4. HIGHLIGHTS

Facilities

Laboratory for Integrated Science and Engineering — Harvard University
Center for Nanoscale Systems — Harvard University
National Nanoscale Infrastructure Network — Harvard University and the University of California at Santa Barbara

Education and Outreach

Frontiers in Nanoscale Science and Engineering International Workshop — March 29–31, 2007, University of Tokyo, Japan
Nanoscale Informal Science Education Network — Carol Lynn Alpert & Larry Bell
Nanotech Symposium for Educators — Museum of Science, Boston
Public Presentations on Nanoscale Science and Engineering — Museum of Science, Boston

Research Cluster 1

CMOS RF Sensor for a Biological Cell — Donhee Ham
Nanoskiving — George Whitesides
Fluorescent and Raman Active Silver Nanoparticles — Xiaowei Zhuang
Multiscale Modeling of DNA Translocation through Nanopores — Efthimios Kaxiras

Research Cluster 2

Band-Engineered Nanocrystal Heterostructures — Moungi Bawendi
Optical Image of Metal-Insulator Domains formed within VO_2 Nanobeams — Hongkun Park
Design of Small p-i-n Radial Core/Shell Nanowire Structures — Charles Lieber
STM Images of MoO_3 Nanostructures — Cynthia M. Friend
Nanowire Optoelectronics — Venkatesh Narayanamurti and Federico Capasso

Research Cluster 3

Magnetoresistance of a Nanowire — Bertrand I. Halperin
Electronic Spectroscopy of Single Electrons in a Single InAs Quantum Dot — Raymond Ashoori
Imaging Magnetic Focusing: Experiment and Theory in Transconductance SPM Imaging — Eric J. Heller and R.M. Westervelt
Magnetic Force Microscope Construction — Jennifer Hoffman
Sensing One Electron as it Hops Onto or Off a Quantum Dot — M.A. Kastner

Laboratory for Integrated Science and Engineering
Harvard University

A computer image of the Laboratory for Integrated Science and Engineering (LISE) that will be completed in summer 2007. The building will house shared facilities for Harvard's Center for Nanoscale Systems and 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 University

Center for Nanoscale Systems

Mission and Goals of the Center for Nanoscale Systems at Harvard University:

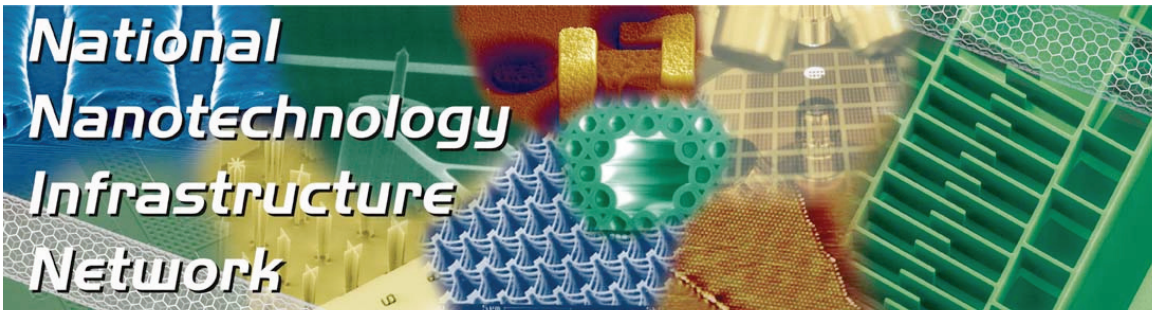
- To provide world-class, centralized facilities and technical support for Harvard faculty research groups as well as the larger community of external users from academia and industry.

- To foster leading-edge, multi-disciplinary research and education in the area of imaging and nanoscale systems, bridging the disciplines of chemistry, physics, engineering, materials science, geology, biology, and medicine.

- To create an environment for collaborative research by providing shared research facilities and meeting places conducive to productive scientific interactions.

National Nanostructure Infrastructure Network

Harvard University and University of California at Santa Barbara



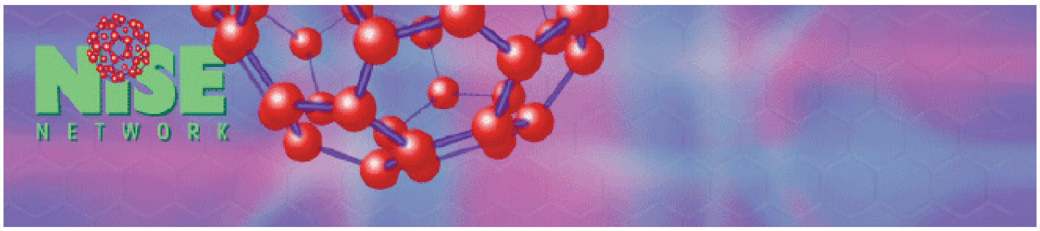
Harvard and UC Santa Barbara are two of an integrated partnership of thirteen user facilities, led by Cornell and Stanford, that provide opportunities for nanoscience and nanotechnology research. At Harvard, the NNIN provides expertise in soft lithography and assembly, and computation, through the Center for Nanoscale Systems. At UCSB, the NNIN provides expertise in optics and electronic materials. The NNIN was funded by the NSF in January 2004.

Frontiers in Nanoscale Science and Engineering
International Workshop
March 29-31, 2007
University of Tokyo, Japan

Our fourth international workshop was held on March 29–31, 2007 at the University of Tokyo in Japan. The workshop brought together international collaborators of the Center including Daniel Loss, Seigo Tarucha, and other outstanding researchers from Japan and Europe. Travel by students and postdocs were supported by Center international travel program.

Nanoscale Informal Science Education Network (NISE Network)

Carol Lynn Alpert, Larry Bell, Robert Westervelt, George Whitesides, Eric Mazur, Kathryn Hollar



(*Left*): A young audience member assists graduate student Tom Hunt with a demonstration during a talk on Atomic Force Microscopy at the Museum of Science, Boston. (*Right*): Michael Stopa discusses issues of privacy during a NanoFutures Forum at the Museum of Science, Boston.

Our NSEC is a strong partner in the Nanoscale Informal Science Education (NISE) Network that links science museums and educational organizations with research institutions. **Robert Westervelt** is Chair of the NISE Scientific Advisory Board that also includes **George Whitesides** and **Eric Mazur**. In 2006-2007, our Center's researchers participated in several NISE programs: **Eric Heller** and **Eric Mazur** visited the Exploratorium as scientists in residence to develop interactive museum demonstrations on waves and optics at the nanoscale. Education Director **Kathryn Hollar**, demonstration expert Daniel Rosenberg, and grad student Tom Hunt participated in the NISE Nanoscale Education Outreach (NEO) Workshop in May 2006, and developed an interactive talk on Atomic Force Microscopy for the Museum of Science, Boston. NSEC researchers have also participated in the NISE Network Forums on Nanotechnology as facilitators.

Nanotech Symposium for Educators

Museum of Science, Boston

More than 100 teachers attended the 2006 Nanotech Symposium for Educators held at the Museum of Science. **George Whitesides** provided an overview of nanoscale science and engineering and discussed potential societal impacts. The Symposium was a collaborative effort by our NSEC, the Museum of Science, the Northeastern NSEC, the National Center for Learning and Teaching in Nanoscale Science and Engineering, the NNIN, SRI, the UW-Madison MRSEC, and the Concord Consortium.

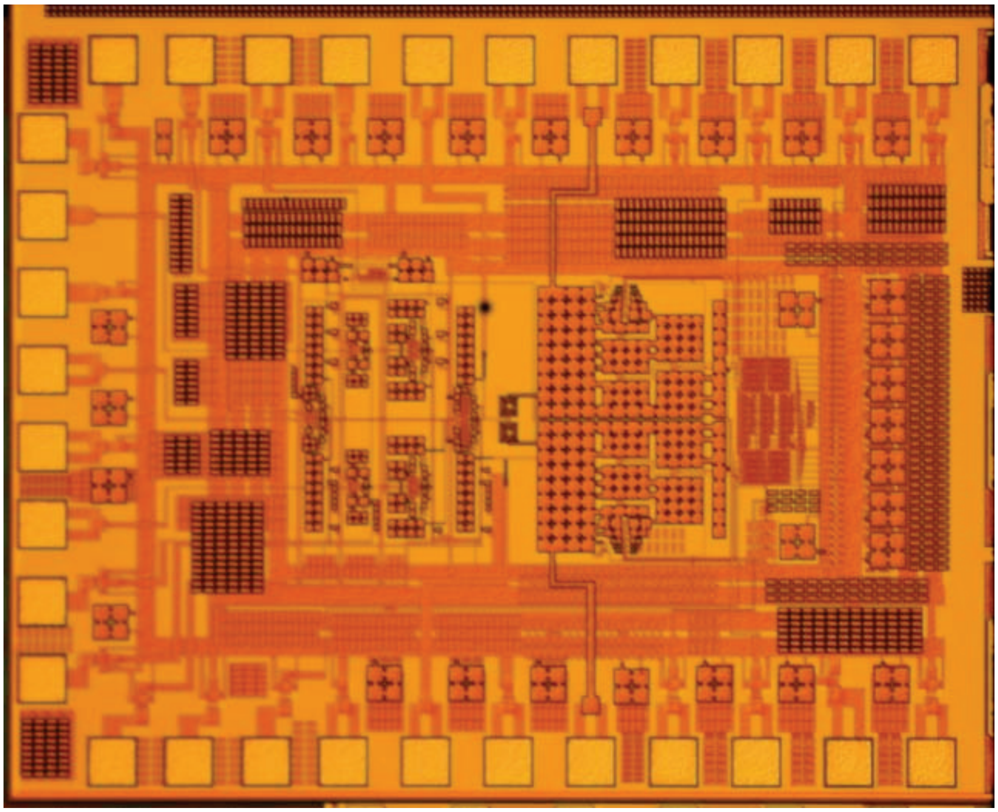
Public Presentations on Nanoscale Science and Engineering

Museum of Science, Boston

Tim Miller, NSEC Education Associate, delivers a talk on the discovery of carbon nanotubes and their remarkable properties and potential applications at the Museum of Science. Tim gives several presentations each week on the Museum's Gordon Current Science & Technology stage, and many of his presentations will be "packaged" and distributed by the Nanoscale Informal Science Education (NISE) Network for use by museum educators across the country.

CMOS RF Sensor for a Biological Cell

Donhee Ham

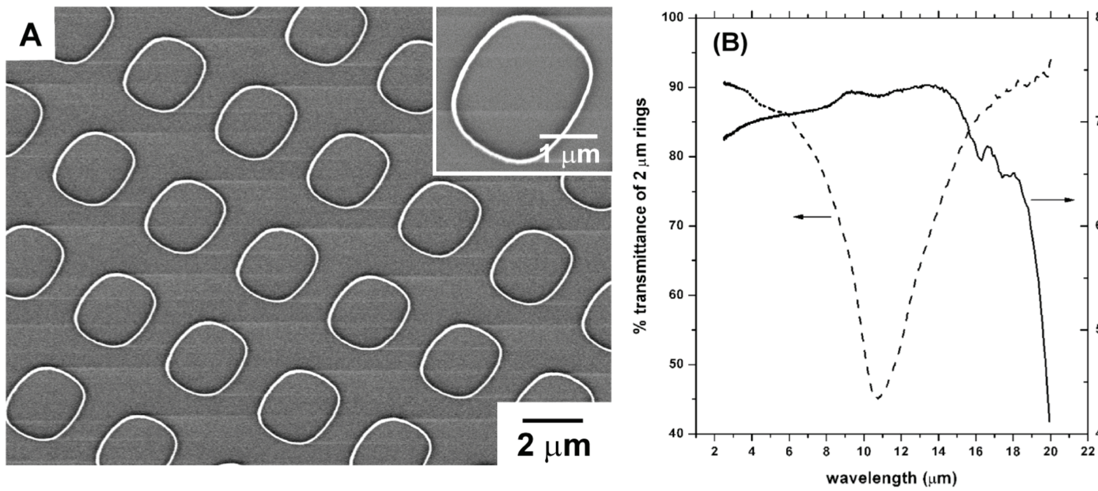


A CMOS microcoil bridge circuit that will act as a front-end of an RF cell detection system.

We've developed a CMOS//Microfluidic chip to manipulate biological cells. A microcoil array in an integrated circuit produces peaks in DC magnetic field that can trap and move cells tagged by a magnetic bead in a microfluidic chamber above. We are now adding a detection capability to the hybrid system, by using an RF magnetic field in a microcoil to detect the prescence of a bead-bound-cell above.

Nanoskiving

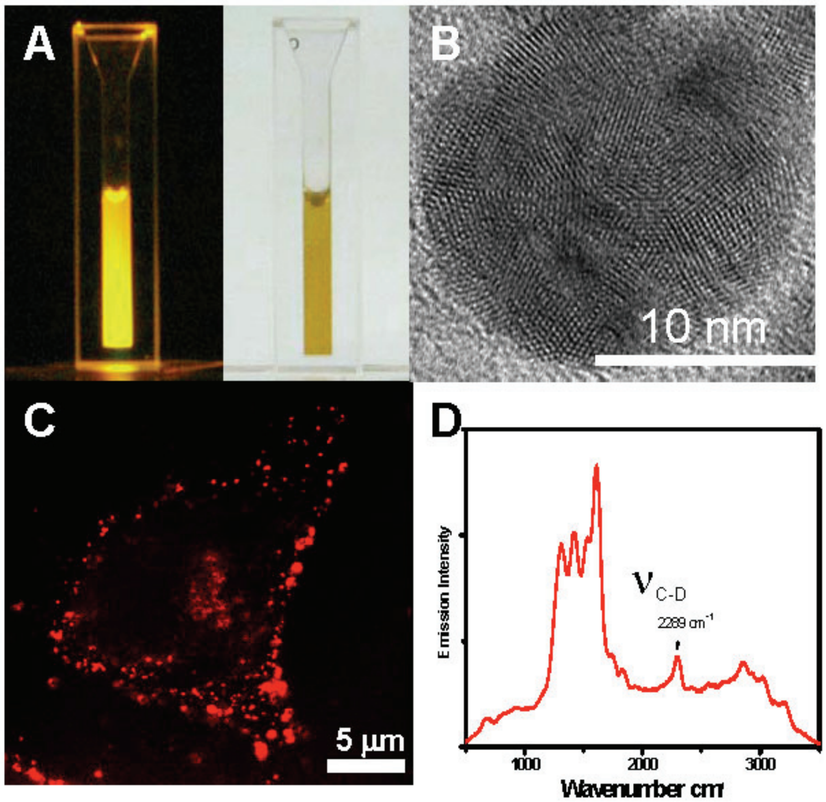
George M. Whitesides



We have developed a new method to fabricate metal nanostructures over a large area using a combination of thin film deposition and sectioning with a microtome (a technique we call "nanoskiving"). These arrays form frequency-selective surfaces and can serve as infrared band-stop and band-pass filters with applications for low-cost, high-performance optical devices including beam-splitters, filters, and polarizers. The dimensions of the resulting nanostructures are controlled by the thickness of the metal film and the epoxy sections. The shape of the nanostructures is defined by the geometry of the template. Figure A is an SEM image of an array of 50-nm wide, 100 nm tall gold loops on a Si(100) substrate. Figure B is the IR transmission spectrum (dotted line) of a loop array on ZnSe. The spectrum of the ZnSe substrate (solid line) is shown for comparison. We measured a single bandstop transmission peak, with a transmittance of 45%.

Fluorescent and Raman Active Silver Nanoparticles

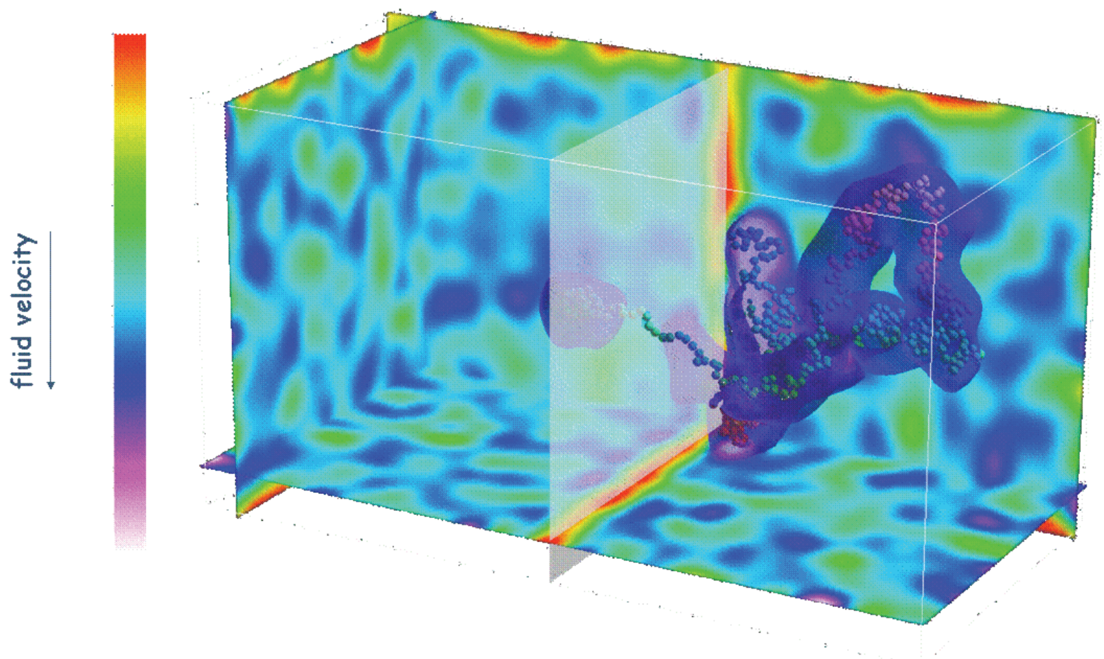
Xiaowei Zhuang



(a) Photos of the silver nanoparticle solution with *(left)* and without *(right)* laser excitation. **(b)** High resolution TEM image of a single silver nanoparticle. **(c)** A live HeLa cell labeled with Fluorescent and Raman active silver nanoparticles. **(d)** A surface-enhanced Raman spectrum of a single silver nanoparticle on the live HeLa cell surface in 90 pg/ml deuterated-glycine solution. Strech vibration of C-D of deuterated-glycine was clearly detected by the silver nanoparticle.

Multiscale Modeling of DNA Translocation through Nanopores

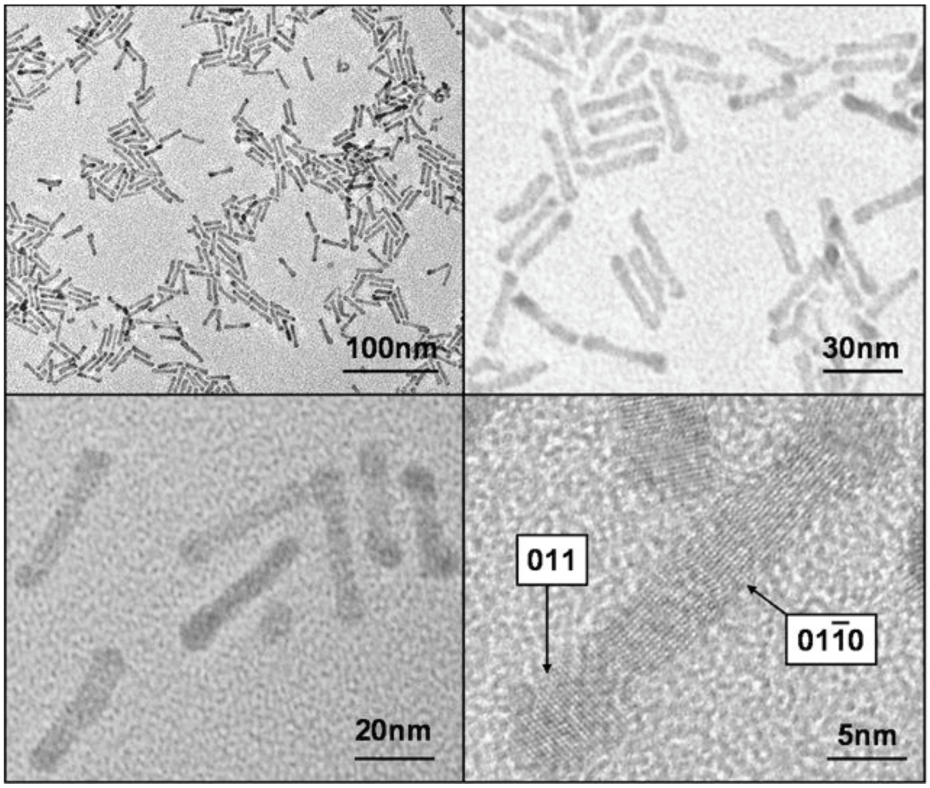
Efthimios Kaxiras



DNA (colored beads) translocating through a pore in the middle of the transparent wall. The fluid velocity is indicated by contour plots on different planes and by a 3-D representation in the vicinity of the beads.

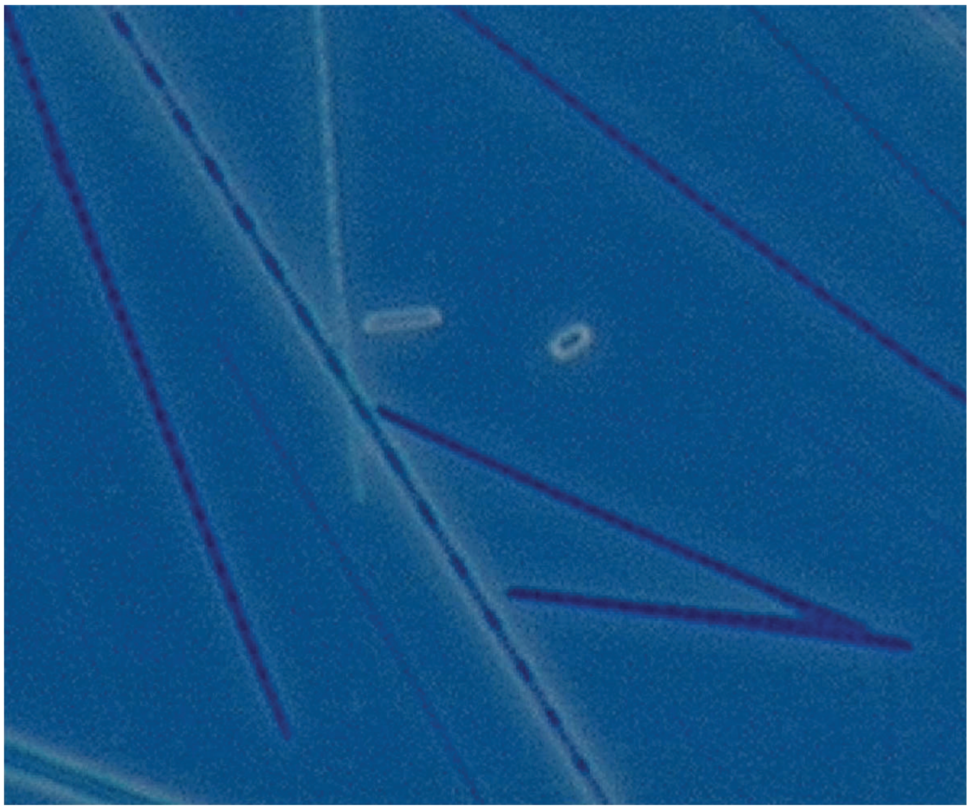
A multiscale computational approach has been developed that involves the spatial and temporal coupling of a *mesoscopic* fluid solvent with the atomistic level. The method was tested by applying it to DNA translocation through nanopores, which is involved in various biological processes. Recent experiments have focused on the possibility of fast DNA sequencing by tracking its motion through nanopores. In our simulations, DNA surrounded by a fluid solvent is pulled through the pore by an electric force at the pore region; we find good agreement with experimental results for the scaling law describing the translocation time as a function of DNA length.

Band-Engineered Nanocrystal Heterostructures
Moungi Bawendi



The transformation of light into current requires as a first step the rapid dissociation of electrons and holes so that they can be carried to opposite electrodes. We have designed and synthesized nano-interfaces in nanocrystal structures specifically to enable the rapid dissociation of electrons and holes at the nanoscale. The "nanobarbells" in the electron microscope image below are made up of two kinds of semiconductors chosen because electrons are drawn the CdSe "bar" while holes are drawn to the CdTe "tips". These nano-heterostructures could potentially be used for nanocrystal-based solar energy conversion.

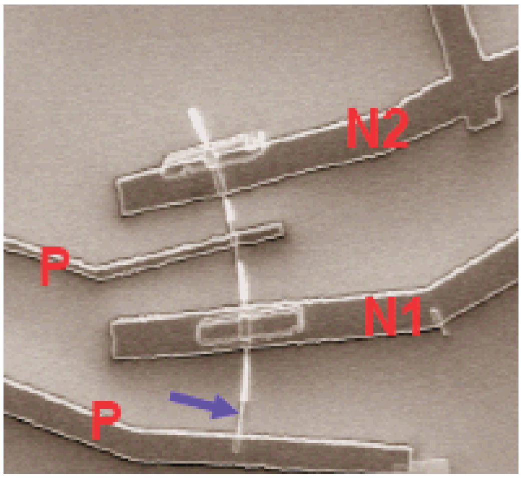
Optical Image of Metal-Insulator Domains formed within VO_2 Nanobeams
Hongkun Park

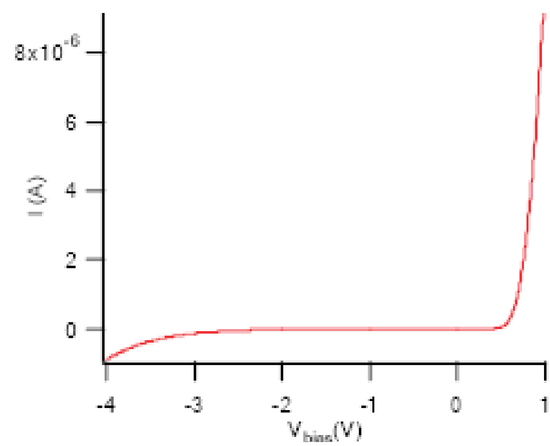


Park's group has synthesized and tested VO_2 nanobeams to understand their potential for using their metal-insulator phase transition as a switch for future nanoelectronics. Cooling VO_2 nanobeams on a SiO_2 substrate leads to a coherent uniaxial strain that creates alternating nanoscale metal-insulator (M-I) domains along the nanowire length as shown in the optical image at $100^{o}C$ above, producing nanoscale M-I heterostructures. These nanobeams behave as a one-dimensional system for the M-I phase transition.

Design of Small p-i-n Radial Core/Shell Nanowire Structures

Charles Lieber

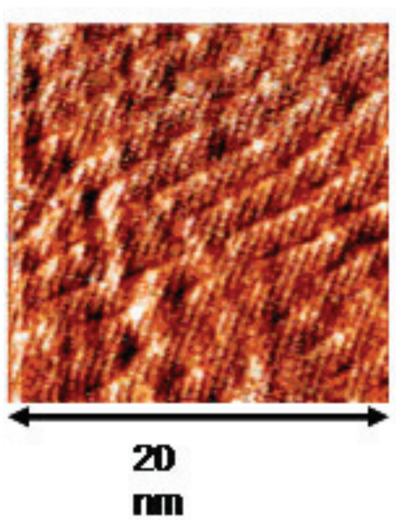


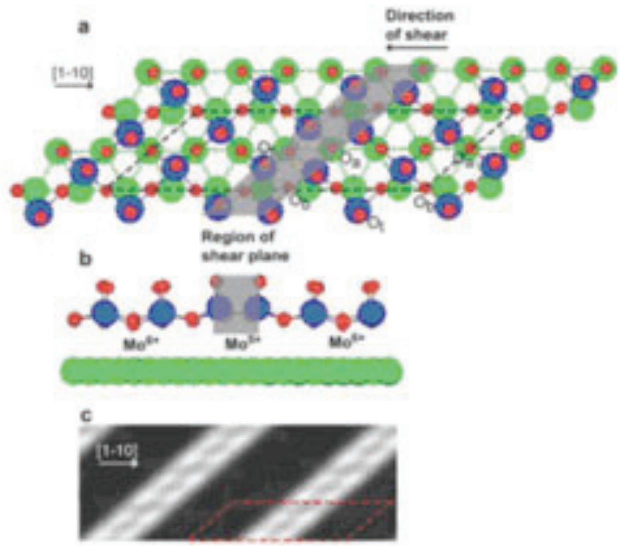


Lieber and coworkers have designed, prepared and characterized the first p-type/intrinsic/n-type (p-i-n) silicon core/shell/shell nanowire structures. The nanowires consist of a single-crystalline p-Si nanowire core and controlled thickness, conformal i- and n-shells. Scanning and transmission electron microscopy analyses demonstrate that the two shells are uniform but polycrystalline with thicknesses determined growth time. Selective wet-etching has been exploited to make electrical devices in which well-defined contacts are made to the p-type core and n-type outer shell, and subsequent transport measurements demonstrate well-defined diode like behavior. These new p-i-n nanowire structures open up unique opportunities as building blocks for the creation of novel photovoltaics and integrated electronic logic gates.

STM Images of MoO_3 Nanostructures

Cynthia M. Friend

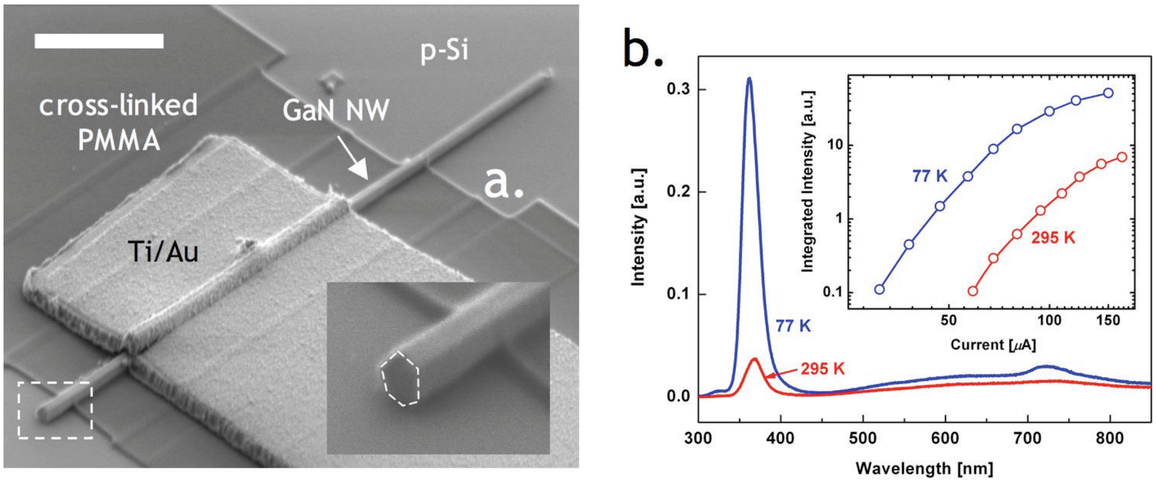




Scanning tunneling microscope (STM) image (*left*) of reduced 1-atom layer high MoO_3 nanostructure supported on Au showing shear planes and the corresponding structure determined by density functional theory (*right*). The lower image on the right **(c)** is the simulated STM image based on the theory.

Nanowire Optoelectronics

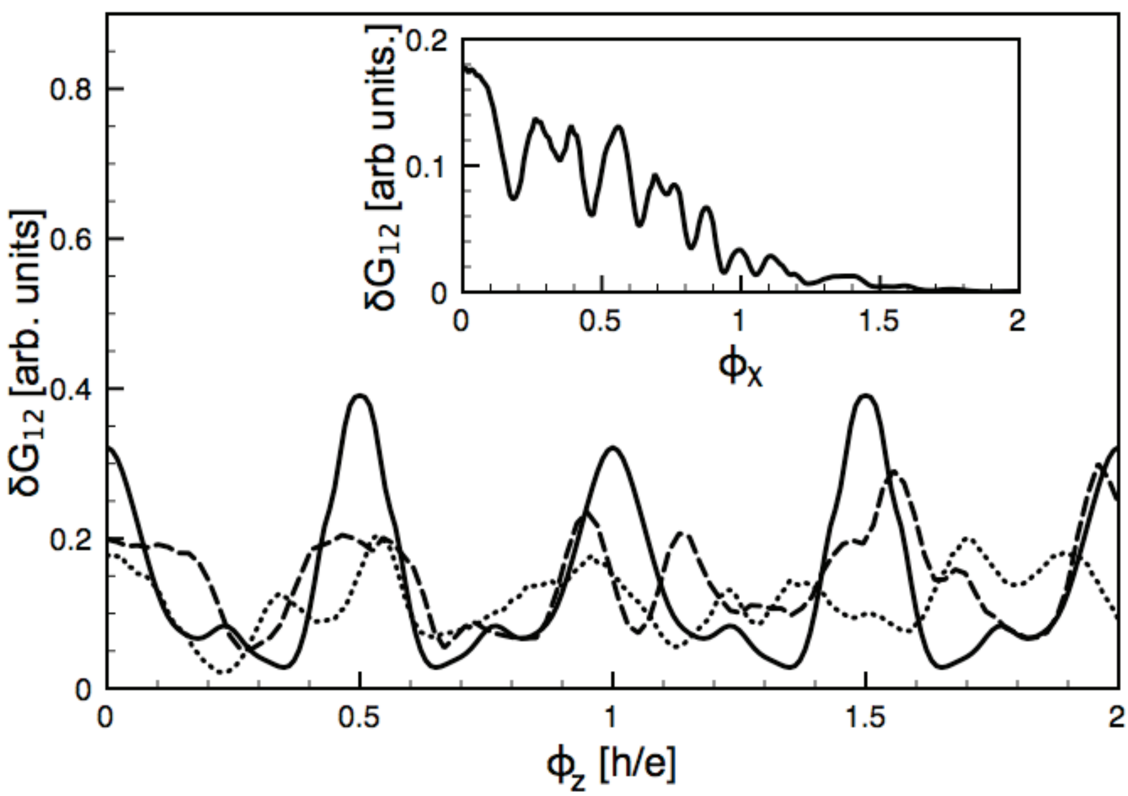
M.A. Zimmler, J. Bao, I. Shalish, W. Yi, J. Yoon, V. Narayanamurti, and Federico Capasso



Single-nanowire Ultraviolet Light-Emitting Diode (LED). **(a)** The basic device geometry consists of an individual nanowire sandwiched between a heavily doped p-type silicon substrate (hole-injecting contact) and a metallic film (electron-injecting contact). The nanowire LED geometry allows uniform injection of current along the length of the Gallium Nitride (GaN) nanowire. **(b)** Electroluminescence spectra of a typical nanowire LED, exhibiting sharp ultraviolet (UV) emission. The inset shows the current dependence of the UV intensity. These devices could become the basis for future integrated photonic circuits, or even find a place in lab-on-a-chip applications where compact light sources are required.

Magnetoresistance of a Nanowire

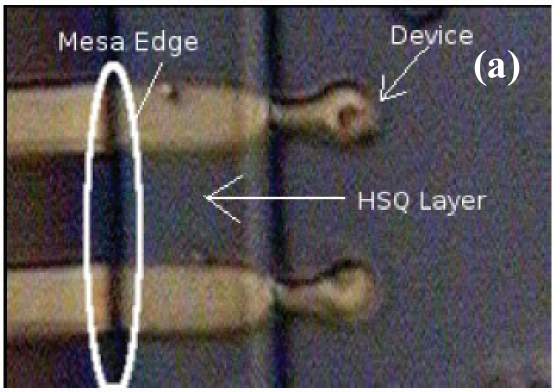
Bertrand I. Halperin

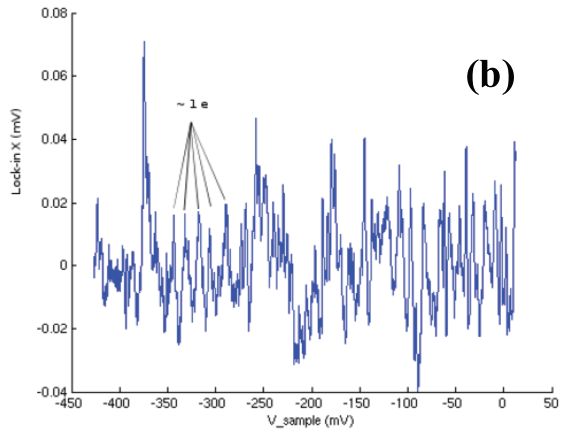


Measurement of electrical conductance through a nanowire, in an applied magnetic field, at low temperatures, can give important information about the electronic structure. The main figure panel shows calculated effects of a magnetic field parallel to the axis of an InAs nanowire, with contact separation L = 300 nm, for **(a)** an idealized model with electrons in a thin shell or radius R = 10 nm, ignoring the Zeeman splitting and Rashba spin-orbit coupling (solid line); **(b)** for the same shell model with Zeeman coupling spin-orbit effects included (dashed line); and **(c)** a model with electrons confined in a triangular well with outer radius 15 nm (dotted line). Inset shows effect of a perpendicular magnetic field, for model **(c)**.

Electronic Spectroscopy of Single Electrons in a Single InAs Quantum Dot

Raymond Ashoori



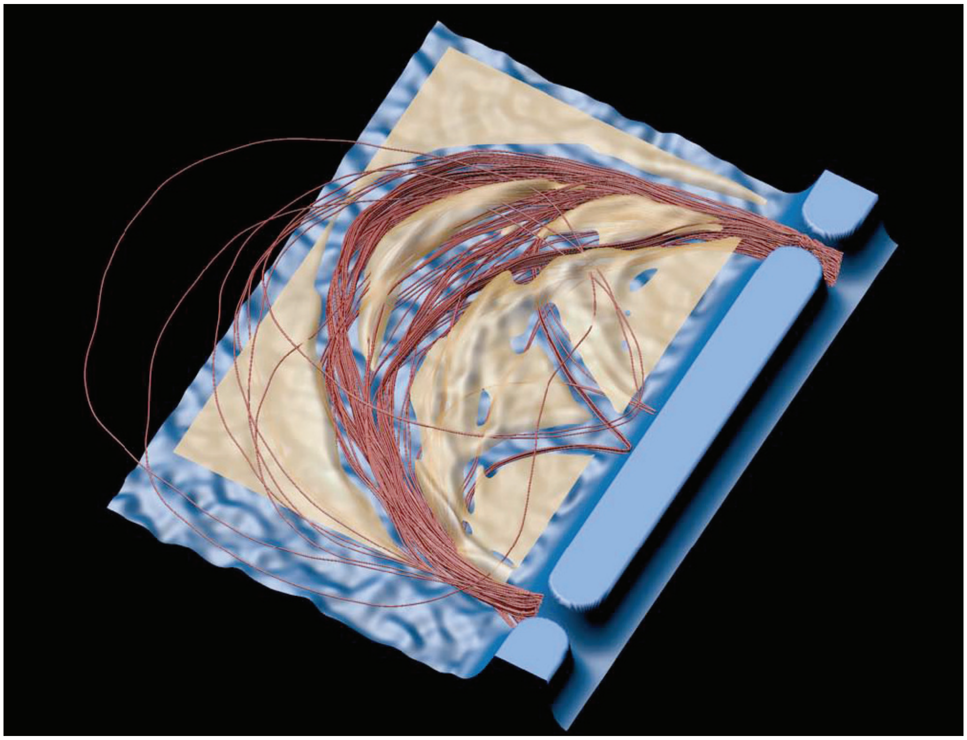


(a) Connections made to top contacts of InAs dot samples. The device size is about 300 nm and, at this size should typically contain a few dots. **(b)** Capacitance spectra showing periodic Coulomb blockade structure apparently from a single quantum dot in the structure.

InAs self-assembled quantum dots have potential applications ranging from single-photon sources for quantum computing, quantum dot lasers, and as floating gate structures for extremely small and reliable flash memories. All prior electrical measurements in this system have been performed in arrays of quantum dots and have not yielded sufficient spectral resolution to ascertain much of the underlying physics of the dots.

Imaging Magnetic Focusing: Experiment and Theory in Transconductance SPM Imaging

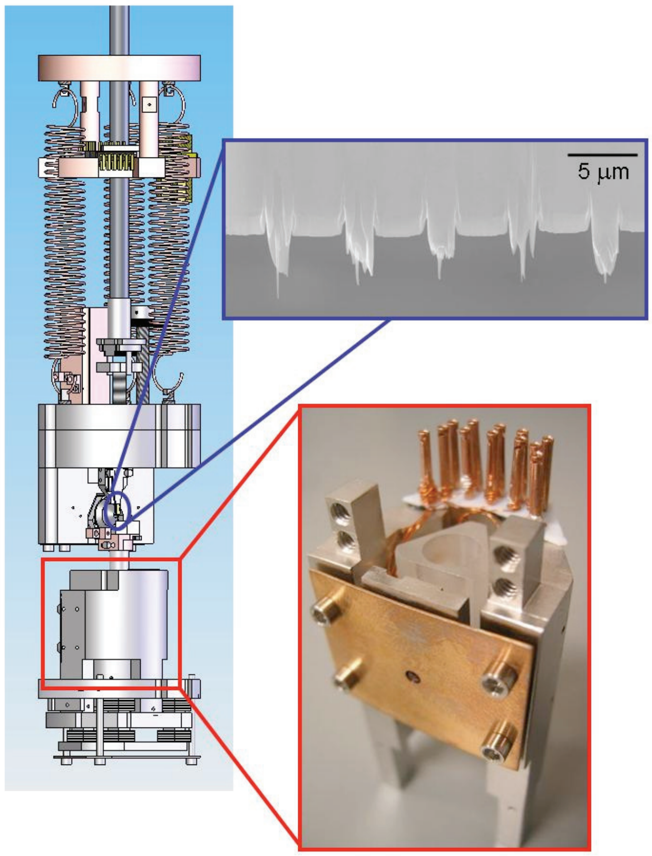
Eric J. Heller and R.M. Westervelt



This layered figure shows how to image electrons as they flow from one Quantum Point Contact (QPC) to another, under the influence of a magnetic field and the random background potential caused by ionized "donor" atoms (blue layer). Classical trajectories are shown in red, while the tan layer shows the *change* in the flux into the second QPC caused by a charged SPM tip that deflects electrons. If the tip is placed in "highways" of high electron flux, it causes the biggest decrease in the flux, as evidenced by the clear areas where the red classical flux is largest. Through simulations like these. we can hope to better understand and control the motion of electrons in very small devices.

Magnetic Force Microscope Construction

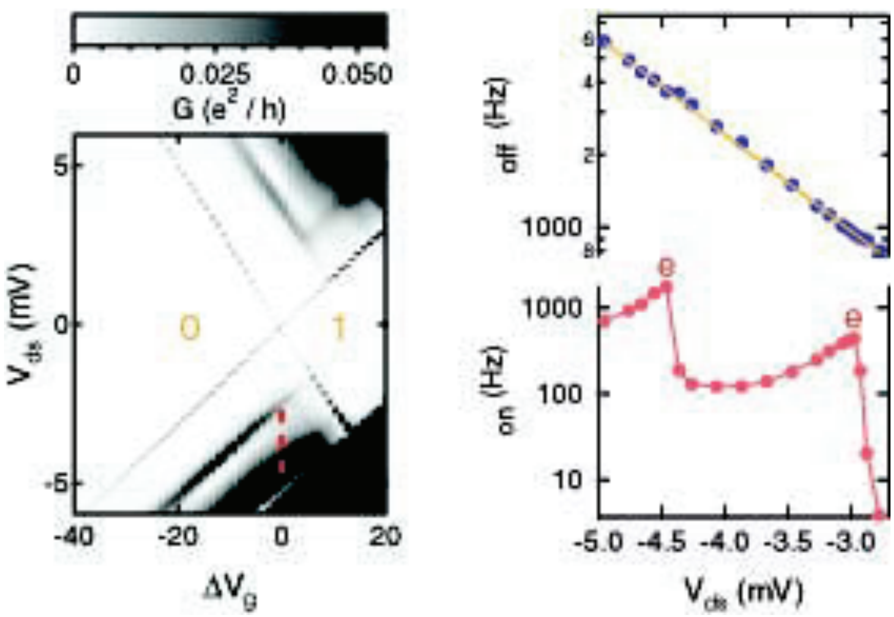
Jennifer Hoffman



To exploit the technological potential of superconductivity, one should better understand superconducting vortices. We have designed and are assembling a new cryogenic magnetic force microscope to detect and measure magnetic forces with 20 nm spatial and sub-pN force resolutions. An unusual vertical cantilever geometry will allow measurement of lateral forces, parallel to the sample surface. The drawing shows the instrument design. The photos show the partially assembled microscope body, and a silicon cantilever die with five tips etched by a focused ion beam (FIB) to have tip radius less than 20 nm.

Sensing One Electron as it Hops Onto or Off a Quantum Dot

M.A. Kastner



There is great interest in using the magnetic moments (spins) of trapped electrons in quantum dots as the bits in a quantum computer. For this, we must know how fast electrons hop onto and off of the dot. The left panel of the figure shows how the electrical current through the dot changes when we change the voltages on a gate (V_g) or across the dot (V_{ds}), clearly indicating when there is 0 or 1 electron on the dot. The right panel shows the rate at which electrons leave (Γ_{off}) or enter (Γ_{on}) the dot, measured by counting individual electrons.