Science of Nanoscale Systems and their Device Applications

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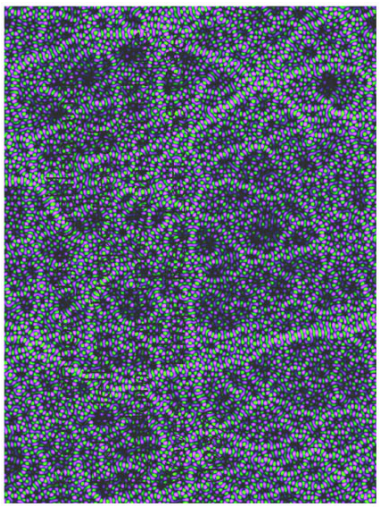
PI: **R.M. Westervelt**, Co-PI: **B.I. Halperin**
Harvard University, Massachusetts Institute of Technology,
University of California, Santa Barbara and Museum of Science, Boston



Simulations of electron waves in a nanoscale structure (Heller).

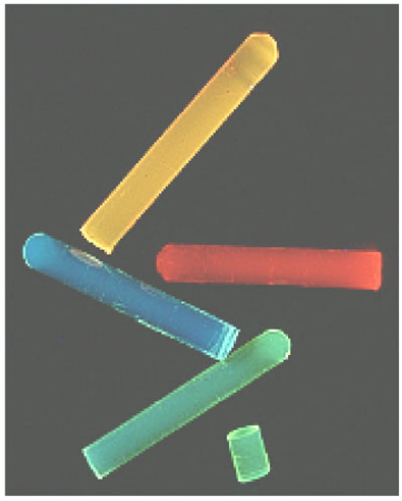
The goal of this Nanoscale Science and Engineering Center is to study the fundamental properties of nanoscale structures with a view toward their possible use in novel electronic and magnetic devices. We concentrate on the movement of spins and charges including their quantum behavior. The following 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 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.

Computer image of the planned Laboratory for Interface Science and Engineering (LISE) that will join McKay, Cruft, and Lyman Laboratories at Harvard University.

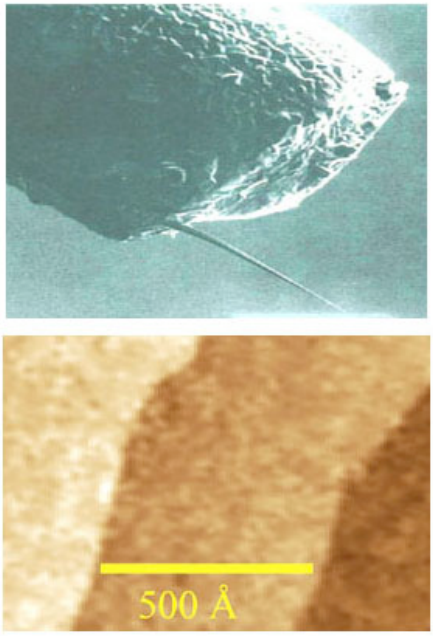
The Center for Imaging and Mesoscale Structures (CIMS) is a major investment by Harvard to promote and aid interdisciplinary research by students and faculty in Chemistry,



Flourescing quantum-dot/polymer composites made from chemically grown nanoparticles (Bawendi, photo by Felice Frankel)

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 plans to construct a new Laboratory for Interface Science and Engineering (LISE), shown in the figure, that will house CIMS shared facilities and provide space for interdisciplinary research. LISE will contain a new Imaging Laboratory for electron, scanning probe, and optical microscopy, a Cleanroom Facility 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.

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.



Fe whisker tip (top) for spin-polarized STM, used to image Si(111) surface (Narayanamurti).

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 and Technology Center* at the *Museum of Science, Boston* and NSEC faculty make presentations, conduct workshops and develop exhibits for the public. 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 lab over the summer to undergraduates and public school teachers. Applied Physics 298, *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 and with 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 is also providing 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. 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** and **http://cims.harvard.edu**.