Nanoscale Science and Engineering Center

The Science of Nanoscale Systems and Their Device Applications

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Massachusetts Institute of Technology
University of California, Santa Barbara
Museum of Science, Boston

With collaborations at…

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University of Tokyo
Brookhaven, Sandia, and Oak Ridge
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Executive Summary

Science Of Nanoscale Systems And Their Device Applications

The goal of this Nanoscale Science and Engineering Center is to combine ‘top down’ (lithographic processing) and ‘bottom up’ (chemical growth) approaches to construct novel electronic and magnetic devices with nanoscale sizes and understand their behavior, including quantum phenomena. The following important questions are addressed concurrently: How can nanoscale structures be grown and fabricated? 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 in four overlapping areas: Growth of Nanoscale Structures ranges from chemical growth of nanocrystals and nanomagnets, to self-organized growth of patterned surfaces, to new types of molecular beam epitaxy. Imaging Electrons inside Nanostructures explores how to image the behavior of electrons in nanostructures by using new techniques in scanned probe microscopy. Spins and Charges in Coherent Electronics investigates methods to move, control, and probe spins and charges in nanostructures, to develop coherent electronics for quantum information processing. Electronic Devices from Nanoscale Structures explores new approaches for making nanoscale electronic and magnetic devices.

These interdisciplinary research topics bring together sixteen participants from three universities — Harvard University, the Massachusetts Institute of Technology, and the University of California, Santa Barbara. Their research areas include Chemistry, Physics, Applied Physics, and Materials Science. The Center will maintain close collaborations with Sandia, Oak Ridge, and Brookhaven National Laboratories, and active international collaborations with Delft University of Technology and the University of Tokyo. A visitor program will encourage students, faculty, and staff to travel between these institutions to carry out collaborative research and use special facilities.

The Center for Imaging and Mesoscale Structures (CIMS) is a major investment by Harvard to promote and aid interdisciplinary research in Chemistry, Physics, Applied Physics, Materials Science, and Biology. Halperin is the Scientific Director and Appleton is the Director. CIMS is creating new, shared facilities at Harvard, and is coordinating their operation with technical staff. A Clean Room Facility has been constructed in McKay Laboratory, equipped with a new Raith electron-beam lithography system and associated equipment. In Mallinckrodt Laboratory CIMS has installed a new JEOL transmission electron microscope and a focused ion beam system. To house CIMS shared facilities and to provide space for interdisciplinary research, Harvard will construct a New Physical Sciences Building that will connect McKay, Cruft, and Lyman Laboratories. The new building will house an Imaging Laboratory equipped with scanning and transmission electron microscopes and scanned probe microscopes, a Clean Room Facility for nanofabrication, and an Advanced Materials Science Laboratory. By providing new facilities and added space, the New Physical Sciences Building will promote interdisciplinary research and make Harvard a very attractive place to carry out nanoscience research.
Our Nanoscale Science and Engineering Center promotes interdisciplinary research by bringing together experts from different research areas. By combining their skills, they will make new discoveries possible.

The Growth of Nanoscale Structures — The Center will focus on promising new approaches: chemical growth of nanocrystals and nanomagnets, self-organized growth on material surfaces, and new approaches to molecular beam epitaxy. Nanocrystals and nanomagnets make possible a range of interesting avenues to the construction of nanoscale structures. Bawendi and Park can grow nanoparticles from semiconductors or magnetic materials in controlled shapes with excellent uniformity and diameters as small as 3 nm. Bawendi and Weitz will use CdSe nanoparticles as fluorophores to track the position and orientation of structures. Aziz, Floro (Sandia), Friend, Hrbek (Brookhaven), and Mazur will investigate the self-organized growth of nanoscale structures on surfaces with theoretical support from Kaxiras and Stone. Self-organized growth can be achieved by tailoring the conditions of thin film growth, and promises to extend patterns made with conventional lithography to smaller sizes. Molecular beam epitaxy (MBE) will provide heterostructures for many of our participants. The MBE Lab at UCSB led by Gossard will make custom-grown GaAs/AlGaAs heterostructures for Center research and will investigate the growth of new materials. Nanoscale devices and circuits are made from these heterostructures in the Clean Room Facility in McKay Lab using electron-beam lithography and processing. Sandia has advanced facilities for research in this area.

Imaging Electrons inside Nanostructures — Our ability to image electrons inside nanoscale structures has been greatly improved by new techniques in scanned probe microscopy (SPM) developed by Center participants. The coherent flow of electrons through a two-dimensional electron gas will be imaged and analyzed by Westervelt, Gossard, and Heller. Methods to image spin flow using SPM will be explored to answer questions in spin injection and spintronics. Imaging of electron charge distributions in nanoscale structures and the manipulation of nanoparticles on surfaces will be done by Ashoori and Kastner. Narayananmurti is developing new approaches in Ballistic Electron Emission Microscopy (BEEM) at low temperatures. Park, Tinkham, and Kouwenhoven use scanned probe microscopy to probe carbon nanotubes, DNA molecules, and molecular clusters, and to do Coulomb blockade spectroscopy of their electron states.

Spins and Charges in Coherent Electronics — The control of the charge and spin of individual electrons will provide new approaches for sensors, electronics and spintronics. Quantum mechanically phase-coherent electronic devices and circuits are particularly interesting, because they may be able to implement proposals for quantum information processing. Methods to control electron charges and spins and to test their coherence will be investigated by a group of experimenters and theorists who are experts in mesoscopic physics — Ashoori, Kastner, Gossard, Halperin, Heller, Kouwenhoven, Marcus, Park, Tarucha, and Westervelt. New quantum dot designs will be developed to manipulate a very small number of electrons, and to couple two quantum dots together via quantum tunneling to form an artificial molecule. New methods are being explored by Marcus and Halperin to polarize and filter spins. Kastner is developing an apparatus to do electron spin resonance (ESR) inside quantum dots at low temperatures to test spin states and coherence. Magnetic
nanoparticles from Bawendi can be integrated with semiconductor nanostructures to help control spins.

**Electronic and Magnetic Devices from Nanoscale Structures** — The construction and testing of new types of electronic and magnetic devices from molecules and nanoscale structures will be explored to connect fundamental advances in Center research with possible applications. Combining expertise in nanocrystal growth, lithography, microfluidics, and scanned probe microscopy, Center participants can move, position, and probe individual nanoparticles. Park, Kouwenhoven, and Tinkham are developing nanoscale electronic devices from carbon nanotubes, DNA molecules, and molecular clusters that show interesting quantum phenomena. Chemically grown nanoparticles are very small (~5 nm) and they have interesting properties, but they are difficult to assemble into devices. Marcus and Kouwenhoven can attract a single nanocrystal or nanomagnet between narrowly spaced electrical contacts to conduct Coulomb blockade spectroscopy and related tunneling measurements. Westervelt, Bawendi, and Stone use lithographically made micro-electromagnets to trap nanomagnets that are suspended in a fluid at room temperature. A micro-electromagnet matrix can move, position, and join together nanomagnets to form custom devices with nanoscale precision. The Center encourages promising new ideas for nanoscale devices.

**Seed Projects** — Throughout each year the Center will provide seed funding for new, high-risk projects that could have important outcomes. This support will allow participants to investigate interesting ideas quickly, and it will help them obtain regular funding if they are successful. Seed funding is very useful for junior faculty and it can help bring newly appointed faculty into the Center.

**Education and Outreach** — The Center presents the basic concepts and the possible benefits of nanoscale science and engineering to the public at all levels. The Museum of Science at Boston works with Center faculty to develop exhibits and workshops for the public. An early awareness outreach program for the Cambridge public schools brings middle school students to Harvard for a day to learn about college education from faculty and students. The Center will expand this program to Boston public schools with help from their teachers. Mazur conducts a PEER Instruction Workshop for local teachers to introduce his innovative science teaching technique that has attracted national attention. College undergraduates can spend ten weeks at college in the summer doing research in the Center’s Research Experience for Undergraduates (REU) Program. The Research Experience for Teachers (RET) program will introduce public school teachers to university research and develop connections with public schools. A course at Harvard will cover the fundamental concepts in nanoscale research as well as possible applications in a series of lectures by Center faculty. A Postdoctoral Research Fellowship for Women and Minorities attracts outstanding candidates to university research.

**Shared Facilities** — High quality shared facilities are essential for research on nanoscale structures. The Center will have access to imaging, clean room, and synthesis facilities at Harvard, MIT, and UC Santa Barbara; at Sandia, Oak Ridge and Brookhaven National Laboratories; and at our international collaborators Delft University of Technology and the University of Tokyo. This group of institutions has outstanding facilities and staff to
help Center students, postdocs and faculty build and test nanoscale structures. In recognition of the importance of the Center and its role in promoting collaborative research, Harvard’s CIMS and the Division of Engineering and Applied Sciences will provide substantial funding for new equipment and staff.

**Collaborations with Industry and other Institutions** will be actively encouraged. An Advisory Committee consisting of leading figures in business and industry will periodically evaluate the industrial relevance of Center research and education and will help students be better aware in research opportunities in industry.

The budget is $10,798,000 for five years including $325,000 to support international collaboration. Harvard has committed $2,475,000 (22.9%) of cost sharing toward the five-year budget. This matching is in recognition of the importance of the Center to interdisciplinary research and education.
Mission and Broader Impact

The goal of this Nanoscale Science and Engineering Center is to combine ‘top down’ (lithographic processing) and ‘bottom up’ (chemical growth) approaches to construct novel electronic and magnetic devices with nanoscale sizes and understand their behavior, including quantum phenomena. The following important questions are addressed concurrently: How can nanoscale structures be grown and fabricated? How can they be imaged and probed? What are the fundamental behaviors of charge and spin? What could be the ultimate applications?

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Two workshops are planned for May 2002 to help build up connections between our Center and industry. A workshop titled “Frontiers in Materials and Nanoscience Research” will invite research personnel from industry to the Division of Engineering and Applied Sciences at Harvard to hear keynote speakers discuss the relation of academic and industrial research. The following day the Nanoscale Science and Engineering Center will hold its annual workshop, at which Center participants will present and discuss their research plans. This workshop will be open to industrial visitors as well as to students and faculty. We expect that discussions at these workshops will lead to new collaborative research projects.
The Center presents the basic concepts and the possible benefits of nanoscale science and engineering to the public at all levels. The Museum of Science at Boston works with Center faculty to develop exhibits and workshops for the public. An early awareness outreach program for the Cambridge public schools brings middle school students to Harvard for a day to learn about college education from faculty and students. The Center will expand this program to Boston public schools with help from their teachers. Center participant Eric Mazur conducts a PEER Instruction Workshop for local teachers to introduce his innovative science teaching technique that has attracted national attention. College undergraduates can spend ten weeks at college in the summer doing research in the Center’s Research Experience for Undergraduates (REU) Program. The Research Experience for Teachers (RET) program will introduce public school teachers to university research and develop connections with public schools. A course at Harvard will cover the fundamental concepts in nanoscale research as well as possible applications in a series of lectures by Center faculty. A Postdoctoral Research Fellowship for Women and Minorities attracts outstanding candidates to university research.

**Significant Advances**

Hongkun Park experimentally characterized electronic shell filling in metallic carbon single wall nanotubes (SWNT) using Coulomb blockade spectroscopy. This study revealed that nanotube devices can exhibit a distinct four-electron periodicity for electron addition, as well as the Kondo resonance and inelastic co-tunneling features (Fig. 1). These observations were analyzed in a unified fashion using a shell-filling model. This study represents the first case where the electronic structure of SWNTs, including the exchange coupling between electrons, is unambiguously and quantitatively determined.

**Fig. 1.** Differential conductance of a nanotube quantum dot vs. voltage $V$ and gate voltage $V_g$ at 1.5 K. The insets show electronic configurations at the blue and yellow dots, corresponding to the ground and excited electronic states.

Michael Tinkham and Leo Kouwenhoven performed scanned conductance microscopy of carbon nanotubes and l-DNA. By scanning an AFM cantilever over a Si wafer with samples on its surface, one can obtain a topographic image that shows, for example, both carbon nanotubes and molecules of DNA (left panel of Fig. 2). By repeating the scan with an electric potential on the tip relative to the grounded oxidized Si wafer, and sensing the phase-shift of the driven oscillatory tip motion, only conductive features are imaged (right panel). The nanotube is clearly

![Fig. 2. Images of a carbon nanotube and a DNA molecule on a substrate via scanned probe microscopy – topographic image, and conductance image.](image-url)
shown, while the DNA is not detected. This shows that the DNA is an excellent insulator under the conditions of this experiment.

Robert Westervelt demonstrated the controlled assembly of magnetic nanoparticles by a micro-electromagnet matrix (Fig. 3). Related work on Co nanomagnets is being pursued with Moungi Bawendi. The photograph shows how a micro-electromagnet matrix can join together two groups of magnetic nanoparticles to assemble them into a larger structure, by moving the particles through a fluid at room temperature. The matrix consists of two arrays of litho-graphically patterned wires, separated by and topped by transparent insulating layers. By adjusting the currents in individual wires, one or more maxima in magnetic field amplitude can be produced. Each maximum attracts and traps magnetic nanoparticles and can move them across the smooth surface of the matrix. Westervelt and coworkers have applied for a patent on this device.

Bertrand I. Halperin has investigated the theory of electron and spin transport in nanostructures in collaboration with Charles Marcus. The strength of spin-orbit coupling in a GaAs two-dimensional electron gas can be altered by application of a gate-voltage perpendicular to the layer, as well as by variations in the design of the confining well. They have shown that there will be particularly interesting consequences if one can create an inhomogeneous spin-orbit coupling in a laterally confined quantum dot via a gate that overlays only a portion of the area of the dot (Fig. 4). This configuration will reduce the suppression of spin-orbit effects due to lateral confinement. This would not only have a quantitative effect on the transport properties, but it should also allow one to attain regimes where the conductance fluctuations and weak localization corrections are described by different symmetry classes than would be possible in the uniform case.

Carol Lynn Alpert, manager of the Current Science & Technology Center at the Museum of Science, Boston, has coordinated the startup of their collaboration with the Center. The CS&T serves as an educational outreach partner. Their role is to interpret the work of the scientific investigators for a broad public audience and for students in middle school through upper grades. CS&T is developing multiple dissemination and educational modalities to accomplish the educational outreach objective including public presentations on the CS&T stage for public audiences and school groups and
digital exhibit kiosk stories about nanoscale research. Education Associate Joel Rosenberg has been appointed at the museum to produce NSEC-related programming. A web page has been created on the www.mos.org/cst website, linking to the NSEC website and to all the NSEC research partners. In the past year CS&T has been selected by the National Institute of Standards and Technology as one of the 50 “Best Practices in Science Communication” worldwide. Carol Lynn Alpert, has been invited to present the CS&T concept at the European ECSITE meeting of science and technology centers and to serve as advisor for NSF’s upcoming international working conference: “Museums, Media, and the Public Understanding of Research.”
Research Accomplishments and Plans

This section will describe the research accomplishment and plans of the Center’s participants over the period of their first research allocation. Because we want to encourage interdisciplinary work, we have chosen not to separate the Center into separate research groups, and the participants can work in two or more areas. The research projects described in this section illustrate how collaborations occur between participants with different expertise.

In the descriptions of research accomplishments and plans, the following important questions are addressed concurrently: How can nanoscale structures be grown and fabricated? How can they be imaged and probed? What are the fundamental behaviors of charge and spin? What could be the ultimate applications? The projects are categorized by four overlapping areas that address these questions: Construction of Electronic Devices from Molecules and Nanoscale Structures, Imaging Electrons inside Nanostructures, Spins and Charges inside Quantum Nanostructures, and Growth of New Types of Nanoscale Structures.

Participants and Seed Funding (Fall 2002)

This table lists the participants in our Center and their fields of research, their institution, and the particular areas of expertise among the three supported by the Center. Many participants are expert in two or more areas.

<table>
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<tr>
<th>Name</th>
<th>Field of Research</th>
<th>Institution</th>
<th>Growth &amp; Assembly</th>
<th>SPM</th>
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Public Outreach and Education
Carol Lynn Alpert
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International Collaborators
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Physics
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Hiroyuki Sakaki
Inst. of Industrial Science
U Tokyo
x
x
Seigo Tarucha
Physics
U Tokyo
x

National Laboratories
Jan Hrbek
Brookhaven
Elias Greenbaum
Oak Ridge
Terry Michalske
Sandia
Construction of Electronic Devices from Molecules and Nanoscale Structures

Quantum Transport in Carbon Nanotubes and Molecular Clusters

Hongkun Park with collaborator Bertrand Halperin

Park’s group has studied electron transport through chemical nanostructures, including single-walled carbon nanotubes (SWNTs) and molecular clusters containing transition metal atoms, using transport spectroscopy. These efforts resulted in (i) the experimental characterization of spin-electronic shell filling and exchange coupling in metallic SWNTs (Fig. 1) and (ii) the first demonstration of Kondo resonances in a single-molecule transistor (Fig. 2). These studies demonstrate that chemical nanostructures provide a powerful system to study a variety of contemporary issues in condensed matter sciences, such as exchange coupling and correlated electronic motion in nanostructures, and lays the groundwork for future transport studies of molecular-cluster systems, an area that represents an exciting intersection between chemistry and physics, but has received little attention to date.

In the first research effort, Park studied transport in nanotube quantum dots with average conductance \( \sim 1-2 \, e^2/h \) and experimentally characterized electronic shell filling in metallic SWNTs. This study revealed that nanotube devices in this intermediate coupling regime exhibit a distinct four-electron periodicity for electron addition, as well as the Kondo resonance and inelastic co-tunneling features. These observations were analyzed in a unified fashion using a shell-filling model. The Hartree-Fock parameters that completely determine the electronic structure of nanotube quantum dots were deduced from this analysis, showing that the energetic contribution of exchange coupling is 10% to 20% of the electronic level spacing. This study represents the first case where the electronic structure of SWNTs, including the exchange coupling between electrons, is unambiguously and quantitatively determined.

**Fig. 1.** Differential conductance (\( \partial I/\partial V \)) plots as a function of bias voltage (\( V \)) and gate voltage (\( V_g \)) for a nanotube device measured at \( T = 1.5 \) K; white corresponds to 0, and the darkest color corresponds to \( 1.5 \, e^2/h \). The sloped white dashed lines delineate conductance-gap regions. The inset diagrams show the electronic configurations at the positions marked by numbered dots. Blue and yellow dots indicate transport features arising from the ground and excited electronic states of the nanotube quantum dot.
In the second research effort (partly supported by the NSF CAREER Award), Park developed an experimental method to reliably incorporate individual molecules into a three-terminal transistor-like configuration and fabricated single-molecule transistors containing individual divanadium molecules \(((N,N'\text{-}N''\text{-}N'\text{-}trimethyl-1,4,7-triazacyclononane)_{2}V_{2}(CN)_{4}(m-C_{4}N_{4}))\); The molecule was synthesized in Prof. Jeffrey Long’s group at UC Berkeley). Low-temperature transport studies showed that single-molecule transistors reproducibly exhibit Kondo resonances, and hence an individual divanadium molecule essentially serves as a spin impurity. Significantly, Park’s group found that the Kondo resonance can be tuned reversibly using the gate voltage to alter the charge and spin state of the molecule. They also found that the resonance persists at temperatures up to 30 K and when the energy separation between the molecular state and the Fermi level of the metal exceeds 100 meV. This study represents the first among a series of studies that will investigate the transport properties of individual molecules containing transition metal atoms.

**Fig. 2.** Differential conductance \((\partial I/\partial V)\) plots as a function of bias voltage \((V)\) and gate voltage \((V_g)\) obtained from single-\(V_2\) transistors measured at \(T = 300\) mK. The \(\partial I/\partial V\) values are represented by the color scale, which changes in from dark red (0) to bright yellow (1.55 e\(^2\)/h). The labels I and II, mark two conductance-gap regions, and the diagrams indicate the charge and spin states of the \(V_2\) molecule in each regions.

**Scanned Conductance Microscopy of Carbon Nanotubes and l-DNA**

Michael Tinkham with Leo Kouwenhoven

By scanning an AFM cantilever over a Si wafer with samples on its surface, one can obtain a topographic image that shows, for example, both carbon nanotubes and molecules of DNA (left panel). By repeating the scan with an electric potential on the tip relative to the grounded oxidized Si wafer, and sensing the phase-shift of the driven oscillatory tip motion, only conductive features are imaged (right panel). The nanotube is clearly shown, while the DNA is not detected. This shows that the DNA is an excellent insulator under the conditions of this experiment.

**Fig. 3.** Images of a carbon nanotube and a DNA molecule on a substrate via scanned probe microscopy – topographic image, and conductance image.
Controlled Assembly of Magnetic Cobalt Nanoparticles by a Micro-electromagnet Matrix

Moungi Bawendi, Robert Westervelt, and Howard Stone

This project combines nanoparticle systems developed and characterized by Bawendi with a novel magnetic device developed by Westervelt with the goal of spatially manipulating and positioning single magnetic nanoparticles on a two-dimensional surface. The micro-electromagnet matrix developed by Westervelt has the capability of producing localized magnetic fields that can trap single magnetic nanoparticles. These traps are the magnetic equivalent of optical tweezers, but they can potentially operate with nanometer resolution. An ultimate goal would be to use Co nanoparticles that may be functionalized with other interesting molecules, including DNA or proteins, as hooks to position these other objects on a 2-D surface with nanometer accuracy, and thereby create complex assemblies at the molecular level.

In this first cycle, Bawendi’s group has refined the synthesis and characterization of Cobalt nanoparticles for incorporation in this system. They use the decomposition of dicobalt octacarbonyl in the presence of trialkyl phosphines at high temperature (>200 C) in a high boiling solvent (dioctyl ether). The phosphine ligands serve as growth inhibitors to allow for controlled growth of nanometer size particles with tight size distributions (<10%). Long chain carboxylates are added to the solution after the growth has ended to functionalize the surface of the Co particles. These acids are stronger ligands than the phosphines and allow further processing of the particles. They have investigated further functionalizing the Co nanoparticles with fluorophores so that the particles can be tracked using far-field or confocal fluorescence microscopy.

Bawendi’s group has also pursued attaching luminescent CdSe nanoparticles to the cobalt. This latter strategy is chemically demanding and they are in the process of engineering ligands that can serve the roles of passivating the semiconductor particles on one end, and passivating the Co particles on the other. They are designing these caps to be multidentate so that the attachment to the semiconductor particles is robust.

Bawendi’s group has obtained preliminary success in attaching dye molecules to the Co particles, and they have established that these dye/Co nanoparticles can be imaged using a far-field microscope. They are now in the process of trapping these Co-fluorophore systems by using a microfabricated current loop from Westervelt to ensure that the fluorophores and the Co particle stay as a robust pair under magnetic manipulations.

Westervelt’s group has demonstrated the control of nanoscale magnetic particles in fluids at room temperature by using a lithographically patterned matrix of wires, shown schematically in Fig. 4. The matrix consists of two wire array layers separated and covered by transparent insulating layers (Lee et al., 2001). A local maximum in magnetic field amplitude can be created by
adjusting the individual wire currents, under computer control. The field maximum creates a magnetic trap that attracts and holds nanomagnets, and can move them to desired positions along the surface. The competition between the trapping potential and thermal excitations gives nanoscale precision for nanoscale magnets, much smaller than the wire spacing. Additional traps can be created at different positions, by adding the appropriate currents to the wires. In this way, two or more nanomagnets can be assembled into a custom-designed structure. A goal is to move and position nonmagnetic objects with the aid of a Co nanomagnet attached to them. Nanofluidics associated with the motion of nanomagnets pulled through fluids by magnetic forces will be studied by theorist Howard Stone.

The Westervelt and Bawendi groups plan to trap and image single Co nanomagnets suspended in a fluid at room temperature. By coating the nanomagnets with a dye or by attaching CdSe quantum dots, they become visible under laser excitation in an optical microscope.

References


**Imaging Electrons inside Nanostructures**

**Development of New Forms of Scanned Probe Microscopy**

Venkatesh Narayanamurti with Arthur Gossard

In their research the primary effort of Narayanamurti’s group has been expended in developing novel variants of Ballistic Electron Emission Microscopy (BEEM) to probe quantum nanostructures below the surface. Three types of new apparatus have been developed: 1) a low temperature BEEM capable of operating down to 1.1 K; 2) UHV BEEM to study epitaxial interfaces (Altfeder *et al*., 2001); 3) Optical BEEM and STM to probe luminescence from localized structures. These provide very complimentary capabilities to those done in the Westervelt and Ashoori laboratories to exploit Scanned Probe Microscopy techniques for studying nanostructures.

During this period, Narayanamurti, his student Wei Yi, and postdoctoral associate Altfeder have made significant progress — especially Ballistic Electron Emission Microscopy (BEEM). The ability to grow epitaxial metal films in situ and to probe BEEM under UHV conditions has now been firmly established. A low-temperature BEEM system capable of operation to 1.1 K has been used to make temperature-dependent transport and scanning tunneling microscopy measurements on GaMnAs material grown by Gossard. Tunneling into the GaMnAs has been observed and both semiconducting and metallic phases have been detected.

Very recently Narayanamurti has established a collaboration with Dong Min Chen of the Rowland Institute of Science. Dr. Chen has recently developed a UHV dual-tip STM capable of operating down to 4.2K. They are currently modifying the sample holder to enable freshly cleaved samples to be studied. This capability would allow them to produce atomic
resolution STM images of GaMnAs structures and to study three-terminal transport along wires.

References


Imaging the Flow of Electron Waves in GaAs/AlGaAs Heterostructures

Robert Westervelt, Eric Heller, Arthur Gossard

By using a scanned probe microscope with a charged tip, it is possible to image the flow of electron waves through a two-dimensional electron gas at liquid He temperatures (Topinka et al., 2001). The tip capacitively couples to the gas and backscatters electrons passing immediately below. Figure 5 shows an experimental image of electron flow from a quantum point contact at the left. Images such as these are in excellent agreement with theory from Heller’s group.

The coherence of the flow is demonstrated by the presence of interference fringes spaced by half the Fermi wavelength. LeRoy et al. (2002) have demonstrated that the fringe spacing and direction can be used to image the density profile of a two-dimensional electron gas.

Much progress has been made by Heller’s group in understanding the fringes in images such as Fig. 4. Multiple scattering calculations have been used to ferret out the effect of direct versus indirect scattering, with the result that direct scattering is sufficient to understand most of the interference structure seen in the experiments, including the robustness against thermal averaging. To check the effects of scattering, Heller and Westervelt have done theory and imaging experiments on a system with an added artificial backscatterer, produced using lithography. This should act to enhance interference fringes in the image at the same radius from the quantum point contact as the lithographic obstruction. Early results, both experimental and theoretical, seem favorable, so we may indeed have the correct explanation of the fringing in the first place.

Meanwhile, Heller’s group proceeds to better understand the branching observed in electron flow through a two-dimensional electron gas (Topinka et al., 2001). A new model based on the classical stability exponents and the orientation of the initial classical manifolds created by a quantum point contact emitter seems to explain much of the data.

Fig. 5. Image of coherent electron flow from a quantum point contact at the left, with interference fringes spaced by half the Fermi wavelength.
Exciting new investigations have been made on the effects of the undulating donor potential near the walls of quantum dots and wires. (See research highlights). Heller has recently determined that backscattering is enhanced at the walls, due to slowing of the motion and the enhanced kinematic effects of the hills and valleys in the potential. These effects need to be taken into account in theories of conductance; they also may lead to interesting dynamics that to some extent might compromise the assumed shape of dots with more diffusive scattering at the walls. Finally Heller’s group has undertaken a fresh look at the theory of decoherence in quantum dots; this is still at an early stage.

References


Spins and Charges inside Quantum Nanostructures

Spin Resonance in Coupled Quantum Dots

Marc Kastner with Charles Marcus, Arthur Gossard, Bertrand Halperin and Robert Westervelt

The primary research proposed by Kastner involves electron spin resonance (ESR) in artificial atoms. Kastner’s group has begun collaborating with Marcus to study the magnetic excitation and relaxation of single-electron transistors containing unpaired electrons. There will, of course, be unpaired electrons when the confined droplet in a single electron transistor (SET) contains an odd number of electrons, but it can also happen with even numbers of electrons because of exchange effects, as recently studied by Halperin in the context of metallic nanoparticles (Oreg et al., 2001).

Kastner’s group has built a cavity resonator in their dilution refrigerator so that the SET can be located at a maximum in the oscillating magnetic field. This is critical because it is known that microwave electric fields cause photon assisted tunneling in SETs, and they want to exclude this process in order to be sensitive to the magnetic excitations of the spins. A constant magnetic field will be applied parallel to the two-dimensional electron gas, to split the energies of the spin states while leaving the orbital motion unaffected. As usual in ESR, the cavity will apply a small transverse oscillating field at a frequency equal to the Zeeman splitting (divided by Planck’s constant), which will cause transitions from one spin state to another. For simplicity, consider the case of an odd number N of electrons confined in the SET. Current flows through the SET only when the chemical potential in the leads balances the energy difference between the states of the artificial atom with N and N+1 electrons. This results in a single peak in the gate voltage dependence of the current for the SET with N electrons. With the constant field applied, this peak corresponds to current flowing via the spin state that has magnetic moment parallel to the field. However, with the oscillating transverse field, there are two states available, one with spin up and the other with spin down,
giving rise to a second, smaller satellite peak. Because the current is so sensitive to the state of the artificial atom, the resonance of a single spin can, in principle, be measured. This and related phenomena have recently been analyzed in detail theoretically by Engel and Loss (2001).

As usual in ESR measurements, the line shape can give information about the lifetime of the excited state. Measurements have already been made of the excited state lifetimes using pulsed voltage excitation (Fujisawa et al., 2001). However, using ESR under the appropriate conditions, one can also determine the spin coherence time. 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.

From a basic physics point of view, ESR will provide interesting information about the many-body ground state of the artificial atom. In particular, it may provide a direct measure of the spin of the artificial atom as a function of electron number. This has been the focus of recent theoretical work of Halperin and co-workers.

Kastner’s work under the first few months of NSEC funding has had two foci. First, they have identified problems that previously limited the temperatures to which they could cool electrons in their SETs. In the past, they and other workers found that although the GaAs crystal containing the SET cooled to 20 mK, the electrons stayed warmer, typically 50-100 mK. They have carefully filtered the leads to the sample to eliminate high frequency pick-up. They often must reduce the applied source-drain voltages to less than $k_B T/e$, where $k_B$ is Boltzmann’s constant. This means applying only a few microvolts at the lowest temperatures, and trying to measure very small currents. In the past few months, they have demonstrated that with proper care, the electrons reach the base temperature of the dilution refrigerator. In the next year, they plan to make the first spin resonance measurements. In addition, they will begin fabrication of pairs of SETs to control the coupling of spins between two artificial atoms.

Marija Drndic, a female Pappalardo Fellow in the Department of Physics at MIT, has been using the scanning probe microscope in Westervelt’s lab. In collaboration with his students, to study the motion of charge on arrays of colloidal artificial atoms. A female undergraduate, Ruza Markov, is working with her to analyze the data.

References


Transport and Capacitance Spectroscopy of Low Density Quantum Dots

Raymond Ashoori with Charles Marcus and Arthur Gossard

Ashoori, in collaboration with Marcus, will study the behavior of low-density two-dimensional electronic systems. Capacitance experiments in this regime have revealed a variety of un-expected results that have not been tested in transport measurements. Ashoori has designed and is building gated GaAs/AlGaAs samples that will allow simultaneous measurement using both capacitance and transport probes. Transport experiments in this regime are difficult, largely because the experiments require separate control of the charge density, and the point contacts that separate a dot from neighboring charge reservoirs do not typically allow this. To control the charge density, Ashoori will produce a control gate that covers the entire dot, and will be attached to its voltage source and sensors via a very fine wire feeding through a small gap (~100 nm) between the gates that define the quantum dot. The wire and the gap must be very fine in order to keep electrons from leaking out of the dot. This work involves using the highest resolutions available in electron beam writing facility at Harvard. A graduate student in Ashoori’s group, Dmitri Pouchine, has learned how to use the e-beam writer, and he is now working to process these samples.

Ashoori’s work in the low-density electron gas also involves imaging electronic distributions in these samples using scanned probe microscopy at low temperatures. They have produced a back-gated sample of high-mobility material, and they are using their method of subsurface charge accumulation imaging to produce images of the low-density electron gas. The eventual plan is to image the charge distribution inside the variable density quantum dots to determine how the charge distribution affects transport properties.

Ashoori has offered (to a representative of the Museum of Science) to give talks at the Museum of Science. These have not yet been scheduled, but he anticipates doing this in the coming year.

Spin Lifetime in Carbon Nanotubes

Charles Marcus with Michael Tinkham

In addition to his collaborations with Ashoori and Kastner described above, Marcus has begun to set up a new project to investigate the spin lifetime in carbon nanotubes. The postdoc Nadya Mason and student Michael Biercuk have made considerable progress in setting up a nanotube growth system, based on a design from Park’s laboratory, and they have grown their first single walled carbon nanotubes, between catalyst islands. Nadya Mason, who is a minority postdoc, recently became a Junior Fellow at Harvard.

In a collaboration with Kouwenhoven, Marcus completed an important investigation of the 0.7 structure in a quantum point contact, showing that it is a system with a free spin that will show a Kondo-like state at very low temperature (Cronenwett et al., 2002).

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Theory of Electron and Spin Transport in Nanostructures

Bertrand I. Halperin with Charles Marcus

A major portion of Halperin’s effort under the NSEC grant has been devoted to understanding effects of spin-orbit coupling on the transport of electron spins in GaAs/AlGaAs structures. This project has been carried out in collaboration with Marcus.

Last year, Halperin and his student Cremers co-authored a paper with Marcus and collaborators demonstrating how confinement in a quantum dot can suppress the effects of spin-orbit coupling in zero magnetic field, but that spin-orbit effects can be turned on again in the presence of a strong magnetic field parallel to the layer (Halperin et al., 2001). In this paper, published in Physical Review Letters, they carried out detailed calculations for the statistical behavior of fluctuations in conductance through the dot, in the case where time-reversal symmetry was broken by a weak field perpendicular to the sample. This was able to account for experimental observations in Marcus’ laboratory (Folk et al., 2001).

Under the NSEC grant, Halperin has been working to understand the behavior in the more complicated case where there is no perpendicular magnetic field, and time reversal symmetry is only broken by effects of the in-plane field. There are a number of subtleties in this case, because of hidden symmetries in the problem. It turns out that there are a number of different regimes in this problem, with various possible crossovers between them. Moreover, in addition to considering the statistics of conductance fluctuations through the dot, one can look for a change in the mean value of the conductance (“weak localization correction”), which will be affected in a subtle way by the spin-orbit coupling. With Halperin’s support, Cremers has been collaborating with Aleiner, Fal’ko, and Brouwer on a detailed analysis of this problem using random matrix theory. Taking into account the interplay between Zeeman splitting and spin-orbit coupling, in the context of the lateral confinement of the dot, it has been possible to obtain explicit formulas for the weak localization correction and the statistics of conductance fluctuations, including crossovers between the possible symmetry classes.

The strength of spin-orbit coupling in a GaAs two-dimensional electron gas can be altered by application of a gate-voltage perpendicular to the layer, as well as by variations in the design of the confining well. Halperin and Marcus have had extensive discussions about possible ways to use this effect to control spin orientations in a nanostructure. There will be particularly

Fig. 6. Schematic drawing of a quantum dot with a metal gate (hatched) over part of the dot. The gate can change the asymmetry of the confining potential of the quantum well beneath it, and change the spin-orbit coupling arising from the Rashba effect.
interesting consequences if one can create an inhomogeneous spin-orbit coupling in a laterally confined quantum dot via a gate that overlays only a portion of the area of the dot. (See Fig. 6) This configuration will reduce the suppression of spin-orbit effects due to lateral confinement, relative to what would occur in a dot with a spin-orbit coupling parameters. This would not only have a quantitative effects on the transport properties, but it should also allow one to attain regimes where the conductance fluctuations and weak localization corrections are described by different symmetry classes than would be possible in the uniform case. An analysis of these symmetry classes, and the crossovers between them, has been carried out (Brouwer et al., 2002).

Halperin and Marcus have discussed ways of using gate-induced inhomogeneities in the spin-orbit coupling parameters to control spin transport in GaAs systems. Emerging from these discussions are several possible designs for experiments, including quasi-one-dimensional geometries, as well as the quantum-dot geometries discussed above.

References

Growth of New Types of Nanoscale Structures

Heterostructures Grown by Molecular Beam Epitaxy

Arthur Gossard with Westervelt, Marcus, Kastner, and Ashoori

A semiconductor heterostructure grown by molecular beam epitaxy at UC Santa Barbara was the basis for a new Applied Physics Letters submission “Imaging Electron Density in a Two-dimensional Electron Gas” by Leroy, Topinka, Westervelt, Maranowski and Gossard. The wafer contained a high-mobility (1x10^6 cm^2/Vs) two-dimensional electron gas designed to be close to the top surface (within 60 nm) for probing by scanning probe microscopy methods.

New modulation-doped heterostructures were developed and grown at UCSB by Hanson and Gossard for studies of the following phenomena at Harvard by Marcus: 1) Optical spin polarization of atomic nuclei in a two-dimensional electron gas, 2) Spin accumulation using point contacts as spin filters, and 3) Use of microfabricated ferromagnets to produce a spin filter action. Results were obtained, which will be presented at the March 2002 American Physical Society meeting. Several iterations of sample design, growth, processing, measurement and feedback between Harvard and UCSB have been made.

During 2001, Gossard received the American Physical Society James McGroddy New Materials Prize, he was elected Fellow of the IEEE, and he was elected Member of the National Academy of Sciences.
Self-Organized Formation of Nanocrystals

Michael Aziz with Lynn Boatner (ORNL), Cynthia Friend, Efthimios Kaxiras, Howard Stone and Jerrold Floro (Sandia).

Vidya Ramaswamy, the first Women/Minority Fellow in the NSEC, has been building an apparatus to externally apply stress in a controlled manner to a semiconductor surface during ripening at high temperature, and thereby induce the self-organized ripening of epitaxial semiconductor quantum dots. She has contacted Floro at Sandia National Laboratory, provided specs for the growth of samples, and arranged for their growth and transport to Harvard. Vidya is being assisted by Taeseok Kim, a DEAS graduate student who Friend and Aziz plan to support on an NSEC allocation in June.

Additionally Vidya is investigating, currently by simulation and discussion with our colleagues at ORNL, the self-organized formation of nanocrystals by ion irradiation. She has initiated the arrangements for her to visit ORNL to use their implantation facilities as a guest. She is also investigating the use of Harvard's ion accelerators for similar purposes. Lynn Boatner at ORNL will visit Aziz at Harvard on April 18, and he will give a seminar in the David Turnbull Room in McKay Laboratory.

Microstructural Evolution of Solid and Fluid Systems: Studies of Surface Evolution below the Roughening Transition

Howard Stone with Michael Aziz

During the first NSEC fiscal year, Stone has been working on theoretical problems motivated by experimental observations of surface morphology changes below the roughening temperature. This research is joint with Michael Aziz and Dionisios Margetis (MIT). Almost all modeling of surface morphology changes below the roughening temperature have relied on kinetic modeling of step-step interactions and line tension. For example, recent work along these lines has been reported by Israeli and Kandel (Phys. Rev. B 1999). In fact, the Israeli-Kandel numerical simulations, as well as experimental work and modeling reported by E. Williams and colleagues, provide evidence for the existence of self-similar descriptions for the evolution of the surface shape. Instead of developing kinetic simulations methods, we have tried to extend continuum ideas, based on principles of macroscopic thermodynamics, since many of the surface structures observed occur on length scales larger than the typical distance between surface steps. This approach leads to a (nonlinear) continuum evolution equation for the surface shape. This partial differential equation has only been studied previously for special situations. Motivated by recent kinetic simulation papers from Israeli and Kandel, Stone has recognized that there is additional structure in their results than has previously been recognized, and we have arrived at new scaling results and analytical descriptions by beginning with the continuum equation.

In particular, Stone has looked at the case that the line tension energy (g1) is large compared to the energy of step-step interactions. Thus, they exploit the fact that g1/g3<<1. The thermodynamic formalism then allows application of boundary methods that they have developed. The approach seems promising as it seems to explain many of the qualitative and quantitative features reported in the kinetic simulations mentioned above. Consequently, they
are currently investigating what appear to be some universal features valid for general aspects of evolution below the roughening temperature. Two papers describing this work are in preparation. The work to date has focused on the diffusion-limited conditions. Upon completion of these studies, we will address the case where transport is limited by attachment and detachment of adatoms.

**Self-organized Growth of Nanometer Islands**

*Cynthia Friend* and *Michael Aziz*

In order to develop means to grow self-organized nanometer islands on surfaces, the herringbone reconstruction of Au(111) has been imaged using scanning tunneling microscopy (Fig. 7) and preliminary experiments of nanostructure growth using this substrate have been performed using thermal decomposition of Mo(CO)$_6$ as a precursor to MoO$_x$ growth. The objective will be to use Au substrates for growth, exploiting the dislocations in the herringbone structure as preferred nucleation sites.

A search for another postdoctoral associate is underway, and Taesok Kim, a DEAS graduate student, will work on the join projects of *Aziz* and *Friend*. The two groups have had several joint meetings and discussions. We plan to have a monthly joint group meeting to facilitate communication and collaboration. Two female postdoctoral associates are affiliated with this project. In addition, *Friend* is actively engaged in recruiting minority REU students.

**Synthesis and Patterning of Semiconductor Nanoparticles Using Fast-laser Chemical Etching**

*Eric Mazur* with *Cynthia Friend* and *Howard Stone*

*Mazur* and *Friend* have begun to systematically study the formation of silicon nanoparticles by laser-assisted etching of silicon in the presence of various background gases. They have determined that the background gas affects the size of the resulting particles. In the presence of SF$_6$, they produced nanoparticles ranging in size from 5 to 20 nm (see Fig. 8). In the absence of SF$_6$, the particle size increases to 200 nm. The nanoparticles were analyzed by transmission electron microscopy at Lawrence Livermore National Laboratory. *Mazur’s* group is currently collecting nanoparticles made in
other background gases and studying the particles optical properties. Mazur and Friend are collaborating with several companies on the use of chemically altered semiconductors in photovoltaics. In collaboration with Radiation Monitoring Devices, Inc., of Watertown, MA, they are studying the use of microstructured silicon for infrared-sensitive avalanche photodiodes. In collaboration with Scanwafer of Norway, they are studying the use of this material for improving solar cell efficiency. Three patents related to this project in process of filing.

Structures for Technological Applications based on Diblock Copolymers

David Weitz with Moungi Bawendi (The work at Harvard is carried out with partial industrial support and collaboration with Rhodia Inc.)

The goal of this project is to engineer the formation of structures useful for technological applications, based on diblock copolymers. Amphiphilic block copolymers can self-assemble in the presence of a selective solvent for one of the blocks to form various aggregates. For example, vesicles, membrane structures that enclose an internal aqueous space, play an important role as encapsulating materials in drug-delivery, cosmetics, detergency, and other encapsulation applications. The morphology of these structures depends on the chain size and chemistry of the diblock copolymers and also on physical variables such as temperature, concentration, solvent condition and the kinetics of preparation.

Weitz’s group studies the formation of vesicles based on a linear diblock copolymer system provided by Rhodia Inc. These synthetic molecules consist of two covalently linked homopolymer chains. The homopolymer chains are designed such that one of them carries hydrophobic functionality while the other one consists of hydrophilic repeating units. The initial goal was to develop methods by which vesicles could be formed from these polymers. Structure formation for two particular diblock geometries was investigated – 1) a diblock with a high hydrophobic fraction and 2) a diblock with equal amount of hydrophobic and hydrophilic fractions.

Weitz’s group has swollen the vesicle membrane with a fluorescently labeled homo-polymer. Fluorescence microscopy images show that the vesicle membrane can be swollen by addition of homopolymer as demonstrated in Fig. 9. The fluorescence in the image only comes from the vesicle membrane, indicating that the labeled homopolymer is located within the bilayer. Furthermore, the amount of swelling is determined by the content of added
homo-polymer, thus providing a novel way for control of the bilayer thickness. This is a unique way to engineer the bilayer of the vesicle, and to control its thickness; this may provide more robust vesicles, and may also provide a new means of encapsulation – the material can be encapsulated within the bilayer itself.

Weitz has also developed the techniques necessary to measure the mechanical robustness of these vesicles. They use the method of aspiration of the vesicle in a fine micropipette, as shown in Fig. 10; once the vesicle is pulled into the pipette, the strength of the vesicle can be determined by using calibrated pressures applied to the pipette.

Positional and Orientational Tracking of Nanostructures Using CdSe Nanoparticles

Moungi Bawendi with David Weitz

This project combines the advantages of semiconductor nanoparticles as fluorophores with methods developed by Weitz for spatial tracking of fluorophores. The main advantage of the semiconducting nanoparticles in this case is their stability compared to dye molecules. If they can be attached to nano-objects, including biological structures, polymers, or other nano-objects, the spatial dynamics of these object can be tracked in real time with ~10 nm resolution and with rotational information. The multicolors with narrow wavelengths that are possible with CdSe particles potentially allow multiple objects to be tracked simultaneously. Success in developing this technology should have high impact in polymer science, and in biology where spatial and rotational nanoprobe could help to unravel the dynamics of polymers, proteins, or DNA in real systems. Unlike other microscopies, including AFM, this probe technology could be used to follow the motion of complex nanostructures at video rates.

Bawendi has shown that CdSe nanoparticles can be used for orientational tracking at the nanometer scale by monitoring the polarization of the output fluorescence. They are pursuing model systems where the particles are spatially confined to two-dimensional motions so that they can be tracked spatially and rotationally without losing focus in a microscope setup. These model systems include bilayer membranes such as those used to form vesicles in aqueous environments. They have also begun addressing one of the primary chemical challenges in this project: appropriate functionalization of the particles to combine them with the objects to be studied while retaining their desired optical properties. Bawendi’s group has developed a series of multidentate ligands that are significantly more stable than the traditional monodentate phosphine based ligands presently used. This new ligand family can be functionalized with carboxylic acids for compatibility with aqueous environments and for further attachment with amine moieties on polymers, proteins, or other molecular objects through the formation of a peptide bond. This ligand family can also simply be functionalized with long chain alkanes for compatibility with hydrophobic environments. They are presently using these hydrophobic nanoparticle fluorophores in collaboration with Weitz to probe the dynamics in the walls of vesicles formed in his group using block co-polymers, described above.
The Current Science & Technology Center at the Museum of Science serves as an educational outreach partner for the Nanoscale Science and Engineering Center. Their role is to interpret the work of the scientific investigators for a broad public audience and for students in middle school through upper grades. At the present, CS&T work with NSEC is in “start-up” mode: CS&T is developing multiple dissemination and educational modalities to accomplish the educational outreach objective:

Public presentations on the CS&T stage for public audiences and school groups
- Digital exhibit kiosk stories about nanoscale research
- Web stories, “news bytes,” and links to researcher pages
- Cablecasting connection through New England Cable News
- Guest researcher appearances

**Significant Accomplishments to Date**

- Appointment and training of Education Associate Joel Rosenberg to produce NSEC related programming. With a B.S. in Mechanical Engineering from M.I.T. and a Masters from Columbia in Journalism, Joel has the right credentials to assist the CS&T team in interpreting NSEC research for public audiences.
- Development of first public presentation on nanoscale science and engineering. Entitled “The Incredible Shrinking Resistor,” this presentation was developed, evaluated, and produced over a two-month period in the fall of 2001, and has been given in the CS&T Center 2-3 times weekly for public and school audiences, replete with props and graphics. The presentation explores three new exciting areas of research in creating nanoscale transistors that could generate a new computing revolution.
- A second public presentation on Quantum Computing has been developed and is being given two to three times weekly.
- A web page has been created on the [www.mos.org/cst](http://www.mos.org/cst) website, linking to the NSEC website and to all the NSEC research partners. All CS&T stories, news items, and presentation descriptions are hot linked to this NSEC this way.
- CS&T staff are speaking with NSEC researchers and attending researcher presentations to help us develop an initiative for a guest speaker series on nanoscale science and engineering.
- Equipment and fiber for our cablecasting endeavor with New England Cable News are being installed in April.
Honors and Awards

⇒ CS&T has been selected by the National Institute of Standards and Technology as one of the 50 “Best Practices in Science Communication” worldwide. CS&T will participate in the NIST “Communicating the Future” Poster Session and Conference in March in Gaithersburg, MD, and will have an abstract published in the conference proceedings.

⇒ The CS&T dynamically updateable operating system has been nominated for an American Association of Museums MUSE award.

⇒ CS&T is being nominated for an American Association of Science & Technology Centers “Innovation Award.”

⇒ Carol Lynn Alpert, manager of CS&T, has been invited to present the CS&T concept at the European ECSITE meeting of science and technology centers and to serve as advisor for NSF’s upcoming international working conference: “Museums, Media, and the Public Understanding of Research.”

⇒ The NSF’s “Public Understanding of Research” initiative is funding a museum collaborative experiment in dissemination CS&T digital kiosk news and stories to other science and technology centers. If this experiment is successful, we may see a broader dissemination of stories from NSEC.
Publications

Note:  
\(^a\)signifies research principally supported by the NSEC  
\(^b\)signifies research partially supported by the NSEC  
\(^c\)signifies research where NSEC Facilities were utilized.


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Electrons injected at the “sun” flow out in a pattern that shows enhanced backscattering at the walls, in a nanowire with a random potential that mimics charged impurities added to the gate-induced wire potential. (Quantum phase is shown in color).