Science of Nanoscale Systems and their Device Applications

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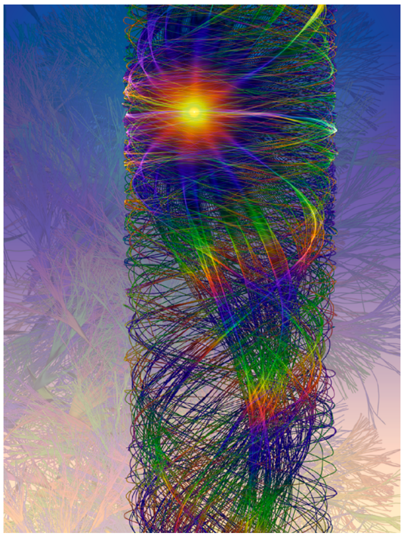
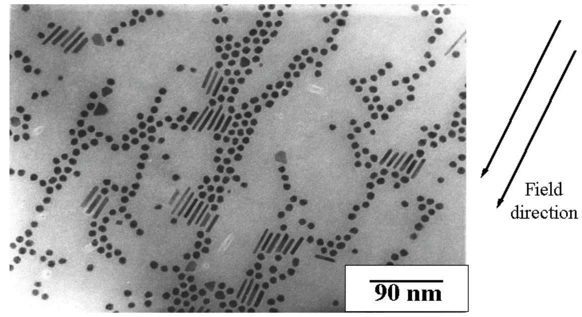


The goal of this Nanoscale Science and Engineering Center is to study the fundamental properties of nanoscale structures with a view toward their possible use in novel electronic and magnetic devices. We concentrate on the movement of spins and charges including their quantum behavior. The following important questions are addressed at the same time: How can nanoscale structures be grown and 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 which encompasses three areas: **The Growth of Nanoscale Structures** uses approaches ranging 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 new ways to image the behavior of electrons in nanostructures using scanning probe microscopy. **Spins and Charges in Coherent Electronics** investigates methods to move, control and probe spins and charges in nanostructures for single-electronics, spintronics and quantum information processing. By combining advances in these three areas, the Center hopes to discover new types of electronic and magnetic devices.

These interdisciplinary research topics bring together participants from three universities - Harvard University, the Massachusetts Institute of Technology and the University of California, Santa Barbara. Their areas of research include 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 allows students, faculty, and staff to travel easily between participating institutions to encourage collaborative research and to use 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 Physics, Applied Physics, Materials Science, Chemistry, and Biology. Professor **Halperin** is the Scientific Director and Dr. **Appleton** is the Director. CIMS is creating a number of shared facilities at Harvard that are operated with the assistance of technical staff. A second cleanroom has been constructed in McKay Laboratory. New equipment installations include a Raith 150 e-beam lithography system, a JEOL 2010 transmission electron microscope, and a FEI dual-beam focused ion beam system. To house CIMS shared facilities and to supply space for interdisciplinary research, Harvard will construct the New Physical Sciences Building, which will connect McKay, Cruft and Lyman Laboratories. In the new building CIMS will create an Imaging Laboratory equipped with scanning and transmission electron microscopes and scanning probe microscopes, a Cleanroom Facility for nanofabrication, and an Advanced Materials Science Laboratory. CIMS and the New Physical Sciences Building will bring valuable new capabilities and research space to NSEC participants and promote new areas of interdisciplinary research.



Magnetic nanospheres and nanorods deposited in the presence of a field. The nanorods are ferromagnetic and align in the field. (**Bawendi**)

The Nanoscale Science and Engineering Center supports interdisciplinary research, that brings together experts from different areas. By combining their skills they will make new discoveries possible. The research areas described below address how nanoscale structures can be made, how they can be imaged and probed, how charges and spin behave inside nanocrystals, and how coherent electronics can be constructed and understood.

The Growth of Nanoscale Structures — The Center will focus on promising new approaches: the chemical growth of nanoparticles, self organized growth and processing on material surfaces, and new types of molecular beam epitaxy. Chemically grown nanoparticles create interesting possibilities for the construction of nanoscale structures. Professors **Bawendi** and **Park** grow nanoparticles in controlled shapes with excellent uniformity. Self-organized growth of nanoscale structures on surfaces can be achieved by tailoring the conditions of film growth and processing. This approach can extend structures made with lithography to smaller sizes. Professors **Aziz**, **Friend** and **Mazur**, in collaboration with Drs. **Floro** (Sandia) and **Hrbek** (Brookhaven), are developing this approach, with theoretical support from Profs. **Kaxiras** and **Stone**. Molecular beam epitaxy (MBE) can grow semiconductor heterostructures with novel properties. Professor **Gossard** at the MBE Lab in UC Santa Barbara is investigating the growth of new materials and structures, which are patterned into quantum dots and circuits in the Center's cleanrooms. Sandia National Laboratory has advanced facilities in this area.

Imaging Electrons inside Nanostructures — Our ability to image electrons inside nanoscale structures has been greatly improved by new techniques in scanning probe microscopy (SPM) developed by Center participants. The coherent flow of electrons through a two dimensional electron gas is imaged and analyzed by Profs. **Westervelt, Gossard** and **Heller**. Imaging of electron charge distributions in nanoscale structures, and the manipulation of nanoparticles is done by Prof. **Ashoori**. Ballistic electron emission microscopy (BEEM) is used by Prof. **Narayanamurti** to discover the properties of semiconductor nanostructures. Methods to image spin flow through two-dimensional electron gases are being developed for use in the fields of spin injection and spintronics.

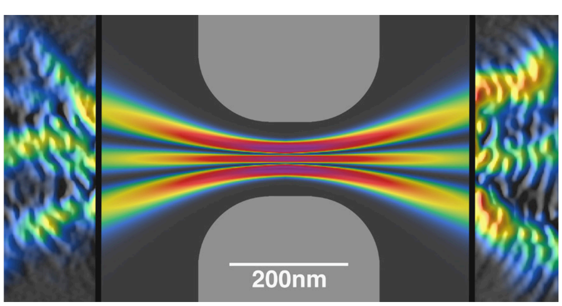
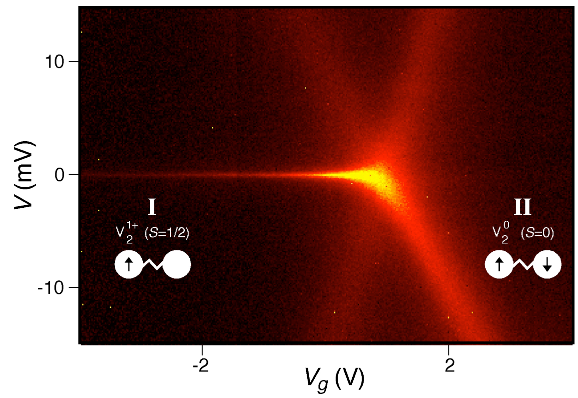


Image of coherent electron flow from a quantum point contact, with theory inside (**Westervelt**, **Gossard** and **Heller**).

Spins and Charges in Coherent Electronics — The Center hopes to understand the behavior of spins and charges in nanoscale systems, to develop coherent electronic devices and circuits for single electronics, spintronics and quantum information processing. Professors **Ashoori**, **Bawendi**, **Kastner**, **Park** and **Westervelt** are developing nanoscale devices based on chemically grown nanoparticles and molecular clusters, using novel techniques for assembly. The properties of ultra-thin superconducting wires are being investigated by Prof. **Tinkham**. Coherent electronics based on semiconductor heterostructures are being developed and studied by Profs. **Ashoori**, **Gossard**, **Heller**, **Kastner**, **Marcus** and **Westervelt**, in collaboration with Profs. **Kouwenhoven** (Delft) and **Tarucha** (U Tokyo), with theoretical support from Prof. **Halperin**.



Single-electron transistor containing individual divanadium molecules that shows a Kondo resonance, tuned by gate voltage V_g to alter the charge and spin state (**Park** and **Long**).

Seed Projects — Each year the Center provides seed funding for new, high-risk projects that can have important outcomes. This support allows participants to investigate interesting ideas quickly, and it will help them obtain regular funding for successful projects. Seed funding is very useful for junior faculty, and it can help bring new participants into the Center. Professors **Demler** and **Zhuang** are currently supported.

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, 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. Professor **Mazur** conducts *PEER Instruction Workshops* for local teachers to introduce his innovative science teaching technique that has attracted national attention. Undergraduates can spend ten weeks in the summer doing research in the Center's *Research Experience for Undergraduates* (REU) Program. The *Research Experience for Teachers* (RET) program introduces public school teachers to university research and develops connections with public schools. A new course at Harvard titled *Nanoscale Science and Engineering*, taught by Center faculty, presents the fundamentals of nanoscale research including possible applications. The *Postdoctoral Research Fellowship for Women and Minorities* attracts outstanding candidates.

Shared Facilities — Excellent shared facilities are essential for research on nanoscale structures. The Center uses imaging, cleanroom, and materials synthesis facilities 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. These institutions have outstanding facilities and staff to help Center students, postdocs and faculty build and test nanoscale structures. 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.

Collaborations with Industry and other Institutions is 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.

For further information, please see **http://nsec.harvard.edu** or email **nsec@deas.harvard.edu.**