3. PROJECT SUMMARY

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons inside nanostructures for new nanoelectronic and nanophotonic devices, and to investigate how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Research Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

Cluster 2: Nanoscale Building Blocks makes new classes of nanostructures that exhibit size-dependent properties. We synthesize structures with unconventional shapes, as well as zero, one- and two-dimensional nanostructures including nanoparticles, nanowires, and heterostructures. New materials are introduced, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks are promising for nanoelectronics and nanophotonics as well as for biosensors.

Cluster 3: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons inside nanostructures using custom-made scanning probe microscopes, including cooled instruments. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing.

The **Center for Nanoscale Systems (CNS)** is a major investment by Harvard to provide shared facilities to conduct research in nanoscience and engineering. A new building, the **Laboratory for Integrated Science and Engineering** was recently completed and being outfitted with equipment. It houses **CNS** facilities for nanofabrication, imaging and materials growth. Harvard and UC Santa Barbara provide nanofabrication facilities to outside users through the **National Nanotechnology Infrastructure Network** (**NNIN**).

Connections with **Industry** are strengthened by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program**. Our Center is funded by the **Nanoelectronics Research Initiative (NRI)** of the **Semiconductor Research Corporation (SRC)** to develop new oxide materials for future logic switches. Many Center participants have collaborations with industry.

Our Center's **educational program** develops **human resources** at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities, including REU and RET programs, a introductory course *Applied Physics 298r* on nanoscience, and a series of workshops. The **Museum of Science, Boston** engages the public and introduces them to the big ideas in nanoscience in an entertaining and informative way, in collaboration with the researcher in our Center. The Museum is a core member of the new **National Informal Science Education (NISE) Network**.

Our Center plans to increase **Diversity** by: recruiting a more diverse group of graduate students and postdocs, increasing the diversity of participating faculty, recruiting members of underrepresented groups by extending REU approaches, introducing public school students to science and engineering, and developing long-term partnerships with predominantly female and minority-serving institutions.

4. LIST OF CENTER PARTICIPANTS AND ADVISORY BOARD

(a) Center Participants

Name	Field of Research	Institution
Joanna Aizenberg	Chemical Biology, Materials	Harvard
Carol Lynn Alpert	Education and Outreach	Museum of Science
Raymond Ashoori	Physics	MIT
Michael Aziz	Physics & Applied Physics	Harvard
Moungi G. Bawendi	Chemistry	MIT
Federico Capasso	Applied Physics & Elect. Eng.	Harvard
Kenneth B. Crozier	Electrical Engineering	Harvard
Eugene Demler	Physics	Harvard
Daniel Fisher	Physics	Harvard
Cynthia M. Friend	Chemistry & Applied Physics	Harvard
Gerald Gabrielse	Physics	Harvard
Arthur C. Gossard	Materials	UCSB
Bertrand I. Halperin	Physics	Harvard
Donhee Ham	Electrical Engineering	Harvard
Eric J. Heller	Chemistry & Physics	Harvard
Jennifer E. Hoffman	Physics	Harvard
Marc A. Kastner	Physics	MIT
Efthimios Kaxiras	Physics & Applied Physics	Harvard
Charles M. Lieber	Chemistry & Applied Physics	Harvard
Marko Lončar	Physics	Harvard
Mikhail Lukin	Physics	Harvard
Charles M. Marcus	Physics	Harvard
Eric Mazur	Applied Physics & Physics	Harvard
Joseph Mizgerd	Biology & Public Health	Harvard
Venkatesh Narayanamurti	Applied Physics & Physics	Harvard
Hongkun Park	Chemistry	Harvard
Mara Prentiss	Physics	Harvard
Kevin (Kit) Parker	Bioengineering	Harvard
Pierre Petroff	Materials	UCSB
Shriram Ramanathan	Materials	Harvard
Howard A. Stone	Materials & Fluid Mechanics	Harvard
Michael Stopa	Computational Materials	Harvard
Michael Tinkham	Physics	Harvard
David Weitz	Materials	Harvard
Robert M. Westervelt	Applied Physics & Physics	Harvard
George M. Whitesides	Chemistry	Harvard
Amir Yacoby	Physics	Harvard
Xiaowei Zhuang	Chemistry & Physics	Harvard

International Collaborators

Fabio Beltram	Physics	NEST, Pisa, Italy
Piotr Garstecki	Chemistry	Polish Academy of Sciences
Leo Kouwenhoven	Physics	Delft University of Technology
Eugenia Kumacheva	Chemistry	University of Toronto
Daniel Loss	Physics	U Basel
Maria-Anita Rampi	Chemistry	University of Ferrara, Italy
Lars Samuelson	Physics	Lund University
Hiroyuki Sakaki	Inst. of Industrial Science	U Tokyo
Seigo Tarucha	Physics	U Tokyo

Domestic Collaborators

Sangeeta Bhatia	HST	MIT
Donald Eigler		IBM, Almaden

Giannoula Klement	Biomedicine	Children's Hospital
Dale Larson	Biophysics	Harvard Medical School
Chinh Pham	NanoTech & Business Forum	Greenberg Traurig, LLP
Richard Rogers	Bioimaging	Harvard School of Public Health

National Laboratories

Julia Phillips	Physical Sciences	Sandia, CINT

Public Outreach and Education

Carol Lynn Alpert	Museum of Science, Boston
Tim Miller	Museum of Science, Boston
Robert Graham	Harvard
Kathryn Hollar	Harvard

(b) Advisory Committee

Kenneth Babcock	Si Biosensors
George I. Bourianoff	Intel Corporation
Donald Eigler	IBM, Almaden Research Center
Steven Girvin	Yale University
Rachel Goldman	University of Michigan
Harald Hess	Howard Hughes Medical Institute
Evelyn Hu	University of California, Santa Barbara
Paul L. McEuen	Cornell University
Carmichael Roberts	WMR Biomedical, Inc.
John Rogers	University of Illinois
Richard Slusher	Lucent Technologies
Tom Theis	IBM, T.J. Watson Research Center
Ellen D. Williams	University of Maryland

(c) Academic Participating Institutions

1. *Domestic*

Boston College
Brown University
California Institute of Technology
CCNE (MIT, MGH, Harvard Medical School)
Columbia University
Harvard Medical School
Harvard School of Public Health
Harvard University NSEC Prime
Harvard University [Center for Nanoscale Systems (CNS); Faculty of Arts and Scienes (FAS); School of Engineering and Applied Sciences (SEAS)]
Indiana University
Massachusetts Institute of Technology
Middlebury College
National Center for Learning and Teaching in Nanoscale Science and Engineering
National Nanotechnology Infrastructure Network
Northeastern NSEC Center for High-rate Nanomanufacturing
Princeton University
Stanford University
Texas A&M
University of Arkansas
University of California, Irvine

University of California, Los Angeles
University of California, Santa Barbara
University of California, Santa Barbara, Center for Nanotechnology in Society
University of California, Santa Cruz
University of California, San Diego
University of Illinois, Urbana-Champaign
University of Maryland
University of Massachusetts at Amherst
University of Texas, Austin
University of Washington
Worcester Polytechnic Institute (WPI)
Yale University

2. *International*

Ben Gurion University, Tel Aviv, Israel
Delft University of Technology, The Netherlands
ESPCI, Paris, France
Koc University, Istanbul, Turkey
Luft I Vast, Uppsala University, Sweden
Lund University, Sweden
Norwegian University of Science and Technology
Technical University of Denmark, Denmark
Universita di Roma, INFM-Soft, Rome, Italy
University of Basel, Switzerland
University of Bern, Switzerland
University of Bremen, Germany
University of British Columbia, Canada
University of Ferrara, Italy
University of New South Wales, UK
University of Regensburg, Germany
University of Stuttgart , Germany
University of Tokyo
University of Toronto
University of Twente, The Netherland
University of Warsaw, Poland
Weizmann Institute of Science, Rehovot, Israel
Zhejiang University, Hangzhou, China

(d) Non-academic Participating Institutions

1. *Domestic*

Alcatel-Lucent, Bell Labs.
Applied Biosystem
Argonne National Laboratories
ARGOS Tech, LLC
BAE Systems
Brookhaven National Lab.
Calvium Networks, Inc., Marlborough MA
Children's Hospital, Boston
CINT Sandia National Laboratory
Davis Foundation
Draper Laboratory
Grace Construction Products
Greenberg Traurig, LLP

Harvard Kavli Institute for Bionanao Science and Technology
Hewlett Packard
Howard Hughes Institute
IBM Almaden
Invitrogen/Molecular Probe
Liminus, Inc.
MARCOP/Fene, Los Angeles
Massachusetts General Hospital
Microsoft Corporation
Museum of Science, Boston
Nanoscale Informal Science Education Network (NISE) Network of Museums
Nanoelectronics Research Institute NRI
National Institute of Standards and Technology
New England Cable News Network
Oak Ridge National Laboratory
Packard Foundation
Petroleum Research Fund
Pranalytica, Inc., Los Angeles
Physical Sciences, Inc. (PSI)
QD Vision
Sandia National Laboratories
Semiconductor Research Corporation
Sharp Laboratories
Schlumberger Doll Research Center, Boston
SRI, International
Unilever, Trumble, CT
Vertex Pharmaceuticals

2. International

BASF, Germany
CINQIE-UT, Japan
Genomics Research Center,Taiwan
Hamamatsu Photonics
ICORP-JST, Japan
Istituto Applicazione Calcole, CNR, Roma, Italy
Japan Science and Technology Agency, Japan
Nano Quine, Japan
NEST (Pisa Italy]
Philips Research (The Netherlands)
Riken, Japan
Saint Gobain Research (Paris)
Samsung Electronics Co., Korea
Unilever, United Kingdom
US. Israel Binational Science Foundation

6. MISSION AND BROADER IMPACT

In the following mission statement, taken from our **Project Summary**, we present the goal of our Center — to develop tools for the study of nanoscale systems — and describe its research, education and outreach programs. The **Strategic Research Plan** presented in Section 8 describes how the three Research Clusters below address important applications, and how our investigators work together to reach these goals.

6a. Mission Statement

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons inside nanostructures for new nanoelectronic and nanophotonic devices, and to investigate how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Research Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

Cluster 2: Nanoscale Building Blocks makes new classes of nanostructures that exhibit size-dependent properties. We synthesize structures with unconventional shapes, as well as zero, one- and two-dimensional nanostructures including nanoparticles, nanowires, and heterostructures. New materials are introduced, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks are promising for nanoelectronics and nanophotonics as well as for biosensors.

Cluster 3: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons inside nanostructures using custom-made scanning probe microscopes, including cooled instruments. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing.

The **Center for Nanoscale Systems (CNS)** is a major investment by Harvard to provide shared facilities to conduct research in nanoscience and engineering. A new building, the **Laboratory for Integrated Science and Engineering** was recently completed and being outfitted with equipment. It houses **CNS** facilities for nanofabrication, imaging and materials growth. Harvard and UC Santa Barbara provide nanofabrication facilities to outside users through the **National Nanotechnology Infrastructure Network** (**NNIN**).

Connections with **Industry** are strengthened by Harvard's **Office of Technology Development** and by the **Industrial Outreach Program**. Our Center is funded by the **Nanoelectronics Research Initiative (NRI)** of the **Semiconductor Research Corporation (SRC)** to develop new oxide materials for future logic switches. Many Center participants have collaborations with industry.

Our Center's **educational program** develops **human resources** at the pre-college, undergraduate, graduate, and postdoctoral levels through a range of activities, including REU and RET programs, a introductory course *Applied Physics 298r* on nanoscience, and a series of workshops. The **Museum of Science, Boston** engages the public and introduces them to the big ideas in nanoscience in an entertaining and informative way, in collaboration with the researcher in our Center. The Museum is a core member of the new **National Informal Science Education (NISE) Network**.

Our Center plans to increase **Diversity** by: recruiting a more diverse group of graduate students and postdocs, increasing the diversity of participating faculty, recruiting members of underrepresented groups by extending REU approaches, introducing public school students to science and engineering, and developing long-term partnerships with predominantly female and minority-serving institutions.

6b. Advances in Fundamental Knowledge and Technology

Cluster 1: Tools for Integrated NanoBiology

This Cluster is based on the development of microfluidic and hybrid biochips. We feature two recent achievements by Donhee Ham and George Whitesides.

Minaturized NMR Relaxometry System

Donhee Ham, in collaboration with Ralph Weissleder at MGH, has developed a miniaturized NMR relaxometry system (Liu *et al.* 2008), shown in Fig. 6.1. The system combines a small fist-sized permanent magnet, a planar microcoil, and a custom-made CMOS RF transceiver integrated circuit chip. This unit can detect biomolecules for diagnostic purposes, by using the 'magnetic switch' technique: Activated magnetic beads clump together when they detect the targeted biomolecules, changing the T2 relaxation time in water molecules nearby. When this change is observed by the NMR relaxometry system, it shows that the compound is present.

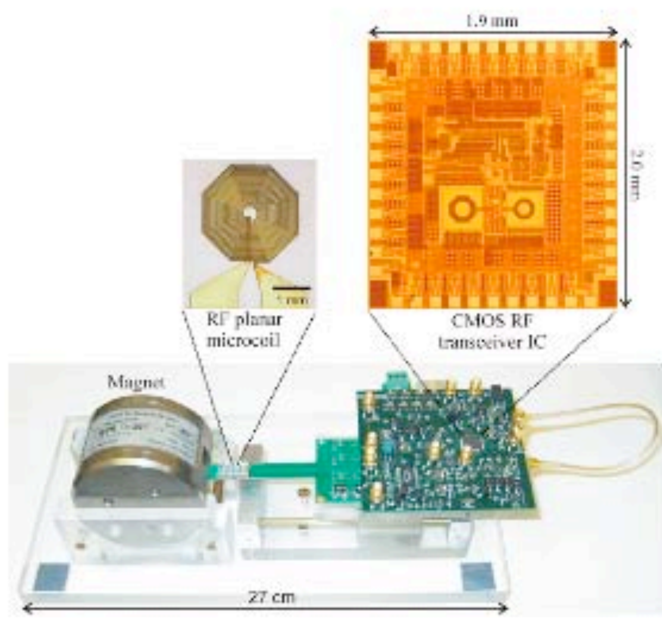

Figure 6.1. Hand-held NMR relaxometry system, based on an RF transceiver integrated into a custom silicon chip, which can detect biomolecules for diagnostic purposes (Liu *et al*. 2008).

The miniaturized NMR system is an important advance over conventional units. The magnetic switch biodetection technique requires a Magnetic Resonance Imaging system for a living patient, or at least a commercial benchtop NMR system for a biosample. The miniaturized unit shown in Fig. 1 is 40 times smaller, 60 times lighter, yet 60 times more sensitive than a state-of-the-art benchtop system. It will open up the use of this biodetection technique for many more situations.

Fabrication of Metal and Metal-oxide Nanotubes by Shadow Evaporation

It is important to find simple ways to make parts of electronic, photonic and chemical devices. George Whitesides has developed a method to fabricate arrays of metal or metal-oxide nanotubes with controlled geometry, like those shown in Fig. 6.2. These structures like this can are useful as electrodes for nanostructured devices such as photocells, light emitting diodes (LEDs), electrochromics and batteries, because they have a high ratio of surface area to volume, and because they can acts as a template for depositing films of small molecules or polymers that serve as optically and electronically active layers for these devices. The indium tin oxide (ITO) material shown in Fig. 2 is a commonly used transparent conductor that is useful for displays and optical devices.

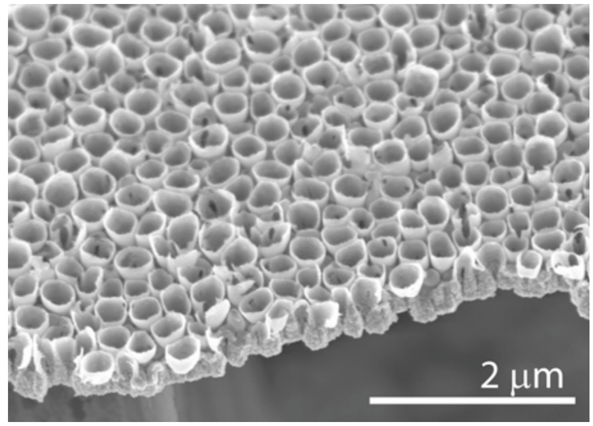

Figure 6.2. A SEM image of indium-tin oxide (ITO) nanostructures formed by line-of-sight evaporation into sacrificial anodized aluminum oxide pores. The heights and diameters of the tubes are ~ 200 nm.

Cluster 2: Nanoscale Building Blocks

This cluster synthesizes nanoscale building blocks of different geometries from new materials, and finds ways to couple them to the outside world. We feature new results from Hongkun Park and from Marko Loncar.

Phase-Change Nanowire Heterostructures

Chalcogenides exhibit a reversible crystalline-amorphous phase change induced by temperature or electric field that is accompanied by dramatic differences in optical reflectivity and electrical resistivity, making these materials promising for optical data storage and phase change random access memory (PRAM). The advantages of PRAM (fast access, low power, low cost, scalable, non volatile) have attracted the electronics industry.

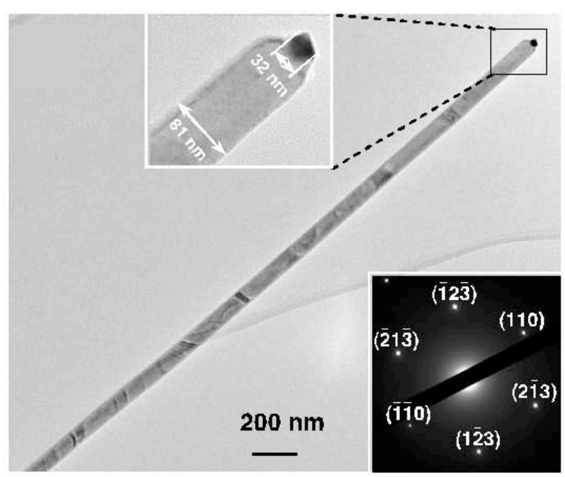

Figure 6.3. Transmission electron microscope (TEM) image of a Sb_2Te_3 nanowire. Top inset: High-magnification TEM image of the nanowire end with a Sb_xTe_y/Au alloy particle. Bottom inset: selected area electron diffraction pattern indexed for rhombohedral Sb_2Te_3.

Hongkun Park is developing methods to synthesize nanowires from chalcogenide materials, which have promise for future applications. Figure 6.3 shows a thin Sb_2Te_3 nanowire grown using a Au particle. The selected area electron diffraction pattern demonstrates that it is crystalline. Park has also grown heterostructure nanowires compsed of an Sb_2Te_3 core and a GeTe shell. The electrical behavior of individual nanowires and nanowire heterostructures confirmed that these nanostructures exhibit the desired memory-switching behavior.

Single-Photon Photonic Devices

Supported by seed funding, Marko Loncar is developing single-photon optical devices, including sources and switches, that based on quantum emitters embedded in nanoscale optical cavities. Nitrogen vacancy (NV) color centers in diamond are promising candidates for single-photon sources (Kurtseifer *et al.* 2000, Wrachtrup and Jelezko 2006, Childress et al. 2006). They have temporal and spectral stability (no blinking, no spectral diffusion, etc.) with a luminescence spectrum still visible at room temperature, and they can be positioned using ion implantation. In order to take advantage of the excellent properties of color centers, it is necessary to embed them into optical cavities. However, diamond has been difficult to work with in photonic systems.

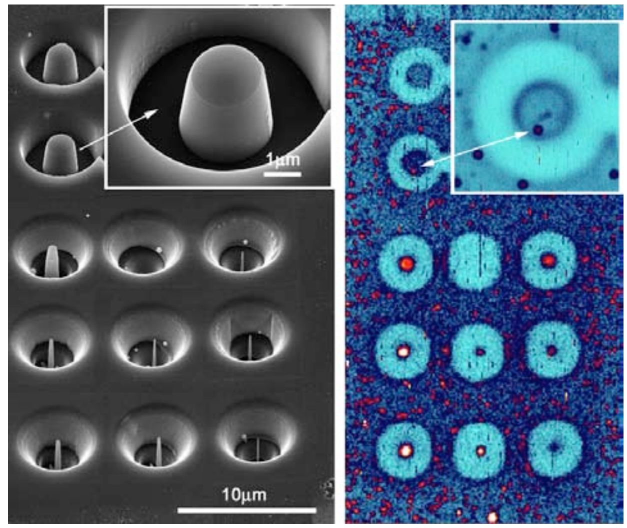

Figure 6.4. (*left*) SEM micrograph of an array of diamond nanowires and microposts fabricated in single crystal CVD synthesized diamond. (*right*) Confocal photo-luminescence image shows presence of single NV color centers (small red dots) inside nanowires, as well as in the large posts (inset).

In the past year, Loncar developed a way to use focused-ion-beam (FIB) milling and nanomanipulation to make photonic structures from diamond. Figure 6.4 shows an array of diamond nanowires milled in a single-crystal CVD synthesized diamond, their width can be adjusted in the milling process. Confocal images on the right demonstrate that NV color centers are present inside individual diamond nanowires. These new fabrication techniques are very encouraging, and they open up new opportunities for photonic systems based on diamond.

Cluster 3: Imaging at the Nanoscale

This cluster develops custom-made scanning probe microscopes, and new imaging techniques to visualize electrons and photons inside nanoscale systems. We feature two recent achievements by Jen

High Spatial Resolution Magnetic and Electrostatic Force Microscope

Jennifer Hoffman has completed the construction of a cooled high-resolution scanning probe microscope, shown in Fig. 6.5. It is a custom design, with a laterally moving tip. High spatial resolution and sensitivity are provided by using a silicon

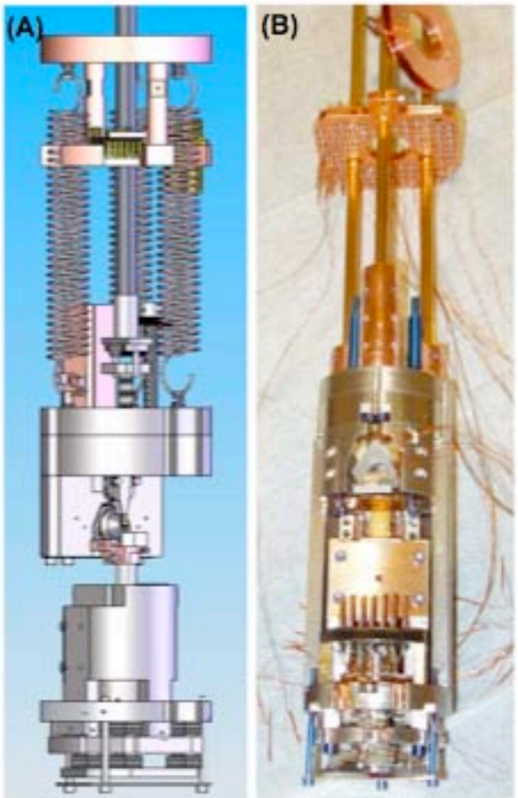

Figure 6.5. (**A**) Magnetic and electrostatic force microscope design. (**B**) Completed instrument.

cantilever tip with a 20 nm radius, or by a carbon nanotube based tip (in collaboration with Alex de Lozanne at UT Austin).

Hoffman plans to use the instrument to image vortices in high T_c superconductors. She also plans to understand the role of impurities in quantum cascade lasers, in collaboration with Capasso, by imaging the surface potential of cleaved laser heterostructures. Multiferroics, materials that combine two of the following properties - ferromagnetic, ferroelectric, and ferroelastic - are also of interest.

Scanning SET Imaging of Graphene

Amir Yacoby has developed a cooled scanning probe microscope that has a single-electron-transistor (SET) charge sensor at the end of the tip. He has used this instrument to image density fluctuations in a graphene flake, as shown in Fig. 6.6.

Graphene is an unusual material that consists of a single layer of carbon atoms. Its energy band structure the same as a massless relativistic particle. Because there is no bandgap, an electron can easily change into a hole, and back to an electron. Disorder is thought to break up the carriers in an uncharged graphene flake into islands of electrons and holes. Using his SET-based microscope, Yacoby has observed this phenomenon, shown in Fig. 6.6. Although the average carrier density is zero, the local density alternates between electron and hole regions. The spatial resolution of the SET imager is not sufficient to see the size of these regions directly, but measurements of the compressibility in a magnetic field show the spatial scale of disorder is ~ 25 nm.

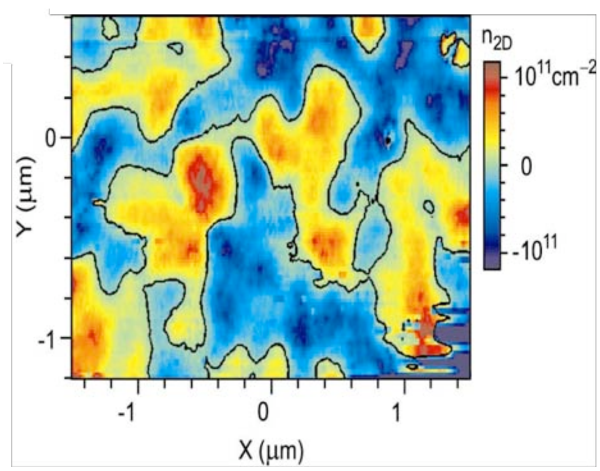

Figure 6.6. Color map of the spatial density variations in the graphene flake extracted from surface potential measurements at high density and when the average carrier density is zero. Blue regions correspond to holes and red regions to electrons. The black contour marks the zero density contour.

References

Y. Liu, N. Sun, H. Lee, R. Weissleder and D. Ham, *IEEE ISSCC*, pp. 140–141 (2008).

C. Kurtsiefer, S. Mayer, P. Zarda, H.

Weinfurter, *PRL* **85**, 290 (2000).

J. Wrachtrup, F. Jelezko, *J. Physics: Cond. Matt.* **18**, S807 (2006).

L. Childress, M.V. Gurudev Dutt, J.M. Taylor, A.S. Zibrov, F. Jelezko, J. Wrachtrup, P.R. Hemmer, M.D. Lukin, *Science* **314**, 281 (2006)

6c. Advances in Education

Education is an important mission of our Center. Kathryn Hollar, the Director of the Educational Program, has done an outstanding job organizing our activities in education, outreach and diversity. A description is presented below in Section 6e.

The Museum of Science, Boston, the Exploratorium in San Francisco, and the Science Museum of Minnesota are core members of the **Nanoscale Informal Science Education (NISE) Network** of museum, and science and research institutions across the US. Carol Lynn Alpert and Larry Bell are co-PI's at the Museum of Science. Our NSEC has collaborated with Carol Lynn Alpert since 2001 to bring ideas from nanoscience to the public in an engaging and enjoyable way. The NISE Network will allow us to reach a nation-wide audience through entertaining presentations and informative exhibits. The Scientific Advisory Board of the NISE Network includes NSEC faculty Eric Mazur, George Whitesides, and Robert Westervelt. We look forward to working closely with the NISE Network to bring the excitement of nanoscience to the public.

Applied Physics 298r is a course at Harvard that is run every other year by our NSEC. The course provides an introduction in nanoscience and engineering to undergraduates and graduate students. The Center's faculty members present a series of tutorial lectures about their field of research, following an overview by the Director. The lecture slides are openly available on the course's website. AP298r was held in Spring 2007, and will be presented again in Spring 2009. It gets excellent reviews.

Section 10 *Center Diversity*, Section 11 *Education,* and Section 12 *Outreach,* present the Center's programs in these areas.

6d. Advances in Industrial Collaborations

Harvard is advancing the way it connects academic research with industry. The University appointed Isaac Kohlberg as Senior Associate Provost and Chief Technology Development Officer. His goals are to properly manage our intellectual property, and to transition new technologies from scientific research at Harvard to industry. The **Office of Technology Development** conducts a broad range of activities ranging from handling inventions, to helping faculty connect with industrial executives. The Center works with Alan Gordon and Daniel Behr of this office. They have become quite familiar with the research of our investigators, and they learn about advances that might have industrial applications. Senior executives from major companies have visited Harvard to learn about new research and possible collaborations. The active approach promises to be very effective.

Our Center was awarded a supplement from the **Nanoelectronic Research Initiative (NRI)** of the **Semiconductor Research Corporation (SRC)**. The semiconductor industry recognizes that technology beyond CMOS will be needed for logic switches in the future, and it is supporting research at universities to help discover the right approach. Our Center is closely related to industry goals, with our emphasis on nanowire devices, nanoelectronics and nanophotonics.

The Center's international *Frontiers in Nanoscale Science and Technology (FNST)* workshops focus on nanoelectronics, nanophotonics, and quantum information processing:

The 2007 FNST workshop, held at the University of Tokyo, included talks by outstanding people from industry and academia. George Bourianoff (Intel, NRI/SRC), Don Eigler (IBM) and Jun'ichi Sone (NEC) talked about the future of electronics, and researchers Tsuneya Ando (Tokyo Tech), Yasuhiko Arakawa (Univ. Tokyo), Federico Capasso (Harvard), Yu Ming Lin (IBM), Daniel Loss (Univ. Basel) Hiroyuki Sakaki (Univ. Tokyo), Friedrich Schaeffler (Linz), and Lieven Vandersypen (Delft) presented talks about nanoelectronics and nanophotonics. The mix was quite successful.

The 2008 FNST Workshop was held at the University of Basel in January, and included talks on nanoelectronics, nanophotonics, and quantum information processing by a steller group including Tony Legget (UIUC), Charles Marcus (Harvard), David DiVincenzo (IBM), Bill Brinkman (Princeton), Seigo Tarucha (Univ. Tokyo), Lars Samuelson (Lund), Amir Yacoby (Harvard), Philip Kim (Columbia), Allan MacDonald (UT Austin), Bart van Wees (Groningen), Atac Imamaglu (ETH Zurich), and Mike Stopa (Harvard).

The *Frontiers in Nanoscale Science and Technology Workshops* have proven to be a very effective way for investigators from industry and academia to discuss the future of nanoelectronics and nanophotonics. We look forward to expanding our interactions with NRI and the semiconductor industry in the future.

6e. Current and Potential Impact of NSEC on Education, Workforce Development, Diversity, and Society

The NSEC based at Harvard University has a wide repertoire of activities that contribute to the public understanding of nanoscale science and engineering, encourage participation of underrepresented groups at all levels of education, enhance the infrastructure of research and education at all education levels both locally and internationally.

The collaboration between the NSEC based at Harvard and the Museum of Science, Boston, has been a model for interaction between an informal science organization and a research and higher education organization. This relationship has informed thousands of people of the risks and benefits of nanoscale science and engineering to society through multimedia, television, museum visits, and public presentations; it has also helped practicing scientists and engineers to engage the public in discussions of the *realistic* risks and benefits of this new technology. Participation in the NISE-Network will not only deepen this level of understanding by researchers of how to effectively listen and respond to public concerns regarding nanoscale science and engineering research, it will also allow us to disseminate these new communication models across a wide network of collaborators.

Through our long-standing relationship with the Cambridge Public Schools, a school system with a minority majority population, we introduce over 300 7^{th} grade students each year to scientific research being conducted at Harvard University. Community activities with Cambridge Public Schools impacted another 250 students and their families. The Research Experiences for Teachers program allows us to develop sustained and close relationships with teachers in the Cambridge Public Schools and surrounding school systems. Modules developed through the RET program have been disseminated to over 150 teachers through teacher workshops. As we continue to develop new modules through the RET program, we expect to impact a wider audience through continued dissemination locally and nationally. In all our K12 outreach efforts, we strive to partner with school systems and programs that have a significant population of underserved students.

The REU program is one of our flagship programs for preparing a diverse pool of future leaders in science and engineering. Through aggressive recruiting efforts, 30–40% of our participants each year are from underrepresented groups. Through professional development activities such as presentation and writing skills and mentor training, we not only prepare the participants and mentors scientifically, but help them develop skills that will enhance their careers in science and engineering.

Last year, local and international workshops and collaborations have brought together over 500 practicing scientists, engineers, as well as leaders in business and government, to discuss new directions in nanoscale science and engineering. For example, the *Frontiers in Nanoscale Science and Engineering* workshop and *Industry Partnership Program* at Harvard are annual events that continue to provide opportunities for our faculty, graduate students and postdoctoral researchers to share research results with a wide array of institutions.