CLUSTER 3: Imaging Electrons at the Nanoscale

Coordinator: Raymond Ashoori

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Eric Heller (Chemistry&Physics, Harvard)	Pierre Petroff (Materials, UC Santa Barbara)
Jennifer Hoffman (Physics, Harvard)	Robert Westervelt (SEAS & Physics, Harvard)

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International Collaborators: Fabio Beltram (NEST, Pisa, Italy), Leo Kouwenhoven (TU Delft, The Netherlands), Daniel Loss (University of Basel, Switzerland), Hiroyuki Sakaki (University of Tokyo, Japan), Lars Samuelson (Lund University, Sweden), and Seigo Tarucha (University of Tokyo and NTT, Japan)

Number of postdoctoral fellows: 2
Number of graduate students: 7
Number of undergraduate students: 4

Introduction

Electrons and photons inside nanoscale structures display striking behavior that arises from the confinement of quantum waves. By visualizing how electrons move through nanoscale systems, we can understand the fundamental science and develop new quantum devices. These devices can direct electron flow or control one electron charge or spin for future nanoelectronics or to implement qubits for quantum information processing.

Nanoscale structures also offer new opportunities for photonics: Electro-optical devices based on nanocrystals or nanowires integrated into photonic systems, and subwavelength optics. Near-field Scanning Optical Microscopy (NSOM) can be used to image and perturb these photonic systems.

The goal of the ***Imaging at the Nanoscale*** cluster is to develop new ways to image electrons and photons inside nanoscale systems, including their quantum behavior. This is difficult for electrons, because they are buried inside the structure, and because low temperatures are necessary. Nanoscale imaging of photonic systems also requires new approaches and devices. Custom-made microscopes and new imaging techniques are needed. This cluster brings together participants who are known for their skill in designing and building scanning probe microscopes (SPMs) to image electrons and photons inside nanoscale systems. Custom-grown heterostructures for this research are provided through a close collaboration with the Molecular Beam Epitaxy Lab at UC Santa Barbara. The cluster has strong international collaborations with Fabio Beltram (NEST), Leo Kouwenhoven (Delft), Daniel Loss (Univ. Basel), Hiroyuki Sakaki (Univ. Tokyo), Lars Samuelson (Luft Univ.) and Seigo Tarucha (Univ. Tokyo & NTT).

Expected outcomes of this research are:

New Approaches to Imaging Electrons and Photons in Nanoscale Systems — New imaging techniques using custom-made scanning probe microscopes, coupled with theoretical simulations, will allow us to probe and to understand the quantum behavior of electrons and photons inside nanoscale systems. These techniques are based on liquid He cooled Scanning Probe Microscopes (SPMs) and Scanned Tunneling Microscopes (STMs). A SPM tip can be used as a movable gate to induce charge in the electron gas below. This enables one to redirect electron flow by creating an electron lens, or to pull an electron onto a quantum dot or localized state. An STM tip can inject hot electrons into a nanostructure for Ballistic Electron Emission Microscopy (BEEM) and Ballistic Electron Emission Luminescence (BEEL) Microscopy. Near-field Scanning Optical Microscopy (NSOM) using custom tips is used to investigate photonic systems. The participants are experts at designing and building new types of scanning probe microscopes.

New Nanoscale Electronic and Photonic Devices — Visualizing and understanding the motion of electrons and photons will allow us to make new types of nanoelectronic and nanophotonic devices and systems. The ingredients used to make new electronic and photonic devices range from nanocrystals and nanowires from the ***Nanoscale Building Blocks*** cluster, to self-assembled InAs quantum dots, GaInAs quantum posts, and two-dimensional electron gas structures grown at the MBE Lab at UC Santa Barbara. These new materials offer exciting opportunities for nanoelectronic and nanophotonic devices and systems. Imaging, coupled with theoretical simulations, will show us to make new nanoscale devices and allow us to understand how they work.

Major Accomplishments

The imagers have made important advances in developing ways to image new types of nanostructures:

Self-assembled InAs quantum dots formed during MBE growth are fascinating structures for nanoelectronics and nanophotonics. They can be so small that they hold only one or two electrons. Using a scanning probe microscope (SPM) to gate InAs dots is very attractive, because one could add single electrons to an individual dot. **Raymond Ashoori** is developing this technique so that he will be able to do Coulomb blockade spectroscopy on an InAs dot, using heterostructures grown by **Pierre Petroff** in the MBE Lab at UCSB. **Ashoori** has succeeded in measuring the Coulomb blockade signal from single electrons added to an individual dot.

Petroff is extending his growth techniques to make GaInAs quantum posts, each seeded by an InAs dot. A quantum post separates photogenerated electrons and holes like the “nanobarbells” synthesized by Moungi Bawendi in the ***Nanoscale Building Block*** cluster — the electrons prefer the post while the holes state in the dot.

Jennifer Hoffman is developing a new variable temperature magnetic force microscope (MFM) to image and manipulate superconducting vortices. One possible long-term application is vortex-based computing. The MFM uses a new approach: a vertical cantilever that is more suitable for studying the lateral pinning of vortices than a conventional horizontal cantilever would be. She expects that the system will be completed in Fall 2007.

Eric Heller is developing a new imaging technique for the motion of electrons through an open two-dimensional electron gas that based on the formation of an electron lens beneath a charged SPM tip. The lens deflects electrons, throwing a shadow downstream, and changes the transmission from one point to another. Heller has tested this approach in collaboration with **Westervelt**'s group by comparing SPM images of magnetic focusing in a two-dimensional electron gas with detailed simulations. The technique works very well, and the images show the expected semicircular cyclotron orbits.

Robert Westervelt has developed a way to image electrons inside a quantum dot, by using the SPM tip as a movable gate. An image is created by displaying the dot conductance *vs.* tip position. A negatively charged tip will push an electron off the dot, as the tip approaches. The result is a ring of high dot conductance surrounding the dot for each Coulomb blockade conductance peak. **Westervelt**'s group first studied one-electron GaAs quantum dots. More recently they began a collaboration with Lars Samuelson to image an InAs dot formed in an InAs/InP nanowire heterostructure. The InAs dot's charge can also be reduced to one electron. This technique has promise for manipulating electrons in tunnel-coupled InAs dots inside an InAs/InP, which are too small to gate using conventional lithography. In addition, Westervelt collaborated with Leo Kouwenhoven to image electron flow through nominally open InAs nanowires

Kenneth Crozier and **Federico Capasso** have developed small optical antennas for subwavelength imaging. The two metal arms of the antenna act as plasmonic resonators, concentrating the electric field in the narrow gap between them. Tests show that this approach can give very high spatial resolution ~ 10 nm. Both investigators are now listed as members of the ***Nanoscale Building Blocks*** cluster, but their interest in imaging remains.

Subsurface Charge Accumulation Imaging of the 2-D Electron Gas

Raymond Ashoori
Physics, Massachusetts Institute of Technology
Collaborators: Bertrand I. Halperin, Eric J. Heller, Hongkun Park, Michael Stopa (Harvard University); Pierre Petroff (UCSB), M. Manfra, L. Pfeiffer, K.W. West (Lucent Technologies)

We have developed a means of imaging charge transport on small length scales in the quantum Hall effect using a scanning charge accumulation microscope [Steele *et al*., 2005]. Applying a DC bias voltage to the tip induces a highly resistive ring-shaped incompressible strip (IS) in a very high mobility 2-D electron system (2DES). The IS moves with the tip as it is scanned, and acts as a barrier that prevents charging of the region under the tip. At certain tip positions, short-range disorder in the 2DES creates a quantum dot island inside the IS that enables breaching of the IS barrier by means of resonant tunneling through the island. Striking ring shapes appear in the images that directly reflect the shape of the IS created in the 2DES by the tip. Our simulations show that native disorder from remote ionized donors can create the islands, and comparison of the images with simulations provides a direct and quantitative view of the disorder potential of a very high mobility 2DES.

Through our measurements of leakage across the IS, we extract information about energy gaps in the quantum Hall system. Varying the magnetic field, the tunnel resistance of the IS varies significantly, and takes on drastically different values at different filling factors. Measuring this tunnel resistance provides a unique *microscopic* probe of the exchange-enhanced spin gap, and potentially of other quasi-particle gaps in quantum Hall systems. We also draw a connection to bulk transport. At quantum Hall plateaus, electrons in the bulk are localized by a network of ISs. We have observed that the conductance across one IS is drastically enhanced by resonant tunneling through quantum dot islands. Similarly, this resonant tunneling process may play a pivotal role in dissipative transport at quantum Hall plateaus.

We have developed simulations of the interaction of a metallic scanning probe with a 2-D electron system (2DES) in the quantum Hall regime. The simulation is based on an electrostatic relaxation method, modified to include the nonlinear screening of the 2-D electron system at high magnetic fields. Using 2-D simulations with cylindrical symmetry that allow us to account for the exact shape of the tip, we predict the diameter and width of ring shaped incompressible strips (ISs) induced by DC tip biases. Extending these results to 3 dimensions, we incorporate the effect of the disorder on the shape of the IS, and predict the formation of quantum dot islands observed in Steele *et al*. (2005). Comparison of the simulation results with experimental data provides a direct and quantitative view of the disorder of a very high mobility 2DES. Michael Stopa of the NSEC provided useful advice in developing the simulations.

We are now working to measure even higher mobility 2-D electron systems using this technique. We wish to measure samples made in different ways and with different mobilities to characterize any correlation between observed quantum Hall behavior and the distribution of hot spots.

Reference

Steele, G.A., R.C. Ashoori, L.N. Pfeiffer, and K.W. West, “Imaging transport resonances in the quantum Hall effect,” *Phys. Rev. Lett.* **95**, 136,804/1–4 (2005).

InAs Self-Assembled Dots

We are are working with NSEC member **Pierre Petroff** to perform capacitance spectroscopy on single InAs self-assembled quantum dots. These 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 capacitance 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.

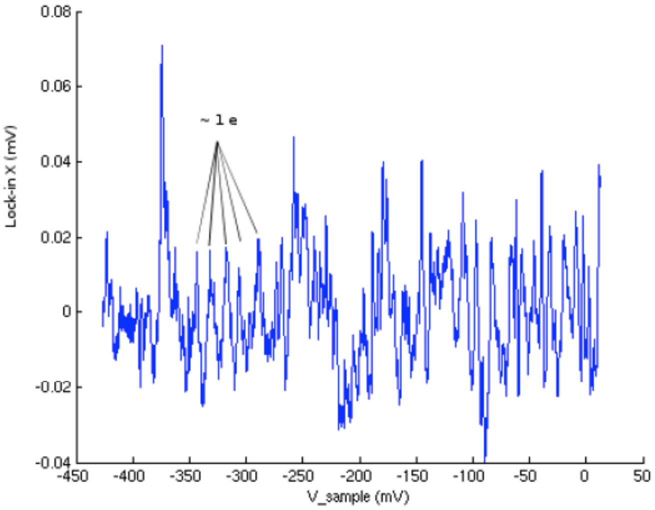

Figure 6.3.1.

We appear to have finally succeeded in measuring single electrons in an InAs quantum dot. Figure 6.3.1 above shows single electron peaks in a capacitance trace of a small (300 nm diameter) structure created from a wafer produced by **Petroff**’s group.

Measurement on a single dot opens the door to determination of the effects of electron-electron interactions and eventual comparison of optical spectra on a single dot. Also, we will be able to study charging in small clusters of dots to observe the effects of Coulomb interactions between dots on the charging spectra. We may eventually learn to control charging in multiple dots that are connected by barriers controllable through gating.

This collaboration represents a merger of world-class molecular beam epitaxial techniques from a pioneer of InAs quantum dot research with single-electron capacitance measurements that are unique to the **Ashoori** laboratory. No other groups have demonstrated the capability of performing precision capacitance spectroscopy with single electrons in semiconductor quantum dots.

Capacitance Imaging of 2-D Hole Systems:

2-D hole systems in GaAs have been proposed as a foundation for spintronic devices. The strong spin-orbit interaction allows the possibility for creating devices using the Rashba effect to preferentially control one spin state. We aim to examine this system, on the microscopic level, in a similar fashion to what we have done with electrons. We can determine the character of the self-consistent electrostatic potential within this system. Moreover, we will examine a system with density that can be varied through the 2-D metal-insulator transition. There is even the possibility of direct observation of Wigner crystallization in this system at low temperatures. The samples are obtained in collaboration with M. Manfra, L. Pfeiffer, and K.W. West, all of Bell Labs, Lucent Technologies. Theory support for this work will come from **Eric Heller** and **Bertrand I. Halperin**.

Physics of Graphene Sheets

Andre Geim's laboratory at the University of Manchester in the UK recently announced a fantastic discovery. They found that by simply rubbing graphite on surfaces (and later applying ultrasound to the surfaces to flake off excess graphite) they can deposit isolated monolayers of graphite (graphene sheets). Extraordinarily, they found it was easy to make electrical contacts and to fashion Hall bars from the material. At low temperatures, the graphene sheets actually display the quantum Hall effect! This effect has been reproduced in Philip Kim's lab at Columbia, and they have found mobilities as high as 15,000 cm^2/Vs. The physics of the QHE in these structures is quite different from other 2-D systems. Other than the valley degeneracy, the band structure has a linear rather than parabolic dispersion relation, and although Landau level structure exists (the levels are no longer evenly spaced in energy), the derivation involves solving a Dirac equation. Another feature of the material is that it can easily be field-effect-doped with a back gate with electrons or holes.

Obviously, this new technology is very interesting for a number of technological reasons. Carbon appears to have an amazing immunity to developing surface traps that drastically lower the mobility of most field effect devices. Indeed, it took many years to develop CMOS transistors, and the main difficulty was overcoming the threshold broadening induced by surface states. Carbon nanotubes transistors, on the other hand, simply worked, essentially on the first try. The carbon nanotubes have also displayed very high current carrying capacities and high transconductances. It is likely that the graphene sheets will display the same characteristics.

An obvious experiment for us is to perform our charge accumulation imaging on the graphene sheets. As the tip can, in this case be moved up directly against the surface, we can expect much higher resolution. Moreover, we will be able to perform direct STM imaging along with our capacitance techniques. We note though that capacitance has an important feature lacking in STM. In STM, the bias set between the tip and the sample controls the tunneling current and cannot be adjusted independently of the tunneling current. Therefore, even at small biases one often ends up with large electric fields between the tip and the sample due to work-function differences. In capacitance, there is no tunneling current, and we can adjust (and null) at will the electric field between the tip and sample and thereby control the perturbation created by the tip. Finally, having the tip so close to the sample will allow for very high resolution scanned gate measurements.

We plan to perform the same types of scanning bubble experiments on graphene in the quantum Hall effect regime as we have done in GaAs. This will give us a good idea of the types of short-range disorder that exist in these structures. Later experiments may examine high current saturation in the material (as occurs in nanotubes) and conducting pathways. This is perhaps the most exciting new electronic materials systems to arise in the last decade. Knowledge both of the underlying physics and techniques for producing graphene gained in this project will have impact on the NSEC further in the future. This work will impact on our understanding of nanotubes and 2-D systems and connect with the work of **Hongkun Park** and also **Bertrand I. Halperin**.

Understanding the Many-body Effects in Quantum Confined Structures

Pierre Petroff
Materials, University of California at Santa Barbara
Collaborators: Ray Ashoori (Physics Department, MIT),

We have developed and grown by Molecular Beam Epitaxy (MBE) a quantum device structure, which is designed to detect the charging of a single electron into a single quantum dot. The device is based on an InGaAs/GaAs layer of self-assembled quantum dots (QDs) embedded into a MISFET structure. The capacitance of the device is measured at low T using a specially designed STM sensing system. **Ashoori** and Wang have successfully fabricated the devices and measured the capacitance change associated with the charging of single electrons in a small device containing 10–20 QDs (see the NSEC report by Wang *et al.*).

We are currently redesigning a new sample structure to optimize this type of measurements and prevent device leakage to minimize noise under high voltage bias.

Dr. Jun He who has been partly supported by the NSEC grant and has been involved in the MBE growth of a novel self-assembled quantum structure: The quantum post (QP). The quantum post is formed of an InAs quantum dot connected to a short quantum wire aligned along the growth axis. The length of the InGaAs quantum wire section is adjustable between 2 nm and 60 nm. The quantum post offers, under optical excitation, the possibility of controlling the dipole moment and opens up new means for tuning the intra-subband transitions by controlling its dimensions. A schematic of the QP structure and cross section TEM are shown in Figure 6.3.2. Micro-PL spectra of a single QP have shown a rich peak structure (Fig.6.3.3) and are consistent with a delocalized electron in

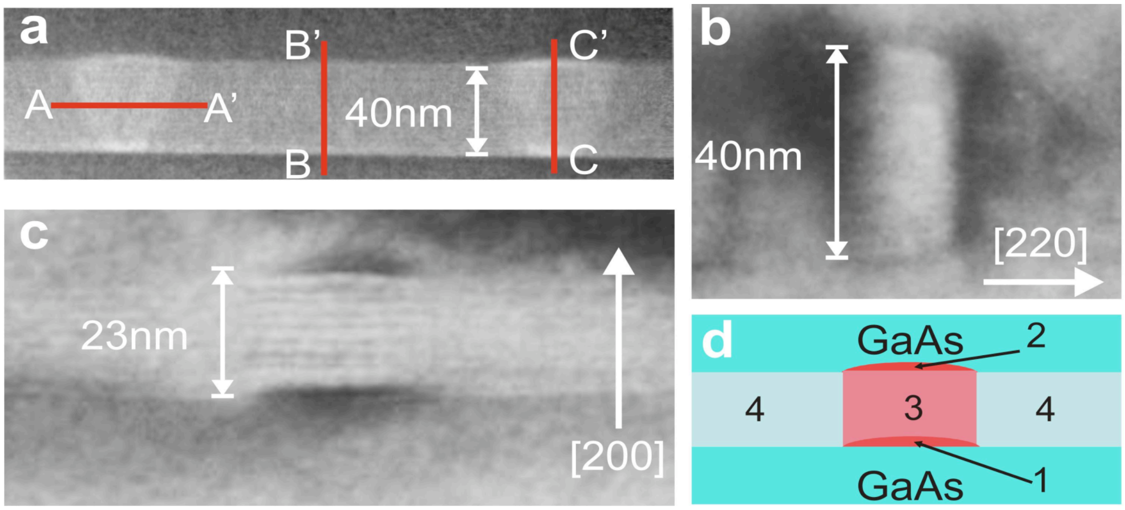

Figure 6.3.2. Cross-sectional images of quantum posts observed in TEM and STEM: (**a**) Z-contrast image from a High-Angle Annular Dark-Field detector in scanning TEM imaging mode. The In rich regions show as bright areas; (**b**) and (**c**) are conventional contrast TEM images of a 40 nm high and a 23 nm high quantum post with the beam of **g** = 220 and 200, respectively.

the quantum wire and a localized hole in the QD. An eight band effective mass k.p modeling of the electronic transitions is in good agreement with the principal lines observed in these spectra.

This QPs structure could easily be integrated in a QDs MISFET structure of the type currently investigated by Wang *et al*. The additional advantage over the QP is that under some voltage conditions, the electron can be delocalized in the quantum wire section or in the QD section of the QP. Thus both the 1-D or 0-D confinement regimes could be investigated using spectroscopic and imaging capacitance techniques.

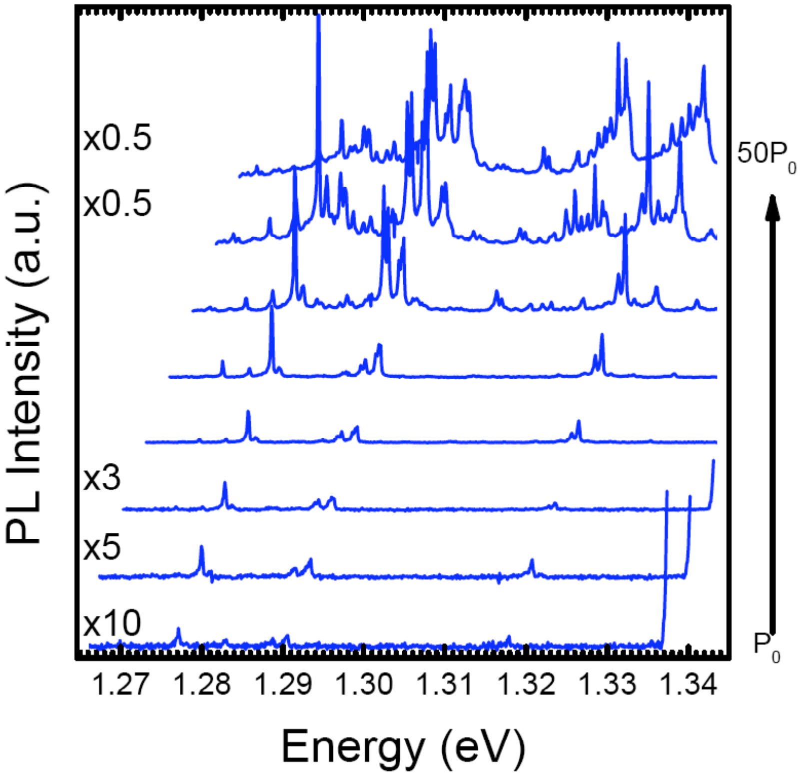

Figure 6.3.3. Micro-PL spectra of a single 20 nm long QP as a function of increasing pump power. $P_o = 0.5\ Wcm^{-2}$ and T = 7K.

Magnetic Force Microscope Construction for Vortex Pinning Studies

Jennifer E. Hoffman
Physics, Harvard
Collaborator: Robert M. Westervelt

The goal of this project is to detect and measure magnetic forces with 10 nanometer spatial resolution and sub-picoNewton force resolution. This imaging technology will be used initially for the study of superconducting vortices with a long-term interest in vortex-based computing.

Superconductors have many potential uses, including:

- macroscopic generation of large magnetic fields, for medical diagnostics or basic scientific research
- microscopic SQUIDS, for sensitive magnetic field detection in medicine, materials quality control, and many other applications

These applications are presently limited by the uncontrolled dissipative motion of vortices (magnetic flux quanta). Although much research has been devoted to understanding average vortex properties, little is known about the microscopic motion and pinning of single vortices.

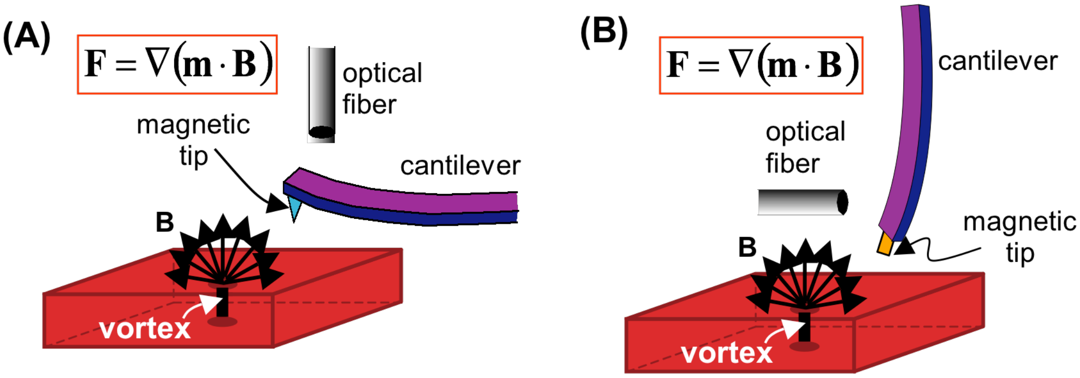

Figure 6.3.4. (**A**) Standard magnetic force microscope geometry: Horizontal cantilever detects vertical force gradients. (**B**) Proposed new magnetic force microscope geometry: Vertical cantilever detects horizontal force gradients. This geometry is much more suitable for studying the pinning of vortices in superconductors.

On the other hand, controlled vortex motion presents new opportunities for computing. Collectively controlled vortex motion can serve as a rectifier [Villegas *et al.*, 2003], a vortex ratchet mechanism can perform clocked logic [Hastings *et al.*, 2003], and vortices can control spins in an adjacent diluted magnetic semiconductor [Berciu *et al.,* 2005].

Given these challenges and opportunities, it is imperative to gain a better understanding of single vortex pinning. During the 2006 calendar year, we have been constructing a magnetic force microscope with geometry tailored to the study of vortices.

G3 student Sang Chu has designed the MFM, fridge, and vacuum system. The MFM parts have been machined, and assembly of the microscope is nearing completion. The long lead-time items (fridge, dewar, magnet, vacuum system components) have been purchased and we are awaiting their arrival. G1 student Tess Williams has created a process to use the focused ion beam to fabricate vertical cantilever tips. Undergraduate sophomore Hasan Korre has worked on microscope coarse motion system: He has built electronics hardware and written software both to control and detect motion. A proposed timeline is as follows:

- Fall 2006 — MFM parts assembled; coarse motion system tested (mechanical hardware, electronic hardware, and software are all functional); purchase orders submitted for custom fridge, dewar, magnet, and vacuum system components; vertical cantilever tips fabricated using FIB
- Jan., Feb., March, April 2007 — awaiting arrival of long-lead-time items; test optical interferometer in assembled MFM; purchase all remaining system electronics and cables; microscope test scan on a hard drive in air at room temperature
- May 2007 — fridge arrives from Janus; begin wiring
- June, July, Aug. 2007 — room temperature testing and debugging; write necessary software for the main control system
- Sept. 2007 — move into new LISE lab; assemble fridge, dewar, vacuum system
- Fall 2007 — low temperature testing and debugging of system

When complete, such a novel magnetic imaging tool may be useful not only for vortex studies, but also for imaging ever-shrinking magnetic storage bits and current patterns in nanowires.

Perhaps even more importantly, the MFM may be used not only for passive imaging, but also for active manipulation of the material or device being studied. The nanoscale magnet on the end of the cantilever may be used to drag vortices between pinning sites, to flip nanoscale bits, or to manipulate spins in diluted magnetic semiconductors.

References

Villegas, J.E. *et al.*, *Science* **302**, 1188 (2003).
Hastings, M.B. *et al.*, *Phys. Rev. Lett.* **90**, 247004 (2003).
Berciu, M., T.G. Rappoport, and B. Janko, *Nature* **435**, 71 (2005).

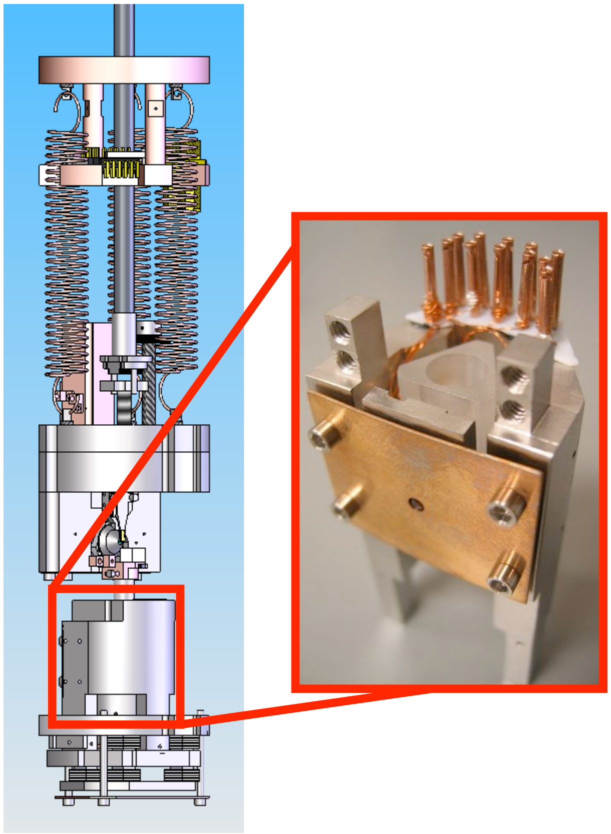

Figure 6.3.5. The magnetic force microscope design has been completed, and the parts machined by the Harvard shop in the Engineering Sciences Laboratory. The drawing shows the instrument layout. The blowup showing a photo of the titanium (non-magnetic) body of the microscope containing the assembled z-axis course motion system: The triangular sapphire (low friction) beam will hold the sample while moving up and down on a six-piezo walker.

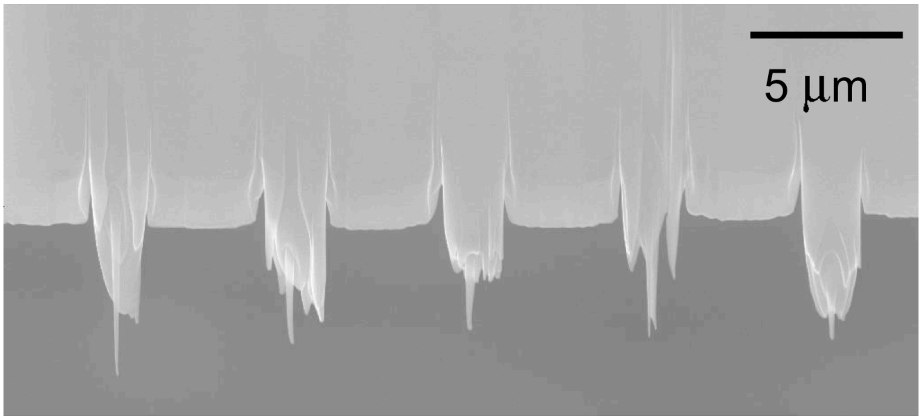

Figure 6.3.6 Five proof-of-principle cantilever tips with radii as small as 20 nm, fabricated using the focused ion beam (FIB) in the Center for Nanoscale Systems (CNS).

Ballistic Electron Emission Luminescence (BEEL)

Venkatesh Narayanamurti
Applied Physics and Physics, Harvard)
***Collaborators**:* R.D. Dupuis (Georgia Tech.), A.C. Gossard, P. Petroff (University of California Santa Barbara)

Currently **Narayanamurti**'s group is developing Ballistic Electron Emission Luminescence (BEEL), an extension of BEEM technique combining three-terminal ballistic carrier injection and interband radiative recombination in semiconductor quantum structures. BEEL provides a unique way to probe luminescent processes within semiconductors. Electrons are emitted from a tunnel junction through a Schottky Barrier (SB) interface into a *bipolar* heterostructure collector, where they recombine radiatively with holes in the optically active region. The ability to vary the collector bias and the externally-injected current and simultaneously monitor the induced interband luminescence allows spectroscopic characterizations. This provides for the first time a unique capability for a synergic study of electrically pumped photonic materials at a local scale. In contrast to two-terminal STM-induced luminescence (STL) which always requires a tip bias larger than the interband transition energies, three-terminal BEEL enables simultaneous measurement of SB heights with sub-bandgap energies.

Recently, progress has been made on exploring the possibilities of BEEM/BEEL on more generalized device structures beyond the specific *p-i-n* heterostructure reported previously. This work is a collaboration with Prof. **Gossard**'s group at UCSB. The original bipolar BEEL device is now replaced by a *unipolar* heterostructure, with optically active layer (InAs/GaAs quantum dots in this case) cladded between undoped layers grown on heavily-doped substrate. Such a doping profile gives rise to a *linear* band profile and therefore a constant electric field in the undoped layer, which can be easily tuned by a collector bias. Remarkably, a nonequilibrium flat-band condition can be reached accommodating BEEM measurement of buried barrier heights. Under forward collector bias, holes are tunnel injected into

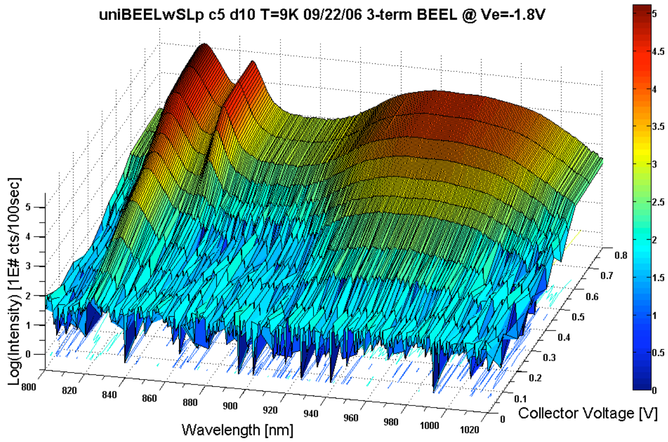

Figure 6.3.7. 3-D surface plot of photon intensity (in log-scale) as a function of wavelength and collector bias acquired on a unipolar BEEL device at 9 K. Emitter bias is kept at -1.8V for hot electron injection. Three peaks are resolved, which are assigned to GaAs emission at 1.51 eV, InAs wetting layer emission at 1.46 eV, and a broad InAs QD emission near 1.3 eV. The QD peak is inhomogeneously broadened by size fluctuations of about 10^6 QDs involved.

quantum dots (QDs) through the triangle barrier underneath, and luminescence would be induced by tunnel injecting *minority* electrons through the metal-semiconductor interface into the QDs.

A planar metal-base hot-electron transistor is used as a solid-state prototype for BEEM/BEEL by replacing a STM tip with a planar tunnel emitter made of aluminum and its oxide. It was utilized to perform spectrograph analysis (e.g., Fig. 6.3.7) of the hot-electron induced luminescence owing to much higher current injection level. It was found to be a complementary method to analyze the luminescent states of the material studied. Simultaneous BEEM measurement was made possible by freezing out the thermionic leakage current at low temperatures, so that the externally injected collector current can be measured. The correlation between collector current and light emission is illustrated in Figure 6.3.8, a three-dimensional surface plots of both integrated intensity of QDs emission and collector current as a function of emitter and collector biases. It was found that light emission only occurs for the regime of minority carrier injection (collector bias larger than flat-band threshold), supporting the picture that luminescence is induced by externally injected electrons through the SB interface.

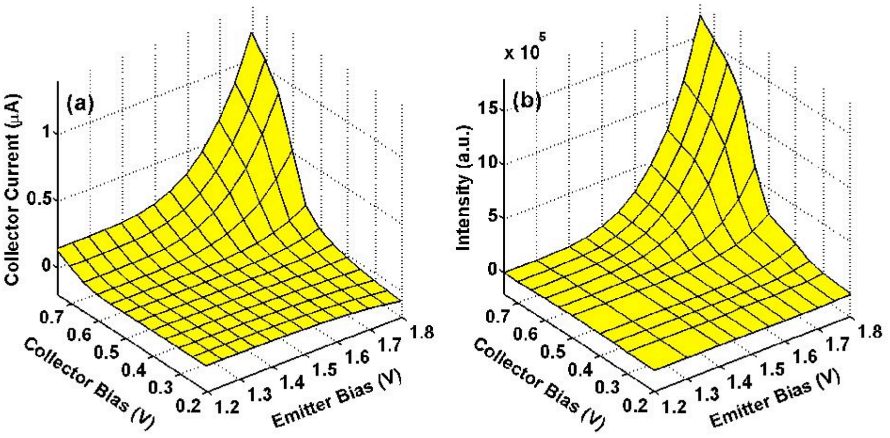

Figure 6.3.8. Emitter and collector bias dependence of collector current (*left*) and integrated BEEL peak intensity of InAs QDs (*right*). All data were collected at T = 9K. (Submitted to *Physical Review B*)

Another progressive research is BEEM study of InAs/InAlAs self-assembled quantum dots (QDs) grown by MOCVD on quaternary InAlGaAs buffer layer and InP substrate. This work is a collaboration with Prof. Dupuis group at GaTech.The material system is of current interest for 1.55 μm QD laser and QD-based light emitting transistor (LET) application. Systematic study has been done by Dupuis' group on effects of growth condition, substrate temperature, and growth interruption on QDs morphology and photoluminescence properties. AFM reveals that QDs grown under optimal condition for 1.55 μm emission are highly uniform, with very high density and uni-modal distributions.

One goal of the planned BEEM study is a careful local characterization of conduction band offset between InAlAs QDs and InAlGaAs cladding layer, which is valuable for the optimization of laser and LET designs. For this purpose, samples terminated with bare

InAs/InAlAs QDs on lightly n-doped InAlGaAs layer is needed. Careful surface passivation scheme is needed to prevent QDs oxidation and contamination before coating of a thin Au film. The Fermi level in InAs/InAlAs QDs layer is pinned near the conduction band minimum, so that a direct measurement of band offset to InAlGaAs layer is possible.

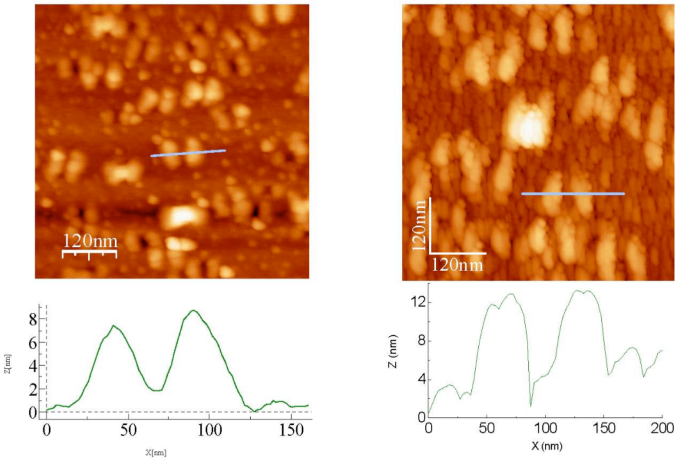

Figure 6.3.9. (**a**) AFM images of InAs QD sample grown on InAlGaAs layer with 5nm GaAs cap layer. Scan size = 600 x 600 nm. (**b**) STM image of the same sample after deposition of 8nm Au film. Tip bias = -0.2V; tunnel current = 0.5nA; scan size = 600 x 600 nm. The bottom plots are line cuts of a twinned QD.

Another interest is to study resonant tunneling phenomena through the quantum-confined states inside individual QDs. Similar work has been performed by **Narayanamurti** group on InAs QDs on GaAs, and InP QDs on AlInP and AlGaInP layers. For such purpose, Well-separated QDs cladded between two barrier layers is needed, and a thin (typically 5 nm) cap layer of GaAs is needed for surface passivation and SB formation. A test sample was grown on n$^+$-doped InP substrate, with undoped InAs QDs grown after a thin layer of undoped InAlGaAs. Non-optimal conditions were used to form relatively low QD density and larger QD sizes, resulting in a bi-modal size distribution. Preliminary AFM images (Fig. 6.3.9a) on bare sample surface and STM images (Fig. 6.3.9b) after deposition of a thin film of Au base confirm the expected bi-modal distribution with larger *twinned* QDs and smaller round QDs. The formation of twinned QDs elongated in [1-10] direction was interpreted to be originated from the anisotropic Al, Ga or In diffusion on surface and possible intermixing of cap layer with QDs. BEEM/BEES measurement on these devices is currently being investigated.

Nanostucture Molecular Beam Epitaxy

Arthur Gossard
Materials Science, University of California, Santa Barbara
Collaborators: Robert M. Westervelt (Harvard)

In the Gossard NSEC work at UCSB, our goal is to use molecular beam epitaxy to grow two-dimensional electron gases in semiconductor heterostructures for low temperature imaging of electron flow and for fabrication at Harvard and MIT into quantum dot nanostructures and structures with coupling of electrons in adjacent quantum dots and channels.

In a first set of experiments, samples were grown to investigate and control instabilities or switching in the electrical properties of nanostructures. Two wafers were grown and characterized by low temperature electrical measurements and supplied to Harvard. One was a standard AlGaAs/GaAs silicon-doped two dimensional electron gas structure. The second sample, grown immediately after the first, had the same doping and structure except that the AlGaAs layer after the doping layer was grown at a lower substrate temperature and was doped with erbium. Erbium should be a mid-gap state in AlGaAs and should pin the Fermi level, thus neutralizing any shallower impurities from ionizing during the measurement and changing the potential during the measurements at Harvard. This provided an artificial way of making a less perfect 2DEG. Hall data showed that the Er-containing sample's mobility was much lower, although the charge was slightly higher. Since high-mobility material seems to make unstable dots, the erbium doped sample provides a way to reduce mobility and possibly to achieve improvement in stability.

In a second area of research, we have installed an ultra-high-vacuum electron-beam-evaporation source in our molecular beam epitaxy system to allow deposition of clean, high-quality metallic gates and contacts on semiconductor heterostructure surfaces. The molecular beam epitaxy system is capable of growing high-mobility semiconductor heterostructures and fully epitaxial metallic layers (erbium arsenide) and/or non-epitaxial refractory metals (molybdenum). These materials provide a path to growth of gated nanostructures with far fewer unintentional defects at the semiconductor to metal interfaces. This increases the design flexibility and decreases possible deleterious switching noise sources. We look forward to working with the Harvard and MIT NSEC groups in evaluating the potential uses of the materials in nanoscale devices and measurement structures.

In a third set of experiments, samples were grown for performing low-temperature imaging of cyclotron motion of electrons with more than one cycle/bounce under magnetic field to produce magnetic focusing. To be able to obtain high quality images and to avoid branching in the flow, we grew high mobility modulation-doped two-dimensional electron gas structures containing the electron gas near the surface of the samples. Low density/high mobility structures were grown in order to highlight the effects of phase-based interference in magnetic focusing. The goal is to get the wavelength larger compared with the device size, and to reduce small angle scattering (both through higher mobility and smaller device size) to avoid forming branches of flow. Four samples were grown with two dimensional electron gases at depths from 60 nm to 100 nm below the sample surface and two dimensional charge densities between 2 x 10^{11} cm^{-2} and 3 x 10^{11} cm^{-2} and mobilities between 260,000 and 370,000 cm^2/Volt sec at T = 20K. All of the samples were then transferred to our Harvard collaborators in the **Westervelt** laboratory.

Imaging Nanoscale Systems

Eric Heller
Chemistry and Physics, Harvard University
Collaborators: Robert M. Westervelt (Harvard)

Our goals have included understanding the physics of SPM tip imaging in semiconductor microstructures, and using that knowledge to understand the physics of the electron flow itself. In addition, we have undertaken a study of spin precession, and its effects on imaging, in these same microstructures.

SPM Imaging

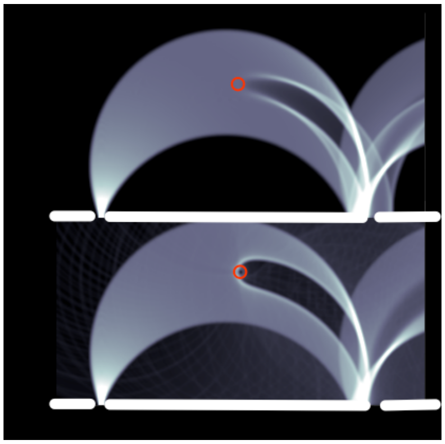

Figure 6.3.10. Theoretical classical flux simulation of magnetic focusing, with the downstream effects of a tip seen for two different SPM tip potentials. Tip imaging in this idealized case is easiest to see: any deflection from the SPM tip which causes flux which would have entered the second "target" QPC to miss it, or any flux which would have missed it which is caused to enter, changes the signal.

The **Heller** group is a theoretical group with long experience in scattering theory and an array of numerical and theoretical tools at our disposal, many of which we developed ourselves. We have previously shown why SPM tip imaging can yield sharp images including quantum fringes [Topinka *et al.,* 2001], and this past year we have extended that work to include the new physics of transconductance imaging in a magnetic field, in a study of magnetic focusing. Here the images were not nearly so clear-cut initially, looking much more complex, although they did show the expected shape for magnetic focusing (see Fig.6.3.10).

More recently, another close collaboration with the **Westervelt** group centered around transconductance experiments imaging electron magnetic focusing [Aidala *et al.,* submitted]. Specifically, the effect of electrons deflected by the scanning probe microscope (SPM) tip potential and reflecting off the walls of the device, or directly toward a second open quantum point contact (QPC) have been seen, also decorated with interference fringes. This is a much more complicated imaging environment than the original single QPC backscattering measurements. Rather than the narrow backscattering "glint" contributing to the signal, any deflection from the SPM tip which causes flux which would have entered the second "target" QPC to miss it, or any flux which would have missed it which is caused to enter, changes the signal (Fig. 6.3.11).

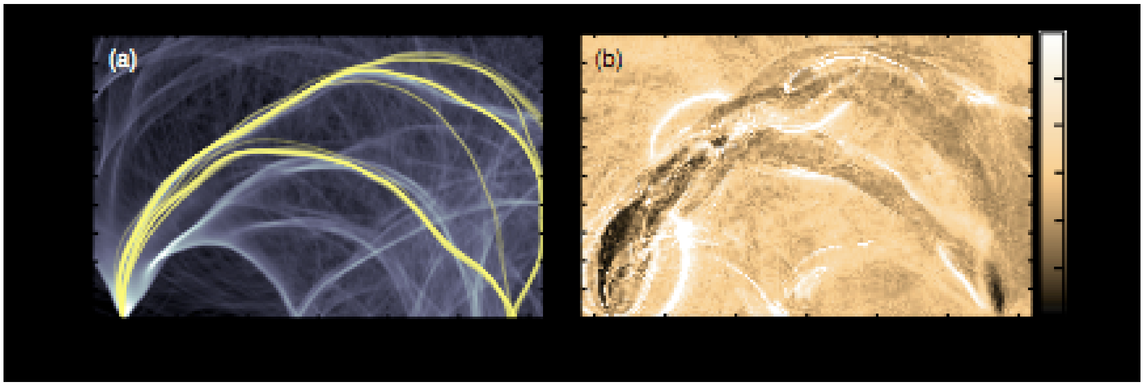

Figure 6.3.11. Classical simulation of electron pathways in a magnetic focusing transconductance experiment, in the presence of potential fluctuations due to charged donor atoms. *Left*: Electron flux, with the trajectories successful in entering the second QPC shown in yellow. *Right*: *Change* in flux through second QPC with tip position. Notice that tracks of successful trajectories are now darker, as flux was lowered if the tip deflected them, and other regions are much brighter, if the tip deflected trajectories into the QPC that had missed before. Some of these did bound off the wall before they went in.

This year we were able to work out the effects, which are finally revealed in the images of magnetic focusing, such as the top panel and lower three panels of Figure 6.3.12.

Rather than being the qualitative morass that it might first appear, the experimental images are in fact quite dense with interesting data. The combined effects of donor atom potentials, magnetic fields, at tip potentials result in qualitative changes which we understand now quite well to involve tip deflections creating new routes to the second QPC which interfere with other routes, give rise to fringes which are spaced by an amount which reveals the angle of scattering of electrons off the tip.

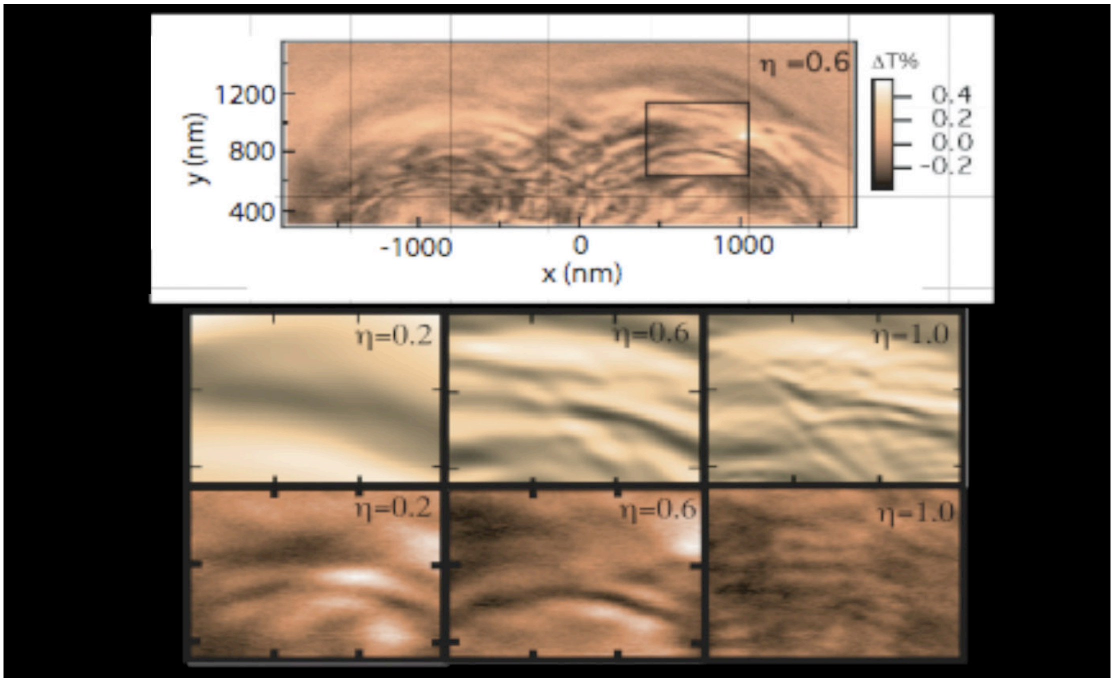

Figure 6.3.12. Experimental data **top** and bottom three panels) compared to simulations (**middle** panels) showing a finer fringe structure with increasing tip strength.

In other work, we investigated Rashba spin precession due to impurity and boundary scattering, and defects [Walls *et al*., 2006].

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Imaging Nanowires and Quantum Dots
Imaging a 1-Electron InAs Quantum Dot in an InAs/InP Nanowire

Robert M. Westervelt
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***Collaborators*:** A.C. Gossard, Donhee Ham, Bertrand I. Halperin, Eric Heller, and Marc Kastner
International Collaborators: Fabio Beltram (NEST, SNS Pisa), Leo Kouwenhoven (Delft), Lars Samuelson (Lund University) and Seigo Tarucha (University of Tokyo).

Westervelt's group has developed a way to image a quantum dot in the Coulomb blockade regime by using a scanning probe microscope tip as a movable gate, and they have demonstrated this technique on a 1-electron GaAs dot (Fallahi *et al.,* 2005). The approach is very promising for the analysis of coupled dots and dot circuits, because the tip acts like a quantum voltmeter probe – it can locate the position of the dot, pull or push electrons on or off it, and measure the electron energy using Coulomb spectroscopy.

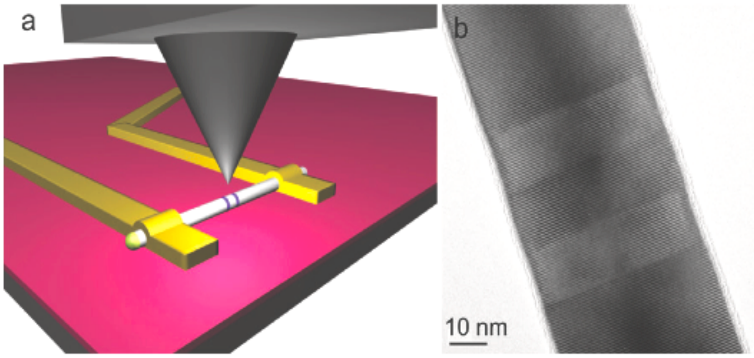

Figure 6.3.13 (**a**) A conductance image is obtained by scanning a metallized SPM tip in a plane 20 nm above the nanowire, with tip voltages -3V to 3V. The image displays nanowire conductance *vs.* tip position. (**b**) TEM photo of an InAs/InP nanowire containing an InAs dot, confined by two InP barriers. Individual atomic layers are visible, demonstrating the high quality of epitaxial growth.

In collaboration with Samuelson, **Westervelt** has recently used this imaging technique to study a very small InAs dot inside a nanowire heterostructure. As shown in Figure 6.3.13, Samuelson's group can grow very high-quality InAs quantum dots in an InAs/InP nanowire. The faces of the hockey puck shaped dot line up with atomic planes. InAs dots in nanowires are attractive for nanoelectronics and spintronics, because the dots are truly small, electrons are attracted to the surface, with a large g-factor. However, it is difficult to gate multiple nanowire dots, due to their very small size, beyond the limits of e-beam lithography.

By using the tip of a cooled SPM as a movable gate, one can locate and gate a single dot inside a nanowire. Figure 6.3.14 shows SPM conductance images of an InAs quantum dot grown inside an InAs/InP nanowire, in a geometry similar to Fig. 6.3.13 (Bleszynski *et al.*, 2007a). The dot is quite small (18 nm thick by 50 nm diameter), and it is easy to reduce the number of electrons to 1, as shown in the Coulomb diamonds on the right of Fig. 6.3.14. An image is obtained by scanning the SPM tip in a plane above the nanowire, with fixed tip voltage. The charge induced on the dot by the tip increases as the tip is brought nearby. A series of concentric rings of high conductance occur in the images – each ring corresponds to a Coulomb blockade conductance peak. The ring between 0 and 1 electron on the dot is shown in Fig. 6.3.14; it completely circles the dot. So one can locate a dot along the nanowire, and push electrons off it using the SPM tip. This capability will be very useful for manipulating coupled double quantum dots, as well as dot circuits. Ania Bleszynski and Linus Fröberg, her grad student collaborator at Lund University, won a best paper award for their talk at the 2006 International Conference on Semiconductor Physics, in Vienna.

In collaboration with Kouwenhoven's group, **Westervelt** has used this approach to study nominally open InAs nanowire devices (Bleszynski *et al.*, 2007b). Some devices showed complex patterns of Coulomb blockade peaks in plots of dot conductance *vs.* back gate voltage. By imaging the samples with the cooled SPM, they indentified a number of accidentally formed dots along the nanowire, and were able to find both their location and their relative size.

The SPM tip can also measure the energy of an electron energy level in a dot. Figure 6.3.15 presents a series of images of a 1-electron GaAs dot, formed in a 2DEG, recorded as the magnetic field *B* was increased (Fallahi *et al.*, 2007). For this tip voltage, the tip pulls an electron onto the dot as it moves close by. The diamagnetic shift increases the

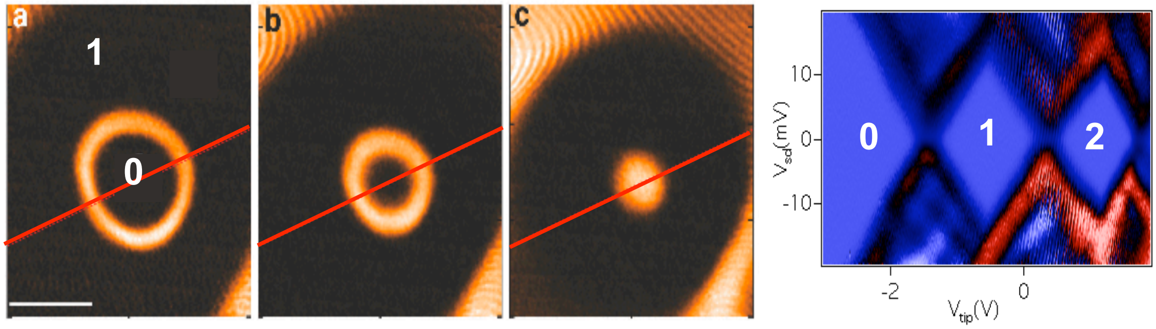

Figure 6.3.14. (**a-c**) SPM Images of dot conductance vs. tip position at 4.2 K for a 1-electron InAs quantum dot in an InAs/InP nanowire. The ring in the image is the Coulomb blockade peak between 0 and 1 electrons on the dot. As the tip voltage V_{tip} is made less negative from (**a**) to (**c**), the first electron is allowed onto the dot. Coulomb diamonds in a plot of dot conductance vs. V_{tip} and source-to-drain voltage V_{sd}. The red line indicates the nanowire position. (Bleszynski *et al.*, 2007a)

energy of the ground state as *B* increases, due to the interaction of the field with the electron orbit. The diameter of the ring decreases in proportion, measuring the diamagnetic energy shift. Comparison with Coulomb blockade spectroscopy allows one to calibrate the imaging technique. **Westervelt** plans to carry out analogous experiments with **Kastner**'s group, to image electron spin.

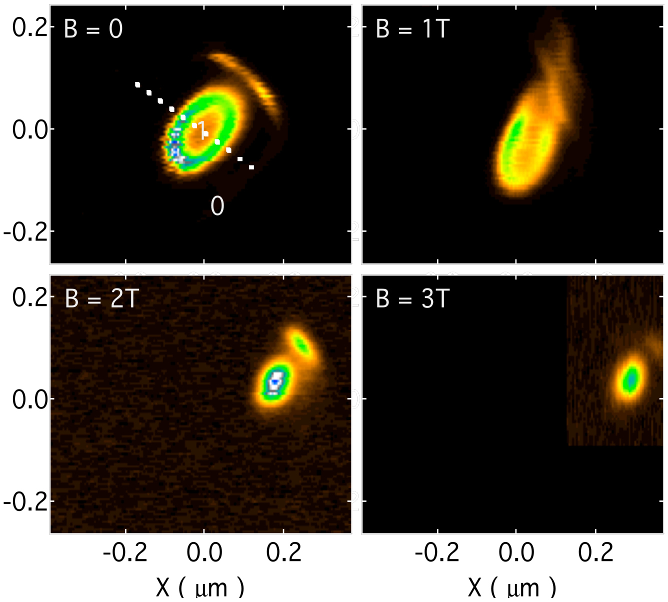

Figure 6.3.15. SPM conductance images of the diamagnetic energy shift a 1-electron GaAs quantum dot in a magnetic field B; the dot is formed in a 2DEG by gates. The change in ring diameter as B increases measures the diamagnetic shift. (Fallahi *et al.*, 2007)

In a collaboration with **Eric Heller**'s group, **Westervelt** has imaged magnetic focusing of electron waves flowing through a 2DEG between two quantum point contacts (Aidala *et al.*, 2007); with partial support from another source. An excellent description of this research is given in **Heller**'s contribution to this report. The images show the circular path of electrons moving along cyclotron orbits, as well as fringes caused by the interference of electron waves traveling along different paths. To carry out this research **Heller** and **Westervelt** developed a new imaging technique based on the deflection of electron waves by an electron lens produced in the 2DEG by a charged SPM tip immediately above. The lens through a shadow downstream that reduces the flow of electrons from one QPC to the other. By displaying the change in transmission as the tip is scanned above the sample, an image is obtained.

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Imaging Spins in Quantum Dots

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The long-range goal of our NSEC work is to image electron spins in quantum dots. **Westervelt**'s group has made great advances in imaging electron charge density. Imaging the spin density of electrons in nanostructures will give additional information about electronic wavefunctions and may be useful in characterizing devices, for quantum computing, for example.

Our approach has been to first control a single spin using microwave excitation. We have attempted this by mounting a lateral quantum dot over a hole in the wall of a microwave cavity in our dilution refrigerator. The dots have been made, so far, from GaAs heterostructures grown by the **Gossard** group. We are now fabricating dots using Si quantum wells in SiGe heterostructures, provided by Xie of UCLA. The low density of isotopes with nuclear spins and, especially, the low hyperfine coupling in Si, should make very long coherence times possible.

Our measurement of the spin state of the quantum dot involves adjusting the energy of the dot so that the excited spin state is above the Fermi energy in the leads, whereas the lower-energy spin state is below E_F. As a result, there is a high probability for ionization of the dot after spin excitation. The latter relies on charge sensing, using a quantum point contact (QPC) adjacent to the quantum dot. To make such measure-ments precise, it is important to thoroughly understand the tunneling of electrons on and off the leads. We have recently completed a study of the way in which this probability varies with source-drain voltage. The measure-ment is described in Figure 6.3.16.

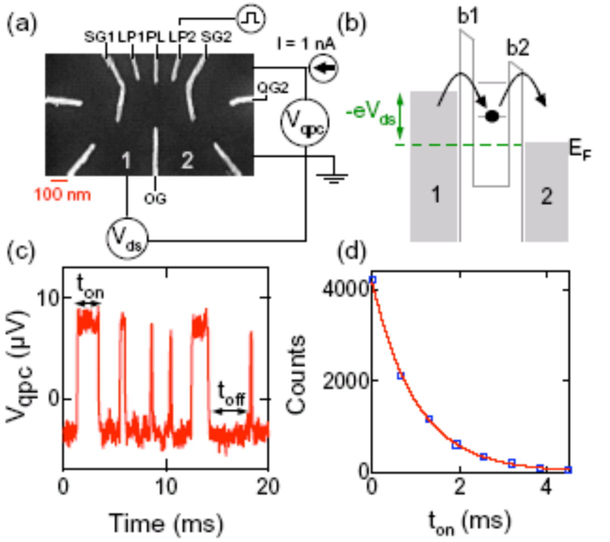

Figure 6.3.16. (**a**) Electron micrograph of the gate geometry and schematic of the measurement circuit. Unlabeled gates are grounded. We measure the resistance of the QPC by sourcing a current through the QPC and monitoring the voltage V_{qpc} across the QPC. (**b**) When a voltage bias V_{ds} is applied across the quantum dot a small current flows and the charge on the dot fluctuates between 0 and 1 as shown in (**c**). We measure the time intervals t_{on} (t_{off}) that the electron is on (off) the dot using an automated triggering and acquisition system. (**d**) Histogram of t_{on} times from data such as in (**c**). Fitting this histogram yields Γ_{off}.

We have developed a sophisticated trigger that allows us to retain only the times of tunneling events and whether they correspond to an electron tunneling on or off the dot. This allows us to accumulate thousands of events without overloading our computer memory. As a result, we have been able to make high precision measurements of the tunneling rates on and off the dot. The results are shown in Figure 6.3.17.

A simple model, in which tunneling is completely elastic, provides an excellent description of the data, including tunneling into excited states (marked *e* in Fig. 6.3.17a).

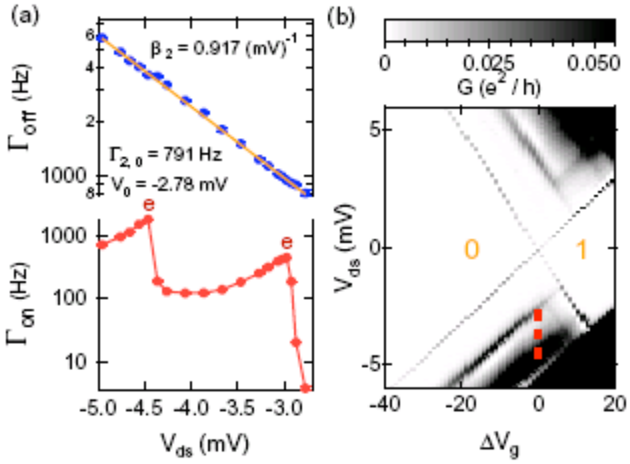

Figure 6.3.17. (**a**). Tunneling off (Γ_{off}) and tunneling on (Γ_{on}) rates as a function of V_{ds} for large negative V_{ds}. The solid line in the upper panel is based on a simple model. (**b**). Differential conductance vs. V_{ds} and V_g, showing the 0 to 1 electron transition. The tunnel rates for this case are made large enough so that the differential conductance can be measured using standard transport techniques. The data shown in (**a**) are taken at the position of the dashed line.

Our plan for the coming year is to characterize Si quantum dots using the same charge sensing techniques as we have with GaAs dots. We have fabricated dots and are now testing them. If we can reproduce measurements like those in Figures 6.3.16 and 6.3.17 with Si dots, we will immediately begin spin resonance experiments.

Theory of Electron and Spin Transport in Nanostructures

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Collaborator(s): Charles M. Lieber (Harvard), Robert M. Westervelt (Harvard)
International Collaborators: Leo Kouwenhoven (Delft), Lars Samuelson (Lund University, Denmark)

The overall goal of this work is to gain a better understanding of the electronic structure of nanoscale building blocks, and of the operations of nanoscale devices, in order to improve our ability to design and construct such devices. A crucial aspect of the development of new structures and devices are measurements to characterize these structures. Theoretical efforts are necessary to understand the results of such measurements as well as to suggest new types of measurements as well as possible improved structures. Our projects are motivated by NSEC-supported experiments including particularly measurements of transport in semiconducting nanowires, and imaging of electron flow and electronic states in structures made from two-dimensional electron systems. Goals include development of theoretical and calculational techniques, as well as applications to specific systems.

Nanowires. InAs nanowires are a particularly interesting system for fabrication of nanoscale semiconductor devices, and they are being actively studied in many laboratories, including the **Westervelt** and the Kouwenhoven groups, among others. We are trying to understand better the nature of the electronic states in these wires, and we are trying to see how much information one may gain by analyzing electrical transport in the presence of an applied magnetic field. Together with Junior Fellow Yaroslav Tserkovnyak, we became interested in this subject several years ago, when researchers in **Lieber**'s group made measurements on several InAs nanowires, and found complex oscillatory behavior as a function of magnetic field, for fields both parallel and perpendicular to the sample.

More recently, there has been renewed experimental interest in InAs nanowires, within NSEC and elsewhere, and there is promise of extensive new magneto-transport data on these systems. Some measurements have already been carried out at Delft, and also by Samuelsen's group in Sweden. Detailed imaging studies of wave functions in nanowires have been carried out in **Westervelt**'s laboratory. Consequently, we have reopened our work on the theory of magnetotransport in these systems.

Using a simple model, we have obtained results that are qualitatively similar to the experimental results. The detailed results are dependent on the assumptions one puts in for such parameters as the mean free path or the carriers, the nature of the contact to leads, and boundary conditions at the ends of the wires. However, if these parameters are reasonably known, the magnetotransport data can give important information about the electronic wavefunctions in the wire. Of particular interest, are the dependencies of results on the nature of the electronic wavefunctions in the radial direction. We obtain substantial differences if we assume that the doping is primarily due to surface charges, and the electron states are confined near the surface of the InAs, or if we assume that the electronic wavefunctions persist into the center of the wire.

Magneto-transport data can give useful information about the wavefunctions as long as the electron mean-free-path is comparable to or larger than the circumference of the nanowire. However, additional information is gained if the contacts are close together and the mean-free-path is equal or greater than the contact separation. In a manuscript, accepted for publication in *Physical Review*, we have presented model calculations, which illustrate these points. (See Fig. 6.3.18)

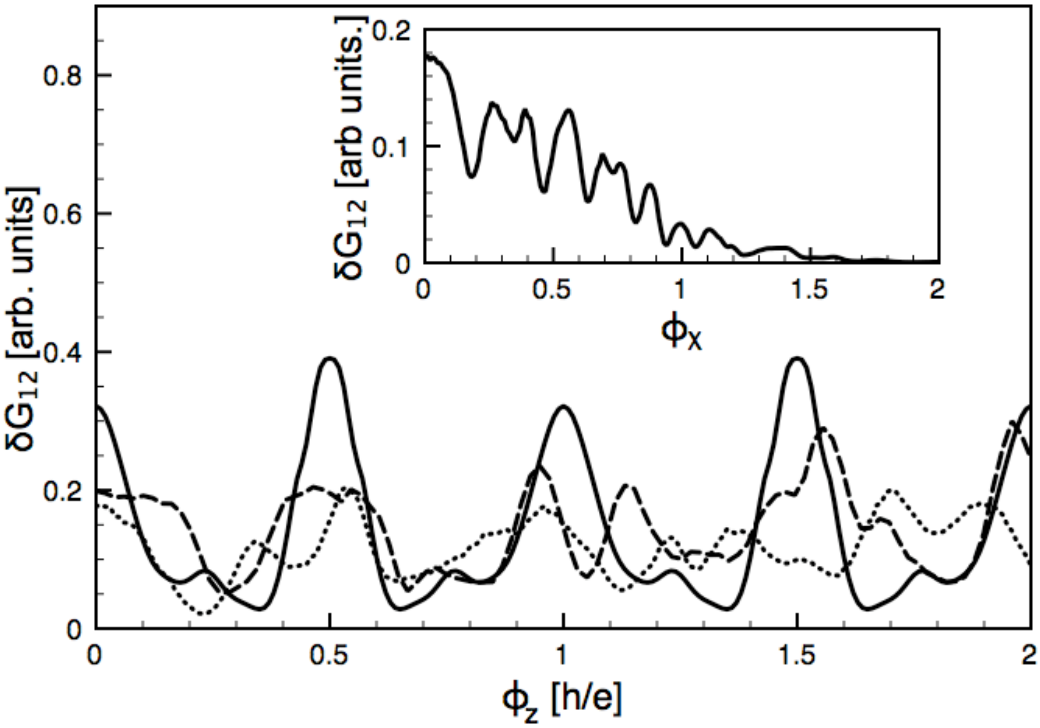

Figure 6.3.18. The main panel shows effects of a magnetic field parallel to the axis of an InAs nanowire, with contact separation $L = 300$ nm, for (**a**) an idealized model with electrons in a thin shell or radius $R = 10$ nm, ignoring the Zeeman splitting and Rashba spin-orbit coupling (*solid line*); (**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**).

Spin-orbit effects. Spin-orbit effects on transport in semiconductor systems have been a major theme of our NSEC-supported work during the past few years, as analysis has shown a remarkable subtlety in these problems. Analysis has shown a surprising subtlety in these problems, which has resulted in a number of conflicting results in the literature. Research by **Halperin** and collaborators has resulted in five papers in this area, published or submitted in 2006 (Shytov *et al.,* 2006; Adagideli *et al.,* 2006; Tserkovnyak, *et al.,* 2006; Engel *et al.*, 2006a,b), of which three received support at Harvard primarily through the NSEC (Shytov *et al.,* 2006; Adagideli *et al.,* 2006; Tserkovnyak *et al.,* 2006).

Research supported by NSEC in 2006 has focused particularly on boundary effects for two-dimensional electron systems in III-V semiconductors such as GaAs, Rashba and k-linear Dresselhaus spin-orbit couplings are important. In one paper, accepted for publication in *Physical Review Letters*, it was shown how, in an appropriate geometry, an electric current through the sample could produce a voltage dependent on the magnetization direction of a ferromagnetic contact (Adagideli *et al.*, 2006).

In another paper, recently completed, **Halperin** and collaborators showed that a current-carrying 2-D electron system can inject spins into another 2-D system with different Rashba coupling, through a lateral (edge) interface, if the two systems have different electron mobilities, or if the mobility near the interface is different from that in the bulk. However, *contrary to beliefs that were previously widespread,* and contrary to at least one previous publication, we find that *there is no spin injection when the mobility is homogeneous across the interface* (Tserkovnyak *et al.,* 2006). Interfaces of both types can be produced in a 2-D system which is partially covered by a gate.

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Shot Noise in Nanoscale Devices

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In the past year we have completed the design and construction of a low-temperature noise measurement system [DiCarlo *et al*., 2006b] and carried out experimental and theoretical explorations of shot noise in mesoscopic electronics, including quantum point contacts [DiCarlo *et al*., 2006a], quantum dots [McClure *et al*., 2006], and graphene. Shot noise is a fundamental characteristic of electron transport that reflects the discrete nature of charge in the regime of partial transmission of modes of conduction. As such, shot noise provides information about the conduction process that cannot be obtained from dc conduction. This is particularly interesting when quantum coherence effects and electron interaction effects are also present.

Measuring shot noise is much more complicated experimentally compared to measuring transport. A detailed report on how to develop low noise amplifiers and room temperature data acquisition is given in DiCarlo *et al*. [2006].

An example of how interactions can affect noise was investigated in McClure *et al*. [2006], where noise cross-correlation in two parallel quantum dots could be modified in sign by tuning the Coulomb blockade of the two dots. It is notable that this paper, in press at *Physical Review Letters*, has an undergraduate first author.

In the last six months, we were pleased to host Michihisa Yamamoto from Seigo Tarucha's group at the University of Tokyo. He worked closely with the "noise team" leading to a paper on shot noise in quantum dots that is currently in preparation. Materials for this project was provided by the **Gossard** group at UCSB.

In the next 12 months, we will refocus our NSEC funding on another project, the study of nuclear hyperpolarization in Si nanoparticles to be used as MRI imaging agents. A proposed Ph.D. student who will work on the project, and be funded by the NSEC, is part of the Harvard-MIT HST program, Jonathan Marmurek. The idea is to produce high nuclear polarizations in nanoparticles and the functionalize the particles so they are attracted to biologically specific areas. This work is a collaboration with Ron Walsworth at CfA and Prof. Sangeeta Bhatia at MIT. In our view, this work fits well into any of the three clusters.

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