Japan workshop Frontiers in Nanoscience and Technology, organized with Sakaki, is held annually, in Tokyo in 2003 and in Boston in 2004. The NSEC supported the Solid State Quantum Information Processing Conference, organized by Kouwenhoven, in Amsterdam in December 2003. Scholarships are provided by the Center for students at both workshops.

Education and Outreach — The Center presents the concepts and the benefits of nanoscale science and engineering to the public at all levels. NSEC supported staff at the Museum of Science, Boston work with NSEC faculty to develop presentations and exhibits for the public. A new staff member Kathryn Hollar at Harvard coordinates educational outreach to public schools and other colleges. A course at Harvard Interdisciplinary Chemistry, Engineering and Physics, consists of tutorial lectures by Center faculty on nanoscale science and engineering and possible applications; a set of lecture notes is made available on the web. Each summer the Center conducts Research Experience for Undergraduates (REU) and Research Experience for Teachers (RET) programs. The Postdoctoral Research Fellowship for Women and Minorities attracts outstanding candidates.
Mission and Broader Impact

The goal of this Nanoscale Science and Engineering Center is to study the fundamental properties of nanoscale structures with a view toward their possible use in novel electronic and magnetic devices. We concentrate on the movement of spins and charges including their quantum behavior. The following important questions are addressed at the same time: How can nanoscale structures be grown and assembled? How can they be imaged and probed? What are the fundamental behaviors of charge and spin? What could be the ultimate applications?

The Center addresses these questions through research that encompasses three areas: **Synthesis and Growth of Nanoscale Structures** uses chemical approaches to synthesize nanoscale structures composed of semiconductors, metals and polymers, and to make electronic devices and sensors from molecules and nanoparticles. Semiconductor heterostructures with novel electronic and magnetic properties are grown using Molecular Beam Epitaxy (MBE). **Imaging Electrons inside Nanostructures** explores new ways to image the behavior of electrons inside nanostructures using scanning probe microscopes (SPMs). **Spins and Charges in Coherent Electronics** investigates methods to use spins and charges in nanostructures for single-electronics, spintronics and quantum information processing. By combining advances in the three areas above, the Center hopes to discover and understand new types of electronic and magnetic devices.

The Center’s interdisciplinary research brings together participants from Harvard University, Massachusetts Institute of Technology and the University of California, Santa Barbara who are experts in Chemistry, Physics, Applied Physics and Materials Science. The Center maintains close collaborations with Sandia, Oak Ridge and Brookhaven National Laboratories, and active international collaborations with Delft University of Technology, University of Basel and the University of Tokyo. A visitor program supports travel for students, faculty, and staff between these institutions to encourage collaborative research and the use of shared facilities.

The Center for Imaging and Mesoscale Structures (CIMS) is a major investment by Harvard to promote and aid interdisciplinary research by students and faculty in Chemistry, Applied Physics, Physics, Materials Science and Biology. CIMS has created shared facilities at Harvard that are operated with the assistance of technical staff. These include a second Cleanroom in McKay Laboratory and an electron microscopy facility in Mallinckrodt Laboratory. Harvard is constructing a new Laboratory for Integrated Science and Engineering (LISE), shown in the figure, that will house CIMS shared

Computer image of the planned Laboratory for Integrated Science and Engineering (LISE) that will join McKay, Cruft, and Lyman Laboratories at Harvard University.
facilities and provide space for interdisciplinary research. LIS will contain a new Imaging Laboratory for electron, scanning probe, and optical microscopy, a Cleanroom for nanofabrication and soft lithography, and an Advanced Materials Science Laboratory. CIMS and LIS will make available valuable new capabilities to NSEC participants, bring students from different fields together, and promote new areas of interdisciplinary research.

**Synthesis and Growth of Nanoscale Structures** — Chemical approaches to the synthesis of nanoscale structures are emphasized, along with MBE growth of novel heterostructures. Nanoparticles of semiconductors and metals can be chemically grown with high uniformity and excellent properties. Center participants are developing ways to synthesize devices and sensors from molecules, nanoparticles and polymers using spatially patterned electromagnetic fields and microfluidic systems. Molecular single-electron transistors are built, and their characteristics are studied using the Coulomb blockade. Self-Assembled Monolayers (SAMs) provide opportunities for organic electronics, fabricated economically by printing, once the properties of electrical contacts and conduction are understood. Soft lithography provides new approaches to the synthesis of nanostructures as well as the fabrication of microfluidic systems. The MBE Lab. at UC Santa Barbara grows semiconductor heterostructures with novel electronic and magnetic properties that are used in the Spins and Charges in Coherent Electronics area of the Center. The Center collaborates with Sandia National Laboratory and the new Center for Integrated Nanotechnologies (CINT), which have advanced facilities for nanofabrication.

**Imaging Electrons inside Nanostructures** — Our ability to image electrons inside nanoscale structures has been greatly improved by new types of scanning probe microscopy (SPM) developed by Center participants. The flow of electron waves through nanostructures in a two-dimensional electron gas is imaged and analyzed in the quantum Hall regime, and in zero applied magnetic field. SPM is used to image electron charge distributions in nanoscale structures, and to manipulate the positions of nanoparticles. Ballistic electron emission microscopy (BEEM) allows one to determine the electronic properties of semiconductor nanostructures. Methods to image spin flow through semiconductor heterostructures are being developed for use in the fields of spin injection and spintronics.

**Spins and Charges in Coherent Electronics** — The development of coherent electronic devices and circuits that make use of the quantum behavior of electron charges and spins is essential for single electronics, spintronics and quantum information processing. Sophisticated experiments on quantum coherence are possible using nanostructures fabricated using e-beam lithography from MBE-grown heterostructures and from superconductors. The Center...
brings together experiment and theory in this area with strong international collaborations with Delft and U Tokyo.

**Seed Projects** — The Center provides seed funding for new, high-risk projects that can have important outcomes. This support allows participants to investigate interesting ideas quickly that can obtain regular funding if the project is successful.

**Education and Outreach** — The Center presents the basic concepts and the possible benefits of nanoscale science and engineering to the public at all levels. NSEC supported staff in the *Current Science & Technology Center at the Museum of Science, Boston* and NSEC faculty make presentations, conduct workshops and develop exhibits for the public. A new staff member **Kathryn Hollar** at Harvard coordinates educational outreach to public schools and other colleges. An early awareness outreach program brings Cambridge public school students to Harvard during each year to learn about college. *PEER Instruction Workshops* for local public school teachers introduce an innovative science teaching technique that has attracted national attention. The Center’s *Research Experience for Undergraduates (REU)* and *Research Experience for Teachers (RET)* programs provide experience in a research laboratory over the summer to undergraduates and public school teachers. Applied Physics 298r, *Interdisciplinary Chemistry, Engineering, and Physics* — a new Harvard course taught by NSEC faculty — presents the fundamentals of nanoscale science and engineering and describes possible applications. The lecture notes for spring 2003 were available on the course’s website. The *Postdoctoral Research Fellowship for Women and Minorities* attracts outstanding candidates.

**International Collaborations** — The Center collaborates closely with U Tokyo, U Basel and Delft. Travel by students and postdocs between Boston, Santa Barbara, Delft and Tokyo to carry out collaborative research, is supported by the Center’s Travel Programs. An annual Japan/US Workshop — Frontiers in Nanoscale Science and Technology — is supported by the Center. The workshop last year was held in Tokyo in July 2003, and attracted participants from the USA, Delft, U Tokyo and NTT. The next workshop will be held in Boston in October 2004. The Center also provided scholarships for students to attend the Solid State Quantum Information Processing Conference in Amsterdam, in December 2003, organized by Delft.

**Collaborations with Industry and other Institutions** are actively encouraged. The *Industrial Outreach Program (IOP)* of the Division of Engineering and Applied Sciences at Harvard is aimed at increasing and strengthening external collaborations with industry. An annual *IOP Workshop* brings industrial researchers to Harvard to discuss future directions for key areas of nanoscale science and technology. This year’s workshop *Frontiers in Materials and Nanoscience—Innovation and Collaboration* is scheduled on May 20–21, 2004. An Advisory Board consisting of leading figures in industry and academia evaluates the Center’s programs for research and education, and helps connect students with opportunities in industry.

**Shared Facilities** — Excellent shared facilities are available at Harvard, MIT and UC Santa Barbara; at Sandia, Oak Ridge and Brookhaven National Laboratories; and at our international collaborators at Delft and U Tokyo. A National Nanotechnology Infrastructure Network (NNIN) grant was recently awarded by the NSF to a group headed by Cornell and Stanford, that includes Harvard and UC Santa Barbara. At Harvard the NNIN will develop shared facilities for soft lithography and the assembly of molecular electronics, and it will set up computer facilities for simulations of nanoscale devices. In recognition of the Center’s importance and its role in promoting collaborative research, CIMS and the Division of Engineering and Applied Sciences at Harvard provide substantial support.

Please see our websites [http://nsec.harvard.edu](http://nsec.harvard.edu) and [http://cims.harvard.edu](http://cims.harvard.edu).
A computer image of the Laboratory for Integrated Science and Engineering (LISE) that will house shared facilities for Harvard’s Center for Imaging and Mesoscale Structures, and the NSEC, and will provide space for interdisciplinary research. LISE will contain an Imaging Laboratory for electron, scanning probe and optical microscopy, a Cleanroom for nanofabrication and soft lithography, and an Advanced Materials Science Laboratory.
Harvard and UC Santa Barbara are two of an integrated partnership of thirteen user facilities, led by Cornell and Stanford, that provide opportunities for nanoscience and nanotechnology research. At Harvard, the NNIN provides expertise in soft lithography and assembly, and computation through the Center for Imaging and Mesoscale Structures. At UCSB, the NNIN provides expertise in optics and electronic materials. The NNIN was funded by the NSF in January 2004.
Cablecasting Nanotech News via New England Cable News
Carol Lynn Alpert

...reaching as many as 2.8 million homes and businesses

a) How to make a nanobattery.
b) How Xiaowei Zhuang videotaped individual influenza viruses.
c) How iron nanoparticles might be used to clean up toxic waste sites.
d) Modeling Eric Mazur and Limin Tong’s method for making glass nanofibers.

Each Thursday morning, New England Cable News anchors visit the Current Science & Technology Center at the Museum of Science via robotic cameras linked by fiber optics to their Needham, MA studio. Once a month, NSEC Education Associate Joel Rosenberg delivers lively three-minute presentations and demonstrations about nanotech research. The cablecasts are repeated throughout the day and archived at <www.mos.org/cst/nano>. This live cablecasting partnership was developed under the direction of NSEC Senior Investigator for Educational Outreach Carol Lynn Alpert, and is the first of its kind in the nation.
Cover of *Physics Today*, Dec. 2003 — Simulation of the flow of electron waves by E.J. Heller

This issue contains a review of imaging electron flow in two-dimensional electron gases by Topinka, Heller and Westervelt including their collaborative research.
Waves injected into two resonators in a two-dimensional electron gas (2DEG) emerge through openings in the cavities. This image illustrates the new capability we have developed for rapid testing of barrier gate structures, by running wave packets inside gates defined by SEM or hand-drawn images.
A thermal wave packet (whose energy distribution is derived from its temperature) is shown emerging from a small opening (a quantum point contact, or QPC) from which is spreads out, hitting impurities. These scatter the waves, some of which head back to the QPC. They can interfere there to produce interference fringes in an image of electron flow only if they arrive at the same time.
Interference of Thermal Electron Wave Packets
Eric J. Heller

A thermal wave packet has been sent through a quantum point contact (QPC) from below, spreading out and bouncing against two mirrors. After one bounce from the farther mirror, and two from the closer one, parts of the wave packet are arriving at the same time back at the QPC. By moving the mirror slightly (about 1/4 of a deBroglie wavelength) the resulting interference from the two paths goes from destructive (left, less flux seen going down) to constructive (right, more flux going down).
Micropost Matrix
Tom Hunt, Donhee Ham and Robert M. Westervelt

Micropost matrix for trapping and manipulating single cells. (a) Micrograph of the micropost matrix. (b) A schematic 3-D view of the device.

We have developed a micropost matrix that can move small particles and biological cells, through a microfluidic system using dielectrophoresis. Rf voltages are separately applied to each post, under computer control. The micropost matrix can independently trap and move a number of particles or cells through the fluid.
Pumping and Focusing Pure Spin
Charles M. Marcus

With growing interest in the spin of electrons comes the need for a spin battery, analogous to a conventional (charge) battery for creating voltages in a circuit. We have used quantum coherence to produce a pump that can independently pump spins of different orientation (with respect to an externally applied magnetic field). When the two independent currents — one for spin-up and one for spin-down — exactly cancel, then no charge is pumped. However, this condition means that a spin-down current is moving to the left, say, and an equal spin-up current to the right. We have realized such a “pure” spin pump. What’s more, we have taken the spin current and made it bend around a loop, focus it, and inject it into a narrow gap.

The figure shows in the top frame total pumped current using a mesoscopic quantum pump. The bottom frame shows spin sensitive (green) and spin insensitive (black) current detection (bottom frame, black) measured at the same time as the current measured in the top frame. At zeros of total current, the spin-dependent current is nonzero. At these points a pure spin current is being pumped. Top inset shows a schematic of the cyclic pumping cycle needed to make a charge or spin pump. The bottom inset shows the measurement set-up where a pumped dot is embedded in a focusing geometry. The quantum point contact on the collector can be made spin sensitive (in an external field) by adjusting the gate voltage to have partial transmission.
Kondo Effect in a Single Electron Transistor Excited by Microwaves
Marc A. Kastner

(A) Evolution of the Kondo peak with increasing microwave voltage $V_{ds}^{osc}$ applied to a single electron transistor SET at $T = 100$ mK. (B) Separation between the satellites and the central peak as a function of the microwave voltage. The horizontal line is $hf/e$ where $h$ is Planck’s constant and $f$ is the microwave frequency.
Growth of Single-Crystal VO$_2$ Nanowires
Hongkun Park

(a) High resolution TEM image of a representative VO$_2$ nanowire, illustrating lattice fringes. (b) Diagram of a nanowire with the growth surfaces indicated.

Synthesis of single-crystal VO$_2$ nanowires was achieved using a simple vapor transport method in a tube furnace. VO$_2$ is an attractive material for a Mott field effect transistor, where the channel undergoes an electrically driven Mott metal-insulator transition.
**Metal-semiconductor Nano-composite Material as Seen in Cross Section in an Electron Microscope Image**

Dmitri Klenov, Daniel Driscoll, Micah Hanson, Susanne Stemmer and Arthur C. Gossard

Dark-colored lines are layers of metal islands (ErAs) in a semiconductor (InGaAs). The unique honeycomb structure shown occurs with alternate growth of ErAs and InGaAs by molecular beam epitaxy. The metal islands form in a spontaneous island mode of crystal growth. Faceting of the surface and appearance of the honeycomb structure occur only for metal depositions and indium content greater than a certain level.
Spintronics devices that simultaneously exploit the spin and charge of the electron, are being explored for promising new electronic applications. Our devices, shown in the SEM image, consist of an aluminum wire contacted with two different ferromagnets (FM) with different coercive fields. Tunnel barriers between the FMs and the Al are grown in situ. The dimensions of the Al and the FMs are well below the spin relaxation length ~300 nm. Measurements show the spin-valve effect at room temperature for positive and negative H-field sweep directions, with ~100 times larger signal than in previous work.
Raman spectroscopy of individual semiconducting carbon nanotubes is used for the first time to measure vibrational frequencies vs. strain. The strain is induced by bending the nanotubes with an AFM tip while the ends of the nanotubes are held fixed by metal electrodes, thus converting the transverse displacement to an elongation. Under strain of 1–2% the vibrational frequency is observed to decrease by up to 40 cm$^{-1}$. The Raman peaks shift back toward their original positions over a time period of order one week, implying strain relaxation over a similar period.
Strategic Research Plan

Research Goals of the Center

The goal of this Nanoscale Science and Engineering Center is to study the fundamental properties of nanoscale structures with a view toward their possible use in novel electronic and magnetic devices. We concentrate on the movement of spins and charges including their quantum behavior. The following important questions are addressed at the same time: How can nanoscale structures be grown and assembled? How can they be imaged and probed? What are the fundamental behaviors of charge and spin? What could be the ultimate applications?

Research Activities

The Center addresses these questions through research that encompasses three areas: Synthesis and Growth of Nanoscale Structures uses chemical approaches to synthesize nanoscale structures composed of semiconductors, metals and polymers, and to make electronic devices and sensors from molecules and nanoparticles. Semiconductor heterostructures with novel electronic and magnetic properties are grown using Molecular Beam Epitaxy (MBE). Imaging Electrons inside Nanostructures explores new ways to image the behavior of electrons inside nanostructures using scanning probe microscopes (SPMs). Spins and Charges in Coherent Electronics investigates methods to use spins and charges in nanostructures for single-electronics, spintronics and quantum information processing. By combining advances in the three areas above, the Center hopes to discover and understand new types of electronic and magnetic devices.

The Center’s research activities are aimed at advancing in our understanding of nanoscale systems and developing the tools needed to develop nanotechnology for future applications. We summarize here the goals of the research in each area Center, the steps needed to reach these goals, and the overlap between different areas.

Synthesis and Growth of Nanoscale Systems

This area develops chemical approaches to build functional nanostructures using unconventional means. Nanoscale devices and sensors are made from molecules, nanotubes, nanofibers and chemically grown nanoparticles, and organic electronics is being developed using self-assembled monolayers (SAMs). New types of nanostructures can be synthesized using soft lithography, and nanoscale metal structures can be made using edge lithography, without the need for conventional cleanroom techniques.

The Center is developing the tools needed to position and assemble nanoscale objects in fluids, to build nanoscale devices and to manipulate biological systems. Whitesides is an expert in microfluidic and nanofluidic systems. Micro-electromagnets are being developed for the magnetic manipulation of particles in fluids, and micropost electrodes for dielectrophoresis.

Chemical approaches to nanotechnology and soft lithography are the focus of Harvard’s role in the new National Nanotechnology Infrastructure Network (NNIN) grant, awarded by the NSF in January 2004, along with computer simulations of electron behavior. The Center for Imaging and Mesoscale Structures at Harvard will appoint additional technicians to assist outside users, as well as NSEC investigators, with projects in these areas.
Art Gossard at the MBE Laboratory at UC Santa Barbara grows custom-made semiconductor heterostructures for Center research. The MBE laboratory has added three new MBE machines this year. It can grow structures containing InAs quantum wells and the magnetic materials (Ga,Mn)As and Fe for spintronics and quantum information processing. Gossard collaborates closely with participants in the Imaging and Coherent Electronics areas.

- Electrical transport through SAMs (2004–2006)
- Edge lithography (2004–2006)
- Control of electron g-factor in MBE-grown heterostructures (2002–2006)

**Imaging Electrons in Nanostructures**

Imaging the motion of electronic charges and spins through nanostructures is required in order to build new devices and to understand their behavior. Although the need is clear, we have only recently been able to obtain such images through advances in scanning probe microscopy. This is because the electrons are often buried inside the sample, and because low temperatures are often needed in order to observe quantum phenomena. A number of participants in the Center have built their own liquid helium cooled scanning probe microscopes (SPMs) for this purpose, including Ashoori, Narayanamurti and Westervelt. Heller is expert in theoretical simulations of electron flow for comparison with the experiments. A new faculty member Jennifer Hoffman will arrive at Harvard in January 2005. She is expert in using a custom-made low temperature SPM to study high-Tc superconductors.

Narayanamurti is a leader in Ballistic Electron Emission Microscopy (BEEM) — an approach that uses high-energy electrons emitted from a scanning tunneling microscope tip to study electron states in nanoscale structures. BEEM is particularly valuable for investigating the properties of nanoscale structures grown by MBE or grown on surfaces, and they provide one of the first ways to understand the properties of a new material structure.

In the future, we also expect to construct new, more powerful, scanning probe microscopes in our laboratories. These instruments are important new tools for the study of nanostructures and the development of new types of devices.

Now that the imaging techniques have been developed, we can pursue a number of projects that are aimed at understanding how electrons move through nanostructures, and we can use these microscopes to approach to design new types of devices. The research topics include:

Liquid helium cooled BEEM system (2001–2006)
Liquid helium cooled BEEM with two STM tips (2004–2006)
Spin state imaging using BEEM with Fe whisker tips (2004–2006)
Spin sensing via light emission from MBE heterostructures (2003–2006)

Spins and Charges in Coherent Electronics

Our understanding of the behavior of electron charges inside quantum dots made by lithography has advanced considerably over the past decade. The quantization of electron charge inside quantum dots by the Coulomb blockade allows one to create single electronics. Sophisticated new approaches have created the field of spintronics by using spins to carry the information instead of charge. By coherently manipulating the interaction of single spins, one can develop systems for quantum information processing.

In order to develop coherent electronics, we need to control the motion of spins. Needed steps include methods to inject polarized spins into an electron gas, control their motion, filter spin states, and detect the arrival of spins. For quantum information processing, one needs to have sufficient sensitivity to manipulate single spins coherently. Heterostructures grown by MBE provide a range of possibilities, including magnetic semiconductors (Ga,Mn)As and magnetic semiconductor heterostructures, and electron $g$-factors in GaAs/AlGaAs that vary with the alloy that are described in *Synthesis and Growth of Nanoscale Systems*. Optical methods are very useful — one could detect the arrival of spins through the photons emitted as through recombination in a quantum well. Research in coherent electronics will develop the components needed for spintronics and for quantum information processing. They will also apply to devices constructed from molecules, nanotube, nanofibers and nanoparticles described above in *Synthesis and Growth of Nanoscale Structures*.

- Kondo effect used to construct a spin filter (2004–2006)

Center for Imaging and Mesoscale Structures — The Center for Imaging and Mesoscale Structures at Harvard has made substantial investments in new equipment and facilities that make it possible to construct advanced electronic devices needed for NSEC research from semiconductor heterostructures and metals (see the website http://cims.harvard.edu for a detailed description). The Division of Engineering and Applied Sciences has constructed a new Cleanroom, located in the basement of McKay Laboratory, that houses the facilities for e-beam lithography. The older Cleanroom has been upgraded, with additional equipment for optical
lithography. Five new technical staff members have been hired by CIMS over the past two years to operate and maintain the facilities and to train students and new users. Recent purchases include:

- JEOL 2010 TEM/STEM in new Mallinckrodt facility (2001)
- Raith 150 Ultrahigh Resolution E-beam Lithography Tool (2001)
- AXIC Jetfirst 100 Rapid Thermal Processor (2002)
- 2 NEXX Cirrus150 High Density Plasma Etching Reactor and Deposition Syst. (2003)
- Multi-Ion Focused Ion Beam and Deposition System (2004)

**Laboratory for Integrated Science and Engineering** — Harvard has begun the construction of a new Laboratory for Integrated Science and Engineering (LISE) that will house CIMS shared facilities and provide space for interdisciplinary research. The facilities and space in LISE will be available to faculty in areas including Applied Physics, Biology, Chemistry, Electrical Engineering, Materials Science, and Physics. LISE will contain a new Imaging Laboratory for electron, scanning probe, and optical microscopy, a Cleanroom for nanofabrication and soft lithography, and an Advanced Materials Science Laboratory. CIMS and LISE will make available valuable new capabilities to NSEC participants, bring students from different fields together, and promote new areas of interdisciplinary research.

**National Nanotechnology Infrastructure Network** — A National Nanotechnology Infrastructure Network (NNIN) grant was recently awarded by the NSF to a group headed by Cornell and Stanford, that includes Harvard and UC Santa Barbara. The NNIN serves a wide range of users who do not have facilities for nanotechnology available at their own institutions. At Harvard the NNIN will develop shared facilities for chemical approaches to nanotechnology, including soft lithography and assembly, and it will set up computer facilities and develop software for simulations of nanoscale devices. In recognition of the NNIN’s importance and its role in promoting collaborative research, CIMS and the Division of Engineering and Applied Sciences at Harvard provide substantial support.

**Interdisciplinary Chemistry, Engineering and Physics** — A primary goal of the Center is to educate and train students in nanoscale science and engineering, so that they can become leaders in this new field. Research in this area requires an understanding of topics in Chemistry, Materials, Physics and Applied Physics, and few texts are available. In order to address this need, the Center has created a new course Applied Physics!298r, *Interdisciplinary Chemistry, Engineering and Physics*, first given at Harvard in spring, 2003, and repeated every other year. In the course, each NSEC faculty member presents a tutorial lecture about their area of research aimed at undergraduate and graduate students. In order to make the material readily available to students and other interested people, the lecture notes are formatted as PowerPoint files, and they are made available on the course’s website. At the end of the course, the lecture notes will be compiled into a graphic course-book that describes the basics of nanoscale science and engineering with examples of applications. The Center’s participants include many leaders in this field, and the course-book will be a valuable source of information.
Research Accomplishments and Plans

This section will describe the research accomplishments and plans of the Center’s participants. Because we want to encourage interdisciplinary work, we have chosen not to separate the Center into separate research groups – many of the participants work in two or more areas. The research projects described in this section illustrate how participants with different expertise collaborate.

In the Center’s research, the following important questions are addressed concurrently: How can nanoscale structures be synthesized and assembled? How can they be imaged and probed? What are the fundamental behaviors of charge and spin? What could be the applications?

Research accomplishments by the Center’s participants that address these questions are presented in three sections: *Synthesis and Growth of Nanoscale Structures, Imaging Electrons in Nanostructures and Spins and Charges in Coherent Electronics.*

Participants 2004–2005

The particular areas of expertise of the Center participants are indicated; many participants are expert in two or more areas.

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<tr>
<th>Name</th>
<th>Field of Research</th>
<th>Institution</th>
<th>Synthesis &amp; Growth</th>
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Introduction

Center for Imaging and Mesoscale Structures — The Center for Imaging and Mesoscale Structures (CIMS) is a major investment by Harvard to promote and aid interdisciplinary research in meso- and nanoscale science and engineering. CIMS is creating shared facilities at Harvard that are operated with the assistance of technical staff. These include a new Cleanroom in McKay Laboratory equipped for e-beam and optical lithography with a Raith e-beam writer, a new imaging facility in Mallinckrodt Laboratory with a JEOL transmission electron microscope, and equipment for materials synthesis.

Laboratory for Integrated Science and Engineering — Harvard has begun the construction of a new Laboratory for Integrated Science and Engineering (LISE) that will house CIMS shared facilities and provide space for interdisciplinary research. The facilities and space in LISe will be available to faculty in areas including Applied Physics, Biology, Chemistry, Electrical Engineering, Materials Science, and Physics. LISe will contain a new Imaging Laboratory for electron, scanning probe, and optical microscopy, a Cleanroom for nanofabrication and soft lithography, and an Advanced Materials Science Laboratory. CIMS and LISe will make available valuable new capabilities to NSEC participants, bring students from different fields together, and promote new areas of interdisciplinary research.

National Nanotechnology Infrastructure Network — A National Nanotechnology Infrastructure Network (NNIN) grant was recently awarded by the NSF to a group headed by Cornell and Stanford, that includes Harvard and UC Santa Barbara. The NNIN serves a wide range of users who do not have facilities for nanotechnology available at their own institutions. At Harvard the NNIN will develop shared facilities for chemical approaches to nanotechnology, including soft lithography and assembly, and it will set up computer facilities and develop software for simulations of nanoscale devices. In recognition of the NNIN’s importance and its role in promoting collaborative research, CIMS and the Division of Engineering and Applied Sciences at Harvard provide substantial support.
Synthesis and Growth of Nanoscale Structures

Overview

The direction of this research area has been refocused toward chemical approaches at truly nanoscale sizes, as described in the Introduction on the previous page. Synthesis and Growth develops chemical approaches to build functional nanostructures using unconventional means. Nanoscale devices and sensors are made from molecules, nanotubes, nanofibers and chemically grown nanoparticles, and organic electronics is being developed using self-assembled monolayers (SAMs). New types of nanostructures can be synthesized using soft lithography, and nanoscale metal structures can be made using edge lithography, without the need for conventional cleanroom techniques.

The Center is developing the tools needed to position and assemble nanoscale objects in fluids, in order to build nanoscale devices and to manipulate biological systems. Whitesides is an expert in microfluidic and nanofluidic systems. Micro-electromagnets are being developed for the magnetic manipulation of particles in fluids, and micropost electrodes for dielectrophoresis.

Chemical approaches to nanotechnology and soft lithography are the focus of Harvard’s role in the new National Nanotechnology Infrastructure Network (NNIN) grant, awarded by the NSF in January 2004, along with computer simulations of electron behavior. The Center for Imaging and Mesoscale Structures at Harvard will appoint additional technicians to assist outside users, as well as NSEC investigators, with projects in these areas.

Participants

George Whitesides, well known for his expertise in soft lithography, microcontact printing, and microfluidics, has been added to the Executive Committee of the Center. He is developing novel approaches to nanofabrication: organic electronics using self-assembled monolayers (SAMs), edge lithography based on sectioning with a glass knife, and novel approaches to nanofabrication. Research on nanoscale devices and sensors made from molecules, nanotubes and nanofibers is being done by Hongkun Park and Xiaowei Zhuang. Park is growing single-crystal VO$_2$ nanofibers to make Mott transistors, and Zhuang is developing nanofiber field effect transistors as single-molecule sensors. Mouni Bawendi is expert in the chemical growth of nanoparticles from magnetic metals, and semiconductors. He is making new composite magnetic nanoparticles with high blocking temperatures. Robert Westervelt uses microelectromagnet matrices and micropost matrices to control the motion of particles and biological cells in fluids, using spatially patterned magnetic fields and dielectrophoresis. Howard Stone has worked on the theory of nanostructure growth; he will continue to collaborate with Whitesides on micron- and nanofluidics. Art Gossard uses molecular beam epitaxy (MBE) to grow custom-made semiconductor heterostructures for Center research. The MBE laboratory at UC Santa Barbara has added three new MBE machines this year. It can grow structures containing InAs quantum wells and magnetic materials (Ga,Mn)As and Fe for spintronics and quantum information processing. Gossard collaborates closely with participants in the Imaging and Coherent Electronics areas. The Center no longer supports research on conventional surface/materials growth using templating or on surface modification using lasers.
Synthesis of New Types of Nanostructures
George M. Whitesides

Overview. Our program combines organic chemistry and materials science to prepare functional nanostructures using unconventional means. We are interested both in developing new synthetic routes to nanostructures, and in using nanostructures as components in a range of studies: We are particularly engaged in cell and molecular biology, fluidic and sub-wavelength optics, electron transport and organic electronics, and development of new materials (for example electrets). Self-assembly is a key component to our synthetic strategy.

The problems on which we work tend to change rapidly, as we finish one and move to another. The following are current areas of high activity that involve nanoscale structures.

Electron Transport Through Self-Assembled Monolayers (SAMs). The field of “organic electronics” has the potential to become a major new area of microelectronics. In this field, the silicon or gallium arsenide semiconductor that is the core of conventional microelectronics (and perhaps, ultimately, the metal conductors) are replaced by organic materials. The performance of these systems is currently lower than those of silicon CMOS, but their potential economics is much better, since they can be prepared by printing rather than by photolithography. Initial applications will be in areas were feature sizes are not critical: flexible displays and bar-coding labels are examples.

A key issue in the science of organic electronics is to understand the physics of the transport of electrons through organic matter. An important problem that has emerged is that of making the contacts to electrodes required in any junction. We have developed a system that is rapidly becoming one of the most attractive. In this system, we form the junction by a two-step process. In the first step, we form a SAM on a metal film by conventional processes. (Although the process—dipping the metal film into a solution of an alkanethiol—is conventional, the metals that are the most useful for this purpose—palladium and platinum—have not been examined as supports for SAMs; characterizing these new classes of SAMs is a part of the program.) In the second step, the supported SAM is brought into contact with a mercury drop, also supporting a SAM. The junction that is formed thus comprises a platinum or palladium electrode and a mercury electrode sandwiching two SAMs, or a Pt/SAM//SAM/Hg junction. These junctions are very reproducible, can be formed in high yield (>90%), and give excellent data.

Since this system is compatible with a wide variety of organic materials in the SAMs, and since the SAMs can even be made to be reactive toward one another if desired, it offers great flexibility as a system with which to study the details of electron transport through nm-thick, structured organic films. We have established in initial studies that electron transport through n-alkane-based SAMs proceeds by tunneling. We will, in future work, synthesize a range of organic materials of potential interest in addressing mechanistic questions, and study electron transport through them using this junction.
**Edge Lithography: Sectioning as a Method of Generating 20-nm Features.** The formation of electrically connected metal features with lateral dimensions below 100 nm remains a challenge. We are developing a new approach to simple systems based on the use of the microtome to generate the required features. This procedure has four steps. i) We prepare an appropriate topographically patterned substrate (typically using an epoxy resin) by soft lithography or photolithography. ii) We evaporate a thin (typically approximately 20 nm) metal film on this substrate. iii) We encapsulate the system (metal film and substrate) in more polymer. iv) We section the encapsulated system (including the metal film) using the glass knife of a microtome; this sectioning exposes the edge of the metal film.

The attractive feature of this method is that it generates metal features with lateral thickness set by the thickness of the film deposited by evaporation. These exposed metal features can be addressed from the backside of polymer slab, and are electrically continuous. The entire methodology can be carried out on the open bench, with essentially no equipment beyond the microtome. The structures that are generated are, obviously, not those that will be used in microcircuits, but they are very well suited for uses as nanoelectrodes in cell biology and for areas such as electrostatic patterning and prototyping nanoelectronics devices (especially in organic materials).

We propose to develop this very attractive new methodology as a new route into nanostructures in organic materials. The immediate experiments will involve stacking multiple layers of deposited and spun-on materials before sectioning to make more elaborate features, developing more complex topographies for the film before encapsulation by bending or folding, and exploiting a range of materials (organic and organometallic polymers; metals, polymers, and ceramics for the deposited films).

This process constitutes a new addition to the suite of techniques aggregated under the title “soft lithography,” and promises to provide facile access to simple nanostructures for use by chemists, biologists, and materials scientists.

**Synthesis of New Types of Nanostructures.** We have an active program in the synthesis of new types of nanostructures, based on combinations of polymer chemistry, organic chemistry, and more conventional techniques of nanosynthesis. We propose to continue

![Figure 1. Encapsulation of patterned metal films. A 50 nm gold film deposited on a molded epoxy surface is sectioned using a glass knife to produce nanoscale features.](image1)

![Figure 2. Palladium cups (300-nm diameter, 8-nm thick) made by evaporation of a metal film on an array of beads.](image2)
this program. Two examples of structures formed are these: i) *Nanopores*. We are exploring a route to nanopores based on the formation of small (but not nanometer-scale) pores in an elastomeric polymeric solid, following by squeezing these structures mechanically. We have demonstrated that we can reduce the diameter of these pores from micron-scale to zero (that is, squeeze them entirely closed). In between these limits, they must have nanometer dimensions. We will prepare and characterize these structures using both function (e.g., ion current in devices of the sort used in electrophysiology) and structure (fracture electron microscopy). ii) *Half-shells*. We begin with an array of polymer or ceramic spheres in a crystalline monolayer array, and evaporate a thin (~10 nm) metal film on the surface of these spheres. Sonication releases them from their support and from one another, and generates an ensemble of nanospheres half-coated with metal. These objects are of substantial interest in themselves (as the basis for sensors and catalysts); dissolving the sphere leaves a metallic half-shell with thickness of only a few nanometers. By working with relatively hard metals (e.g., palladium), these structures can be manipulated without damage; because they are half-shells, they do not pack or cold-weld.

We propose to continue to develop the leads provided by these two proof-of-concept experiments, and also to develop new methods of synthesizing new types of nanostructures. The emphasis in this work is on the use of organic and organometallic materials, and on the development of techniques that are very simple. Our experience has been that the simplest techniques are those that are the most rapidly developed, and thus that have the greatest impact.

**Synthesis and Characterization of Single-Crystalline VO₂ Nanowires**

*Hongkun Park* and *Bertrand I. Halperin*

Over the past 40 years, we have witnessed a remarkable miniaturization trend in semiconductor-based electronic circuits, which, were the trend to continue, would soon reach the nanometer scale. At the core of the current circuit architecture is a field-effect transistor (FET) that acts as a switch between insulating and conducting states upon the application of a gate voltage. The extension of the current silicon-based FET technology to the true nanometer scale is believed to be difficult, however, because the ultrahigh doping levels (on the order of 10²¹ or 10²² cm⁻³) required for reliable switching operation, are currently unachievable. As a consequence alternative FET operating principles have been actively sought in the scientific and engineering communities. One promising candidate is the Mott transistor, where the channel material undergoes an electrically driven Mott metal-insulator transition in its native form.

Vanadium dioxide (VO₂) is a particularly attractive material for realizing the Mott transistor because the compound undergoes a Mott metal-insulator transition at Tᵣ = 340 K, as signified by an abrupt increase in its resistivity (by a factor 10⁴ to 10⁷) upon cooling. Underlying this metal-
insulator transition is the structural change from a high-temperature tetragonal rutile structure to a low-temperature monoclinic structure. In the year 2003 grant period, we have developed a method to synthesize VO₂ in single-crystalline nanowire form (Fig. 3). The nanowire geometry of VO₂ enables detailed characterization of the Mott transition as a function of nanowire diameter and may also allow the facile fabrication of nanometer-scale FET devices. The research effort is jointly supported by the Harvard NSEC grant and the NSF CAREER Award.

The synthesis of single-crystalline VO₂ nanowires was achieved using a simple vapor transport method: specifically the bulk VO₂ powder was evaporated in a horizontal tube furnace while temperature (T), pressure (P), evaporation time (t), and argon carrier gas flow rate (k_flow) were accurately controlled. The nanowire product was collected on a substrate at the cooler end of the furnace, roughly 12 to 15 cm from the VO₂ starting material. Optimal reaction conditions were: T = 900°C, P ~12 to 14 torr, t = 5 hours, and k_flow = 12 sccm. Significantly, we found that the reliable production of nanowires depended on the choice of substrate surface: the greatest wire density was achieved using a Si₃N₄ substrate, whereas a SiO₂ substrate resulted in extremely low densities of very long wires. The strong dependence of nanowire growth and morphology on the substrate type suggests that the growth mechanism is probably a vapor-solid (VS) or a vapor-liquid-solid (VLS) mechanism in which the substrate acts as a nucleation site for nanowire growth.

The crystal structure of VO₂ nanowires was characterized using X-ray diffraction (XRD), transmission electron microscopy (TEM), and selected area electron diffraction (SAED). Figure 4(a) shows a high-resolution TEM image of a representative VO₂ nanowire with clear lattice fringes, thereby demonstrating its high crystallinity. Both XRD and SAED analyses have revealed that the nanowires are single crystalline and are composed of monoclinic VO₂ with the wire axis pointing in the [100] direction. Careful analysis of SEM and TEM images has further suggested that the nanowires have a rectangular cross section and are bounded by crystallographically equivalent (011) and (011) facets, as shown in Fig. 4(b).

![Figure 4. (a) High resolution TEM image of a representative VO₂ nanowire, illustrating lattice fringes. (b) Schematic of a nanowire with the growth surfaces indicated.](image)

The successful synthesis of single crystalline VO₂ nanowires opens up many exciting possibilities for further investigation. These nanowires may present a new model system to study nanoscale Mott metal-insulator transitions. They may also allow the fabrication of nanometer-
scale Mott FET devices if the Mott transition can be driven electrically. We are actively investigating these possibilities.

Developing Nano-Electronic Devices for Single-Molecule Sensing
Xiaowei Zhuang

Biological processes have complex dynamic behavior. Many of these processes involve multiple kinetic paths and transient intermediate states. These intricate dynamics can be directly observed in single-molecule measurements that allow one to record time-trajectories of individual molecules. This approach has the potential to bring our understanding of biological systems to a new level. However, current single-molecule techniques all have limitations. For examples, the patch clamp technique cannot be used to characterize proteins other than ion channels. Optical tweezers and other force apparatus are largely limited to motor proteins. Fluorescence spectroscopy usually requires the attachment of external fluorescent probes to bio-molecules. New single-molecule detection technology is thus in demand.

In collaboration with the Lieber group, we proposed to develop nano-electronic devices for single bio-molecule detection. These devices are based on nanoscale field effective transistors (FETs) made of semiconductor nanowires. Figure 5 shows the principle concept of using a nanowire FET to sense biological molecules. Specific binding of charged bio-molecules to receptors on the nanowire can lead to depletion or accumulation of carriers in the nanowire and result in a change of its conductance, an effect similar to changing voltage of the backgate of FET. Lieber’s group has demonstrated that such a device can sense pico-molar concentration of proteins, such as cancer marker PSA molecules.

As an initial step, we will test nanowire devices for ultra-sensitive viral sensing and try to detect single viruses electrically. Non-infectious model influenza viruses will be used. To detect the viruses electrically, the nanowires will be modified with anti-viral antibody to allow specific binding of viruses. As viruses contain charged biomolecules, a viral binding event should lead to a change in the nanowire conductance. We have tested viral binding to nanowires using optical imaging and achieved excellent specific binding of viruses to...
functionalized nanowires. While viruses clearly bind to the nanowire surfaces functionalized with specific antibodies to influenza, the wire functionalized with a different kind of antibody (anti-PSA) completely rejects viral binding (Fig. 6). With a simultaneously optical and electrical detection of viruses binding to nanowires, we plan to test the performance of nanowire sensors and develop virus sensors with single-virus sensitivity.

Our major goal of the project is to detect single protein molecules using the nanowire FET sensor. Our preliminary measurements showed that such detection may indeed be possible. Figure 7 shows two conductance traces of the nanowire FETs in the presence of low concentrations of PSA molecules. The nanowires are modified with anti-PSA antibody to allow specific binding of PSA molecules. The stochastic fluctuations of the conductance suggest that the conductance changes may be due to stochastic binding and dissociation events of single PSA molecules to the nanowire sensors.

To test whether the stochastic conductance changes shown in Figure 7 are indeed due to single protein molecules, we have constructed an optical microscope that allows detection of single biomolecules. Figure 8 shows that individual PSA molecules on nanowires can be detected by our fluorescence microscope setup. We will conduct such optical measurements at various concentrations of PSA molecules in the solution and test the binding and dissociation kinetics of PSA from the antibody-treated nanowires. The results will be compared with the conductance traces to test whether the conductance fluctuation as seen in Figure 7 is due to the binding and dissociation of individual PAS molecules.

Next, we propose to detect the binding of PSA proteins to nanowire sensors with optical microscopy and electrical measurement simultaneously (Fig. 9). The number of PSA molecule bound to a single nanowire device and the PSA binding and dissociation kinetics will be measured optically. These results will be correlated with the time trajectories of nanowire conductance to unambiguously test the single-molecule sensitivity of nanowire devices.

We expect this new technique to strongly enhance our ability to detect and characterize a large variety of microscopic biological entities at the single-unit level, opening a new realm of single-molecule biophysics and biological sensing technology.
This project, in collaboration with Westervelt, combines nanocrystal systems developed and characterized by Bawendi with novel magnetic devices developed by Westervelt, with the goal of spatially manipulating and positioning magnetic nanocrystals on two-dimensional surfaces. The microelectromagnets developed by Westervelt produce localized magnetic fields that can trap single or multiple Co nanocrystals. These traps are the magnetic equivalent of optical tweezers, but with potential nanometer spatial resolution. A long-range goal of the project is to use magnetic nanocrystals that are functionalized with interesting molecules or nanostructures, including DNA or proteins. The nanocrystals will then act as hooks to position these other objects on a two-dimensional surface with nanometer accuracy, thereby creating complex nanoscale assemblies with molecular spatial resolution.

In the last year, we have approached this project in two directions. Our initial goal had been to use magnetic Co nanocrystals. We discovered that the native oxide shell on our Co nanocrystals gave unexpected interesting new magnetic behavior. We have since systematically grown oxide shells of defined dimensions properties. Our Co(core)/CoO(shell) nanocrystals have a Co core that is ferromagnetic below the blocking temperature, and a CoO shell that is antiferromagnetic below the Néel temperature. We have also studied pure CoO nanocrystals. Zero field cooled temperature-dependent data are shown in Fig. 10 for an applied field of 100 Oe for different extents of oxidation. The pure Co NCs have a
blocking temperature of 120 K. After partially oxidation, the blocking temperature increases to 170 K—due to localized exchange biasing in each NC—and there is a spike at low temperature. For comparison, Co NCs with 3 nm diameter were prepared, and their blocking temperature was found to be 50 K. Thus, even a thin 3 nm shell of CoO serves to significantly stabilize Co NCs at increased temperatures, as evidenced by the increase in the blocking temperature from 50 K for a 3 nm core to 170 K for the same core with a CoO shell. For a pure CoO nanocrystal, the magnetization decays asymptotically with temperature, in accordance with Curie-Weiss law.

The field-dependent data in Fig. 11 were taken after cooling in a 5 T field from room temperature to 5 K. As oxidation proceeds, many effects are observed: (1) The moment decreases as the ferromagnetic Co becomes antiferromagnetic CoO. (2) The NCs require much higher fields to saturate. (3) The coercivity decreases, because the ferromagnetic volume is reduced. (4) The loop for the partially oxidized sample consists of two asymmetric lobes. (5) Exchange biasing gives rise to an exchange field that is observed in the field-shifted hysteresis for both oxidized samples. (6) Both oxidized samples are shifted along their moment axes, which suggests that some uncompensated moments are frozen during field cooling and remain pinned as the field is scanned. We believe these effects are from interfacial and surface CoO moments.

We are currently investigating the origin of the unusual shape in the asymmetric field-dependent curve for the partially oxidized sample and the extent to which the orientations of the exchange field and uncompensated CoO spins can be independently controlled.

Our second direction has been to turn to iron and iron oxide nanocrystals as the magnetic center. We are beginning incorporating iron and Fe₂O₃ nanocrystals in ~50 nm silica microspheres. We are also investigating various aqueous solubilization methods for ~15 nm iron oxide nanocrystals.

**Microelectromagnet Matrix and Micropost Array to Manipulate Magnetic Particles and Biological Cells**

Robert M. Westervelt, Mounji Bawendi, Donhee Ham and Federico Capasso

Developing methods to manipulate small particles and biological cells in a fluid will allow us to trap, move, assemble and sort these objects into custom-made structures and artificial tissues. Previously, we have fabricated and tested a micro-electromagnet matrix that can independently control the motion of a number of magnetic particles at the same time. This year we have constructed a micropost matrix that produces spatially patterned rf electric fields dielectrophoresis to manipulate nonmagnetic particles and cells.

Hakho Lee in Westervelt’s group, has constructed micro-electromagnet matrices using lithographic techniques, as shown in Fig. 12. The matrix consists of two layers of regularly spaced wires, perpendicular to each other, that are separated and topped by insulating layers. A microfluidic chamber is constructed on top of the matrix to hold suspended particles and cells. By controlling the currents through each wire, a peak in magnetic field amplitude can be created, that can trap a magnetic particle. By adjusting these currents, the peak and magnetic particle can be moved continuously to any location on the surface of the matrix.
Figure 12. Schematics and a micrograph of a microelectromagnet matrix. (a) The matrix consists of two arrays of straight wires aligned perpendicular to each other. The first set of conducting wires (bottom wires) is covered with an insulating layer, on which the second set of conducting wires (top wires) and an additional insulating layer are fabricated. (b) Micrograph of a completed matrix with 10 wires in each layer (a 10 × 10 wire matrix) with an 8 mm wire pitch. (c) Schematic cross section of a matrix along with a fluidic channel. The inset shows an image of a yeast cell attached to a magnetic bead.

Figure 13 shows how a matrix can be used to sort living (viable) from dead (nonviable) yeast cells, each attached to a magnetic bead. The top series of images show a viable cell selected and sorted out from a group of two nonviable cells. This is done by creating two peaks in magnetic field, one centered on the viable cell and one on the nonviable cells, and independently moving the viable cell away. This ability to sort cells by their observed characteristics is very useful. Because a matrix can manipulate many cells at once, it can perform many sorting operations simultaneously.

Figure 13. (Top) Series of optical images showing a viable yeast cell separated from two nonviable cells by the electromagnetic matrix; each yeast cell is attached to a magnetic bead. (Bottom) Corresponding series showing simulations of the magnetic field amplitude produced by the matrix. The grid shows the location of matrix wires.

In the past year, Tom Hunt in the Westervelt group has developed a micropost matrix, that uses electric fields and dielectrophoresis (DEP) to control the motion of biological cells and nonmagnetic particles. Figure 14 shows how a micropost matrix is constructed. A series of micron scale posts is created using optical lithography and electroplating. The use of posts allows one to concentrate the electric field at the tip of each post, and minimizes the effect of the electrical leads. A microfluidic channel is created on top of the micropost matrix to hold particles or cells suspended in the fluid. The voltage applied to each post is controlled by an array of rf-voltage sources. By varying these voltages, one can use positive or negative DEP to trap and move particles with polarizability greater or less than the fluid.

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Figure 14. Micropost matrix for trapping and manipulating single cells. (a) Micrograph of the micropost matrix. (b) A schematic 3D view of the device. (c) Cross section including the microfluidic channel above the micropost electrodes.

Figure 15 is a series of optical images that show how a single yeast cell is trapped by the micropost matrix and moved in a controlled path across the matrix. Because the voltages on each post are separately controlled by a computer, the motion of many cells can be simultaneously controlled.

The micro-electromagnet matrix and the micropost matrix promise to have a broad range of applications, when they are combined with microfluidic systems, for the assembly and sorting of small magnetic particles and biological systems.

**Microstructural Evolution of Solid and Fluid Systems**

**Howard A. Stone, Michael J. Aziz, and Eric Mazur**

During the past year, I have continued several projects that are collaborations with other NSEC scientists. This research involves two main themes: (i) analysis of nanostructure decay using step-flow inspired models (joint with Aziz and D. Margetis [MIT]) and (ii) analysis of the energy and surface modifications of femtosecond laser processing of glass surfaces (joint with Mazur and A. Ben-Yakar [Stanford]). In

Figure 16. Comparison of kinetic simulations of Israeli and Kandel (symbols) with our theoretical predictions. The upper curve shows the maximum of the step density and the lower curve shows the distance to the maximum density as a function of the ratio $g$ of the step-step interaction energy to line tension.
addition, motivated by conversations with a Harvard undergraduate, I undertook a research project in the area of deposition of carbon nanotubes on curved substrates. Papers on each of these topics have appeared, or are in press.

The project where I have made the most significant progress is in the area of the theoretical description of the evolution of surface morphology below the roughening temperature. We have developed a complete analytical description in the terms of a new nonlinear partial differential equation for the decay of a class of nanostructures. The predictions of the analysis include scaling relations for the surface shape as a function of the ratio of a step-step interaction energy to a line tension energy and the predictions are in excellent agreement with recently published kinetic simulations. I have also recently extended these ideas to describe grooving at a grain boundary.

In addition, we have extended the state of modeling of some femtosecond laser processing methods by recognizing that sufficient energy is deposited to melt the surface, after which external forces (e.g., the pressure of a plasma formed during laser processing) rearrange the liquid in the thin melted layer; the adjacent figures show an experimental profile with a crater formed after one 100 femtosecond laser pulse, and the figure to the right shows the results of our numerical simulations. We have provided both an analysis of the energy deposition and the motion of the thin liquid film.

Finally, we have experimentally shown how a dip coating method can be used to control the alignment of carbon nanotubes on a curved substrate such as a cylindrical fiber.

\textbf{Molecular Beam Epitaxial Growth of Quantum Structures and Nanostructures}

Arthur C. Gossard, Charles M. Marcus, Venkatesh Narayanamurti, Robert M. Westervelt, and Marc Kastner

In this work, we extended our active collaboration with NSEC researchers at Harvard on the growth of quantum structures and nanostructured materials at UC Santa Barbara for study at Harvard and at MIT. The materials were grown in the UCSB molecular beam epitaxy laboratories, which now include eight different MBE systems, three of which were acquired and installed during this year.

Our principal Harvard experimentalist collaborators are in the groups of Westervelt, Marcus and Narayanamurti. Our principal MIT collaborators are in the group of Marc Kastner. With Westervelt’s group, we extended our production of modulation-doped two-dimensional electron
gas materials for study of charge distribution and propagation in quantum point contact structures. We made specially designed InAs two-dimensional electron gases in which it will be possible to observe spin-dependent images and transport. Ideas for these experiments were already discussed by Gossard and the members of the Westervelt group during Gossard's previous sabbatical visit to Harvard and then during subsequent exchange visits of the Westervelt graduate students to UCSB and of Gossard and his students to Harvard this year.

With the Marcus group, we produced GaAs/AlGaAs quantum structures for fabrication with nanostructured gates for study of one-dimensional Coulomb drag, Rabi oscillations in coupled quantum dots and antilocalization in high-density two-dimensional electron gases. Our work with the researchers in this group led to a new Physical Review Letter on gate-controlled spin-orbit quantum interference effects. Preliminary samples for the new experiments have already been grown, and discussions of further iterations of the material designs are under way.

In our work with Narayanamurti’s research group, we made structures for observation of electro-optic up conversion via internal photoemission and observation of ballistic electron

Figure 17. Metal-semiconductor nano-composite material as seen in cross section in an electron microscope image. Dark-colored lines are layers of metal islands (erbium arsenide) in a semiconductor (indium gallium arsenide). The unique honeycomb structure occurs with alternate growth of ErAs and InGaAs by molecular beam epitaxy. The metal islands form in a spontaneous island mode of crystal growth. Faceting of the surface and appearance of the honeycomb structure occur only for metal depositions and indium content greater than a certain level.

emission luminescence in p-i-n AlGaAs junctions containing a GaAs quantum well. We grew the inverse n-i-p structures that enable ballistic hole emission luminescence. We also made structures for spatially resolved spin injection studies. We initiated study of epitaxial metal films and epitaxial metal nano-islands on semiconductor surfaces that are now being made at UCSB with erbium arsenide and erbium antimonide epitaxial semimetals on GaAs and GaSb.

Structures for the NSEC have been grown by several researchers at UCSB, with the principal growers having been Micah Hanson (4G), Dr. Christoph Kadow and Mr. Jeramy Zimmerman (2G) and this last summer by visiting Professor Werner Wegscheider of the University of Regensburg (Germany). Professor Wegscheider is a world leader in quantum structure growth, including materials with ultra-high carrier mobilities, nanostructures grown on cleaved edges of quantum structures, and most recently spintronic structures. He received support from the UCSB NSEC subcontract during his stay this summer.
In addition to our work with the NSEC experimentalists, we had discussions with the NSEC theoretical groups on issues of electron propagation and scattering in realistically non-uniform heterostructure potentials (Heller), growth and electronic energy level structure of epitaxial metal nanoparticles in semiconductors (Kaxiras) and Bose condensation phenomena of excitons in tunnel-coupled quantum wells (Halperin).

Exchanges of personnel between UCSB and Harvard also included a visit of Erli Chen from Harvard to UCSB to review materials processing and facilities. UCSB graduate students Driscoll and Hanson and Professor Gossard participated in the Harvard-University of Tokyo workshop in Tokyo this past summer.
Imaging Electrons in Nanostructures

Overview

The Imaging area of the Center develops new approaches for imaging the quantum behavior of electrons inside nanostructures, and understanding the results. The experimentalists have designed and constructed scanning probe microscopes (SPMs) that operate at low temperatures to maximize quantum effects. Investigation of the behavior of electron spins and charges in nanostructures is the focus of this area, and the participants are involved in the Coherent Electronics area of the Center through collaborative projects.

Simulations of electron motion in nanoscale structures is a focus of Harvard’s role in the new National Nanotechnology Infrastructure Network (NNIN) grant, awarded by the NSF in January 2004, along with chemical approaches to nanotechnology and soft lithography. Center participants Eric Heller and Efthimios Kaxiras are in charge of this project. The Center for Imaging and Mesoscale Structures at Harvard will appoint a Ph.D. computer scientist to develop new codes for use in simulations to assist outside users, as well as NSEC investigators.

Participants

Venky Narayanamurti is an expert in Ballistic Electron Emission Microscopy (BEEM), which uses hot electrons to probe the quantum states of nanoscale particles. He is developing methods to inject polarized electron spins from an iron whisker tip to investigate the surface states of semiconductor heterostructures with near atomic spatial resolution, for spintronics and quantum information processing. Robert Westervelt uses scanning probe microscopy to image the coherent flow of electron waves through nanostructures containing a two-dimensional electron gas. He recently developed an imaging interferometer that directly measures the electron wavelength and acts as a quantum phase shifter. Eric Heller is expert in the theory of the quantum mechanical motion of electrons and atoms through structures. He has developed an approach using thermal electron wave packets to understand interference patterns in images of electron flow. With Mark Topinka, Westervelt and Heller published a review “Imaging Electron Flow” in the December 2003 issue of Physics Today. Raymond Ashoori is well known for his beautiful images of electrons in a two-dimensional electron gas in the quantum Hall regime obtained using subsurface charge accumulation (SCA). He is currently investigating stripe structures imaged with this technique.

STM/BEEM Imaging and Hot Electron Transport in Semiconductor Nanostructures

Venkatesh Narayanamurti, Arthur C. Gossard (UCSB), D.M. Chen (Rowland Institute), and Charles M. Marcus (Harvard)

The emerging spin-polarized STM (SP-STM) technique enables simultaneous imaging of the surface topography and the spin-polarized surface states to nearly atomic resolution, which may provide new insight into the electronic states of novel quantum-confined magnetic nanostructures, such as quantum wells, quantum wires and quantum dots of ferromagnetic metals.
and dilute magnetic semiconductors (DMS). We have proposed single-crystal Fe whisker as a candidate spin-polarized probe for SP-STM. Compared with the in situ magnetically coated W tips, Fe whisker tips are robust against the easy loss of monolayer-thick magnetic coatings due to with the surface magnetization of the sample. The magnetic stray field from the domain boundaries can be avoided in the case of Fe whiskers because of their relatively large domain sizes (typically a few μm).

Figure 18. (A) A typical needle-shaped Fe whisker tip selectively grown on a W wire. Inset shows the end of the whisker. (B) A room-temperature STM image of Si(111) surface by Fe whisker tip with atomic miscut steps resolved. (C) A room-temperature STM image of Si(111) surface by Fe whisker tip that shows nearly atomic lateral resolution.

Single-crystal Fe whiskers with [100] axes and {100} side facets are prepared [1] by the chemical reduction of ferrous chloride (FeCl₂) at typical growth temperature of 600°C. The crystallographic analysis is done by ex situ SEM, TEM and electron diffraction. The elemental analysis by combined STEM and energy-dispersive X-ray analysis (EDS) confirms the chemical purity of Fe whiskers, as well as the absence of oxide after a post-growth H₂ treatment.

Electrochemical etching is found to be not suitable for transition metals due to their feasibility of oxidation in solutions. However, SEM images revealed that some of the Fe whiskers have tapered shapes with the ends in sizes of less than a few tens nm. Therefore, they naturally form sharp STM tips. We have selectively grown Fe whiskers near the end of polycrystalline W wires. Then the sharpest Fe whiskers were selected by SEM and used as STM tips.
Preliminary test of Fe whisker tips has been done in an UHV-STM setup operating at room temperature. The Fe whisker tips were cleaned in UHV by field emission and by applying short voltage pulses under the tunneling condition. Si (111) surface pre-cleaned by thermal annealing was used as the test sample. Atomic miscut steps on Si (111) are clearly resolved, which indicates that Fe whisker tips have very good spatial resolution.

Concurrently with the development of novel tips, we have been studying the MBE growth of thin magnetic layers in Si (111). On this surface direct deposition techniques yield metal-silicides. In order to avoid strong interfacial alloying, we deposit a single monolayer of Ga on Si (111). See Figure 19.

Annealing this system to 300°C creates a closely packed bilayer, where every other Si atom is substituted by a Ga atom (Fig. 19). This form of surface passivation is more efficient than the traditional H-passivation, due to the larger coordination of Ga atoms (3) as compared to H atoms (1) on Si(111). Deposition of Ni on this surface and subsequent annealing to 200°C yields atomically flat nanostructures. One of them is shown in Fig. 20. No signatures of in-depth alloying (formation of pinholes) were observed, indicating that even at elevated temperatures the bilayer prevents nickel-silicide formation. The technique is promising for the growth of transition and rear-earth metallic nanostructures on Si and Ge surfaces.

It is currently believed, that the injection of spins into a semiconductor becomes more efficient for abrupt epitaxial interfaces, i.e., highly resistive interfaces, rather than for alloyed (low-resistive) interfaces with a transverse composition gradient. The experimental study of electron confinement and interactions in magnetic thin films using low-temperature STM is planned as a next step.

Figure 19. Ga monolayer predeposited on Si(111) surface and annealed to 300°C creates a diffusion barrier for the magnetic layers deposited on top of the Ga-Si bilayer.

Figure 20. Epitaxial Ni (111) island grown on a Ga-terminated Si (111) surface.
In related experiments, Narayanamurti in collaboration with Marcus and Gossard has explored [2] hot electron transport and luminescence through magnetic multilayers deposited on specially grown GaAs quantum well structures. Luminescent spin-valve transistors have recently been fabricated [3] and show for the first time a magnetically switchable optical device. Its counterpart, a spin valve photo-diode [4] has also been invented and demonstrated.

References


Imaging Electron Interferometer
Robert M. Westervelt, Eric J. Heller and Arthur C. Gossard

We have developed liquid-He cooled scanning probe microscopes (SPMs) that can image the flow of electron waves through nanoscale devices formed in a two-dimensional electron gas inside a GaAs/AlGaAs heterostructure (Topinka et al., 2003). A close collaboration with Heller’s group allows us to use simulations of the flow of electron waves to understand what we observe in the SPM images, and to develop new ideas for experiments.

Figure 21. (left) Schematic diagram showing the charged SPM tip above a quantum point contact (QPC) formed in a two-dimensional electron gas by electrostatic gates. Simulations of scattering of the electron waves by the tip are shown. (right) Schematic diagram of the V-shaped interferometer. Electrons passing from the QPC travel along two paths: QPC to a mirror formed by a reflector gate, and backscattering by the charged tip. An image of electron flow in the area shown (blue) shows interference fringes when the reflector gate is energized.

The left panel in Figure 21 illustrates how the scanning probe microscope images the flow of electron waves at liquid He temperatures. The charged tip digs a ‘divot’ in the electron gas, by locally depleting it, and backscatters electrons arriving from a quantum point contact (QPC),
reducing the QPC conductance. By plotting the QPC conductance as the tip is scanned across the sample, a two-dimensional image of electron flow is obtained. The spatial resolution is quite good, because only the ‘glint’ backscattered from the divot changes the conductance. Interference fringes spaced by half the Fermi wavelength are clearly visible in images, demonstrating that the electron waves are coherent (Topinka et al., 2003).

In recent work, we have created an electron interferometer with a V-shaped path, shown in the right panel of Fig. 21 (Westervelt et al., 2004; LeRoy et al., 2004). Electron waves traveling away from a quantum point contact are reflected by an electron mirror created by a reflector gate, forming one leg of the V, and they are also reflected from the depleted divot beneath the SPM tip, forming the other leg. When the waves traveling along both legs return to the QPC, they interfere and change its conductance. As the distance of the SPM tip from the QPC is changed, the QPC conductance oscillates due to this interference, creating fringes in the image.

Energizing the mirror creates strong fringes in images formed by plotting the QPC conductance as the tip is scanned over the sample. This is demonstrated in Figure 22, which shows SPM images of electron flow, before (left) and after (right) the mirror is turned on, demonstrating how the mirror creates a V-shaped interferometer. This device acts as a quantum phase shifter — when one moves the mirror in one leg, the fringes in the other leg move by a corresponding amount. The interferometer can also act as a spectrometer for hot electron waves, by directly measuring the electron wavelength. Theoretical simulations of electron flow through the V-shaped interferometer are shown in Eric Heller’s section of this report, showing clearly how it operates.

Electron interferometers allow one to perform experiments in 2DEGs that are analogous to optical experiments done with pulsed lasers. Because the spatial resolution is sharper than the electron wavelength, one can record events at energies approaching the Fermi energy, corresponding to frequencies in the THz regime. Eric Heller has discovered that the thermal average over the electron energy distribution effectively produces wave packets that exist for very short times (< 1 psec) and decrease in duration as one raises the temperature. This effect allows one to perform time-dependent experiments by bouncing electron waves along multiple paths, like laser physics. Electron interferometers can also be used to make spectroscopic measurements of hot electrons, by directly measuring the distribution of electron wavelengths.

![Figure 22. Images of electron flow recorded by the scanning probe microscope before (left) and after (right) the reflector gate is energized at T = 2K. Interference of electron waves traveling along the two legs of the V-shaped interferometer creates strong fringes spaced by half the Fermi wavelength.](image)
**References**


**Simulations of Electron Flow in a Two-Dimensional Electron Gas**

*Eric J. Heller* and *Robert M. Westervelt*

**Significant Research Accomplishments:**

This year was a productive one, with several advances and discoveries along theoretical lines and in collaboration between theorists and experimentalists.

On the pure theory side, we realized that it was possible to replace the tedious procedure of running energy specific calculations again and again at slightly different energies to get a thermal average, with a “thermal wave packet,” whose energy distribution is the square root of the derivative of the Fermi function. The wave packet has a width equal to the thermal length, which decreases with increasing temperature. This means that raising the temperature is like an ersatz nano- or picosecond time-dependent measurement, and it greatly simplifies calculations. It also provides new insights into what interference structures survive thermal averaging, and to the interpretation of the patterns that do survive.

![Figure 23. A thermal wave packet (whose energy distribution is derived from its temperature) is shown emerging from a small opening (a quantum point contact, or QPC) from which it spreads out, hitting impurities. These scatter the waves, some of which head back to the QPC. They can interfere there only if they arrive at the same time.](image)

We also developed a code that requires only a TIFF file to give the potential field experienced by the electrons in a 2DEG, and another TIFF file specifying the absorbing boundary. These TIFF files can be scans or hand drawn images. Thermal wave packets can be run under a new potential
in a matter of minutes. The potential itself might have been sketched seconds before (see Nugget).

There were numerous ideas and interchanges with the Westervelt group that led to experiments and theoretical models and tests. One such idea is the electron interferometer, which accomplishes control of the electron flow in a 2DEG via interference effect analogous to Michelson interferometry.

Figure 24. A thermal wave packet has been sent from below, spreading out and bouncing against the two mirrors shown in the right and left portions of the image. After one bounce from the farther mirror, and two from the closer one, parts of the wave packet are arriving at the same time back at the QPC. By moving the mirror slightly (about 1/4 of a deBroglie wavelength) the resulting interference from the two paths goes from destructive (left, less flux seen going down) to constructive (right, more flux going down).

Figure 24 shows simulations of the flow of a thermal wave packet for electrons flowing through a V-shaped interferometer with two mirrors, one at twice the distance from the quantum point contact as the other. Interference only occurs when both wave packets return to the QPC at the same time.

**Charging, Transport, and Imaging in Low Density Quantum Dots**

Raymond Ashoori and Charles M. Marcus

We have continued our efforts in studying low-dimensional and highly confined electron gases over the range of electron densities where theory and experiments have led us to expect to find evidence for novel transitions in electronic properties. For instance, experiments by Kravchenko and coworkers have suggested the existence of an unexpected two-dimensional (2-D) metal-insulator transition. Changing electron density directly tips the balance between wave-like and
particle-like properties of electrons. The ratio of electron-electron interaction energies to mean electron kinetic energy is the fundamental parameter determining the behavior of electrons. We have developed three methods for studying such systems.

**Capacitance of electrons in confined two-dimensional hole gases**

As holes in GaAs have a significantly higher mass than electrons, theorists expect that they tend to behave more as classical particles at the same particle densities at which electronic systems display properties more consistent with a quantum fluid. The range of particle densities over which holes should undergo interesting quantum-to-classical transitions is therefore higher and, as higher density systems can better screen disorder, one can more easily produce low-disorder hole systems with densities in the interesting regime. For this reason, we have commenced a project to build quantum dots and to study other systems of holes.

As a first step in these measurements, we have produced novel samples with 2-D hole gases, allowing us to study both the features of tunneling of individual holes into the 2-D hole system along with capacitance measurements. Production of such sample requires new techniques for both growth of samples (using molecular beam epitaxy) as well as new methods for processing and contacting samples. We have built a “tunnel capacitor” consisting (from bottom to top) of a metallic p-doped substrate, a tunnel barrier, a quantum well for confining the 2-D hole gas, a blocking barrier that prevents the passage of holes, and a top metallic electrode. We can vary the hole density in the 2-D hole system by changing the voltage applied between the top metallic electrode and the metallic substrate.

![Figure 25. Capacitance C of the system vs. via voltage Vbias (see text).](image)

Measurements on this sample have led to an impressive observation. The capacitance of the system, at low-hole densities is considerably higher than one would expect for a quantum fluid or for a standard parallel plate capacitor. In Figure 25, the hole gas is fully depleted at around 0 mV applied bias on the top plate at 4 Kelvin. As the bias is made more negative, the hole gas fills, and simple geometric considerations suggest that the capacitance should rise as the hole gas fills and then plateau at a constant value. Instead, the capacitance peaks at about –70 mV. This is
a sign of a phenomenon known as “negative compressibility.” Essentially, correlations in electron positions diminish the energy cost for adding an electron to the 2-D hole system below the level than one would expect for charge uniformly distributed in two dimensions. These correlations only exist in the range of the quantum-to-classical transition described above.

The 2-D metal-insulator transition occurs for hole densities in the vicinity of the negative-compressibility peak seen above. We are now cooling this sample in our dilution refrigerator to observe how this phenomenon might vary at the low temperatures at which the metal-insulator transition appears. To date, no one has observed the negative compressibility phenomenon in 2-D hole samples appropriate for studying the metal-insulator transition. The measurements will also reveal effects of hole correlations in tunneling spectra. Finally, we will work to build laterally confined quantum dots from this material to study these phenomena at the single hole level.

The Ashoori group has observed a striking feature in the electron addition spectra of low-density quantum dots. Typically, in a quantum-dot electron addition spectrum, one tunes a gate voltage and denotes the voltages at which individual electrons enter the quantum dots. For high electron density quantum-dots, experiments reveal single electron peaks that are nearly uniformly in gate voltage. This phenomenon, known as “Coulomb Blockade” occurs because existing electrons in the quantum dot repel successive ones. Each electron requires an increment (a nearly fixed increment) more energy to enter the dot. Ashoori’s group has observed that in low-density dots, electrons can enter as pairs or even bunches of three or more as the gate voltage is tuned. This means that it cost no more energy to add a second dot after a first. Ashoori’s experiments differ from typical “lateral” quantum dot experiments in that electron additions are measured by sensing individual charges capacitively rather than sensing the effect of electron additions on currents passed through the quantum dot. This capacitive sensing scheme allows sensing of charges entering the dot even when the dot is not electrically conducting and facilitates measurement at very low densities.

Imaging nanoscale features in 2-D electron systems

We have continued work studying nanoscale electronic structures with our subsurface charge accumulation (SCA) imaging microscope. It has revealed some fascinating structures within the 2-D electron gas. At high Landau level filling factors (low magnetic fields), theorists predict that the electron gas can segregate into stripes. This is thought to occur due to competition between long-range Coulomb repulsion between electrons and short-range attraction due to exchange and correlations between the electrons. The widths of the strips should be in the range of 100nm. Although transport experiments have demonstrated effects possibly arising due to the existence of charged stripes, no experiments have directly detected the existence of stripes.

We have worked to image stripe structures using SCA imaging. SCA imaging consists of scanning a sharp metal tip close to the
insulating surface of GaAs to study patterns in the electronic density of states for charging an underlying layer of electrons. In the case discussed here, a 2-D electron system exists about 900 Angstroms beneath the sample surface. Several sets of images suggest that we have seen these structures, and the observed widths and periodicities appear close to those expected by theory. An example is shown in the picture (3 x 3 micron) on in Fig. 26.

A major difficulty in these measurements is that the signals are very faint, and we must scan our microscope tip very close to the sample surface (within 50 Å) observe the stripes. Small drifts in our scanning probe microscope (in our liquid helium-3 system) then often lead to the scanning tip touching the sample surface and destroying the observed features. We are then forced to move elsewhere to try the imaging again.

In order to solve this problem, we have designed a new microscope that will work in our dilution refrigerator, where thermal drifts will likely be strongly attenuated. Moreover, a series of quantum Hall phenomena develop at these lower temperatures. The microscope is now functioning at 1.7 Kelvin, and we expect to deploy it this year.

In order to develop a quantitative understanding of our measurements, we have developed methods to perform electrostatic simulations of the expected charge signal on the tip resulting from charge accumulating within the 2-D layer beneath the surface. Our simulations now allow us to distinguish several key features in our data. For instance we can readily determine the sharpness of our scanned metal tip by comparing the shape of the capacitance vs. tip to sample distance curve to the simulations. This has proven to be of enormous usefulness in understanding our images and eliminating artifacts.
Spins and Charges in Coherent Electronics

Overview
The Coherent Electronics area of the Center is developing methods for the quantum mechanically coherent control of spins and charges in devices for spintronics and quantum information processing. To maintain quantum coherence, high quality devices are fabricated from semiconductors and superconductors in the Cleanroom Facilities of CIMS at Harvard. Semiconductor heterostructures are grown in the MBE Laboratory at UC Santa Barbara for this research by Gossard, who collaborates with a number of participants. Transport measurements in Coherent Electronics are closely coupled with imaging of electron flow in the Imaging area of the Center.

Participants
Charles Marcus is developing methods to control the motion of electron spins inside semiconductor nanostructures by using electrostatic gates. He has developed a spin pump that operates by changing the shape of a quantum dot. Bertrand Halperin investigates the theory of spin motion inside nanostructures, particularly the effects of the spin-orbit interaction in a two-dimensional electron gas and in quantum dots. He collaborates with number of experimentalists. Marc Kastner is developing methods to perform electron spin resonance on few electron quantum dots, and has recently discovered microwave-photon induced Kondo satellites in quantum dot transport. Michael Tinkham has developed an efficient spin valve structure made from Al and two different ferromagnetic metals, for the control of spins in metals. Tinkham and theorist Eugene Demler are studying the conditions required for the existence of superconductivity in ultra thin nanowires. In a new direction, Federico Capasso is using NanoElectroMechanicalSystems (NEMS) to investigate the Casimir force.

International Collaborations
Participants in the Coherent Electronics area of the Center collaborate closely with Leo Kouwenhoven (TU Delft), Daniel Loss (U Basel), and with Seigo Tarucha and Hiroyuki Sakaki (U Tokyo). Students and postdocs travel between groups with support from the Travel Programs. A joint Japan/US workshop Frontiers in Nanoscale Science and Technology is held annually, alternating between Japan and the US; this workshop also invites investigators from Europe. The Center also supported the Solid State Quantum Information Processing Conference held in Amsterdam in December 2003, organized by Delft.

Spin Manipulation in Quantum Dots
Charles M. Marcus, Bert I. Halperin, Leo Kouwenhoven, and Arthur C. Gossard

There is a growing interest in the use of the spin degree of freedom of electrons for information processing. This application goal has focused attention on controlling and measuring electron spin, with the ultimate goal of rotating, setting, and reading out single electron spins. Many issues of fundamental scientific interest are raised by these goals, including the nature of spin-orbit coupling, many-electron effects, the role of quantum coherence, and the back-action of the detection of spin.
In the past year we have continued to explore gate control of spin in quantum dots. Most significant among this work was the development of a quantum spin pump that is capable of pumping pure spin, with no associated charge pumping. This was published in *Physical Review Letters*.

We also continued to explore how an in-plane magnetic field applied to a two-dimensional electron gas couples to the orbital degree of freedom of the electron. A prediction that the coupling appears only as a higher power of the magnetic field was verified, and various aspects of the symmetry and correlation functions of conductance fluctuations in the presence of an in-plane were measured and compared to theory. The publication, to appear as a Rapid Communication in *Physical Review B* also presents original theory, developed in collaboration with co-authors Vladimir Falko and Tomas Jungwirth. The relevance of this result is that at low fields, below 200 mT, an in-plane field couples predominantly to spin because of the high power of field for the orbital coupling.

In addition we developed methods of non-invasive (capacitive) charge sensing, which will be used in future experiments for single spin detection with one-shot readout.

**Significant Research Accomplishments**

In 2003 seven papers were published, five of which were in collaboration with other NSEC members. The subject of these papers concerned:

- Fano resonances in quantum dots (closely related to work in the group of NSEC participant M. Kastner).
- One-shot detection of the excited states of a quantum dot, a warm-up for one-shot spin detection, which is now underway.
- Charge detection of delocalized states in a double quantum dot.
- Realization of a spin-valve photodiode allowing, for instance, photodetection of local magnetic fields. In collaboration with Venky Narayanamurti (cover of *Applied Physics Letters*).
- Quantitatively verified theory of orbital coupling of an in-plane magnetic field, investigated how in-plane fields remove symmetry of conductance as a function of perpendicular field.
- Realized a pure spin pump using conductance fluctuations.
- Demonstrated control of spin-orbit coupling in a GaAs 2-D electron gas, including the first demonstrated crossover from weak localization to weak antilocalization as a function of gate voltage. Was able to quantitatively extract separate density dependences of Rashba and Dresselhaus contributions to spin orbit coupling.
In his NSEC project, Halperin has been working on the theory of superconductivity in very thin wires, on transport through single molecules with magnetic atoms, and on effects of spin-orbit coupling in transport through semiconductor nanostructures. The most significant progress has been made in the last of these areas.

Within the Harvard NSEC, much of the experimental work on charge and spin transport uses nanostructures build with lithographic patterning of a two-dimensional electron gas in a GaAs/AlGaAs heterostructure. This system is attractive because of its long electron mean free paths, and because there is a well-developed technology for fabricating high-quality gates and nanostructures. In GaAs 2DEGs, spin-orbit effects arising from the so-called Rashba and Dresselhaus terms imply that for electrons with a given momentum in the plane of the sample, there is a spin-quantization axis, also in the plane, such that electrons with spin parallel or antiparallel to this axis have different energies. If an electron of given momentum has its spin polarized in a direction that is not collinear with this quantization axis, then its spin will precess as the electron moves ballistically in the plane. If the electron travels more than a few microns without change of direction due to scattering from impurities or reflection from the boundaries, then the spin can precess through a large angle.

In order to discuss the time and space evolution of a collection of electrons, it is often convenient to employ a Boltzmann-like equation for the Wigner distribution, which is the quantum mechanical analogue of the classical distribution in phase space. When spin is taken into account, the Wigner distribution becomes a two-by-two matrix in spin space. Halperin and postdoctoral fellow Eugene Mishchenko, were able to derive, from first principles, a generalization of the Boltzmann Equation for a two-dimensional electron system with spin-orbit coupling of the Rashba or Dresselhaus form, in a situation where the background potential is either constant or slowly varying in space. The transport equations were applied to calculate the dynamic conductivity and structure factor, as well as the possibility of separation between spin components in a ballistic wave packet. These results were published in [1].

Work is continuing on the application of the Boltzmann approach to more complicated geometries. We are also using this approach to examine recent proposals that in the presence of a uniform electric current, spin-orbit effects can lead to a non-vanishing spin-current in the perpendicular direction. It is not clear, however, whether such spin-currents have observable effects; these would depend sensitively on effects of boundaries and impurity scattering, which need to be carefully considered.

In a related work, Mishchenko, together with Yaroslav Tserkovnyak (initially a graduate student, now a postdoctoral fellow) and visitor Arne Brataas, have discussed a method for spin-detection in quantum dots by electric currents [2]. They considered transport through a quantum dot connected to a reservoir via spin-polarized ballistic contacts, and showed that both the ac admittance and the frequency-dependent shot noise are controlled by spin-flip scattering and that they can be used to detect spin polarization and to quantify spin-flip scattering in the dot.
References


Spin Resonance in Coupled Quantum Dots
Marc A. Kastner, Charles M. Marcus, and Arthur Gossard

Our goal is to study the magnetic excitation and relaxation of single-electron transistors (SETs) containing unpaired electrons. We have built a cavity resonator in our dilution refrigerator so that the SET can be located at a maximum in the oscillating magnetic field. A constant magnetic field applied parallel to the two-dimensional electron gas splits the energies of the spin states while leaving the orbital motion unaffected. As usual in electron spin resonance (ESR), a small transverse oscillating field at a frequency equal to the Zeeman splitting (divided by Planck’s constant) is expected to cause transitions from one spin state to another. Our goal is to detect these transitions through their effect on the current through the SET. From the width in static field of the resonance, one can determine the spin decoherence time of the system, which is of intrinsic scientific interest. It has been suggested that SETs might be useful for the construction of quantum computers. This will require very long coherence times, so measurement of these is an important first step toward this technology.

In our first experiments we discovered two things which show that the ESR will require substantial modifications of the experiment. First, the Zeeman splitting in our SET is much smaller than expected. We believe that this is the result of the unusually high carrier density in the devices we have used, which pulls the electrons in the 2DEG into the AlGaAs where the $g$...
value is of opposite sign. We are planning to use a device made by the Marcus group which has a g-value somewhat larger than the standard one for GaAs. We are also trying to make InAs SETs which would have g-values ~30 times bigger than our current devices. More disconcerting, the electric excitation of our device caused by the cavity is much larger than we expected. This will be harder to solve but it has led to the discovery of a phenomenon predicted almost a decade ago and never before seen: photon-induced Kondo satellites. We discuss this exciting discovery next.

The discovery of the Kondo effect in SETs has created great excitement because the SET allows one to study this quantum mechanical many-body system in new ways. In particular, one can apply voltages between the leads and study the Kondo effect out of equilibrium. In the late 1980s theorists had proposed that a quantum dot containing an unpaired electron coupled to conducting leads would be analogous to a magnetic impurity coupled to its host metal, in which the unpaired electron is coupled with the delocalized electrons in the metal to form a singlet state. In the absence of the Kondo coupling, the conductance of an SET at zero drain-source bias V_{ds} is very small except for values of the gate voltage at which two charge states of the quantum dot are degenerate. Thus the zero-bias conductance as a function of gate voltage consists of a series of peaks, one for each electron added to the dot. The Kondo effect enhances the conductance between these peaks when the number of electrons is odd but not when it is even, because the screening of an unpaired electron by the electrons in the leads creates a new quantum mechanical many-body ground state that extends from one lead through the dot to the other lead.

The Kondo effect gives rise to a sharp peak in the density of states in each lead and at zero bias these peaks coincide in energy, giving excess conductance for small voltages. As early as the mid-1990s theorists predicted that microwave excitation would lead to satellite peaks in the density of state and excess conduction at a voltage such that eV_{ds} = hf where h is Planck’s constant and f is the microwave frequency. However, searches for this effect had been unsuccessful. We have recently submitted the first report of this phenomenon. Figure 27(A) shows a plot of the differential conductance as a function of V_{ds} and microwave excitation. At low microwave voltage one sees the sharp peak at V_{ds} = 0. As the microwave excitation is increased, the central peak decreases and two satellites grow. Figure 27(B) shows that the position of one of the satellites as a function of microwave voltage is in good agreement with hf at low excitation levels, as expected. The details of this experiment are giving new insight into the Kondo effect and decoherence phenomena.
Transport Properties of One-Dimensional Nanostructures
Michael Tinkham, Eugene Demler, Bertrand I. Halperin and J.U. Free (Eastern Nazarene College)

Our research on one-dimensional nanostructures involves three distinct classes of systems: superconducting nanowires, carbon nanotubes, and nanoscale spin-valve structures, in each of which we have made substantial progress during the past year.

We have included above a “nugget” reporting our direct measurement for the first time of the reduction of the Raman frequency shift in individual carbon nanotubes when they are mechanically stretched by use of an AFM tip. This quantity measures the reduction of the elastic constants under tensile strain, which provides a new test for theories of the electronic structure of these novel materials that have been worked out by the group of Demler, and also provides basic information about nonlinear elastic properties for potential nanotube applications.

In a second “nugget,” we have reported our success in fabricating an improved version of a “spin valve” nanostructure. When a current is passed to an Al film strip through tunnel contact with a ferromagnetic film strip crossing it, the induced spin polarization in the Al causes the voltage drop between the Al and a second magnetic film to depend on the relative direction of spin polarizations of the two ferromagnets. These can be reversed independently by varying a magnetic field parallel to the ferromagnetic strips, because they are chosen to have different coercive fields. The sign of the voltage reverses when the two magnetic strips are oppositely polarized compared to when they are polarized in parallel. The magnitude of the effect is ~100 larger than in earlier work by van Wees because our sample dimensions are much smaller and our ferromagnets are more strongly polarized.

In the work on superconducting nanowires, the central issue is identifying the controlling parameter(s) that determine whether a given nanowire can appear superconducting despite the Mermin-Wagner theorem. We have shown experimentally that neither the normal resistance of the wire $R_n$, nor the resistance/length $R_n/L$ (which is inversely proportional to the cross-sectional area of the wire) alone provides an answer. This result fits well with recent work by our

![Figure 28. Phase Diagram](image-url)
theoretical collaborators in the Demler group, who have generated a phase diagram (Figure 28) based on both $R_n$ and $R_n/L$ that appears to account for the data on most of the wires which we have studied. [The solid triangles denote “superconducting” samples (i.e., ones where $R(T)$ drops strongly), the x’s indicate normal samples (where $R(T)$ appears to be heading toward a non-zero value at $T = 0$), and the hollow symbols denote samples for which the extrapolation of $R(T)$ to $T = 0$ is ambiguous.] Further experimental and theoretical work will be required to obtain a more definitive resolution of these issues.

![Figure 28](image)

Although there is a clear distinction between resistive or insulating behavior in very thin nanowires, and superconducting behavior in thicker ones, it is not yet clear whether these two behaviors are separated by a phase transition or simply by a crossover, since the distinction is clearly defined only at the inaccessible $T = 0$. We have increased our sensitivity to this issue by extending the resistance measurements to the nonlinear resistance $dV/dI$ as function of $I$. (We have recently published a paper showing that heating effects could account for hysteresis in some samples, but here we are concerned with lesser levels of nonlinearity.) As shown in Figure 29, at $I \approx 0$ this $dV/dI$ is elevated or depressed relative to the normal resistance depending on whether the wire is “insulating” or “superconductive.” We are comparing our results with various theories that predict details about the form of $dV/dI(I)$, including a parallel between the dependences on current and temperature.

**Dissipation and Decoherence in Quantum Systems**

**Eugene Demler and Michael Tinkham**

As part of this NSEC project we worked on the problem of superconductor to insulator transition in one-dimensional systems in the presence of dissipation: Chains of mesoscopic grains and nanowires. We considered a model of mesoscopic superconducting grains coupled by Josephson junctions and shunting resistors. We also allowed for a finite rate of the superconducting-normal charge relaxation inside the grains. We found that in the case of fast charge relaxation there may be two superconducting phases: The locally superconducting phase, FSC, for strong dissipation,
and the globally superconducting phase, SC*, for weak dissipation. For slow charge relaxation, only the SC* phase is possible. For the SC* to normal phase transition we found that the long wavelength fluctuations dominate, the dissipation is irrelevant, and the dynamical critical exponent of the transition is one. For the FSC to normal phase transition the dissipation suppresses fluctuations at wavelengths longer than the superconducting-normal charge relaxation length, and the dynamical critical exponent becomes infinite. We showed that both kinds of the superconductor to normal phase transition have regions of the super-metallic behavior, in which the resistivity first decreases gradually with decreasing temperature to values smaller than normal state resistance, but then eventually starts to increase. We extended our analysis from discrete Josephson junctions to continuous superconducting nanowires and showed that the latter may only be in the SC* phase. This suggests that the crossover between the superconducting and the normal behavior of the nanowires occurs either when their total normal state resistance equals the quantum resistance, \( R_0 = h/4e^2 = 6.53 \, \text{kOhm} \); or when the fugacity of the quantum phase slips, which depends exponentially on the normal state resistivity, becomes too small. These results are in agreement with the recent experiments of Tinkham’s group on superconducting nanowires.

**Measuring and Tuning Casimir Forces with NanoElectroMechanicalSystems (NEMS)**

**Federico Capasso**

The Casimir effect, i.e., the attraction between two uncharged surfaces as a result of quantum mechanical vacuum fluctuations of the electromagnetic field, is one the most striking manifestation of Quantum ElectroDynamics. During the last few years Capasso pioneered the use of MicroElectroMechanicalSystems (MEMS) in the high precision measurement of Casimir forces. Micro- and nanofabrication techniques allow the assembly of devices whose mechanical components move at submicron distances. Thus the Casimir force might play an important role in future NanoElectroMechanicalSystems (NEMS). A fascinating question is whether one can tune and control it by altering the electronic and optical properties of the interacting surfaces.

In order to explore this point, Capasso’s group has carried out experiments aimed at understanding the dependence of the Casimir force on the optical properties of the interacting surfaces. Using a micromachined torsional device (Fig. 30) postdoc Davide Iannuzzi measured the Casimir force between a gold-coated plate and a sphere coated with a Hydrogen Switchable Mirror (HSM). HSMs

**Figure 30.** Optical profilometer image of a microtorsional MEMS device used in the Casimir force measurements. When a metallized microsphere is brought in close proximity (<100 nm) to the top Au coated Silicon, the latter rotates about the central axis. This rotation is capacitively measured using metal pads under the plate.
are shiny metals in their deposited state. However, when they are exposed to a hydrogen atmosphere, they become optically transparent (see Fig. 30). This remarkable effect is reversible: A hydrogenated HSM, exposed to air, switches back to the high reflective state. On intuitive grounds, the Casimir force between a gold plate and a HSM in air is expected to be larger than the force between the same surfaces exposed to hydrogen due to the strongly reduced reflectivity of the HSM. The measurements of the Casimir force between the HSM-coated sphere and the gold-coated plate both in air and in hydrogen are shown in Fig. 31. No significant change of the force was observed. This counterintuitive result can be explained by an elusive property of the Lifshitz theory, which describes the Casimir force between dielectrics and metals. In a nutshell, it can be shown that even dramatic changes in the optical reflectivity of the interacting surfaces do not necessarily give rise to significant variations of the Casimir attraction. This result has received considerable attention in the scientific community, leading to invited talks at two international meetings (Casimir Forces: Recent Developments in Experiment and Theory, Nov. 14–16, 2002, Cambridge, MA, and 6th Workshop on Quantum Field Theory Under the Influence of External Conditions (QFEXT03), Sep. 15–19, 2003, Norman, OK). A paper describing these results will soon appear in the Proceedings of the National Academy of Sciences.

Capasso’s group also investigated the Casimir force between a gold-coated plate and a transparent sphere covered with thin metallic films. The thickness of the films was chosen to be smaller than the skin depth of the electromagnetic modes that mostly contribute to the interaction. According to commonly accepted intuitive arguments this should lead to a significant reduction of the Casimir force. Preliminary measurements by undergraduate students Mariangela Lisanti and Davide Iannuzzi have shown no appreciable reduction of the force. Capasso will continue the investigation of these effects and plans to engage several theorists at Harvard and MIT in their interpretation.

Figure 31. Measured Casimir force between a gold-coated plate and a sphere coated with a Hydrogen Switchable Mirror as a function of the distance, in air (green dots) and in argon-hydrogen (red dots). Inset: A Hydrogen Switchable Mirror in air and in hydrogen. A similar mirror was deposited on the sphere of our experimental apparatus.
Current Science & Technology Center at the Museum of Science, Boston

Carol Lynn Alpert, Senior Investigator and Director, Strategic Projects at the Museum of Science, and Joel Rosenberg, Education Associate for Nanoscale Science and Engineering, at the Current Science & Technology Center, Museum of Science, Boston.

Project Title: NSEC Informal Education and Public Outreach
The participants and their colleagues develop innovative science communication strategies for disseminating information and enhancing public understanding of research in nanoscale science and engineering, engaging a broad range of audiences within and without the Museum.

Significant New Accomplishments During this Reporting Period

1. Monthly Cablecasting of Nanotech News Via New England Cable News

In August, CS&T launched monthly live cablecasts on nanotech research in partnership with New England Cable News. NECN reaches 2.8 million New England households. The “SciTech Today” segment is cablecast live from CS&T on Thursday mornings, and it is repeated throughout the morning. NSEC Education Associate Joel Rosenberg’s past cablecasts can be accessed at <mos.org/cst/nano>.

In addition to presenting nanotech research from around the world, Joel has highlighted NSEC researcher Xiaowei Zhuang’s work on imaging single influenza viruses and Eric Mazur’s work on nanoscale fiber optics. The Museum of Science is the first science museum in the world to cablecast on a regular basis from our exhibit floor.

2. Nanoscale Science and Engineering Presentations: Live and on the Web

NSEC Education Associate Joel Rosenberg develops and delivers live presentations to Museum audiences 2–3 times weekly. Over 3,000 people, including school group, family, and adult audiences have attended these popular programs during the current reporting period. Several of the presentations have been videotaped and edited and are available at <mos.org/cst/nano>. Current titles include “What is Nanotechnology? (Even the Experts Don’t Agree)” and “The Wonderful (and not-so-wonderful) World
of Carbon Nanotubes.” Another current title, “The Incredible Shrinking Transistor,” traces the
describes current efforts to create single
electron and molecular transistors that will revolutionize computing. This talk explores the work
of several members of the NSEC, including Marc Kastner, Seigo Tarucha, and Leo Kouwenhoven.

3. NSEC Guest Researcher Appearances: Live and on the Web

The Museum works closely with NSEC investigators
to prepare a popular series of live weekend guest
researcher events at the Museum of Science. Some of
the talks are videotaped and edited and accessible at
<www.mos.org/cst/nano>. Here are some highlights:

• **Eric Mazur** spoke several times before enthusiastic
crowds about the historical and scientific context for
his research on “Stopping Time” using Femtosecond
lasers.

• In a Friday evening lecture, **Charles Marcus**, shown
in the picture to the right, delivered a dynamic portrayal of quantum computing.

• **Eric Heller** delivered his “Making Waves” presentation. For the talk, Joel Rosenberg modified
the Museum’s permanent Chladni plates exhibit to have oval- and stadium-shaped plates. Heller
used the plates to compare the behavior of sound waves confined on a vibrating plate to the
behavior of electron waves confined in an atomic corral — a focus of Heller’s research. **Eric Heller**’s artistic images were also displayed in CS&T on a super-high resolution LCD screen for
several months over the holiday season.

• **Howard Stone** presented, “Go with the (micro-) Flow,” giving our public audience the opportunity
to think the way a chemical engineer does about fluid flows on the micro- and nanoscale.

4. Multimedia Research Updates

CS&T produces multimedia science research
stories for exhibit touchscreens and for the web,
accessible at <www.mos.org/cst/nano>.

Recent stories have included a profile of **Marc Kastner**, shown to the left, and a more in-depth exploration of **Xiaowei Zhuang**’s influenza imaging work.
EDUCATIONAL COLLABORATIONS and DISSEMINATION ACTIVITIES

As part of Harvard’s Project TEACH program, Joel Rosenberg delivered his presentation, “The Wonderful (and not-so-wonderful) World of Carbon Nanotubes” to a group of visiting seventh-graders. The talk was written up in the Harvard Gazette, accompanied by the picture to the right: <www.news.harvard.edu/gazette/2003/04.10/11-teach.html>.

Carol Lynn Alpert and Joel Rosenberg spoke about NSEC collaborative educational partnership activities at three different conferences: The Collaboration Between Researchers and Museums, held at the SciTech Hands-On Museum in Aurora, Illinois; the 2003 Connecticut Nanotechnology Initiative Symposium in Storrs, Connecticut; and the 2003 Association of Science-Technology Centers conference in St. Paul, Minnesota. Carol Lynn Alpert also served as a panel member at the Societal Implications of Nanotechnology workshop held at the National Science Foundation in December 2003, Alpert’s paper, “Engaging Public Audiences in Nanotechnology,” will be included in the Workshop Proceedings. While on other NSF business, Alpert also visited the Tokyo Museum of Emerging Science and Innovation, and has plans to initiate a collaboration with the group that developed the museum’s extensive nanotech exhibit.

Upcoming…

Alpert and Rosenberg will be giving a talk on NSEC educational outreach at the upcoming Nanotech 2004 Conference in Boston.

In the fall of 2004, the Museum of Science will be hosting “Strange Matter,” a traveling exhibit developed by the Ontario Science Centre in collaboration with the Materials Research Society (MRS). The Museum of Science is working with MRS to hold materials science education training workshops for teachers during the December 2004 MRS meeting in Boston, and to bring conference participants to the exhibit and related activities at the Museum.

Long-Term Plans

One of the more significant results of this unique NSEC-Museum collaboration is that the Museum of Science’s long-term strategic plan now includes provisions for a new exhibit area on nanotechnology. Alpert is exploring the idea of establishing a Nanotech Informal Science Education Resource Center at the Museum of Science that would foster broad collaboration among research institutions and science museums, documenting and sharing best practices in nanotech outreach exhibits, programs and materials, and facilitating their further development.
Education and Human Resources

The NSEC offers unique opportunities to integrate education and research. Our Center actively promotes programs for graduate and undergraduate students, facilitating collaborative interactions among the participants at Harvard, MIT, UCSB, Delft, Brookhaven, Oak Ridge, and Sandia National Laboratories; introduces a new course at Harvard on nanoscale science and engineering; provides fellowships to increase the participation by members of underrepresented groups in science and engineering; develops new methods of teaching science and helping public school teachers; and transfers new discoveries and technology to pre-college students and the general public through partnerships with the Museum of Science, Boston (and associated science museums). In September, Dr. Kathryn Hollar (Fig. 1) joined us as Director of Educational Programs. Dr. Hollar came from the Department of Chemical Engineering at Rowan University in Glassboro, NJ. She helped create outreach efforts to 7th/8th grade female students and also helped develop the training programs for graduate teaching fellows at Cornell where she took her Ph.D. in 2001. She is coordinating the educational programs of the NSEC and serving as a liaison to the efforts at the Museum of Science, Boston.

Graduate Activities

Harvard has made a fundamental commitment to support and stimulate interdisciplinary research by creating the Center for Imaging and Mesoscale Structures (CIMS). The experimental facilities and those provided by CIMS are natural meeting places for researchers from all parts of the Center to learn from one another and share their expertise. Visits and exchange programs with our international collaborators also expand the education of our students. Floris Zwanenburg and Chris Lodewijk (right) from the Kouwenhoven group in Delft working in the Marcus group at Harvard.

Figure 1. Dr. Kathryn Hollar (left), Director of Educational Programs, discusses the REU program during a minority undergraduate recruitment fair, October 2003.

Figure 2. Floris Zwanenburg (left) and Chris Lodewijk (right) from the Kouwenhoven group in Delft working in the Marcus group at Harvard.
Lodewijk, Master’s students from Delft, visited the Marcus group for three months to learn about transport systems (Fig. 2). Leo Kouwenhoven oversees a 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. Hiroyuki Sakaki and Seigo Tarucha look after similar visits with the University of Tokyo.

To bring the concepts, practice, and possible outcomes of research in nanoscale systems to a broad range of students, a course—Applied Physics 298r “Interdisciplinary Chemistry, Physics, and Engineering,” was taught in the spring semester of 2002/03. At each class a faculty participant of the Center (Fig. 3) described a particular aspect of nanoscale research and discussed possible new applications. This course was interdisciplinary, including faculty from the Division of Engineering and Applied Sciences, the Department of Physics, and the Department of Chemistry and Chemical Biology. Twenty-five students were enrolled for credit, but lectures were regularly attended by more than fifty people. The course will be given again in the spring semester 2004/05.

**NSEC Fellowships for Women and Minority Researchers**

We have established Center fellowships to encourage the participation of women and minority groups in science and engineering (Fig. 4). In the case of minority scholars, connections are made with minority faculty throughout the university to help promote career development in a broad sense. The fellows are provided with a basic level of research support and access to research facilities. The access to cutting-edge research facilities and the intellectual environment promotes the career development of Fellows and provides a strong pool of potential faculty candidates for Center universities and the scientific community at large. The NSEC is currently supporting three Fellows: Vidya Ramaswamy (Aziz), Amy Prieto (Park), and Laurie Calvet (Kastner).
Undergraduate Activities

The Research Experience for Undergraduates (REU) program immerses undergraduates in all aspects of ongoing NSEC research during the ten week summer period. Table 1 shows the participants for the summer 2003 in the REU program (Fig. 5) that was integrated with the Materials Research Science and Engineering Center (MRSEC) in 2002. Substantial support was also provided by the Division of Engineering and Applied Sciences (DEAS) and Harvard College.

Table 1: REU Program, 2003

<table>
<thead>
<tr>
<th>REU Participant/Institution</th>
<th>Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>John Biddle/Harvard College</td>
<td>Rapid Thermal Annealing of Ni/Au/Ge Ohmic Contacts to GaAs/AlGaAs Heterostructures with Two-Dimensional Electron Gases</td>
</tr>
<tr>
<td>David Bullon Patton/Eastern Nazarene College</td>
<td>Magnetoresistance in 10-15 Ni Nanowires</td>
</tr>
<tr>
<td>Annushka Chin Fong/Howard University</td>
<td>Chemical Vapor Deposits</td>
</tr>
<tr>
<td>Tzahi Cohen/Technion, Israel</td>
<td>Fe-Pd Alloy Ferromagnetic Shape Memory Thin Films</td>
</tr>
<tr>
<td>Nathaniel Craig/Harvard College</td>
<td>Spin Statistics and Fermionic Entanglement in Mesoscopic Quantum Dots</td>
</tr>
<tr>
<td>Sharon Oboshie Doku/Harvard College</td>
<td>Self-Organized Growth of Molybdenum Oxide Nanoparticles on Reconstructed Au(111) Surfaces</td>
</tr>
<tr>
<td>Christina Ann Fields/Harvard</td>
<td>Microscopic Beads in a Viscous Solution Using CARS Spectroscopy</td>
</tr>
<tr>
<td>Emmanouela Filippidi/Harvard University</td>
<td>Mechanical Properties of an Expanding Glioblastoma Tumor</td>
</tr>
<tr>
<td>Kirsten Frieda/Harvard College</td>
<td>Gene Expression: A Timer for In Vivo Venus Maturation</td>
</tr>
<tr>
<td>Christopher Holland/Morehouse College</td>
<td>A Density Separation in a Fluidic Channel by an Inhomogeneous External Magnetic Field</td>
</tr>
<tr>
<td>Stefan Ichim/Harvard College</td>
<td>Nanoscale Semiconductor Surface Self-Organization under Ion Bombardment</td>
</tr>
<tr>
<td>Legena A. Jack/Howard University</td>
<td>Timing Film Formation during the T-1 Process</td>
</tr>
<tr>
<td>Tyrone Jackson/Norfolk State University</td>
<td>Properties of Superconducting Dots</td>
</tr>
<tr>
<td>Emily Kendall/Harvard College</td>
<td>Using Kinesin to Probe the Mechanical Properties of Biopolymer Networks</td>
</tr>
</tbody>
</table>

Figure 5. Dr. Nadya Mason (left) from Harvard’s Society of Junior Fellows mentored REU students Tyrone Jackson (Norfolk State) and Hem Wadhar (right, Univ. of Penn.) in 2003.
The REU program is heavily subscribed and students apply online from across the country. Professors Stone and Friend along with the Assistant Director, Graham made a number of recruiting visits during the academic year to Historically Black Colleges to recruit students. These recruiting efforts, initiated in 2001, have resulted in a steady increase in participation in the REU program by females and members of underrepresented groups. In 2003, 48% of the REU participants were from underrepresented groups and 58% were women. There will be increased opportunities with support from the National Nanotechnology Infrastructure Network (NNIN) announced in January 2004. Applications are taken until February. The Director of Educational Programs, then works with senior researchers at Harvard, MIT, and UCSB to identify projects appropriate for undergraduate study. Nearly all of the investigators in the Center have participated in this rewarding program. The REU participants present their work at a
seminar at Harvard at the end of the summer and those students supported through the NNIN will also travel in mid-August to Penn State for the joint NNIN presentation. The NNIN program also includes the opportunity to include societal and ethical issues of nanotechnology as part of the joint REU summer program.

**K-12 Teacher Programs**

A *Research Experience for Teachers (RET)* program began in the summer of 2002 to involve local middle and high school science teachers with Center researchers for a six- to eight-week summer period. During 2003, the focus of our RET efforts was to introduce the *Peer Instruction* teaching methodology developed by **Eric Mazur** into local public high schools by working closely with RET physics teachers. The Peer Instruction method is now being used in public high schools in Cambridge (John Samp), Concord (Kristy Beauvais) and Marblehead (Meghan Walbran) through RET and local outreach efforts (Fig. 6). In March 2004, Kristy Beauvais, Meghan Walbran, and **Eric Mazur** led a workshop on Peer Instruction methods for other local science teachers (Fig. 7). The workshop was also a recruiting tool for the upcoming RET program in 2004. Participating teachers included physical sciences, mathematics, biology, chemistry, physics, and technology teachers from the 6th–12th grade level. Post-workshop communication has resulted in a community of teachers at high schools from New Hampshire to south of Boston who have implemented the *Peer Instruction* method in their classrooms with great success, and who are eager to share materials with other teachers. In the words of a Physical Sciences Teacher from NH, “I have already begun to start implementing the Peer Instruction method with my upper level students. It works fabulously and I am encouraged by how much my students are engaged in the process.” A Math Teacher from a Regional Technical High School says, “I enjoyed the workshop very much and have already tried it several times with tremendous success! I also found several resources for excellent concept questions, which I will be happy to share with the other math teachers.” As a result of the overwhelming interest in

![Figure 6.](image-url) John Samp (left), teaches high school physics at Cambridge Rindge and Latin High School using Peer Instruction via the Personal Response System (PRS) method (right).
using the *Peer Instruction* method and participating in follow-up workshops, we are planning future workshops that will run in conjunction with our summer RET experience.

The RET program allowed teachers to work directly with the NSEC investigators gaining first-hand knowledge of current research. We invited the teachers to return to the Center during the academic year with their students, where they can take the lead in explaining the research project.

Often teachers and undergraduates will work side-by-side on NSEC research projects during the summer RET and REU programs. This daily contact deepens the “experience” between these two groups of scientists. Where proximity permits, we encourage the REU students to visit the classrooms of the RET participants to describe their shared research and serve as role models for this larger group of students. Having made this introduction, we invite the classroom students to continue this dialogue when they visit the laboratories at the Center during the academic year.

**Outreach to K-12 Students**

Harvard University has established early awareness, outreach programs for middle school students in the Cambridge Public Schools. These programs are targeted at the entire city community to reach the broadest and most diverse population. During the academic year, classes and their teachers are invited to Harvard for a day where they meet with former Boston and Cambridge public schools students now in college, learn about college life, tour the campus, are exposed to critical thinking in a science presentation, have lunch with freshman in the dining halls, and hear about preparation for college and financial aid. This is an ideal environment for Center faculty to explain the research and societal benefits of studies at the interfaces between the micro- and macro-worlds to the public school middle students (Fig. 8).
Knowledge Transfer to the Public

To bring the research and technological advances from our Center to the public and to additional school populations, we have a close partnership with the Museum of Science, Boston. Materials developed in the collaboration with the Museum of Science, Boston will be shared with the Oak Ridge National Laboratory Museum of Science and Energy and the Sandia Atomic Energy Museum.

The Museum of Science, Boston is New England’s largest informal science and technology center, with decades of experience providing innovative programming to the public. The Museum entertains an audience of about 1.7 million visitors a year, including 270,000 students on school field trips and camp-in programs and enjoys a well-earned international reputation as one of the leaders in hands-on science education learning experiences. The Museum has opened a new Current Science & Technology Center that is equipped with a presentation stage, exhibit space, and large plasma digital imaging displays. The Current Science & Technology Center has state-of-the-art satellite and fiber optic connections, remotely-controlled cameras, web-streaming, and video-conferencing capabilities.

Center faculty members are collaborating with the Museum’s new Current Science & Technology Center (CSTC) in order to produce 3–5 weekly live presentations on various topics in nanoscale research (Fig. 9). Information on NSEC-related presentations are posted to the CSTCs website at http://www.mos.org/cst/article/3410.

Figure 9. Professor Howard Stone speaks at the Current Science & Technology Center at the Museum of Science, Boston.
Outreach and Knowledge Transfer

Developing Collaborations

The Center is developing strong partnerships with researchers at Sandia, Brookhaven and Oak Ridge National Laboratories, and with industry. The goals of these collaborations are to show students the range and quality of research on nanoscale systems at the national laboratories (Fig. 1) and in industry, and to allow them to use synthesis and processing facilities at these institutions with guidance from local researchers. Research on nanoscale systems can require equipment and processing techniques that are too complex and too expensive for universities to support. Access to the national laboratories and industry greatly expand the range of topics that can be addressed and improve the sophistication of the experiments. The national laboratories are excellent places to learn about research topics of national importance. Nanoscale science and technology is clearly one of these areas.

The senior participants closely involved with NSEC research at the National Laboratories are Dr. Terry Michalske, at Sandia and Dr. Jan Hrbek, Brookhaven. These senior participants also bring collaborative research projects to the Center’s attention, and oversee the exchange program. Robert Westervelt serves on the Advisory Board at the Center for Integrated Nanotechnologies (CINT) at Sandia National Laboratory, and Bill Appleton, the Director of CIMS at Harvard, was previously a senior manager at Oak Ridge and maintains active research interests there.

Visitor Exchange Programs

The Center is exchanging visitors between Center universities and the national laboratories, to share facilities, and carry out collaborative research. As described in the Section on Education, the Center’s Visitors Program, managed by a staff member, encourages collaborative work and supports student travel. Leo Kouwenhoven oversees the student exchange with Delft, which has excellent

Figure 1. Juan Abeyta (left) of Sandia National Laboratories talks with undergraduate and graduate students about research opportunities at SNL during a visit to the Center.

Figure 2. Hahko Lee, a graduate student in Prof. Westervelt’s group, traveled to South Korea in October 2003 and spoke at the 1st Korean/U.S. Nanotechnology Forum.
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. Hiroyuki Sakaki and Seigo Tarucha look after similar visits with the University of Tokyo (Fig. 3).

During the past year, 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. Graduate students Joshua Folk and Dominic Zumbühl, for example, had extended visits at both Delft Technical University and at the University of Tokyo. Zumbühl, who is completing his Ph.D. thesis with Charles Marcus in June 2004, will be taking a postdoctoral fellowship with Marc Kastner illustrating how technology is transferred through the training of talented students within the Center.

**International Workshops and Lecture Series**

We have cosponsored two International Workshops. The first (Fig. 4) was held in Japan on July 10–12, 2003 on, “Frontiers in Nanoscale Science and Technology.” This workshop organized just prior to the Electronic Properties of Two-dimensional Systems Conference drew a large audience from the U.S., Europe and Japan. The NSEC supported scholarships for graduate students from the NSEC International Travel program. The second workshop was held on December 15–18, 2003 on Solid State Quantum Information Processing Conference (Amsterdam, the Netherlands). The NSEC again sponsored scholarships for U.S. graduate students to attend the workshop (ssqip.tudelft.nl). Building on these successful workshops, we are planning the next workshop to be held in the Boston area in October 2004. We are now discussing possible research topics with our collaborators for this workshop.
There were also several special visits to the NSEC by distinguished lecturers in the Spring of 2004 to facilitate new interactions. In most cases, the lecturers visited the Center for several days to allow discussion with Center faculty and researchers. Lecturers included Daniel Loss (University of Basel), David Awschalom (UCSB), Boris Altschuler (Princeton), Michael Stopa (ERATO, Japan), Angela Belcher (MIT), Dragomir Davidovic (Georgia Institute of Technology), Alex Rimberg (Rice), Yigal Mier (Ben Gurion University), and Lieven Vandersypen (Delft, Fig. 5).

**Industrial Outreach Program**

In April 2003, NSEC members participated in the annual meeting of the Industrial Outreach Program (IOP) sponsored by Harvard’s Division of Engineering and Applied Sciences (DEAS). The IOP is aimed at strengthening external collaborations by facilitating mutually beneficial relationships between outside groups and DEAS interdisciplinary research groups. The program invited leading scientists from academia, industry, and a network of national laboratories to participate in workshops, research, and recruitment activities. Industrial sponsors, along with DEAS faculty and students, focus on problems that confront industry.

The day following the IOP meeting in April 2003, the NSEC held its annual workshop at which all NSEC participants presented their research (Fig 6), including talks on our educational programs, shared experimental facilities and outreach activities. The meeting also included poster sessions with students and time to visit laboratories. Nearly 100 senior researchers attended the IOP and NSEC annual meetings. Collaborations with industry (Unilever and Philip Morris) have developed from discussions initiated during these annual meetings. The IOP meeting will be held on May 20–21, 2004. Based on our experience from the past two years, we are selecting a smaller number of themes drawn from Center research and then targeting industries with whom we would like to establish new collaborations.
Other International Collaborations

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

delegations from Norway, Switzerland, UK (Imperial College), Northern Ireland, and several groups from Japan. After several meetings with members of National Nanotechnology Laboratory at Lecce, Italy, there was a high level meeting in April between the Italian Minister of Education, Letizia Moratti, and the Dean of Physical Sciences at Harvard, Venkatesh Narayamurti. Professors Federico Capasso and Robert Westervelt are members of the Committee exploring research fellowships and visitor exchange programs between Harvard and the National Nanotechnology Laboratory in Italy (Fig. 7).
**Shared Experimental Facilities**

**Overview**

The shared facilities are operated to encourage both 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 open 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. This state-of-the-art instrumentation brings new capabilities to the Center in the areas of nanofabrication, imaging and growth of nanoscale structures for ongoing research.

![Figure 1](image.png)

**Figure 1.** Construction underway at Harvard University (left) to prepare for the new Laboratory for Integrated Science and Engineering (LISE), April 2004. Computer-aided design of the completed LISE building (right) that will be the new home of the shared experimental facilities.

**New Laboratory Construction**

During the last year, Harvard University approved the construction of a new Laboratory for Integrated Science and Engineering (LISE). The Faculty Planning Committee viewed the construction of LISE, in close proximity to other science buildings in the north Yard, as a singular opportunity to create a research environment that will centralize major experimental facilities and foster cross-disciplinary research. The principal architect of LISE is Jose Rafael Moneo who served as Chairman of the Architecture Department of the Harvard Graduate School of Design (1985–1990). The building will include extensive vibration-free space to house the shared facilities including major cleanroom and nanofabrication facilities, advanced imaging laboratories, and facilities for materials synthesis. The building will also have space for new faculty (Interdisciplinary Research Laboratories) to advance cross-disciplinary research. A third programmatic element will be common spaces to promote collaborative exchanges. The project to reroute utility lines is now complete (Fig. 1) and excavation for the underground laboratory space just beginning with University contributions this past year already passing $12M. LISE is scheduled to open in 35 months.
Integrated Management

Harvard University supports the Center for Imaging and Mesoscale Structures (CIMS) to stimulate research and education in the area of nanotechnology and mesoscale science. A main mission of CIMS is the provision, operation and maintenance of complex facilities for imaging and fabrication. The management of the shared facilities at Harvard from CIMS, MRSEC and NSEC were integrated in 2002; the management boards of the Centers work closely together. Major equipment to be purchased with CIMS matching funds is selected by the NSEC Executive Board, in coordination with CIMS. In addition, the NSEC Executive also recommends the acquisition of instrumentation solely from CIMS funding. 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 collaborators described in the research sections (Fig. 2). User fees for the shared facilities, while not generally set at a level high enough to recover capital costs, are established so that operating and maintenance costs are divided equitably among all users. Since 1999, CIMS has acquired over $8M in instrumentation in the areas of cleanroom/nanofabrication; electron-beam and optical lithography; advanced electron-beam, optical and atomic imaging; materials synthesis and characterization; ion beam processing and characterization; and new equipment development. A complete list of CIMS supported instrumentation is at www.cims.harvard.edu.

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 (Fig. 3). 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. In the past two years, CIMS has hired four additional staff members; the NSEC makes a contribution of $50k/year to support technical staffing in the shared facilities. These policies ensure significant leveraging of NSEC resources.
National Nanotechnology Infrastructure Network (NNIN)

Harvard University is one of the twelve members of the recently announced National Nanotechnology Infrastructure Network (NNIN). CIMS will be responsible for also managing the Harvard portion of the NNIN activity (www.nnin.org) that will further reach 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; and the establishment of core computational resources to assist users in the understanding and visualization of new device structures. The areas have significant overlap with ongoing research with the NSEC. Discussions are already underway about tracking users, user rates, safety requirements, training and educational/ethical programs (3 additional REU students will be supported to carry out research this summer and have already been recruited). Possibilities for collaboration at the NSEC and NNIN were discussed in presentations at the recent Nanotech2004 Conference (Boston, March 2004; Fig. 4) and the third annual National Nanotechnology Initiative Conference (DC, March 2004).

Other Available Facilities

Center participants have access to other imaging, cleanroom, and synthesis facilities at MIT and UC Santa Barbara. With the installation of three new systems (Fig. 5), there are now a total of eight different MBE machines available for sample growth at UC Santa Barbara (www.materials.ucsb.edu/~mbe/lablayout.html). The NSEC has supported exchanges through the travel program by students expert in materials growth (UC Santa Barbara) to meet with students working in sample analysis (Cambridge). It is been very valuable in moving research forward for these different groups to gain an understanding of each other’s approaches and capabilities. The National Laboratories have excellent capabilities that also help NSEC researchers, particularly those in scanned probe microscopy at Brookhaven and the micro-electromechanical structure (MEMS) fabrication facilities at Sandia (www.cint.lanl.gov).

Center participants also 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 *Outreach and Knowledge Transfer*, above).

**Future Directions**

The addition of highly trained technical staff members, drawn from industry and academe, allows training of greater numbers of researchers. There are presently some 275 active users of the shared facilities. Since July 2002 this has included 112 postdoctoral fellows, 137 graduate students, 38 undergraduates, and 38 external users. The technical staff not only gives laboratory courses in analytical techniques but also contributes presentations (Fig. 6) during AP298r (see also *Education and Human Resources*, above). The staff also assists in instrumentation development that is essential to finding new tools for research. The completion of the LISE building will bring shared facilities together in one physical space, but we are continuing to move forward in our nanoscience program and with NNIN will interact with an even larger number of users throughout the nation.

![Figure 6. Dr. Eric Chen (right), discusses fabrication techniques in AP 298r.](image)
Publications

Note:  
as 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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to appear.


52. $^b$Mazur, E., inventor(s); “Infrared-absorbing, field-emitting, and photo/electro luminescing microtextured silicon devices including infrared absorbing, field-emitting and photo/electro luminescing microtextured active elements fabricated by laser/chemical etching,” Patent 60/293,560, May 25, 2001 (2001).

53. $^b$Mazur, E., inventor(s); “Subwavelength-diameter silica wires for low-loss optical waveguiding,” December 17 (2003).


Biographical Information

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Education
B.S. 1996, Physics, Seoul National University
M.S. 1999, Physics, California Institute of Technology
Ph.D. 2002, Electrical Engineering, California Institute of Technology

Professional Experience
2002–present Harvard University, Assistant Professor of Electrical Engineering, Division of Engineering and Applied Sciences
2000 IBM T. J. Watson Research Center, Mixed-Signal Communications IC Group

Selected Related Publications
Synergistic Activities and Awards

2003 IBM Faculty Partnership Award for his research, “Novel RF silicon integrated circuits for wireless networks beyond 50GHz.”

2002 Charles Wilts doctoral thesis (best thesis) Prize Winner at California Institute of Technology, “for outstanding independent research in electrical engineering leading to a Ph.D.”

IBM Research Fellowship Award and a former IBM Research Design Challenge co-winner where he with his team built a memory metal device that was presented later in the 2000 National Engineering Week.

Dr. Ham earned both the Presidential Top Honor Prize and the Valedictorian Prize on graduation from Seoul National University, ranked top 1st in his class across the School of Natural Sciences and Engineering.

Dr. Ham has developed two new courses on Electromagnetic Engineering and RF and High-Speed Integrated Circuits Design at Harvard University.

Dr. Ham has been working in the ABET committee, DEAS (Division of Engineering and Applied Sciences) undergraduate engineering education committee, and DEAS graduate admissions and scholarship committee, all in Harvard University.

Dr. Ham was the Silver Medal Winner of the 1990 Korean Mathematical Olympiad.

Collaborators

Robert Westervelt, Harvard University
Federico Capasso, Harvard University
Vahid Tarokh, Harvard University
Mehmet Soyuer, IBM T. J. Watson Research Center
Daniel Friedman, IBM T. J. Watson Research Center
Larry DeVito, Analog Devices, Inc.
Susan Feindt, Analog Devices, Inc.
Ichiro Aoki, Axiom Inc.
Hossein Hashemi, University of Southern California
Hui Wu, University of Rochester

Graduate Advisors

Ali Hajimiri, California Institute of Technology (Doctoral thesis advisor)
Barry Barish, California Institute of Technology (Master advisor)

Ph.D. and Undergraduate Students

Yong Liu, Ph.D. Candidate, Harvard University
David Ricketts, Ph.D. Candidate, Harvard University
Xiaofeng Li, Ph.D. Candidate, Harvard University (will arrive summer 2004)
Kyoungho Woo, Ph.D. Candidate, Harvard University (will arrive summer 2004)
William Andress, Undergraduate Student, Harvard University

Senior researcher

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Education

A.B. 1960, Chemistry, Harvard University, Cambridge, MA
Ph.D. 1964, Chemistry, Cal Tech, Pasadena, CA (with J.D. Roberts)

Professional Experience

1987 – present Harvard University, Mallinckrodt Professor of Chemistry (Chairman 1986–1989)
1983 – 1986 Harvard University, Professor of Chemistry
1980 – 1983 Massachusetts Institute of Technology, Haslam & Dewey Professor of Chemistry
1978 – 1980 Massachusetts Institute of Technology, Arthur C. Cope Professor of Chemistry
1974 – 1978 Massachusetts Institute of Technology, Professor of Chemistry
1969 – 1973 Massachusetts Institute of Technology, Associate Professor of Chemistry
1963 – 1969 Massachusetts Institute of Technology, Assistant Professor of Chemistry

Recent Professional Activities and Awards

2000 Von Hippel Award
1999 Award for Excellence in Surface Science
1999 The Wallac Oy Innovation Award in High Throughput Screening
1999 Sierra Nevada Distinguished Chemist Award
1998 National Medal of Science
1996 Madison Marshall Award
1996 Defense Advanced Research Projects Agency Award for Significant Technical Achievement
1995 Arthur C. Cope Award
1994 James Flack Norris Award, ACS New England
1989 Arthur C. Cope Scholar Award
1983 Remsen Award, ACS Maryland
1980 Alumni Distinguished Service Award, California Institute of Technology
1979 Harrison Howe Award
1975 American Chemical Society Award in Pure Chemistry
1968 Sloan Fellowship

Most Relevant Recent Publications


Synergistic Activities
1. Defense Science Board: Advisory board to the DoD on matters of S&T relevant to national security.
2. Defense Sciences Research Council: Advisory group to DARPA focusing on materials science.
3. National Research Council: A variety of activities, including decadal examination of chemistry and chemical engineering under the auspices of the Board on Chemical Science and Technology.

Collaborators and Other Affiliations

a. Collaborators and Co-Editors

Senior investigators with whom we have shared authorship on one or more papers since 1998 include: Ralph Nuzzo, U. Illinois; Anthony G. Evans, Princeton; Galen Stucky, UC-Santa Barbara; Don Ingber, Childrens Hospital-Boston; Mara Prentiss, Harvard; Howard Stone, Harvard; Klaus Jensen, MIT; John Rogers, Lucent; John Hutchinson, Harvard; Eugene Shakhnovich, Harvard; John Gillaspy, NIST; Younan Xia, U. Washington; Bob Weiss, Umass-Amherst; Paul Laibinis, MIT; Greg Girolami, U. Illinois; Ilhan Aksay, Princeton; Sal Torquato, Princeton; A. Dodabalapur, Lucent; John Deutch, MIT; Maria Rampi, U. Ferrara; Michael Grunze, U. Heidelberg; George Maracas, Motorola; Donovan Chin, Moldyne; Doug Laufenberger, MIT; Alex Rich, MIT; Richard Smith, Pacific Northwest Laboratories; Robert Westervelt, Harvard; Jonathan Sweedler, U. Illinois.

b. Graduate and Postdoctoral Advisors

J. D. Roberts, California Institute of Technology (PhD advisor; no postdoctoral advisor)

c. Thesis Advisor and Postgraduate-Scholar Sponsor (since 1998)

*Graduate Students* (25): George Sigal, IGEN; Enoch Kim, Surface Logix; Eric Simanek, Texas A&M; Mathei Mammen, AMI, Inc.; Younan Xia, U. Washington; Jinming Gao, Case Western; Robert Bird, CAS; Rebecca Jackman, The Commonwealth School; Laura Goetting, Shell, Inc.; Andrew Black, Patent Office, Australia; Insung Choi, MIT;
Emanuele Ostuni, Surface Logix; Tao Deng, MIT; Scott Brittain, Georgia State College; Jianghong Rau, UCSD; Ned Bowden, Stanford; Joe Tien, Johns Hopkins; Xiao-mei Zhao, Goodrich, Inc.; Bartosz Grzybowski, Northwestern U.; JC McDonald, Clark & Elbing, LLP; Janelle Anderson, self-employed; Kateri Paul, Xerox PARC; Ming-Hsien Wu, self-employed; Abraham Stroock, Cornell U.; Hongkai Wu, Stanford (The 24 current graduate students are not listed).

Postdoctoral Fellows (42): Joanna Aizenberg, Lucent; Seok-ki Choi, AMI; Ian Colton, Canada; Junmin Hu, HP, Inc.; Lyle Isaacs, U. Maryland; Christain Marxolin, France; Dong Qin, U. Washington; John Rogers, Lucent; Nik Wilmore, Columbia U.; Younan Xia, U. Washington; Lin Yan, Bristol-Meyers Squibb; Carmichael Roberts, Surface Logix; Andreas Terfort, Germany; Jeff Carbeck, Princeton; Francisco Arias, P&G, Inc.; Tricia Breen, IBM; Bob Chapman, Signature Bioscience; Daniel Chiu, U. Washington; Peter Glink, UNSW, Australia; Rainer Haag, U. Freiburg; Wilhelm Huck, Cambridge U., UK; Noo Li Jeon, Shriner’s Burns Institute; Paul Kenis, U. Illinois; Joydeep Lahiri, Corning, Inc.; Michael Liang, Cortek, Inc.; Scott Oliver, SUNY-Binghamton; Olivier Schueller, Surface Logix; Shu Takayama, U. Michigan; Marcus Weck, U. Georgia; Bing Xu, Hong Kong; Jason Wiles, Achillion Pharmaceuticals; Laurie Calvet, MIT; Venkat Thalladi, WPI; Teri Odom, Northwestern U., Cheolmin Park, Yonsei U., Korea; Alex Schwartz, McKinsey & Co.; Abraham Stroock, Cornell U.; Bartosz Grzybowski, Northwestern U.; Chengde Mao, Purdue U.; Rosaria Ferrigno, U. Lyon, France; Jerry Yang, UCSD; Babak Amirparviz, U. Washington (The 19 current postdoctoral fellows are not listed).
Honors and Awards

Moungi Bawendi

Fellow, American Association for the Advancement of Science (Feb. 2003)

Federico Capasso

Goff Smith Lecture and Prize, University of Michigan (3/15/03)
Honorary Doctorate in Electronics Engineering, University of Bologna (5/26/03)

Cynthia Friend

Distinguished Lecture in Chemistry, Wooster College, Ohio (May 1, 2003)

Bertrand Halperin

Wolf Prize in Physics. Awarded by the Wolf Foundation. Received from the President of the State of Israel, May 11, 2004.

Eric Heller

Joseph O. Hirschfelder Prize in Theoretical Chemistry, Theoretical Chemistry, University of Wisconsin, October 2003

Charles Marcus

Alexander Johnson: Harvard Physics Department Merit Scholarship

Venkatesh Narayanamurti

2 invited talks at major conferences (2003)
5 university colloquia (2003)
Member Advisory Committee MPS Directorate (2003–2006)
Advisory Board Miller Inst. for Basic Science, UC Berkeley (2000–2006)
Member, Brookhaven National Lab. Board (2004–)

Hongkun Park

Ho-Am Science Prize (2003)
Camille and Henry Dreyfus Teacher Award (2003)

Howard Stone

Fellow, Division of Fluid Dynamics of the American Physical Society (November 2003)
Midwest Mechanics Lecturer, 2002–3 (lectures at 9 Midwestern universities) (September 2002–May 2003)
Visiting Professor, Institut de Mecanique de Fluides, Universite Paul Sabatier, Toulouse France (January 2003)
Secretary-Treasurer, APS Division of Fluid Dynamics (2001–2003)
Vice-Chair, APS Division of Fluid Dynamics (2004)
Harvard College Professor (2000–present)
Robert Westervelt
Benson Lecturer, Miami University (2003)

George Whitesides
Pittsburgh Analytical Chemistry Award (Society for Analytical Chemists of Pittsburgh, 2003)
Kyoto Prize

Michael Fuerstman (Graduate student): U.S. Department of Energy Lindau Nobel Symposium Attendee

Xiaowei Zhuang
Searle Scholarship, Searle (2003)
Career Award, National Science Foundation (2003)
Beckman Young Investigators Awards (2003)
Alfred P. Sloan Research Fellowship, Sloan Foundation (2004)