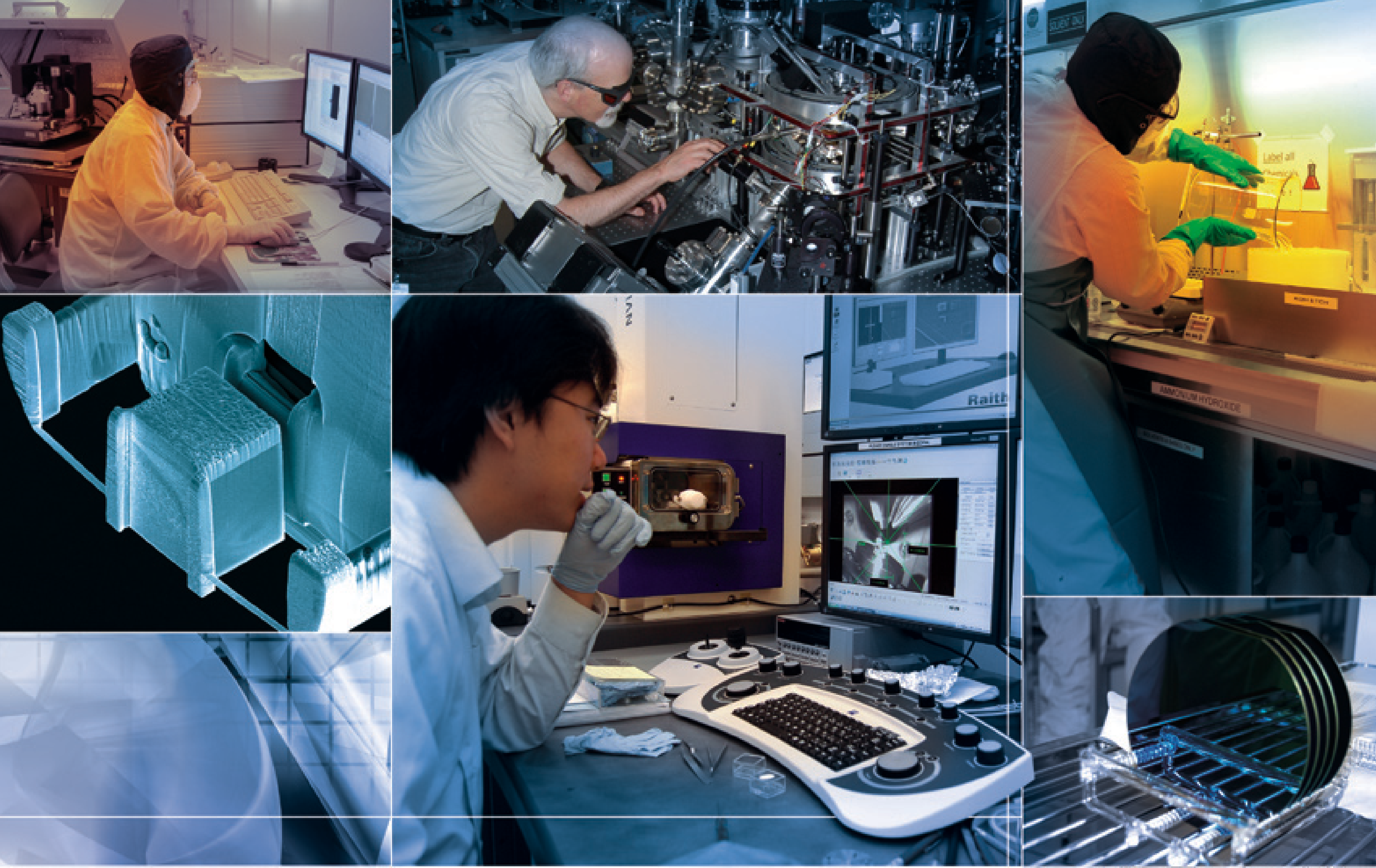
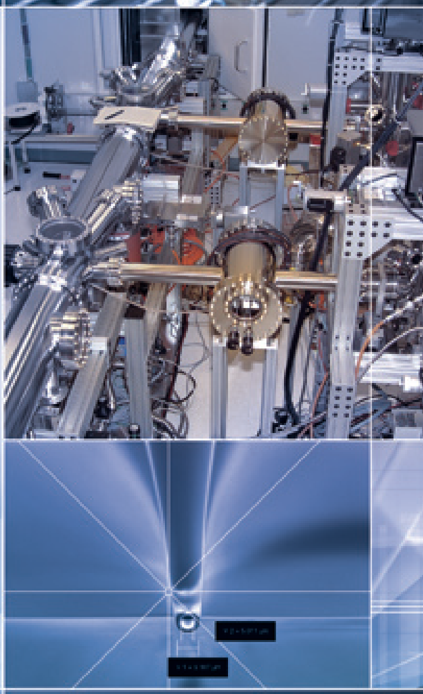


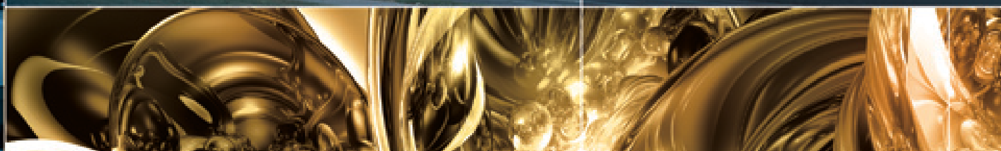


CNST Center for Nanoscale Science & Technology

Supporting all phases of nanotechnology development

from discovery to production.

NIST
National Institute of Standards and Technology
U.S. Department of Commerce



The Center for Nanoscale Science and Technology at a Glance

Purpose

To support the development of nanotechnology from discovery to production.

Mission

The mission of the Center for Nanoscale Science and Technology is to support the development of nanotechnology through research on measurement and fabrication methods, standards and technology, and by operating a state-of-the-art nanofabrication facility, the NanoFab. The Center promotes innovation by using a multidisciplinary approach to research, maintaining a staff of the highest caliber and leveraging our efforts by collaborating with others.

Vision

We envision that the quality of life for all will be enhanced by the impact of nanotechnology on energy, sustainability, climate, health, education, manufacturing and commerce. The Center for Nanoscale Science and Technology will be recognized as a leading contributor to the research that made these advances possible.

Research

The CNST research program, accessible to other researchers through collaboration, is currently focused in three research areas.

- Future electronics
- Nanofabrication and nanomanufacturing
- Energy transport, storage and conversion

The research staff is currently organized into two groups.

- Electron Physics Group
- Nanofabrication Research Group

Research in future electronics is concentrated in the Electron Physics Group, with nanofabrication and nanomanufacturing research concentrated in the Nanofabrication Research Group. As additional staff focusing on energy joins the CNST in 2009, a third research group—the Energy Research Group—will be created.

NanoFab

The CNST NanoFab facility operates on a shared-use, cost-reimbursable basis. Fifty five tools representing an investment of over $19 million are available for e-beam lithography, photolithography, nanoimprint lithography, metal deposition, plasma etching, chemical vapor diffusion, wet chemistry and silicon micro/nano-machining. The facility is accessible through a straightforward application process designed to get users into the cleanroom in a few weeks.

- 1,800 m^2 (19,000 square feet) cleanroom, including 750 m^2 (8,000 square feet) at class 100
- State of the art electron beam lithography and microscopy tools
- Additional shared-use tools outside the cleanroom
- Experienced staff to train users or operate the tools
- Open to all users, from NIST to worldwide

Resources

- $22 million annual budget
- 70 staff (58 technical) with expertise in:
  - Atomic-scale characterization and manipulation
  - Laser-atom manipulation
  - Nanophotonics
  - Nanoplasmonics
  - Optical micro and nanoelectromechanical systems (MEMS and NEMS)
  - Nanomagnetic imaging and dynamics
  - Directed assembly
  - Nanoscale stochastic processes
  - Nanoscale electronic and ionic transport
  - Theory, modeling and simulation of nanostructures

Web site

http://www.cnst.nist.gov/

From the Director

This publication represents a significant milepost for a new institution at the National Institute of Standards and Technology (NIST). In May 2007, NIST established its first laboratory dedicated to helping clear the path for nanotechnology to become an integral part of U.S. innovation and industrial competitiveness.

This is the first report on the activities within the **Center for Nanoscale Science and Technology (CNST)**, covering the 20 months from its inception through the end of 2008. Although a new organization, we are already conducting significant research and development in one of the fastest growing fields in the new millennium. Our start is deliberate but the work is expanding steadily; we expect that our accomplishments will grow rapidly as we continue to build our staff and laboratories.

One private research estimate illustrates the potential for growth, projecting the market for engineered nanomaterials alone—carbon nanotubes, nanoparticles, quantum dots, dendrimers, etc.—will rise from $413 million in 2005 to approximately $3.6 billion by 2010. When the wide variety of products expected to incorporate such nanotechnology-related innovations are included, the 2010 estimate rises to $1.5 trillion. Clearly, nanotechnology will be crucial to U.S. commerce.

There are other nanotechnology centers around the world, but the CNST offers a unique combination of attributes. First and foremost, what truly sets our center apart is a focus on *measurement sciences* dedicated to solving interdisciplinary problems in nanotechnology.

We also operate differently than any other center.

The CNST is a hybrid of a traditional national research laboratory and a national user facility. It is organized as two interdependent and cooperative functions: a research program that investigates processes and concepts for nanoscale measurement applications, and a shared-use nanofabrication facility for creating the devices and processes needed to move new nanotechnologies into the marketplace.

Both the Center's research and fabrication labs are open to the world; the research labs, via collaboration, and the NanoFab on a shared-use, cost-reimbursable basis.

Researchers from outside the CNST can access our resources efficiently and economically based on their individual research and development needs. We offer research collaborators and facility users the following resources:

- Essential measurement and fabrication methods, standards and technology to support all phases of nanotechnology development, from discovery to production.
- Experts in a wide variety of disciplines; from physics, chemistry, materials science, molecular biology, computer science, and electrical, mechanical, chemical and aeronautical engineering.
- A world-class, state-of-the-art nanofabrication facility—with over 19,000 square feet (1,800 m^2) of cleanroom laboratory space.

We are hiring exceptional scientists and engineers—who come from many different countries and academic and business institutions—and inviting the world's experts to help us solve interdisciplinary measurement problems in nanotechnology. This first report is designed to describe our permanent staff, our visiting fellows and our postdoctoral researchers and their work, along with the resources provided by the NanoFab. In the following pages, we will also highlight the initial progress of our research program, some of the instruments and processes we have pioneered and our work with U.S. businesses dedicated to creating products and jobs based on nanotechnology.

We invite you to keep abreast of our ongoing progress by visiting our Web site, *www.cnst.nist.gov.*

Robert Celotta, Director
Center for Nanoscale Science and Technology
National Institute of Standards and Technology
December 31, 2008

Introducing the Center for Nanoscale Science and Technology

The Vision

NIST began a major initiative in 2007 aimed at accelerating innovation in nanotechnology-based commerce. This initiative included the formal establishment on May 1, 2007 of the CNST as a new operating unit at NIST, one dedicated to tackling the metrology barriers hindering the development of nanotechnology. The CNST also serves as a hub linking the nanotechnology community to the comprehensive measurement expertise within all the NIST Laboratories.

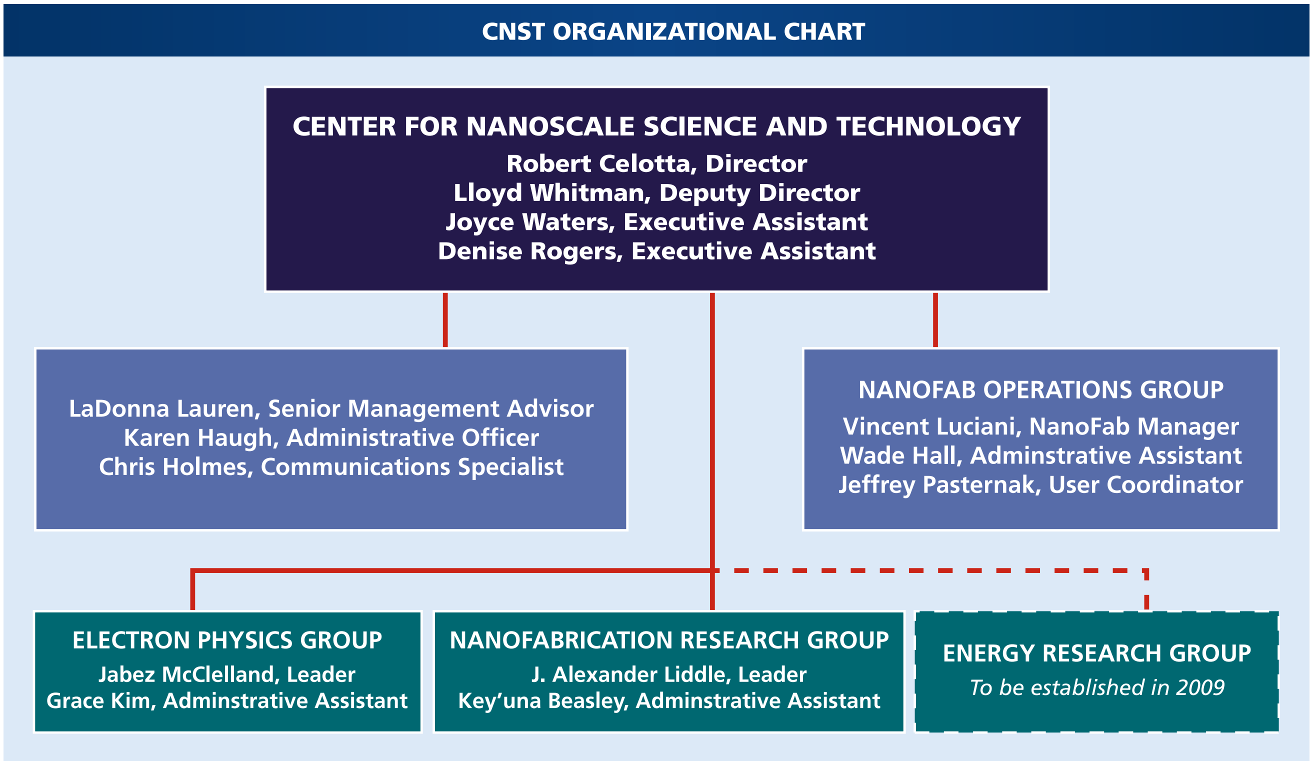
The CNST operates as a multidisciplinary center for developing and disseminating new nanoscale measurement and fabrication technologies, with the goal of increasing the competitiveness of U.S. industry in nanotechnology and nanomanufacturing. By creating a strong research program and establishing a national shared-use nanofabrication facility, NIST aims to close gaps in the understanding of nanoscale phenomena, and thereby accelerate innovation in a wide range of applications with broad societal impact.

The CNST mission is guided by an understanding that rapid commercial development of nanotechnology—in particular, the speed with which industry can bring a specific new nanotechnology from discovery to production—depends critically on the availability and efficacy of applicable metrology tools and processes at each stage of the transition. Developing these tools and processes will have an immediate and significant impact on the commercial viability of nanotechnologies in a diverse array of fields, such as electronics, computation, information storage, medical diagnostics and therapeutics, and national security and defense.

Centered within the suite of high-performance buildings that constitute NIST's Advanced Measurement Laboratory Complex, the CNST operates within a NIST research environment that fosters innovation in advanced manufacturing and rapid exploitation of new discoveries. NIST continuously strives to advance the state of the art and thereby further its understanding of the fundamental science and engineering essential to fostering the growth of technology-based commerce.

Cooperative Agreements

The CNST has established major Cooperative Agreements with two academic institutions that share our passion for the science and technology of measuring materials at the nanometer scale. In addition to enabling productive collaborations that leverage the institutions' collective intellectual and physical resources, through these agreements the CNST is helping to educate the next generation of nanotechnologists.



Creating a New Organization

As a new organization, both the CNST research program and the NanoFab are works in progress. The CNST has not yet reached its fully funded size in either activity. The kernel of the CNST was the Electron Physics Group from within NIST's Physics Laboratory, and the cleanroom operational staff—a group of 30 scientists, postdoctoral researchers, support engineers and an administrative assistant spread across multiple buildings.

In the 20 months since being established, the CNST has grown to 70 people, including research groups, a cadre of postdoctoral researchers and visiting fellows, a professionally-staffed NanoFab facility, and the full cohort of administrative staff needed to run both a NIST operating unit and a national facility. Moreover, the CNST is now concentrated in a single building, having coordinated a complex cascade of laboratory and office moves. Within the next year the CNST expects to grow to a total roster of approximately 90.

In order to promote a research environment without discipline or management "silos," the CNST has a flat management structure, with only Group Leaders and a Center Office management and support team; it does not have the Division structure common to most NIST operating units. Rather than building a large, static research staff, approximately half of the CNST scientists are postdoctoral researchers. In addition to creating a dynamic research culture, this staffing philosophy will help to produce the well-trained nanotechnologists needed for the success of the U.S. nanotechnology economy. When the CNST reaches its full strength, it will graduate a fully trained postdoctoral researcher every two weeks.

Building Our Staff

The CNST is establishing a community of high-caliber research scientists who are passionate about metrology and nanofabrication, and who appreciate research motivated within a problem-based environment. The CNST does not perform research simply because a specific discipline can be advanced; the CNST does research because specific technological barriers need to be surmounted to achieve the economic and societal progress promised by nanotechnology.

Within this context, the CNST has brought together and will continue to add talented, motivated scientists from many disciplines—including physics, chemistry, materials science, molecular biology, computer science and electrical, mechanical, chemical and aeronautical engineering—who are open minded about other fields and eager to collaborate on important problems in nanotechnology.

The University of Maryland Cooperative Agreement

In September 2006, the CNST and the University of Maryland began a cooperative program to enhance work on both the Center's and the university's respective and interlocking missions; to tackle the problems obstructing the development of nanotechnology and, in the process, to train the next generation of nanotechnologists.

The bulk of the competitively awarded $1.5 million annual grant funds the work of about a dozen research scientists and engineers. The grant is renewable for up to a total of five years.

The university participates in the cooperative program through its Maryland Center for Integrated Nanoscience and Engineering. University of Maryland Physics Professor Ellen Williams, a member of the National Academy of Sciences, serves as the school's principal investigator.

The University of Maryland postdoctoral researchers and engineers work primarily on jointly defined projects aligned with the CNST's mission to develop the knowledge and technical infrastructure for nanotechnology development. They also collaborate with visiting researchers who come to the CNST to use measurement instruments and other advanced equipment in the NanoFab.

A smaller portion of the grant is used for national outreach and education efforts directed toward young faculty members and postdoctoral researchers.

"We are pleased to support the efforts of the Center. Our partnership with NIST is central to our extensive research efforts in nanotechnology. The special opportunity provided through the partnership of a national laboratory and a university allows us both to do work we could not otherwise do. This is an exciting time and we expect great achievements," said University of Maryland President C.D. Mote, Jr.

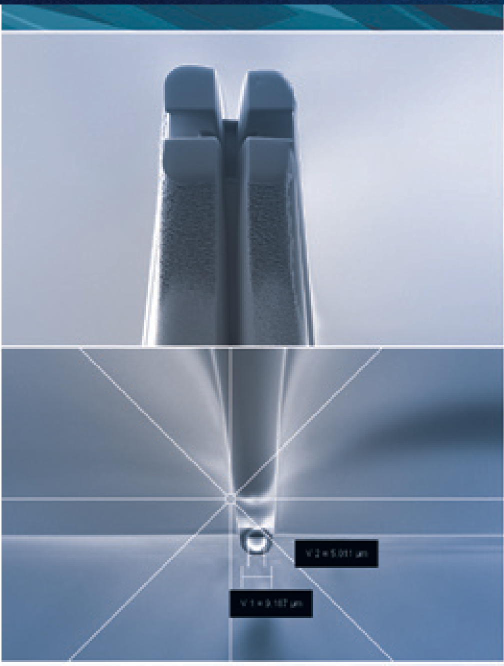
The foundation of the CNST research program is a group of staff scientists who serve as Project Leaders for one or more projects. Each project typically has one or two postdoctoral researchers assisting the leader; but the structure is flexible, with projects typically involving collaboration between Project Leaders and others from beyond the Center, and postdoctoral researchers often working jointly on several projects. In addition, a variety of simple mechanisms have been established to quickly bring collaborators to CNST research projects, such as academic researchers, industrial research staff, professors on sabbatical and foreign experts. The CNST also actively participates in NIST's Summer Undergraduate Research Fellowship (SURF) program, bringing students from universities nationwide to NIST where they work closely with mentors on various projects, and hopefully are inspired to pursue careers in nanoscience and technology.

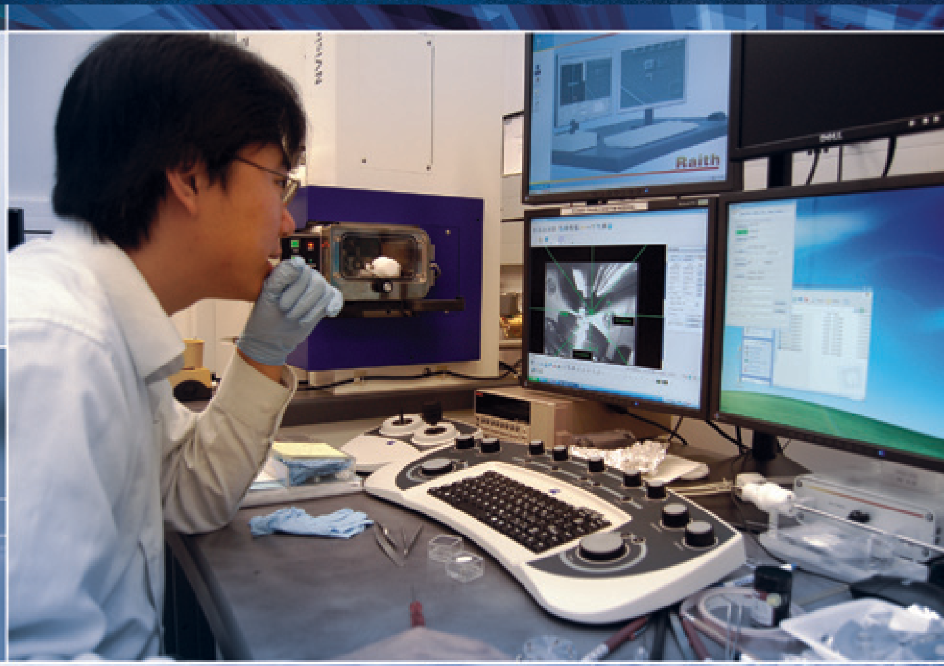
The CNST structure and staffing philosophy is designed to enable an agile research portfolio that can quickly evolve in response to the rapid developments underway in the field. Additional flexibility in the CNST's technical expertise is provided by its strategic collaborations with visiting scientists (CNST Fellows) and external researchers.

A key facet of the Center's flexibility is a Cooperative Agreement with the Center for Integrated Nanoscience and Engineering at the University of Maryland, College Park. This agreement, led by Distinguished University Professor Ellen D. Williams, provides the CNST with ready access to the diverse faculty, students and postdoctoral researchers at this major research university. University faculty, postdoctoral researchers and students directly collaborate on site at NIST, working alongside the CNST staff in its laboratories. The agreement also facilitates outreach to the broader research community, publicizing the capabilities of the NanoFab and offering travel support for research at the CNST.

Establishing the Research Program

The CNST is a highly multidisciplinary organization that identifies, establishes and maintains selected core competencies in nanoscale science and technology. These competencies allow its researchers to solve nanometrology problems in collaboration with partners from other NIST programs, academia, government laboratories and industry. The research program was established to develop novel measurement methods, instru-





ments and processes for nanofabrication and nanomanufacturing, along with best practices for use of commercial instrumentation, standards and reference materials. The CNST also applies these new tool sets to make significant fundamental discoveries in nanoscience.

It is critical that research in the CNST be directed at problems of high national importance. In order to maintain such a research portfolio, mechanisms are institutionalized that help CNST Project Leaders identify the most important problems. A constant effort is made to reach out to the broader community in industry, other government agencies and academia so that the staff remains cognizant of the future metrology needs in nanotechnology.

The CNST uses a number of mechanisms to identify and prioritize the barriers to be addressed by the research program, such as workshops, interviews, the U.S. Measurement System Survey, industrial roadmaps and direct industrial and commercial contacts.

One avenue that provides invaluable input is the CNST's active solicitation of advice from outside experts. As part of a regularly scheduled Nanotechnology Seminar Series, leading experts in various fields of nanotechnology spend a day at the Center, giving a public lecture and meeting with CNST management and technical staff.

Advice is also solicited through longer-term relationships developed with a select group of experts from industry, academia and other government agencies who provide special insight into specific nanometrology needs. Several major U.S. corporations have shared such needs with the CNST, including Agilent, GE, Intel, Motorola, SIA, TIA and Zyvex.

Based on the collective input of our customers, analysis of ongoing research in NIST's discipline-oriented laboratories and advice from NIST's Nanotechnology Strategic Working Group, the CNST research program is initially focused in the following three areas:

- **Future electronics.** In support of continued growth in the electronics industry beyond complementary metal-oxide-semiconductor (CMOS) technology, CNST researchers are developing new methods to create and characterize devices, architectures and interconnects for graphene, nanophotonic, nanoplasmonic, spintronic and other future electronics.

- **Nanofabrication and nanomanufacturing.** The Center is advancing the state of the art in nanomanufacturing by developing measurement and fabrication tools for both lithographic ("top-down") and directed assembly ("bottom-up") approaches.

- **Energy storage, transport and conversion.** The CNST is building a program that will create new methods for elucidating light-matter interaction, charge and energy transfer processes, catalytic activity and interfacial structure in energy-related devices.

The College of Nanoscale Science and Engineering of the University at Albany Cooperative Agreement

NIST entered into a Memorandum of Understanding with the College of Nanoscale Science and Engineering (CNSE) at the University at Albany, State University of New York in April 2008, extending and enlarging a previous relationship with the University. The memorandum outlines and formalizes a relationship between the CNST and the College.

Both the CNST and the College share a goal of developing the measurement science essential to U.S. innovation and economic competitiveness in nanotechnology.

As a result of that common goal, the College and CNST researchers are beginning to establish policies and procedures for cooperating and coordinating efforts in areas of common interest, including the science and technology of measuring materials at the nanometer scale, as well as creating new standards for nanomanufacturing.

NIST provides funding for the New York Center for National Competitiveness in Nanoscale Characterization (NC3) at the College. By working to advance innovations in nanometrology, NC3 strives to strengthen the relationships between nanotechnology research and development, manufacturing and commercialization.

In addition, the Institute for Nanoelectronics Discovery and Exploration (INDEX) at the College is a regional research center, and part of the NIST-supported Nanoelectronics Research Initiative (NRI). The NRI is a public-private partnership aiming to develop electronic devices that exploit the unique properties of materials at the nanometer scale. NIST has contributed over $2.75 million to the nationwide NRI effort thus far, and the agency is making its expertise in nanoscale measurement available to INDEX and the other similar research centers across the United States.

The University supports the latest research and development agreement at its NanoTech Complex, a $4.2 billion, 450,000 square-foot facility which houses more than 2,000 employees, including many from the semiconductor industry.

Researchers at the CNST are actively collaborating with CNSE faculty.

Within the CNST's research program, it has established initial core competencies in the following areas:

- Atomic-scale characterization and manipulation
- Laser-atom manipulation
- Nanophotonics
- Nanoplasmonics
- Optical micro and nanoelectromechanical systems (MEMS and NEMS)
- Nanomagnetic imaging and dynamics
- Directed assembly
- Nanoscale stochastic processes
- Nanoscale electronic and ionic transport
- Theory, modeling and simulation of nanostructures.

The CNST research programs and accomplishments are described in more detail in the next section of this report.

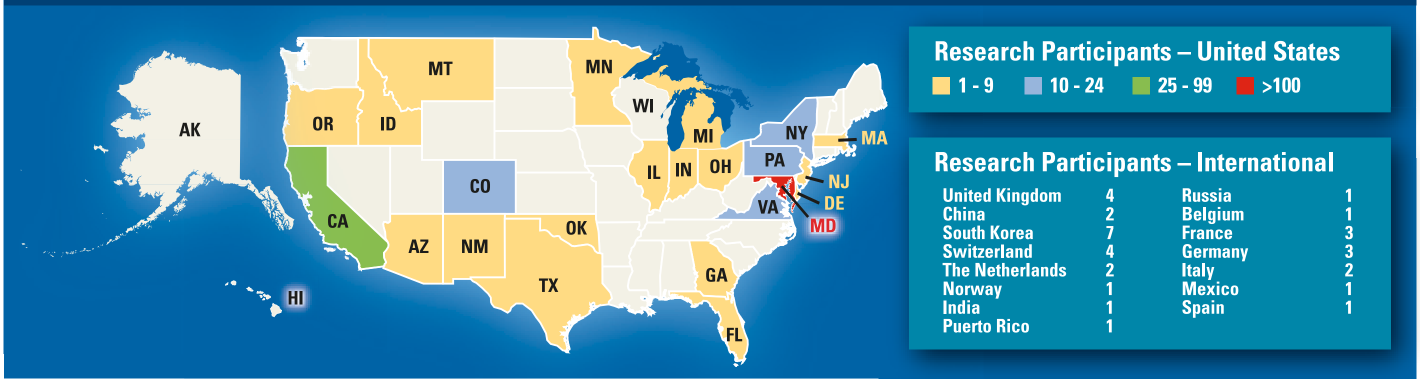
Establishing the NanoFab

The NanoFab has been established to provide researchers access to and training on the advanced tool set required for cutting-edge nanotechnology development. It is located in a large, dedicated cleanroom (with all the tools within class 100 space) and adjacent laboratories.

The cleanroom was originally constructed as part of the $235M Advanced Measurement Laboratory Complex to support NIST research in semiconductor processing and microelectronics. With the establishment of the CNST, the cleanroom became the heart of the NanoFab, now operated to support researchers world-wide, from novices to the most advanced experts in nanofabrication.

The NanoFab presently contains a wide assortment of instrumentation, including systems for patterning semiconductor and other materials via photolithography and electron beam lithography, in addition to optical, electron and ion-based measurement tools. Fifty tools worth approximately $16M are currently operational, with six additional tools valued at $3M to be installed in

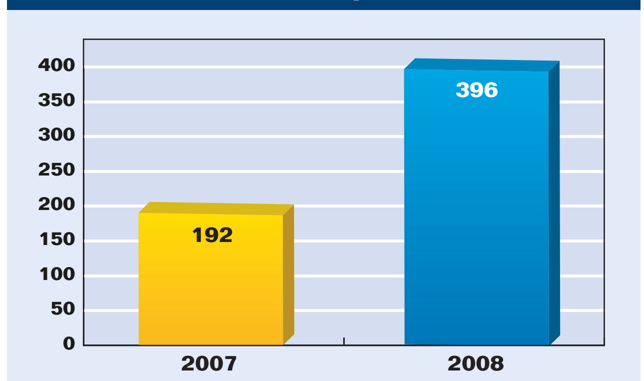
2008 Geographic Distribution of Research Participants



2009, including a second electron beam lithography system and multiple deposition and etching tools. The purchase of a transmission electron microscopy system is also planned in 2009.

The staff has grown to include 11 full-time employees, including a manager with over 30 years of private industry experience in the field, a facility user coordinator and eight technicians and process engineers dedicated to supporting the users. The operation of the NanoFab, including the growth in its use, is described in more detail in a later section of this report.

Research Participant Growth



Where We Are Today

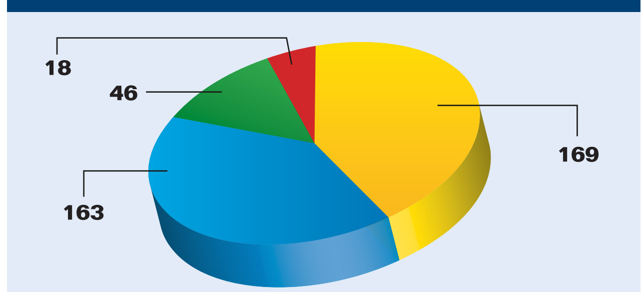
The CNST research program is developing in three concurrent phases. The future electronics focus area is well underway, with substantive research programs reporting new results. The staff members focusing on nanofabrication and nanomanufacturing are largely on board and setting up their research programs. Finally, the Center is actively recruiting researchers to build its program on nanoscale energy processes, and anticipates the arrival of several new staff members in 2009.

The number of scientists participating in research at the CNST has more than doubled in its first 20 months, expanding from less than 200 in May 2007, to about 400 at the end of 2008. Over half of the research participants are affiliated with businesses and institutions other than NIST, coming from 23 US states and 17 other countries.

As the CNST's marketing and outreach efforts continue, most of the future growth is expected to come from outside NIST, including additional small businesses for which the CNST is a unique government resource.

By the end of 2008, the newly hired researchers are moving into their laboratories, designing experiments and ordering equipment.

CNST Research Participants
December 2008



University	169
NIST	163
Industry	46
Other Government	18
Total	**396**

The NanoFab is installing tools and developing both base line and innovative fabrication processes, and actively marketing its capabilities. Although the CNST has only recently gotten underway, there are significant accomplishments to report.

CNST Research

The CNST research program provides innovative nanoscale measurement and fabrication capabilities, and is accessible to other researchers through collaboration with the CNST staff. As described above, the program is designed to respond to nanotechnology needs identified by a diverse set of approaches, and is currently focusing on three research areas: Future Electronics; Nanofabrication and Nanomanufacturing; and Energy Transport, Storage and Conversion.

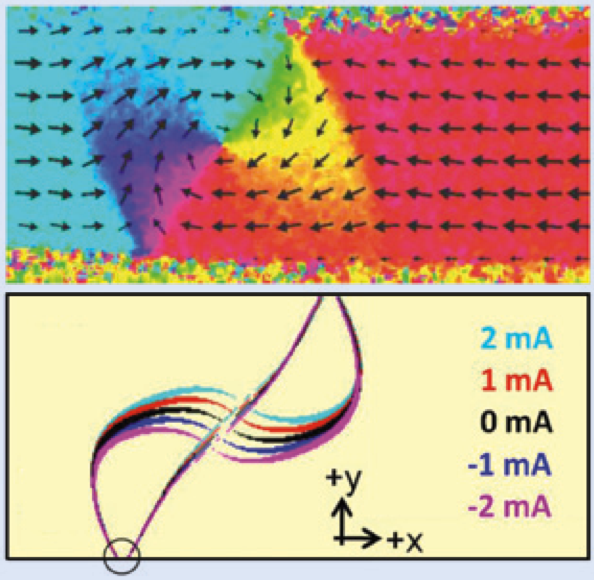
The research staff is currently organized into two groups, the Electron Physics Group (EPG) and the Nanofabrication Research Group (NRG). Although research within the groups is cross-cutting, research in Future Electronics is concentrated in the EPG, with Nanofabrication and Nanomanufacturing research concentrated in the NRG. The nascent Energy research program is currently within the NRG, but as additional staff working in this area joins the CNST in 2009, a third research group—the Energy Research Group—is planned.

Note that the NanoFab is operated by staff in the NanoFab Operations Group. Although the NanoFab processing engineers are focused on supporting the facility users, running the tools and establishing consistent baseline processes, they also participate in research in the course of developing new processes for and with the users. Similarly, members of the research program regularly apply their expertise to help evaluate and consult on NanoFab user projects.

Electron Physics Group

The Electron Physics Group (EPG) conducts a wide range of cross-disciplinary research focused on innovative measurement science in nanotechnology. Building on a rich history of influential research in electron-surface interactions, electron-atom scattering, electron optics and electron spectroscopy established while within NIST's Physics Laboratory, the EPG has expanded over the years into new technology areas as fundamental measurement science needs have arisen. The Group served as the initial "seed" for the CNST research program. Current research activities include the following topics.

Nanomagnetics. EPG research in nanomagnetics is currently aimed at addressing two of the most important measurement issues in the development of magnetic nanotechnology: measurements of the magnetic properties of magnetic nanostructures; and measurements of the interaction between



Top: *SEMPA image of a pinned domain wall in a 300 nm-wide NiFe stripe during current flow.* *Bottom:* *Modeled contours of the magnetization as a function of the current.*

magnetism and spin-polarized electrical currents. Magnetic property measurements are important because magnetic nanostructures differ from macroscopic magnets in the structure of the magnetic domains, in the nature of their magnetic interactions and in the properties of the surfaces. Measurements of these properties provide a foundation for the design of magnetic nanodevices. This foundation is extended by EPG measurements of the interaction between electric current and magnetism, which is based in angular momentum transport by spin-polarized currents. This interaction provides a new method for manipulating magnetism in nanodevices, a relatively new development in magnetic nanotechnology that is only partly understood.

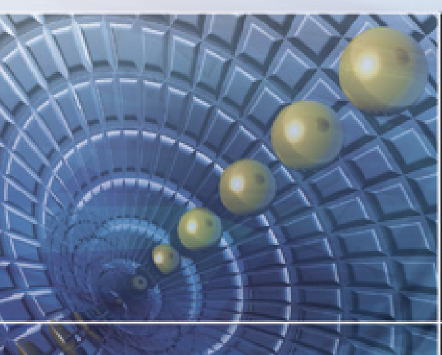
Scanning Electron Microscopy with Polarization Analysis (SEMPA) measurements of the current-driven motion of vortex and transverse domain walls in nanowires provides an unprecedented, high resolution view of these magnetic nanostructures while current is flowing through the wires. The SEMPA images show how domain walls, initially pinned by defects, are first distorted by the current-induced spin torque, and then break free and jump to the next pinning site. This motion is frequently associated with a transformation between vortex and transverse wall states. Understanding and controlling this domain wall pinning will be critical in building devices based on current-induced magnetic manipulation.

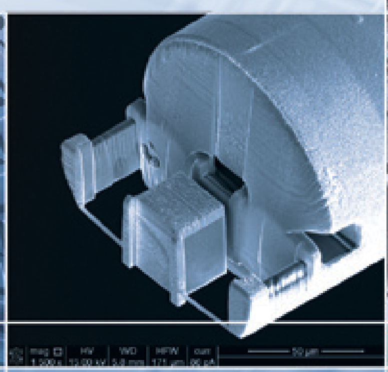
An alternative measurement of the interactions between magnetism and spin-polarized currents is under development in an EPG experiment called the "spin wave Doppler effect." In this experiment, spin-polarized current in a magnetic metal stripe changes the velocity of spin waves that are launched and detected using nanostructured spin wave antennas. This approach is expected to provide accurate measurements of the velocity associated with angular momentum transfer in magnetic metals.

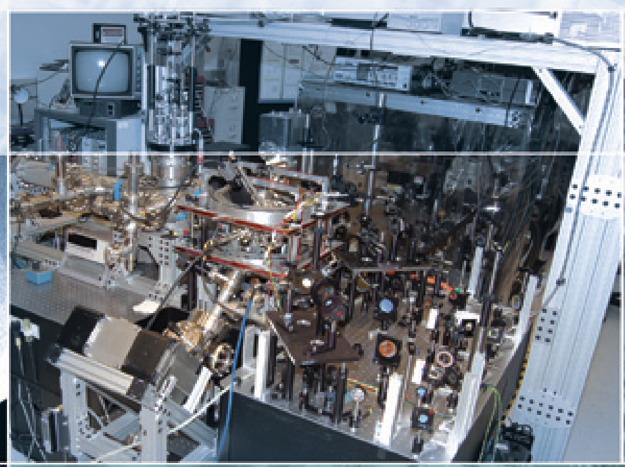
SEMPA is also being used to determine the phase diagram of patterned magnetic nanostructures. These structures are used in various applications ranging from information storage to magnetic sensing. Although these structures are small enough to be single domain, they still exhibit a rich variety of magnetic nanostructures. For example, SEMPA measurements of magnetically soft NiFeMo disks show that the triple point for the coexistence of in-plane, out-of-plane and vortex states occurs at a thickness of 35 nm and a diameter of 40 nm, in good agreement with predictions from micromagnetic modeling. Because this work requires the highest spatial resolution, considerable effort has been spent on optimizing the SEMPA probe. The EPG has found that a fundamental limitation arises from backscattered electrons that generate secondary electrons far from the incident beam; work is underway to quantify and minimize this backscattered contribution.

A new technique is being extended and improved in the EPG to measure the magnetic properties of the edges of lithographically fabricated nanostructures. The properties of the edges become more important for smaller structures simply because more of the structure is close to an edge. Using resonances in the magnetization dynamics that are localized near perpendicularly magnetized film edges, the magnetic properties of the film edges are being measured. Recently, the theoretical groundwork was laid for extending this measurement to edges of multilayered films.

The EPG has responded to constantly changing magnetic measurement needs by continually upgrading and modifying the various optical, microwave, cantilever and electron beam probes we use, as well as the supporting micromagnetic modeling and theory. In the past year, the EPG added a microwave probing facility, an optical interference lithography setup and a Kerr imaging microscope to existing facilities for







Electron Physics Group
December 2008

Jabez J. McClelland, *Group Leader*
Grace Kim, *Administrative Assistant*

Project Leaders

Robert McMichael
Mark Stiles
Joseph Stroscio *(NIST Fellow)*
John Unguris

Postdoctoral Researchers

Seok-Hwan Chung
Paul Haney
Hongki Min
Sander Otte
Gregory Rutter
Young Jae Song
Meng Zhu

CNST Visiting Fellows

Phillip First *(Georgia Institute of Technology)*
Young Kuk *(Seoul National University)*
Daniel Pierce *(NIST Fellow Emeritus)*
David Penn *(NIST Emeritus)*

Graduate Researchers

Kevin Kubista *(Georgia Institute of Technology)*
David Miller *(Georgia Institute of Technology)*
Anthony Richardella *(Princeton University)*

Engineering and IT Support Staff

Alan Band
Steve Blankenship
Barbara Coalmon
Frank Hess
Matthew Manganello
David Rutter

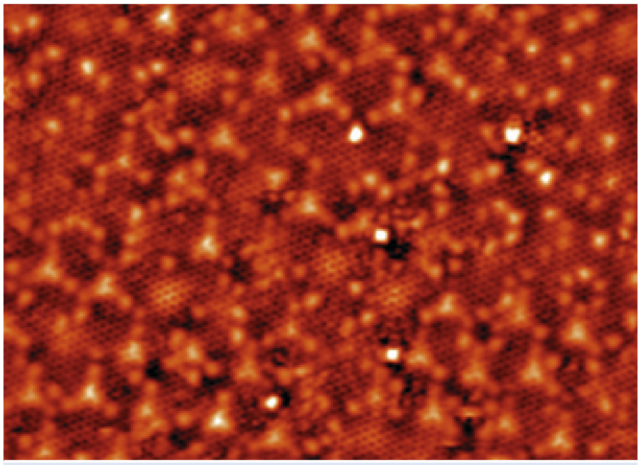
Kerr effect measurements and magnetic force microscopy. In addition, the capabilities of the EPG SEMPA facility have been upgraded with a new plasma cleaning station for delicate samples and multi-contact sample holders for measuring the magnetic structure in electrically active devices.

Accomplishments:

- Measured and modeled spin current effects on domain walls in nanowires.
- Measured and modeled the ground state phase diagram of nanodisk magnetic structures.
- Modeled edge property measurements via precessional dynamics in multilayers.
- Obtained images of magnetic structures in materials and devices used for ultra-high sensitivity magnetic sensors.
- Modeled precession mode dynamics, localization and inhomogeneity in nanostructure arrays.
- Designed, fabricated samples and installed an instrument for measuring the interactions of spin waves with spin-polarized currents.
- Measured the resolution limits on SEMPA caused by backscattered electrons.
- Collaborated with the Department of Energy to investigate permanent magnet deterioration caused by radiation in particle accelerators.

Atomic scale characterization and fabrication. This research is focused on developing new metrology and fabrication methods with atomic-scale precision. The experimental research emphasizes the design of custom instrumentation intended to push the frontiers of nanoscale measurement. Using state of the art scanning probe techniques, a diverse set of research areas are being explored, including future electronics and spintronics, atom manipulation, epitaxial growth of materials, correlation of microstructure and magnetism and electronic properties of nanostructures.

Recent work has focused on measurements of two material systems, graphene and the dilute magnetic semiconductors Mn/GaAs and Mn/InAs. Graphene is a single sheet of carbon that holds potential for future electronic material applications because of its low scattering rates and high carrier mobilities.



STM topographic image, 20 nm x 20 nm, of a single layer of graphene grown on SiC. The image shows a combination of the graphene lattice and the underlying SiC surface reconstruction, visible because the graphene is "semi-transparent" under these imaging conditions. This transparency allows structural aspects of the buried interface to be discerned.

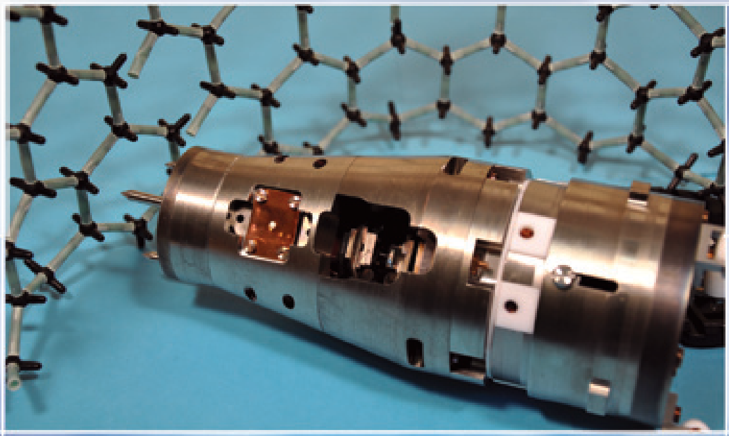
The EPG is developing atomic scale measurements to characterize graphene grown on SiC substrates in collaboration with the research groups of Professors Phillip First and Walter de Heer at the Georgia Institute of Technology. This work utilizes the EPG's ultra-stable cryogenic scanning probe system to obtain detailed spatial maps of the scattering patterns from defects in the graphene lattice. These maps show for the first time how defects lead to scattering in graphene that would otherwise be forbidden by conservation of the material's newly discovered pseudo-spin degree of freedom.

Mn in III-V semiconductors is a dilute magnetic semiconductor that holds potential in spintronic applications. Understanding the role of the substitutional Mn in the III-V host is critical to achieve higher Curie temperatures. The EPG is developing measurements to characterize and manipulate single Mn impurities on III-V surfaces in order to gain a better understanding of the electronic properties. The STM probe tip has been successfully used to induce an adsorbed Mn atom to substitute for a lattice In atom, thereby becoming magnetically active. The process has been characterized as a function of tunneling voltage and current, and is being modeled in collaboration with Dr. Steven Erwin at the Naval Research Laboratory.

Accomplishments:

- Imaged the interface beneath epitaxial graphene on SiC and measured scattering interference patterns from defects in the graphene.
- Developed non-linear control algorithms for atomically precise motion of piezo-electric actuators.
- Completed an autonomous atom assembler for perfect nanostructure fabrication.
- Used atom manipulation techniques to substitute single magnetic impurities into a semiconductor lattice and to fabricate molecular lattices on metal surfaces with intentional defects that mimic photonic band gaps in photonic crystals.
- Developed a unique ultra-low temperature (10 mK) scanning probe instrument for the study of the quantum electronic properties of nanostructures.

Nanoscale measurement and fabrication using laser-controlled atoms. The central theme of this research is the unconventional application of laser-based neutral atom manipulation techniques, including laser cooling, magneto-optical trapping and atom-optical focusing. Laser light can control neutral atoms in remarkably diverse ways, ranging from quantum state-selection, to trapping and cooling at the microkelvin level, to focusing to nanoscale dimensions. The extreme level of control that these processes represent opens up a number of completely new approaches to creating and characterizing nanostructures. Putting these processes to use has enabled us to address such diverse needs as production of high resolution focused ion beams for nanofabrication and imaging, deterministic production of single atoms "on demand" and resist-free in situ fabrication of nanoscale features.



Research is currently focused on the demonstration of a new concept in ion sources for focused beam applications and on expanding the applicability of laser cooling methods to a wider range of atomic species. The new ion source, referred to as a magneto-optical trap based ion source, or MOTIS, takes advantage of the 100 μK temperatures available in a magneto-optical trap to create an ion beam with very low emittance and high brightness. By ionizing neutral atoms in the trap and extracting them, a beam is created without the need for an extremely small source size such as is found in conventional liquid metal ion sources. The result is an ion source with focal properties rivaling or surpassing existing sources, with the added benefits of: a wide variety of possible ionic species; a very narrow energy spread; and the potential ability to implant single ions "on demand" with nanometer precision using techniques developed in previous years in the EPG. This new ion source will enable a diverse new set of focused ion beam applications, including contamination-free milling, damage-free ion microscopy with new contrast mechanisms and controlled doping of semiconductors.

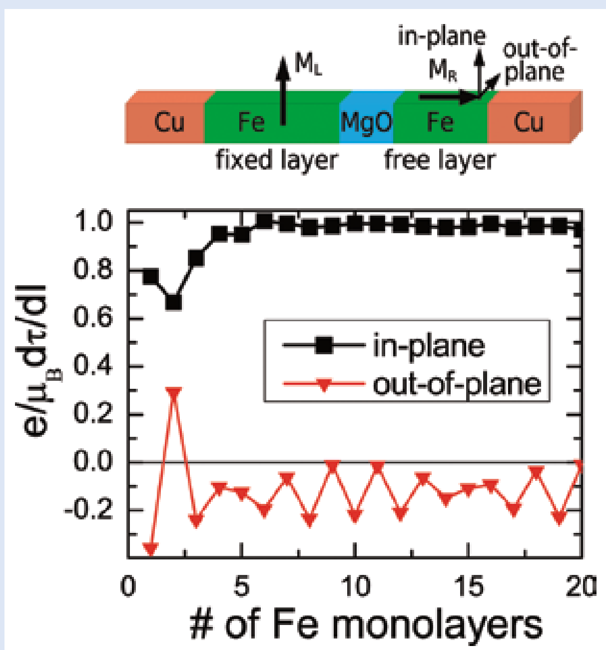
While laser cooling has been demonstrated for over 20 different atomic species, there is a need to expand the list of coolable atoms so that even more applications can be realized. To address this need, a study of laser cooling of rare earth atoms has been conducted, resulting in the first demonstration of laser cooling and trapping of erbium. In the process, some new effects have been discovered that make laser cooling applicable to a wider range of atoms than previously thought. In erbium, and by inference in other atoms with similar electronics structure, this study showed that a population trapped in metastable states actually recycles and is not lost to the cooling process as predicted by conventional wisdom. Furthermore, when a strongly magnetic atom such as erbium is cooled to very low temperatures on a narrow line transition, a magneto-optical trap can be formed with only one blue-detuned laser beam, instead of the usual six red-detuned beams. These discoveries have shown that atoms with complex electronic structures – most of the periodic table, in fact – may well be more accessible to laser cooling than previously thought.

Accomplishments:

- Developed a magneto-optical trap-based ion source (MOTIS) that greatly expands the capability of focused ion beam technology.
- Laser cooled rare-earth atoms to develop MOTIS as a source of optically active dopants.
- Discovered new laser cooling processes that arise when strongly magnetic atoms are trapped in a magneto-optical trap and cooled on a narrow line transition.

Modeling nanostructures in mesoscopic environments. The EPG is using theory, modeling and simulation to understand the structural, dynamic, electronic and magnetic properties of nanostructures and associated systems. The goal is to elucidate the science underlying the measurements of these systems. One aspect is to reveal the new physics that becomes important as electronic and magnetic devices approach nanometer length scales. Using various theoretical methods, this research interprets experiments, suggests new directions, and identifies possible improvements in measurements, devices, processes or systems.

One recent focus has been spin-transfer torques — the "forces" on magnetic systems that arise when electrical current passes through a non-uniform magnetization either in a multilayer or across a domain wall. The torques, which are strong enough to induce magnetic dynamics, are being intensely studied for device applications, with experiments underway at the CNST



Spin transfer torque in an Fe/MgO/Fe tunnel junction as a function of the thickness of the free layer. The schematic of the junction (top), shows the magnetization of the fixed magnetization, M_L, the free layer magnetization M_R and the in-plane and out-of-plane torques.

Nanofabrication Research Group, ***December 2008***

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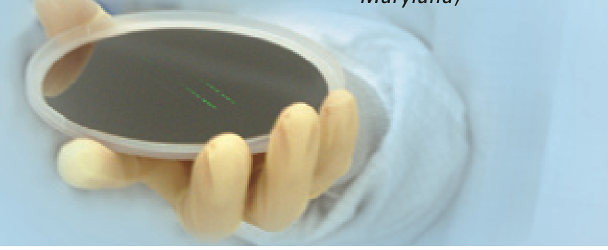


and around the world. One possible application is in Magnetic Random Access Memory (MRAM), in which memory elements consist of two ferromagnetic elements separated by a thin MgO tunnel barrier. EPG theorists have computed the spin-transfer torques for such cells to help the development of current-induced switching to set the state of these MRAM cells. In another application, spin transfer torques are used to move domain walls in magnetic wires. Information is stored in the positions of these walls, which are moved past a sensing element. The velocity of the domain wall motion depends sensitively on the magnetic damping and related transport parameters. Models have been developed in the EPG for these processes and the important parameters computed.

Another focus of this research has been developing models to compliment measurements of graphene by STM, as discussed above. A variety of approaches have been used to help interpret the data, including developing models for the observed structures and computing their electronic structure.

Accomplishments:

- Carried out detailed calculations of spin transfer torques for comparison with experimental measurements, including measurements on Fe/MgO/Fe tunnel junctions.
- Calculated the electronic structure of graphene layers on silicon carbide for comparison with scanning tunneling microscopy measurements at the CNST.
- Calculated the damping parameters for transition metal ferromagnets, and the interplay between magnetic damping and current induced domain wall motion.

Nanofabrication Research Group

The Nanofabrication Research Group (NRG) conducts research to advance the state of the art in nanomanufacturing techniques. The NRG is developing tools and processes to enable nanoscale fabrication and characterization by both lithographic ("top-down") and directed assembly ("bottom-up") approaches. Research in this group has only recently begun, with more than half the technical staff members joining the Center within the past year. Current research interests include the following topics.

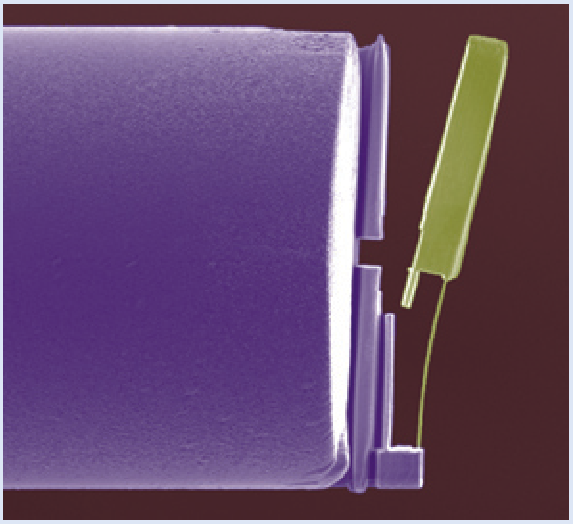
Electronic nanodevices. This research is focused on providing the measurement capabilities to enable the integration of novel materials into electronic nanodevices. As traditional CMOS electronics reaches the physical limits of scaling, the NRG is screening new materials that may scale to smaller dimensions and enable new applications beyond computation. One of the biggest challenges is that many potentially important materials such as thin organic layers, some inorganic layers and many nanostructured materials are either completely incompatible with standard patterning techniques, or the patterning process can significantly alter their electronic properties. The NRG is therefore evaluating alternative patterning schemes that enable electrical characterization at the intermediate stages of fabrication. It is also assessing any material transformations that occur during processing.

Focus Areas:

- Nanoscale patterning of novel electronic materials
- Sensors on scanning probes
- Electronic transport in nanoscale organic/inorganic devices

Nanoplasmonics. Collective charge oscillations at the boundary between an insulating dielectric medium (such as air or glass) and a metal (such as gold, silver or copper) are able to sustain the propagation of infrared or visible-frequency electromagnetic waves known as surface-plasmon-polaritons (SPP). SPPs are guided along metal-dielectric interfaces much in the same way light can be guided by an optical fiber, with the unique characteristic of subwavelength-scale confinement perpendicular to the interface.

Nanofabricated systems that exploit SPPs offer fascinating opportunities for crafting and controlling the propagation of light in matter. In particular, SPPs can be used to channel light efficiently into nanometer-scale volumes, leading to direct modification of mode dispersion properties (substantially shrinking the wavelength of light and the speed of light pulses for example), as well as huge field enhancements suitable for enabling strong interactions with nonlinear materials. The resulting enhanced sensitivity of light to external parameters (for example, an applied electric field or the dielectric constant of an adsorbed molecular layer) shows great promise for applications in sensing and switching.



False-color scanning electron microscopy (SEM) image of a metamaterial cantilever used for demonstration of negative radiation pressure at visible frequencies. Using focused-ion-beam milling, the cantilever has been monolithically integrated on the end of a 125 µm-diameter optical fiber.

NRG research is focused on the design and fabrication of novel components for measurement and communications based on nanoscale plasmonic effects. These devices include ultra-compact plasmonic interferometers for applications such as biosensing, optical positioning and optical switching, as well as the individual building blocks (plasmon source, waveguide and detector) needed to integrate a high-bandwidth, infrared-frequency plasmonic communications link on a silicon chip.

In addition to building functional devices based on SPPs, the NRG also plans to exploit the dispersion characteristics of SPPs traveling in confined metallo-dielectric spaces to create photonic materials with artificially tailored bulk optical characteristics, otherwise known as "metamaterials."

Focus Areas:

- Plasmon-interferometers for sensing and switching
- Integrated plasmonic communications links on a silicon chip
- Three-dimensional (3D) plasmonic metamaterials with a negative index of refraction
- Focused-ion beam nanofabrication, construction analysis and metrology

Nanophotonics. Nanofabrication technology can be used to pattern and etch sub-micrometer-scale features in semiconductor and dielectric materials such as gallium arsenide, silicon and silicon nitride. In an appropriate geometry, such as a resonant cavity, these etched features can confine light to wavelength-scale dimensions, generating intense intracavity optical fields for modest input powers. The NRG's research is focused on the design, fabrication and characterization of such structures, and their application in areas such as cavity quantum electrodynamics with semiconductor quantum dots, novel light-emitting devices utilizing introduced and embedded gain media, and sensitive micro/nanophotonic-based detectors and transducers.

Focus Areas:

- Novel cryogenic optical probes for characterizing nanophotonic devices
- Strong light-matter interactions in chip-based optical cavities

Nanofabrication and directed self-assembly. As conventional fabrication technologies such as optical lithography are applied to ever smaller dimensions, they begin to run up against fundamental limits. New measurement methods are needed to understand and help mitigate the effects of those limits, and to extend the lifetime and applicability of existing techniques. In addition, novel fabrication techniques are required to address new applications; particularly those that require low-cost, large-area patterning. The NRG's research is aimed at creating the measurement and fabrication methods needed for approaches such as directed self-assembly, which combines existing patterning methods with self-organizing systems, such as diblock copolymers. This research will create nanomanufacturing techniques that can be readily integrated into existing device fabrication processes and that will also enable new processes.

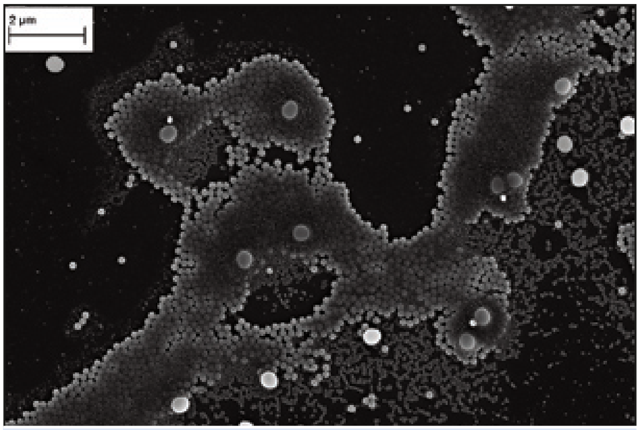
Focus Areas:

- Directed assembly of diblock copolymers
- Nanoparticle tracking for fluidic self-assembly
- Nanoscale system measurement and control
- Embedded nanoplasmonic sensors to create "smart" substrates

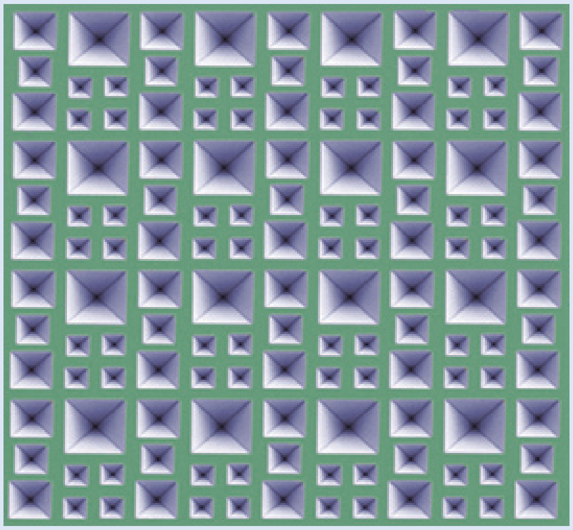
Optical MEMS and NEMS. The NRG is developing integrated optical microelectromechanical systems (MEMS) with nanoscale elements (NEMS) that will enable novel nanoscale imaging, metrology, manipulation and assembly techniques.

Focus Areas:

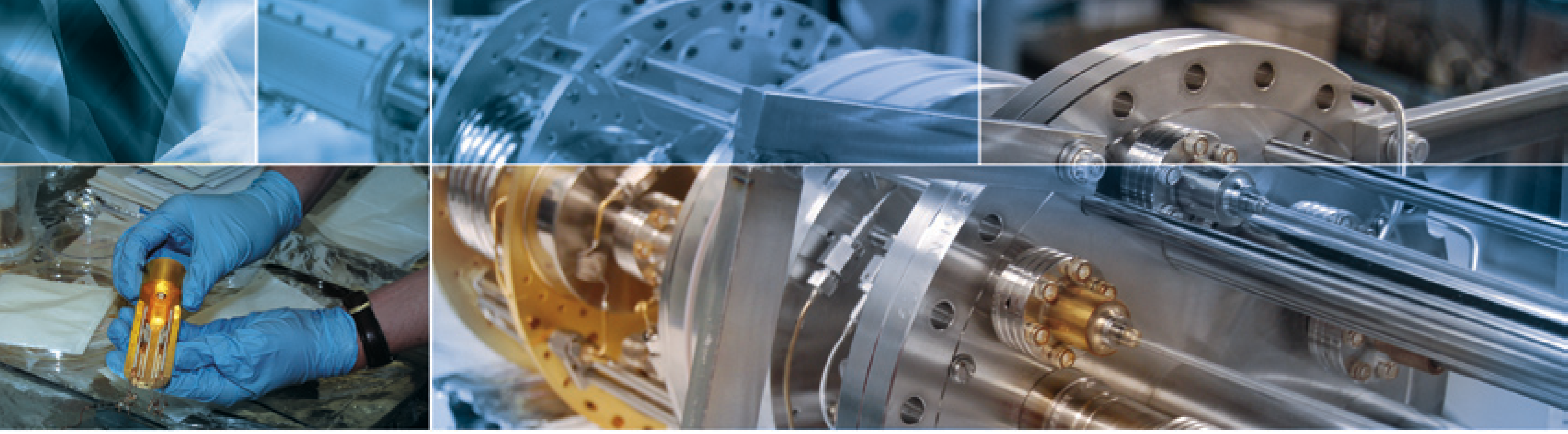
- Mechanically agile scanning probes
- MEMS with integrated, highly accurate optical sensing and actuation
- Holographic optical tweezers for manipulation of MEMS and NEMS
- Nanofabricated optical reference structures for high throughput, near-field optical imaging



SEM image (17 µm wide) of spontaneous structure formed by evaporation-driven self-assembly of an aqueous suspension containing three different sizes of polystyrene beads: 520 nm, 190 nm and 55 nm.



False-color SEM image of pyramidal micromirror wells etched in silicon. The microwells can be used to track diffusing nanoparticles in three dimensions with high precision. The largest wells are 30 µm wide.



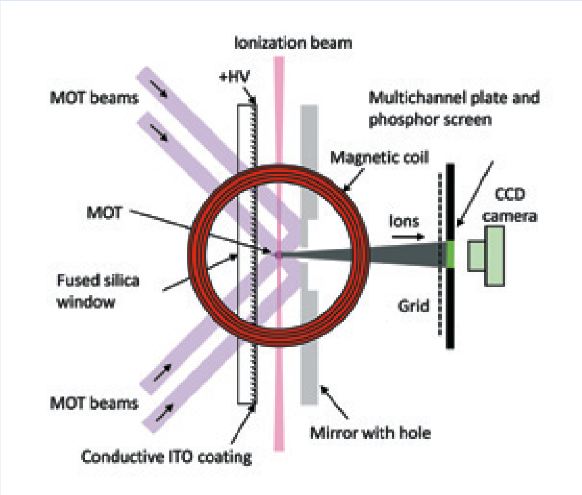
Featured Research

MOTIS: A New Source for Focused Ion Beams

Over the past 30 years, the focused ion beam (FIB) has emerged as one of the premier tools for nanofabrication. A beam of ions focused to a spot less than one nanometer in diameter can be used as a "nanoscalpel" to carve out complex, three-dimensional nanostructures in a wide variety of materials, or in a microscope to create images that surpass what can be done with an electron microscope. Current methods for producing such ion beams, however, have a few disadvantages, hindering use of this technology in a broader range of applications.

The most widely used ion source employs a sharply pointed tip at high voltage to generate a beam of ions by field ionization. Known as a liquid metal ion source, or LMIS, this device relies on liquid metal to wet the tip and supply the ions. For practical reasons, liquid gallium is by far the most common metal used in these sources. Despite its prevalence, however, gallium is not the ideal ion for milling and microscopy. A problem arises because the high energy needed to accelerate and focus gallium ions causes them to implant into most targets, resulting in contamination during fabrication that may alter the properties of the nanofabricated structure. Also, gallium is a relatively heavy element, so that when it is used for ion-based microscopy, sputtering of the surface can be a significant problem, severely damaging the sample during inspection.

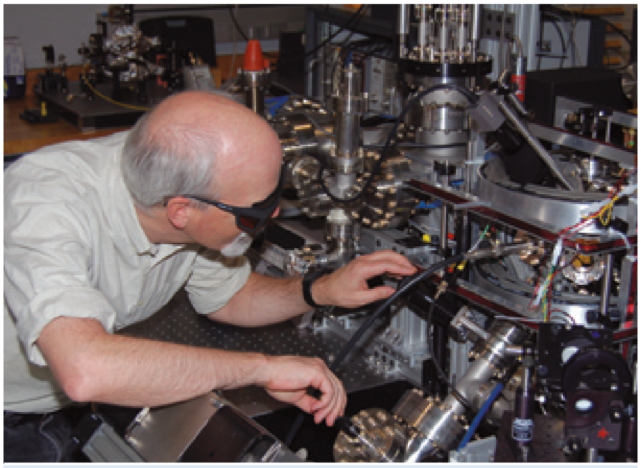
Researchers have tried to remedy these problems by using other elements in an ion source, but have so far failed to produce a source with a brightness or intensity that can rival the LMIS. For microscopy, some success has been achieved with helium ions, but a robust source in which a choice of ions is available has been elusive. In the CNST a different approach to producing ions has recently been developed that addresses nearly all the issues with current sources and promises to expand greatly the capabilities of FIB systems.[1]



Schematic diagram of a magneto-optical trap based ion source.

The new magneto-optical trap-based ion source (MOTIS), which has evolved from CNST research on nanoscale measurement and fabrication using laser-controlled atoms, can produce ions of many different atomic species that can easily be focused

[1] Magneto-Optical Trap-Based, High Brightness Ion Source for Use as a Nanoscale Probe, J. L. Hanssen, S. B. Hill, J. Orloff, and J. J. McClelland, *Nano Letters* **8**, 2844-2850 (2008).



Project leader Jabez McClelland and MOTIS.

down to the nanometer scale while still providing an amount of current suitable for high-resolution microscopy or nanoscale milling. The new source is based on a radical approach in which laser-cooled atoms are confined in a magneto-optical trap and then ionized and extracted through an aperture to produce a focused ion beam.

The ultra cold temperature of the atoms (about 100 microkelvin) results in an ion beam with extremely low angular divergence, which translates into a very small emittance. Small emittance is the key characteristic of a source that makes high resolution focusing possible.

The new ion source was initially demonstrated with Cr ions, but could be used with many different ionic species, including alkalis, alkaline earths, noble gases, rare earths and some metals. This flexibility opens possibilities for ion microscopy without damage by using light ions, or ion microscopy with chemically-enhanced contrast by using specific ion species. It also could enable contamination-free nanomachining with heavy, inert species. The CNST is now working on the next generation of MOTIS, which will be used to test focusing capabilities and explore new contrast possibilities for microscopy.

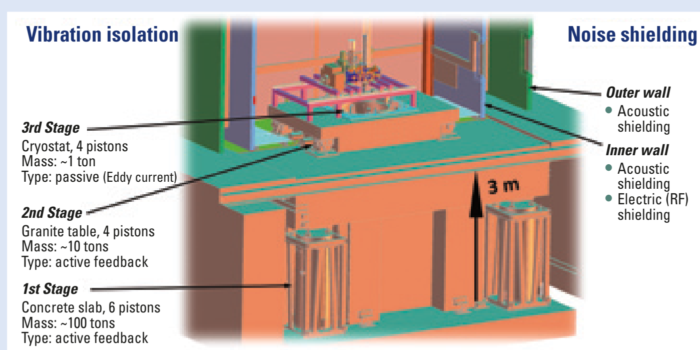
The worldwide market for analytical instruments based on focused ion beams is currently about $300M to $600M. With the introduction of the MOTIS, this market could expand significantly. A patent application has been filed for the invention, and the CNST is working with leaders in the FIB technology industry to explore further development and applications of this new ion source.

The Atomic Scale Quantum Nanoelectronics Laboratory

As materials and devices are reduced to nanometer scales, confinement of the electron systems leads to quantization of the electron energy levels and a range of new physical phenomena. Measurements that can separate these quantized levels with high spatial and energy resolution are required to understand and exploit such systems for future electronics, quantum information technologies and nanomanufacturing.

For example, all modern electronic devices rely on the transport of charge carriers from one location to another to transmit information. Although these devices continue to shrink in size, there is a broad consensus that the underlying CMOS technology will reach its physical limits within a decade. This looming limitation has motivated an intensive world-wide search for new material systems and measurements that can help extend or take the place of CMOS, and thereby continue the development and growth of the information technology industry.

In order to achieve the high-resolution measurements needed to understand and exploit post-CMOS material systems, the CNST is in the final stages of constructing a new ultra low temperature scanning probing microscope (SPM) laboratory. The laboratory, with unprecedented acoustic, electromagnetic and thermal isolation and control, will enable measurements of the quantum electronic structure of nanometer scale systems with an unprecedented combination of spatial and energy resolution. The measurement space incorporates multiple extreme environments, including low temperature, ultra-high vacuum (UHV) and high magnetic fields, all of which create significant measurement challenges for SPM operation.



Schematic illustration of the multi-stage vibration isolation system and surrounding shielded laboratory that houses the ultra-low temperature scanning probe microscope. The system enables the nanometer gap between a probe tip and sample to be maintained with a stability better than 0.1 pm (10^{-13} meters).

The laboratory utilizes the NIST Advanced Measurement Laboratory inertial mass isolation concept for its first stage of vibration isolation. This system is comprised of a 110-ton concrete mass suspended on air springs with an active feedback network. Two additional stages of vibration isolation mounted on this mass create a three-stage vibration isolation system that enables a sample-probe separation stable to 10-13 meters or less. The SPM system is contained in an acoustically and electromagnetically shielded room for additional noise reduction.

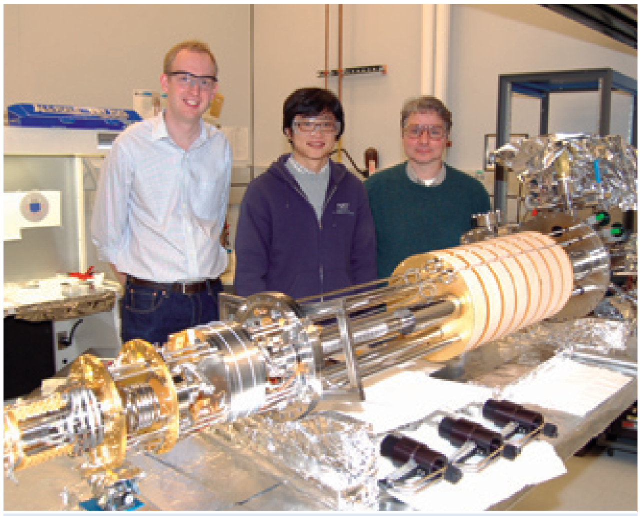
The SPM is incorporated within a custom, low noise cryogenic refrigeration system—created to CNST specifications by the Janis Research Company—capable of cooling the sample and probes to 10 mK. The refrigeration system is specifically designed for SPM application with UHV capability and a low noise Joule-Thomson condensing system. The SPM system has been designed to incorporate multiple measurement probes based on quantum tunneling, and novel approaches such as spin polarized probes and single electron transistor probes to allow a variety of measurement modes.

The SPM module is a self-contained unit that is transportable between the cryogenic and room temperature environments. This allows multiple SPM modules to be used that are tailored for specific applications. The laboratory also features multiple, UHV sample and probe preparation and characterization chambers interconnected via a sample transport system. Probes can be prepared in a field-ion microscope and coated with a variety of materials for specific probe functionality. Novel metal and III-V compound semiconductor structures can be fabricated with molecular beam epitaxial growth facilities and transferred in vacuum into the SPM system.

The initial materials and devices of interest include novel metal and semiconductor structures fabricated to elucidate the fundamental principles that govern electronic behavior on the nanoscale. The first results are expected in the fourth quarter of 2009.

Tracking Nanoparticles in Three Dimensions

One of the grand challenges in nanotechnology is to enable nanomanufacturing, which may be envisioned as the precise arrangement of arbitrary nanoscale building blocks in specific

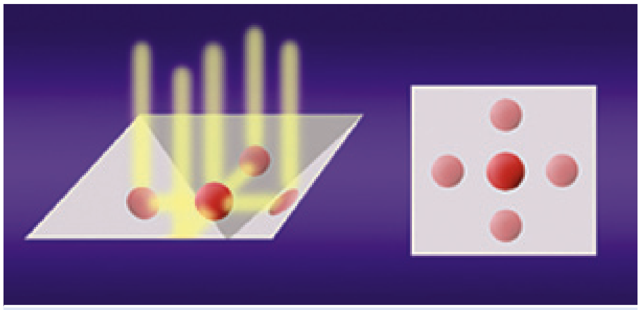


Drs. Sander Otte, Young Jae Song and Joseph Stroscio with the cryostatic refrigeration unit. The team performed several calibrations on the device prior to its installation in the highly shielded Ultra Low Temperature Scanning Probing Microscope Laboratory.

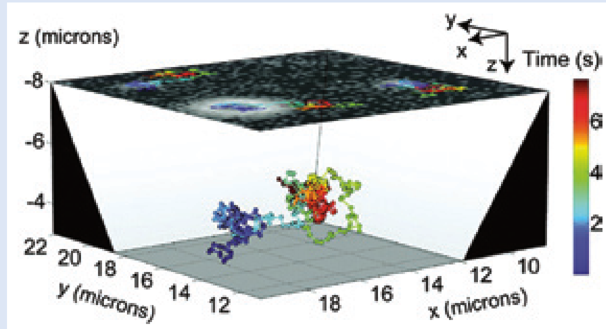
device structures and at speeds approaching those that are now routinely achieved in the semiconductor industry. Although an impressive range of functionality can be achieved with the limited set of materials amenable to conventional semiconductor fabrication, there is an enormous materials parameter space that could be usefully exploited if nanomanufacturing processes existed.

Chemists are continually introducing nanoparticles with novel shapes, sizes and compositions, typically synthesized through solution-phase processing. The nanomanufacturing challenge is to harness the unique physical and chemical properties of such nanoscale building blocks by arranging them from within the solution as quickly as possible into specific, fixed locations on a substrate. This challenge is exacerbated by the challenge of observing and controlling nanoparticles that are randomly diffusing within the solution.

One promising candidate for nanomanufacturing is the idea of directed self-assembly, in which a relatively coarse substrate template is used to guide the finer, nanoscale self-arrangement of the nanoparticles. Until now, this technique has been refined primarily by trial and error, because measurement methods have not existed to study the dynamics of particle-template interactions in three dimensions. The CNST has recently devel-



The heart of the orthogonal tracking microscope system is a sample well etched in silicon containing a solution of nanoparticles. Precise orientation of the silicon crystal makes it possible to chemically etch angled sides in the well so smoothly they act as mirrors. In this configuration, four side views of a nanoparticle floating in solution (left) are reflected up. A microscope above the well sees the real particle (center, right) and four reflections that can be used to calculate the particle's vertical position.



3D reconstruction of the diffusion of a 190 nm-diameter particle in a water/glycerine solution. Direct and reflected images of the particle in a micromirror well are captured simultaneously by a single camera, as in the overlaid image. The full 3D trajectory is reconstructed from the three observed 2D trajectories, which are analyzed with fast centroid-finding algorithms.

oped such a method to measure 3D particle diffusion directly and quickly.[2]

The preferred method for observing nanoparticles in a solution has been optical microscopy. Conventional optical microscopes, however, provide essentially a 2D view of a 3D region of interest. Whereas the 3D position of a defocused sub-wavelength particle can be estimated from scalar diffraction theory computations, this process is mathematically complex and computationally slow. The CNST Nanofabrication Research and Electron Physics Groups have jointly developed a new 3D tracking technique based on two realizations. The first realization was that 2D position estimation is much simpler and faster than 3D position estimation. The second realization was that particle position along the third dimension, the optical axis, could be found quickly by using angled micromirrors to project a side-view image alongside the direct image of the particle.

First, angled micromirrors are fabricated lithographically by etching silicon wafers with potassium hydroxide, creating pyramidal micromirror wells whose faces are smooth and reflective Si(111) crystal planes. The wells are then filled with a dilute suspension of fluorescent polystyrene nanoparticles, sealed with a coverslip, and placed on an inverted fluorescence microscope for imaging with digital video cameras. With this approach, both direct and reflected images of moving nanoparticles can be observed simultaneously; both images can be analyzed quickly with 2D centroid-based algorithms, giving four measurements of three position coordinates. Because one coordinate is redundant, the two orthogonal 2D measurements can be instantly converted to a single 3D measurement. The redundancy also improves the signal-to-noise.

The CNST has demonstrated experimentally that the 3D position can be found with a precision better than 20 nm at imaging rates above 330 frames per second. The first detailed study has been completed of the precision and accuracy of the technique, and an iterative centroid-finding algorithm has been developed that dramatically reduces the image processing time required to find the 3D particle position. The CNST expects that the technique will lead to a better understanding of the dynamics of particle/template interactions and, ultimately, process control techniques to optimize the assembly of nanoscale devices.

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[2] Fast, Bias-free Algorithm for Tracking Single Particles with Variable Size and Shape, A. J. Berglund, M. McMahon, J. J. McClelland, and J. A. Liddle, *Optics Express* **16**, 14064-14075 (2008).

3D Particle Trajectories Observed by Orthogonal Tracking Microscopy, M. McMahon, A. J. Berglund, P. Carmichael, J. McClelland, and J. A. Liddle, *ACS Nano* **3**, 609-614 (2009).

The NanoFab

An essential element of the CNST mission is operation of the NanoFab as a national facility that provides researchers with efficient access to cutting-edge nanofabrication and measurement instrumentation on a cost-reimbursable basis. The NanoFab has two distinguishing features. The first is ease of access, with a straightforward application process designed to get researchers into the facility in a few weeks; the second is the availability of expert training and assistance by an experienced, professional staff. With an unusual level of operational flexibility, the CNST NanoFab can accommodate the needs of researchers with a wide range of fabrication experience and technical requirements.

How We Operate

Whereas other national nanofabrication facilities share many of the same tools, the CNST NanoFab has been designed to operate in a unique way that offers a number of advantages, particularly for small businesses in the early stages of developing nanotechnology-based products.

The U.S. Department of Energy (DOE) and National Nanotechnology Infrastructure Network (NNIN) both provide vital resources for general research in nanotechnology, including nanofabrication. It is useful to contrast the CNST's operation with these facilities.

Like other DOE user facilities, the DOE nanocenters are accessed through a semi-annual submission of proposals that are peer-reviewed by independent proposal evaluation boards. If selected, a user is provided access to technical staff and equipment for the proposed nanoscale science research. There is no cost to users except for approved proprietary research, for which full cost recovery is required. (See *www.sc.doe.gov/BES/User_Facilities/dsuf/nanocenters.htm*.)

The NNIN Centers, supported by the National Science Foundation (NSF), provide opportunities for research at 14 fee-based user facilities. Each center provides specialized instruments and support in areas that mirror the strengths of the host university's faculty. External projects are reviewed for technical feasibility only, and the academic community is charged a rate that is substantially less than that for proprietary research. Users are

We have found the CNST to be a valuable partner in the identification and exploration of emerging technology that is relevant to our business.

The CNST staff understands the needs of our customers and has been proactive in alerting us to opportunities that can significantly extend the state of the art in our markets. In our experience, NIST's CNST stands out as a research partner among the federal laboratories because of their industrially-oriented charter, the resources available in their labs and the quality of their excellent research staff.

Dr. David H. Narum
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FEI Company
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typically provided training sufficient to become capable operators of the tools required for their work. (See *www.nnin.org*.)

The CNST NanoFab operates differently than the DOE or NNIN facilities. The CNST was not specifically designed to encourage discovery research, as is the case for the DOE and NNIN Centers. Rather, the CNST NanoFab aims to advance the production of nanotechnology-based applications by solving metrology and processing problems hindering their development.

At the CNST, as in the NSF-supported NNIN, fees based on full cost recovery are charged for proprietary research. However, for researchers performing non-proprietary work that will advance nanoscale measurement and fabrication and, thereby, the productive use of nanotechnology, the CNST Director may grant a partial fee waiver. For such work, the fees for use of the NanoFab are comparable to the academic rates charged at NNIN facilities.

Supporting users. The CNST's operating structure allows it to provide a high level of staff support.

The CNST NanoFab is operated by a staff of engineers and technicians—who collectively have over 170 years of process development experience—dedicated full-time to user and tool support. The CNST research staff scientists do not have responsibilities in the NanoFab, and are therefore dedicated to research. They engage with NanoFab users and other CNST research participants through collaboration.

The NanoFab's business and operational model positions the CNST very well to accomplish its mission. It allows the CNST to provide dedicated resources to industrial, academic and government agencies eager to partner with it on solving important measurement and fabrication problems in nanotechnology. The CNST is eager to provide access to researchers from such agencies, including those with projects that might not receive high ratings in a peer review process designed for discovery-based research despite addressing a critical industrial need. The CNST's business model also allows industrial and commercial users to perform proprietary research in the CNST NanoFab without endangering intellectual property rights.

The NanoFab also supports users by keeping them informed about the facility, and providing mechanisms for user input. The NanoFab publishes a quarterly NanoFab News, providing up to date information about fabrication process development, tool installations, safety and access policies and other notable news. Feedback from users is acquired through periodic User Group Meetings and an on-line forum.

Becoming an external user. Industrial, commercial, academic, government and foreign researchers may access the NanoFab as external facility users. All prospective external facility users must complete an application process, including a brief project description. [Note that researchers from NIST, including the CNST staff, follow essentially identical procedures and pay the same fees.]

The CNST NanoFab's application process is designed to get a potential user through the registration process and working in the NanoFab in the shortest time possible, typically a few weeks or less.

The CNST NanoFab staff first reviews each project to ensure it is safe, that it will not compromise the cleanliness of the facility or degrade the tools, that it will not unduly prevent others from using necessary tools, and that it is feasible with the available resources. If a researcher from outside NIST has requested a partial fee waiver, the project is rated on its potential to advance the CNST mission. In addition to providing the Director with guidance on granting the waiver, this rating can be used to prioritize projects in the event that needed resources are oversubscribed.

Following project approval, a researcher signs a User Agreement, establishes an account and transfers funds to cover the estimated costs. Before a researcher is allowed operational access to the NanoFab, he or she must go through a NanoFab orientation, learn the cleanroom protocols, take a safety training course and pass a written safety examination. An external facility user may need to fulfill some additional requirements to obtain access to the NIST campus.

NanoFab tool users are required to either take a training course or demonstrate proficiency on all tools they wish to use. When tool time is not oversubscribed, the use of the NanoFab is generally scheduled on a first-come, first-served basis.

Services provided by the staff. The NanoFab staff offers three levels of service to researchers:

- *Equipment training:* The NanoFab staff will give a new tool user basic, hands-on training on any specific tool required, which will permit the user to operate the tool in a safe manner while running standard processes. The training itself is free of charge, with no costs associated for staff time or tool usage. However, if the tool is located in the cleanroom, the hourly cleanroom entry fee applies.

- *Tool operation:* Process engineers can operate the tool for a user to run a pre-determined process. This operation incurs a charge for the staff time in addition to the normal hourly cost of using the tool.
- *Process Development:* If a project requires the development of a non-standard process aimed at specialized goals, the NanoFab staff will assist the user in developing the needed processes. Examples might include achieving a given thin film roughness, using non-standard substrates or precise plasma etching of a new material. Process engineering time plus normal hourly tool costs will be charged.

Cost recovery. Each tool has an hourly usage fee which includes the cost of most supplies, maintenance and training. There is also a nominal hourly charge for cleanroom access that covers the associated costs, such as gowning and incidental supplies. The hourly rates for using the CNST are similar to the full cost recovery rates charged for proprietary research at the NNIN Centers. However, as discussed above, users performing non-proprietary research that supports the CNST's mission may be granted a partial fee waiver, resulting in rates similar to those charged academic researchers at the NNIN Centers.

Resources and Equipment

The NanoFab is housed in a 19,000 square feet (1,800 m^2), class 1000 cleanroom, with 8,000 square feet (750 m^2) at class 100, and high-performance laboratories nearby within the Advanced Measurement Laboratory Complex. These laboratories include superior vibration, temperature and humidity control and air quality. The NanoFab is open from 7 am to 7 pm, Monday through Friday; hours can be expanded to support access needs.

The NanoFab cleanroom has a raised floor, bay-and-chase design that enables tools to be serviced without disrupting other operations. Safety is a primary concern; the facility is monitored by closed-circuit video and round-the-clock air and hazard monitoring, and a staff member is always present during normal operating hours.

A comprehensive list of the NanoFab equipment is included below; over a third of the 55 tools have been added since the NanoFab was established within the CNST 20 months ago. Of particular note are the CNST's electron beam lithography tools, which include a Vistec VB300 in the cleanroom with <10 nm line width, and a JEOL JBX-6300FS system with comparable capabilities that will become available outside the cleanroom in late 2009. Other important capabilities are enabled by the CNST's Zeiss NVision 40 focused ion beam system incorporating a Gemini scanning electron microscope and four-channel gas injection system. It can accommodate from millimeter-sized samples to 100 mm-diameter wafers for nanometer-scale patterning, etching, nanomanipulation and transmission electron microscopy sample preparation.

NanoFab Operations Group
December 2008

Vincent Luciani, *NanoFab Manager*
Wade Hall, *Administrative Assistant*
Jeff Pasternak, *User Facility Coordinator*

Process Engineers and Technicians

Laurence Buck	Gerard Henein
Marc Cangemi	Michael Hernandez
Lei Chen	Richard Kasica
Russell Hajdaj	William Young

NanoFab Equipment

Lithography

- E-beam Lithography System: Vistec VB300[1]
- E-beam Lithography System: JEOL JBX-6300FS[1,2]
- Laser Pattern Generator: Heidelberg DWL-66FS[1]
- Nano-Imprint Lithography Tool: Nanonex NX-2000[1]
- Nanonex Ultra-100 Integrated UV-Ozone Cleaner/Molecular Vapor Coater[1]
- Contact Aligners (2): Suss Microtec MA6 and MA8
- Spinners (2): Laurell Technologies Series WS-400 and WS-500
- Spinner/Hotplate: Brewer Science CEE Model 100CB
- Process Benches (2): E-Beam Resist Processing Stations[1,2]

Furnaces

- General Thermal Oxidation and Diffusion (Bank 2)
- CMOS Thermal Oxidation and Diffusion (Bank 1)
- Low Pressure Chemical Vapor Deposition (LPCVD) Furnace (Bank 3)
- Rapid Thermal Annealer: Modular Process Technology
- PECVD-Unaxis 790

Senspex, Inc. is a small business that provides custom photonic technology solutions for security, surveillance, chemical analysis and detection applications. Our products and services include thermal imaging solutions, customized security management systems, video test equipment and chemical identification instruments. Senspex is a certified U.S. General Services Administration Contractor.

We inquired if the CNST NanoFab's electron beam lithography system could produce a pattern of 25 nm-sized features over a one mm^2 field. We needed that specific size in order to develop our latest line of sensors that specialize in detection of very low molecular concentrations.

We developed a workable plan after several conference calls between the NanoFab staff and our engineering staff—a work plan that centered on using the CNST NanoFab Vistec VB300 Electron Beam Lithography system.

We were able to quickly create a budget estimate for the work we needed based on those conversations. Before we arrived on site, the CNST staff also did significant process development work, and they provided us with proof of principle results on our first day on site.

Because of our success at the CNST, we now are developing even more projects in concert with their staff. It's an ideal place for a small business to gain access to the tools and processes needed to get a nanotechnology-based product to market quickly.

Dr. Edward Gillman
Senior Research Scientist
Senspex, Inc.
Rio Rancho,
New Mexico

Metal Deposition

- Sputterers (2): Denton Vacuum Discovery 22 and Discovery 550[1]
- E-beam Evaporator: Denton Infinity 22
- Thermal Evaporator: Denton Discovery 22

Wet Chemistry

- Heated Wet Chemical Benches (2): 2 m and 2.4 m
- KOH/TMAH Wet Etch Bench: Reynoldstech[1]
- Acid Etch Bench: Reynoldstech[1]
- Spin Rinse Dryers: Semitool PSC-101

Dry Etch

- Deep RIE: Unaxis SHUTTLELINE DSEII
- Metal RIE: Unaxis 790
- Silicon RIE: Unaxis 790
- Multipurpose RIE Systems (2): Oxford[1,2]
- ICP Metal Etcher: Unaxis SHUTTLELINE ICP
- XeF_2 Silicon Etch: Xactix Xetch e1 Series
- Microwave Plasma System: PVA Tepla 300[1]

Specialty Tools

- Atomic Layer Deposition: Oxford FlexALRPT[1,2]
- Parylene Deposition System: Specialty Coating Systems PDS-2010[1]
- Wafer Bonder: Suss Microtec SB6e[1]
- Focused Ion Beam: Zeiss NVision 40[1]

Inspection

- Stress Measurement Tool: Toho Technology FLX-2320[1]
- Table-top SEM: Hitachi TM-1000[1]
- Scanning Electron Microscope: Zeiss Ultra-60 FESEM
- Atomic Force Microscopes (2): Veeco Dimension 3000, Dimension 3100[1]
- Contact Angle Goniometer[1]
- Spectroscopic Ellipsometer: Woollam XLS-100
- Reflectometers (2): Filmetrics, Nanometrics
- Contact Profilometer: Dektak 6M
- Optical Microscope with Image Capture: Nikon
- Four-Point Probes (2): Jandel RM2
- High Power Inspection Microscopes: Olympus
- High Power Nomarski Microscope: Nikon[1,2]

Post Process

- Wafer Dicing Saw: Disco Model 341
- Wire Bonder: Kulicke and Soffa Model 4526
- Critical Point Dryer[1]

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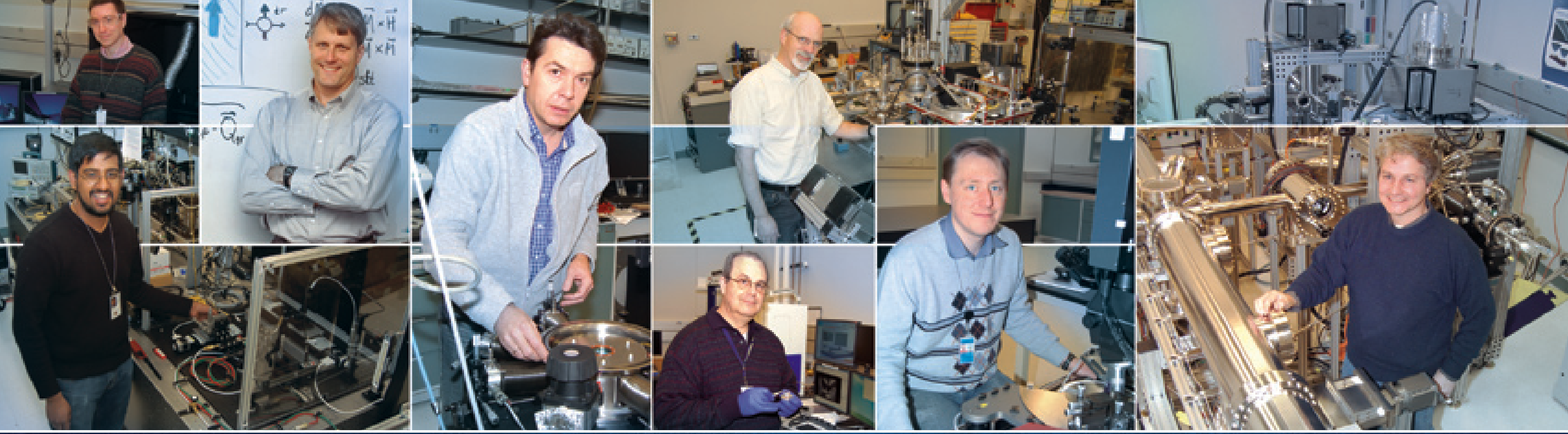
[1] *Equipment added since the CNST was established in May 2007.*

[2] *Equipment purchased, to be installed in 2009.*



CNST Leadership

Robert Celotta, Director

Robert Celotta is the current and founding Director of NIST's Center for Nanoscale Science and Technology. He received his B.S. in Physics from the City College of New York, and his Ph.D. in Physics from New York University. Following postdoctoral studies with Nobel Laureate John Hall at JILA in Boulder, CO, Robert joined the staff at NIST in Gaithersburg, MD. During his career at NIST, he was a long-time Leader of the Electron Physics Group, during which time he became a NIST Fellow. Robert has over 250 publications, has given more than 350 presentations and has been issued four patents in the fields nanotechnology, surface and multilayer magnetism, spin polarized electron interactions, scanning tunneling microscopy and nanostructure fabrication. He also co-edited *Experimental Methods in the Physical Sciences*, a series of over 20 books on experimental physics. Robert has received the American Vacuum Society's (AVS) Gaede-Langmuir Prize, New York University's Alumni Achievement Award, the Federal Laboratory Consortium's Excellence in Technology Transfer Award, two IR-100 Awards, NIST's Edward Uhler Condon Award, NIST's William P. Slichter Award, the U.S. Department of Commerce's Silver and Gold medals, the Maryland Academy of Sciences' Distinguished Young Scientist Award and the Washington Academy of Sciences' Outstanding and Distinguished Career in Science Award. He is a Fellow of the American Physical Society, the American Association for the Advancement of Science, the AVS and the Washington Academy of Sciences.

Selected Publications:

- Laser Focused Atomic Deposition, J.J. McClelland, R.E. Scholten, E.C. Palm, and R.J. Celotta, *Science* **262**, 877-880 (1993).
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- Manipulation of Adsorbed Atoms and Creation of New Structures on Room-temperature Surfaces with a Scanning Tunneling Microscope, L.J. Whitman, J.A. Stroscio, R.A. Dragoset, and R.J. Celotta, *Science* **251**, 1206-1210 (1991).
- Scanning Electron Microscopy With Polarization Analysis (SEMPA), M.R. Scheinfein, J. Unguris, M.H. Kelley, D.T. Pierce, and R.J. Celotta, *Review of Scientific Instruments* **61**, 2501 (1990).

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Lloyd Whitman, Deputy Director

Lloyd Whitman joined the Center for Nanoscale Science and Technology as Deputy Director in April 2008. He received a B.S. in Physics from Brown University (with honors, magna cum laude), and M.S. and Ph.D. degrees in Physics from Cornell University. After an NRC Postdoctoral Research Fellowship at NIST, he joined the research staff at the Naval Research Laboratory (NRL). At NRL, Lloyd served as the Head of the Surface Nanoscience and Sensor Technology Section, a multidisciplinary research group working at the nexus of nanoscience, biotechnology and microsystems. He led a diverse portfolio of research studying semiconductor, organic and biomolecular nanostructures, their use in novel functional surfaces and their integration into advanced sensor systems for national security applications. In addition to leading research at NRL, Lloyd served as a Science Advisor to the Special Assistant to the Secretary of Defense for Chemical and Biological Defense and Chemical Demilitarization Programs. In this capacity, he represented the U.S. Department of Defense on the National Science and Technology Council, Committee on Technology Subcommittee on Nanoscale Science, Engineering and Technology. Lloyd has over 140 publications and pending patents in the areas of nanoscience and sensor technology, and numerous media citations and awards, including the Navy Meritorious Civilian Service Award.

Selected Publications:

- Magnetic Labeling, Detection, and System Integration, C. R. Tamanaha, S. P. Mulvaney, J. C. Rife, and L. J. Whitman, *Biosensors and Bioelectronics* **24**, 1-13 (2008).
- Optically Mapping the Electronic Structure of Coupled Quantum Dots, M. Scheibner, M. Yakes, A. S. Bracker, I. V. Ponomarev, M. F. Doty, C. S. Hellberg, L. J. Whitman, T. L. Reinecke, and D. Gammon, *Nature Physics* **4**, 291-295 (2008).
- Site-Specific Chemistry of Ethylene on Si(114)-(2×1), D. E. Barlow, S. C. Erwin, A. R. Laracuente, J. N. Russell, Jr., and L. J. Whitman, *Journal of Physical Chemistry C* **112**, 3349-3357 (2008).
- Independent Control of Grafting Density and Conformation of Single-Stranded DNA Brushes, A. Opdahl, D. Y. Petrovykh, H. Kimura-Suda, M. J. Tarlov, and L. J. Whitman, *Proceedings of the National Academy of Sciences USA* **104**, 9-14 (2007).
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Jabez McClelland, Group Leader, Electron Physics Group

Jabez McClelland received a B.A. in Physics and Music from Wesleyan University, and M.A. and Ph.D. degrees in Physics from the University of Texas at Austin. As part of his graduate studies, he spent a year as a Fulbright Fellow at the Freie Universität Berlin. Jabez came to NIST as a postdoctoral research associate in the Electron Physics Group, where he subsequently served as a research physicist, and most recently as Group Leader. Jabez's research at NIST has covered a number of topics ranging from spin-polarized low-energy electron scattering from laser excited atoms, to laser focused atomic deposition, metastable-atom lithography and deterministic single-atom sources. He has over 90 publications, including several in high-impact journals such as *Science* and *Physical Review Letters*. He is a frequently invited speaker at international meetings, and is considered one of the world's experts on atom optics. Jabez holds four patents, is a Fellow of the American Physical Society and the Optical Society of America, has received the Sigma Xi Award for Excellence in *Science*, and has been awarded both Silver and Gold Medals from the U.S. Department of Commerce. He currently leads projects on focused ion beam sources based on magneto-optically trapped atoms, laser cooling of novel atomic species and atom-based metrology.

Selected Publications:

- Laser Cooled Atoms As a Focused Ion Beam Source, J. L. Hanssen, J. J. McClelland, E. A. Dakin, and M. Jacka, *Physical Review A* **74**, 063416 (2006).
- Laser Cooling Without Repumping: A Magneto-Optical Trap for Erbium Atoms, J. J. McClelland and J. L. Hanssen, *Physical Review Letters* **96**, 143005 (2006).
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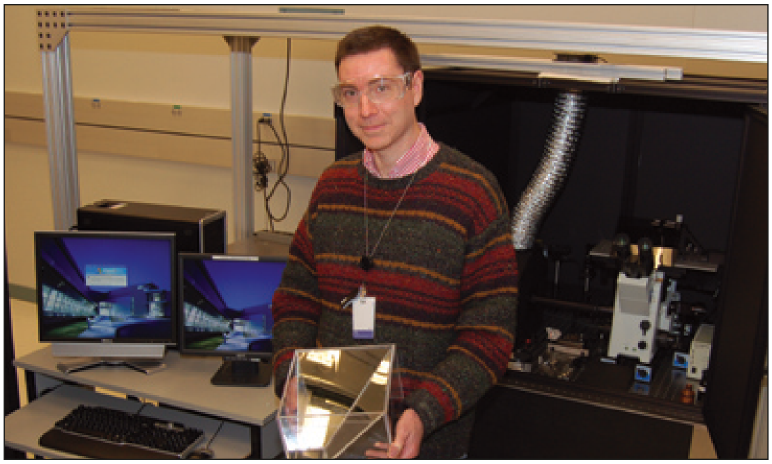
J. Alexander Liddle, Group Leader, Nanofabrication Research Group

J. Alexander Liddle received his B.A. and D. Phil. degrees in Materials Science from the University of Oxford. Alex worked for 11 years at Bell Laboratories, beginning as a postdoctoral researcher and advancing to a staff scientist and technical manager. He then spent four years at Lawrence Berkeley National Laboratory in the Center for X-ray Optics, and then as Lead Scientist of the Nanofabrication Facility in the Molecular



Foundry. Alex's research at NIST is focused on the physics of self-assembly, where he leads several projects on the measurement of the self-assembly of nanostructures. He holds 16 U.S. patents and has over 200 publications, including several in high-impact journals such as *Nature* and *Nano Letters*. Alex has also helped organize a number of international conferences and workshops on nanofabrication and self-assembly.

Selected Publications:

- Sculpting the Shape of Semiconductor Heteroepitaxial Islands: From Dots to Rods, J. T. Robinson, D. A. Walko, D. A. Arms, D. S. Tinberg, P. G. Evans, Y. Cao, J. A. Liddle, A. Rastelli, O. G. Schmidt, and O. D. Dubon, *Physical Review Letters* **98**, 106102 (2007).
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- Morphological Evolution of Ge Islands on Au-patterned Si, J. T. Robinson, J. A. Liddle, A. Minor, V. Radmilovic, and O. D. Dubon, *Journal of Crystal Growth* **287**, 518-521 (2006).
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- Lithographically-Directed Self-Assembly of Nanostructures, J. Alexander Liddle, Y. Cui, and P. Alivisatos, *Journal of Vacuum Science and Technology B* **22**, 3409-3414 (2004).
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Vincent Luciani, NanoFab Manager

Vincent Luciani joined the CNST in November of 2008 as Group Leader of the NanoFab Operations Group. He has over 30 years of private industry experience in semiconductor and nanotechnology process development and project management. Vincent began his career at Solarex Corp. producing photovoltaic solar cells. He then joined the Bendix Advanced Technology Center, developing electronic and nanotechnology devices and processes in a variety of semiconductor material systems, including silicon, gallium arsenide, indium phosphide and lithium niobate. When Bendix became part of Allied-Signal, Vincent went on to lead their advanced process development team, and was awarded an Allied-Signal Premier Achievement Award for excellence in Engineering. Prior to joining NIST, he led the process and product engineering teams at Covega Corporation, developing and ramping up the production of novel indium phosphide photonic devices. Vincent is an expert in Project Management, with a Six Sigma Blackbelt, and holds five patents in semiconductor and nanofabrication technology.

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Vladimir Aksyuk, CNST Visiting Fellow

Vladimir A. Aksyuk is a CNST Visiting Fellow in the Nanofabrication Research Group and an Associate Research Scientist at the Electrical and Computer Engineering Department of the University of Maryland. He received a B.S. in Physics from Moscow Institute of Physics and technology and a Ph.D. in Physics from Rutgers University. Following research as a Member of Technical Staff and then Technical Manager at Bell Laboratories, he joined the research staff at NIST. Vladimir's research focuses on the design and fabrication of novel optical MEMS systems. He holds more than 30 patents, and has published over 40 papers. In 2000 he received the Bell Labs President's Gold Award, in 2005 was named among *MIT Technology Review* magazine's TR35, and in 2008 received a Distinguished Alumni award for Early Career Accomplishments from Rutgers Graduate School. He is currently developing multiple projects in the use of optical MEMS and NEMS to address fundamental problems in nanomanufacturing.

Selected Publications:

- Spatial Light Modulator For Maskless Optical Projection Lithography, G. P. Watson, V. Aksyuk, M. E. Simon, D. M. Tennant, R. A. Cirelli, W. M. Mansfield, F. Pardo, D. O. Lopez, C. A. Bolle, A. R. Papazian, N. Basavanhally, J. Lee, R. Fullowan, F. Klemens, J. Miner, A. Kornblit, T. Sorsch, L. Fetter, M. Peabody, J. E. Bower, J. S. Weiner, and Y. L. Low, *Journal of Vacuum Science and Technology B* **24**, 2852-2856 (2006).
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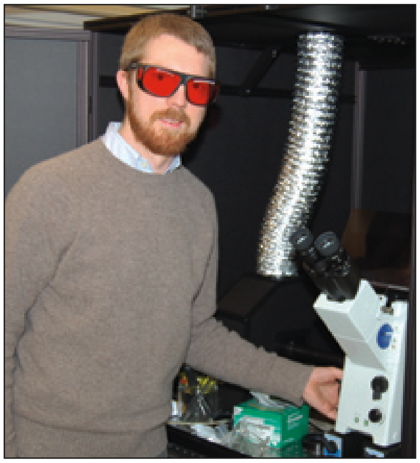
Andrew Berglund, Project Leader

Andrew Berglund is a Project Leader in the Nanofabrication Research Group. He received an A.B. in Physics with a minor in Mathematics from Dartmouth College, where he was a Barry M. Goldwater scholar, and a Ph.D. in Physics from the California Institute of Technology, where he was an NSF Graduate Research Fellow. While earning his Ph.D., he pioneered a new method for studying fluorescent nanoparticles by controlling their motion with real-time feedback. Andrew spent two years as an NRC postdoctoral research associate in the CNST Electron Physics Group, where he worked on laser cooling of novel atomic species with applications to nanofabrication, and he closely collaborated on nanoparticle tracking research. He joined the Nanofabrication Research Group in 2008, where his main research interests are the effects of fluctuations and noise in nanoscale systems, and strategies for controlling these systems with real-time feedback.



Selected Publications:

- Fast,Bias-Free Algorithm for Tracking Single Particles with Variable Size and Shape, A. J. Berglund, M. D. McMahon, J. J. McClelland, J. A. Liddle, *Optics Express* **16**, 14064-14075 (2008).
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- Sub-Doppler Laser Cooling and Magnetic Trapping of Erbium, A. J. Berglund, S. A. Lee, and J. J. McClelland, *Physical Review A* **76**, 053418 (2007).
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Kamil Ekinci, CNST Visiting Fellow

Kamil Ekinci is a CNST Visiting Fellow in the Nanofabrication Research Group and an Associate Professor of Mechanical Engineering at Boston University. He obtained B.S. degrees in electrical engineering and physics from Bogazici University in Turkey, and a Ph.D. degree in Physics from Brown University, working on low temperature scanning tunneling microscopy of thin films. During postdoctoral research at the California Institute of Technology, he carried out research on NEMS. His current research is focused on understanding the fundamentals of NEMS and developing NEMS devices for a variety of applications. He is also developing a high frequency scanning tunneling microscope. Professor Ekinci is the recipient of a 2007 NSF CAREER award.

Selected Publications:

- Radio-frequency scanning tunneling microscopy, U. Kemiktarak, T. Ndukum, K.C. Schwab and K.L. Ekinci, *Nature* **450**, 85-88 (2007).

- High-Frequency Nanofluidics: An Experimental Study Using Nanomechanical Resonators, D. Karabacak, V. Yakhot and K.L. Ekinci, *Physical Review Letters* **98**, 254505 (2007).
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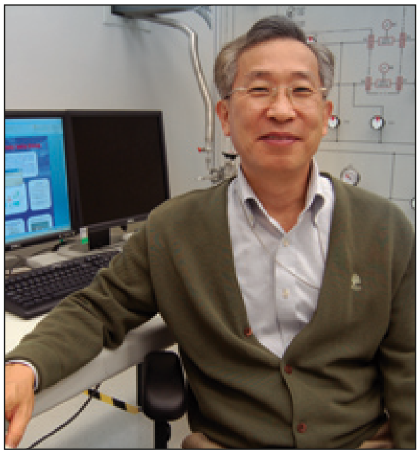
Young Kuk, CNST Visiting Fellow

Young Kuk is a CNST Visiting Fellow in the Electron Physics Group and a Professor of Physics and Astronomy at Seoul National University, Seoul, Korea. He is spending his sabbatical leave at the CNST from September 2008 through August 2009. Professor Kuk received his Ph.D. in Physics from Pennsylvania State University, and spent the following decade as a Member of the Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ. In 1991 he became a Professor of Physics at Seoul National University. Professor Kuk is a Korean National Fellow, a recipient of the Korean National Academy of Science Award, the Erwin Mueller Young Scientist Award and the American Vacuum Society Graduate Student Award. In October 2008, he received the Inchon "Academy" Prize, one of South Korea's most prestigious awards for academic achievement. He has co-authored hundreds of journal articles and book chapters, and co-edited two books in the field of nanoscience. Professor Kuk's research is focused on understanding physics at the nanometer scale as observed with scanning probe microscopy. He has been active in scanning tunneling microscopy (STM) since its



earliest development, contributing to its application for dynamic imaging of chemisorption, measuring carrier dynamics on semiconductor surfaces, and characterizing the structure and transport properties of nanowires. He has also studied the role of the tunneling tip in STM, local photovoltage with STM, nanomagnetism with spin polarized STM, and conformal transformation of molecules.

Selected Publications:

- Cesium-filled Carbon Nanotubes Conducting Nanowires, S. H. Kim, W. I. Choi, G. Kim, Y. J. Song, G.-H. Jeong, R. Hatakeyama, J. Ihm, and Y. Kuk, *Physical Review Letters* **99**, 256407 (2007).
- Conformational Molecular Switch of Azobenzene Molecule, B.-Y. Choi, S.-J. Kahng, S. Kim, H. Kim, H. W. Kim, Y. J. Song, J. Ihm, and Y. Kuk, *Physical Review Letters* **96**, 156106 (2006).
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- Metallofullerene Peapods: One-dimensional Multiple Quantum Dots for Molecular Nanowires, J. Lee, H. J. Kim, G. Kim, Y.-W. Son, J. Ihm, S. J. Kahng, H. Kato, Z. W. Wang, T. Okazaki, H. Shinohara, and Y. Kuk, *Nature* **415**, 1005-1008 (2002).

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Henri Lezec, Project Leader

Henri Lezec is a Project Leader in the Nanofabrication Research Group. He received B.S., M.S., and Ph.D. degrees in Electrical Engineering from the Massachusetts Institute of Technology. Following postdoctoral research at NEC Fundamental Research Laboratories in Tsukuba, Japan, he worked as an applications specialist for Micrion and FEI Corporations in both Germany and in the United States, and subsequently as a Research Director at the Centre national de la Recherche Scientifique (CNRS), Louis Pasteur University in Strasbourg, France. Immediately prior to joining NIST in 2007, he was a Visiting Research Associate at the California Institute of Technology. Henri's research in the CNST focuses on nanoplasmonics, nanophotonics and nanofabrication with focused ion beams; he is currently leading a project to develop and exploit negative-index metamaterials at visible frequencies. Henri holds 10 U.S. patents and has over 50 publications, including several in *Science* and *Nature*, and is a frequent invited speaker at international meetings.

Selected Publications:

- Beaming Light from a Subwavelength Aperture, H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martin-Moreno, F. J. Garcia-Vidal, and T. W. Ebbesen, *Science* **297**, 820-822 (2002).
- Diffracted Evanescent Wave Model for Enhanced and Supressed Optical Transmission through Subwavelength Hole Arrays, H. J. Lezec and T. Thio, *Optics Express* **12**, 3629-3651 (2004).
- The Optical Response of Nanostructured Surfaces and the Composite Diffracted Evanescent Wave Model, G. Gay, O. Alloschery, B. Viaris de Lesegno, C. O'Dwyer, R. Mathevet, J. Weiner, and H. J. Lezec, *Nature Physics* **2**, 262-267 (2006).
- Negative Refraction at Visible Frequencies, H. J. Lezec, J. A. Dionne, and H. A. Atwater, *Science* **316**, 430-432 (2007).
- All-optical mMdulation by Plasmonic Excitation of CdSe qUantum Dots, D. Pacifici, H. J. Lezec, and H. A. Atwater, *Nature Photonics* **1**, 402-406 (2007).
- Universal Optical Transmission Features in Periodic and Quasiperiodic Hole Arrays, D. Pacifici, H. J. Lezec, L. A. Sweatlock, R. J. Walters, and H. A. Atwater, *Optics Express* **16**, 9222-9238 (2008).

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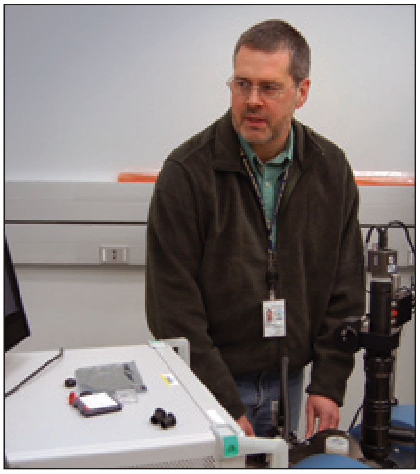
Robert McMichael, Project Leader

Robert (Bob) McMichael is a Project Leader in the Electron Physics Group. He received a B.S. in Engineering-Physics from Pacific Lutheran University, and M.S. and Ph.D. degrees in Physics from The Ohio State University. He came to NIST on an NRC Postdoctoral Research Fellowship, served on the research staff of the Metallurgy Division in the Materials Science and Engineering Lab, and then joined the CNST in 2007. Bob's research at NIST has touched on a broad spectrum of phenomena in magnetic thin films and nanomaterials, but remains centered on micromagnetics and magnetization dynamics in magnetic thin films. He has over 120 peer-reviewed publications, and is a frequent invited speaker at international meetings. Bob has helped organize numerous international conferences and currently serves on the AdCom of the IEEE Magnetics Society. Bob has received NIST's Samuel Wesley Stratton Award and the Bronze Medal Award from the U.S. Department of Commerce, and in 2004 was selected as an IEEE Magnetics Society Distinguished Lecturer.



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- Variation of thin film edge magnetic properties with patterning process conditions in $Ni_{80}Fe_{20}$ stripes, B. B. Maranville, R. D. McMichael and D. W. Abraham, *Applied Physics Letters* **90**, 232504 (2007).
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- Effect of 3d, 4d, and 5d transition metal doping on damping in Permalloy thin films, J. O. Rantschler, R. D. McMichael, A. Castillo, A. J. Shapiro, W. F. Egelhoff Jr., B. B. Maranville, D. Pulugurtha, and A. P. Chen, *Journal of Applied Physics* **101**, 033911 (2007).
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Daniel Pierce, CNST Visiting Fellow, NIST Fellow Emeritus

Daniel Pierce, a NIST Fellow Emeritus, is a CNST Visiting Fellow in the Electron Physics Group. He received a B.S. in Physics from Stanford University, a M.A. in Physics from Wesleyan University, and a Ph.D. in Applied Physics from Stanford University, where he was also a Postdoctoral Research Associate for one year. Following three years at the Swiss Federal Institute of Technology, he joined the research staff at NIST (then National Bureau of Standards) in 1975. Dan's research has been in the area of surface physics, with special emphasis on the development of spin-based measurements and their application to surface and thin film magnetism, such as imaging magnetization in magnetic nanostructures and measuring the interlayer coupling of magnetic multilayers. His work led to two "R&D 100" awards, the E. U. Condon and William P. Schlichter awards from NIST, Silver and Gold Medals from the U.S. Department of Commerce, and the Gaede-Langmuir Prize from the American Vacuum Society (AVS). Dan has three patents and over 170 publications, and is a Fellow of the American Physical Society and the AVS. He is currently working on applying scanning electron microscopy with polarization analysis (SEMPA) to new materials and devices in the CNST nanomagnetics program.

Selected Publications:

- Tunneling Spectroscopy of bcc(001) Surface States, J. A. Stroscio, D. T. Pierce, A. Davies, and R. J. Celotta, *Physical Review Letters* **75**, 2960-2963 (1995).
- Homoepitaxial Growth of Iron and a Real Space View of Reflection-High-Energy-Electron Diffraction, J. A. Stroscio, D. T. Pierce, and R. A. Dragoset, *Physical Review Letters* **70**, 3615-3618 (1993).
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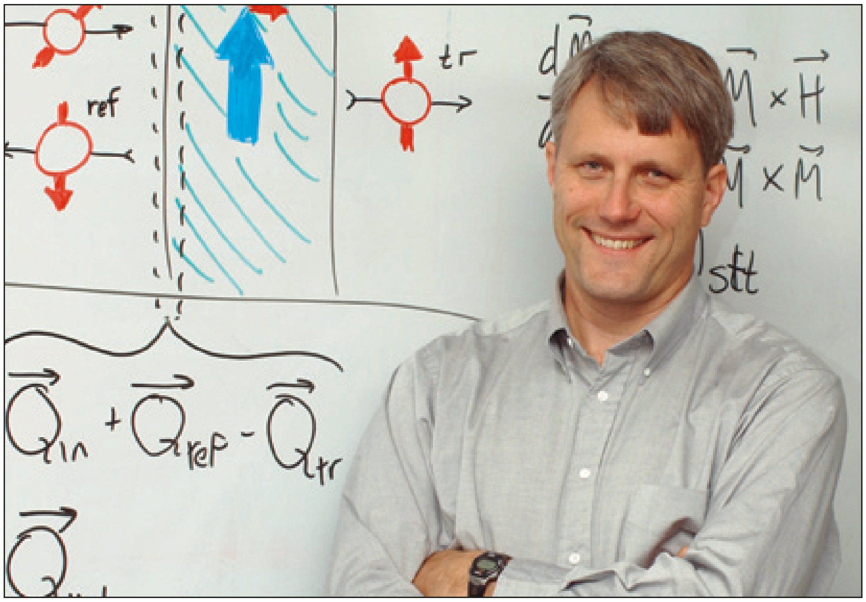
Mark Stiles, Project Leader

Mark Stiles is a Project Leader in the Electron Physics Group. He received a M.S./B.S. in Physics from Yale University, and M.S. and Ph.D. degrees in Physics from Cornell University. Following postdoctoral research at AT&T Bell Laboratories, he joined the research staff at NIST. He is also an Adjunct Professor in the Department of Physics and Astronomy at the Johns Hopkins University. Mark's research at NIST has focused on the development of ab initio theoretical methods for predicting the properties of magnetic nanostructures. He has over 80 publications and is a frequent invited speaker at international meetings. He has helped organize numerous conferences and has served the American Physical Society on the Executive Committees of the Topical Group on Magnetism and of the Division of Condensed Matter Physics. He has also served Physical Review Letters as a Divisional Associate Editor. Mark is a Fellow of the American Physical Society, and has been awarded the Silver Medal from the U.S. Department of Commerce. He currently leads multiple projects investigating the fundamental physics of nanostructures.



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- Identification of the Dominant Precession Damping Mechanism in Fe, Co, and Ni by First-Principles Calculations, K. Gilmore, Y. Idzerda, and M. D. Stiles, *Physical Review Letters* **99**, 027204 (2007).
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- Model for Exchange Bias in Polycrystalline Ferromagnet-Antiferromagnet Bilayers, M.D. Stiles, and R.D. McMichael, *Physical Review B* **59**, 3722-3733 (1999).
- Exchange Coupling in Magnetic Heterostructures, M.D. Stiles, *Physical Review B* **48**, 7238-7258 (1993).

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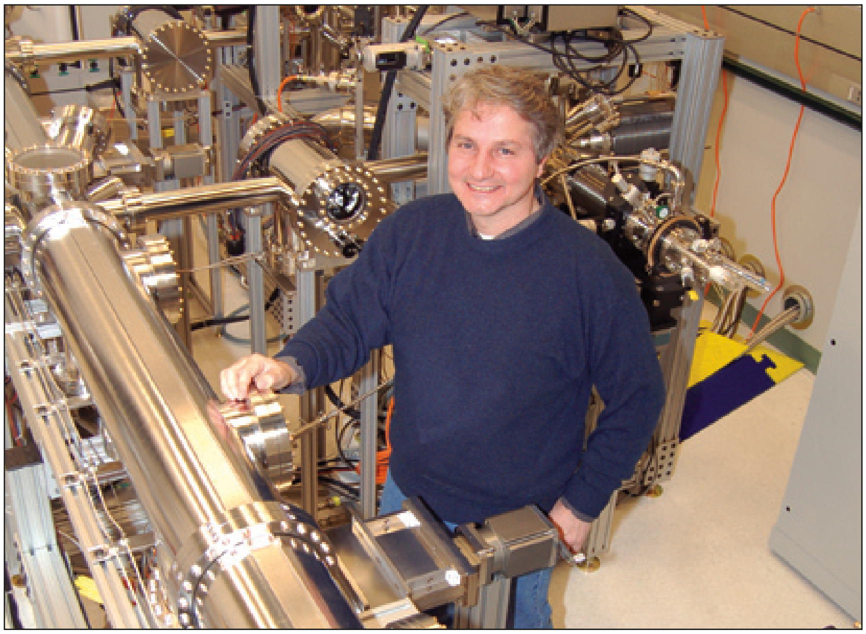
Joseph Stroscio, Project Leader, NIST Fellow

Joseph Stroscio, a NIST Fellow, is a Project Leader in the Electron Physics Group. He received both B.S. and M.S. degrees in Physics from the University of Rhode Island, and a second M.S. degree and a Ph.D. in Physics from Cornell University. Prior to joining NIST in 1987, he did two years of postdoctoral research at the IBM T. J. Watson Research Center, where he pioneered the development of scanning tunneling microscopy and spectroscopy measurements. At NIST Joe leads multiple projects in nanoscale physics and technology. His research has encompassed areas including atomic manipulation, the physical properties of nanostructures, low dimensional electron systems, nanoscale magnetism and the epitaxial growth of metal and semiconductor systems. To achieve this research, Joe has designed and constructed numerous state-of-the-art scanning probe systems, including custom designs that operate in ultra-high vacuum, cryogenic and ultra-high magnetic field environments. Joe has authored or coauthored over 70 publications. He is a Fellow of the American Physical Society (APS) and the American Vacuum Society (AVS), and has received the Arthur S. Flemming Award, the U.S. Department of Commerce Silver Medal Award, the Sigma Xi Young Scientist Award, the U.S. Department of Commerce Gold Medal Award and the Nano50 Award. He has served on numerous committees of the AVS and the APS, and on the Editorial Board of the Review of Scientific Instruments.



Selected Publications:

- Scattering and Interference in Epitaxial Graphene, G. M. Rutter, J. N. Crain, T. Li, P. N. First, and J. A. Stroscio, *Science* **317**, 219-222 (2007).
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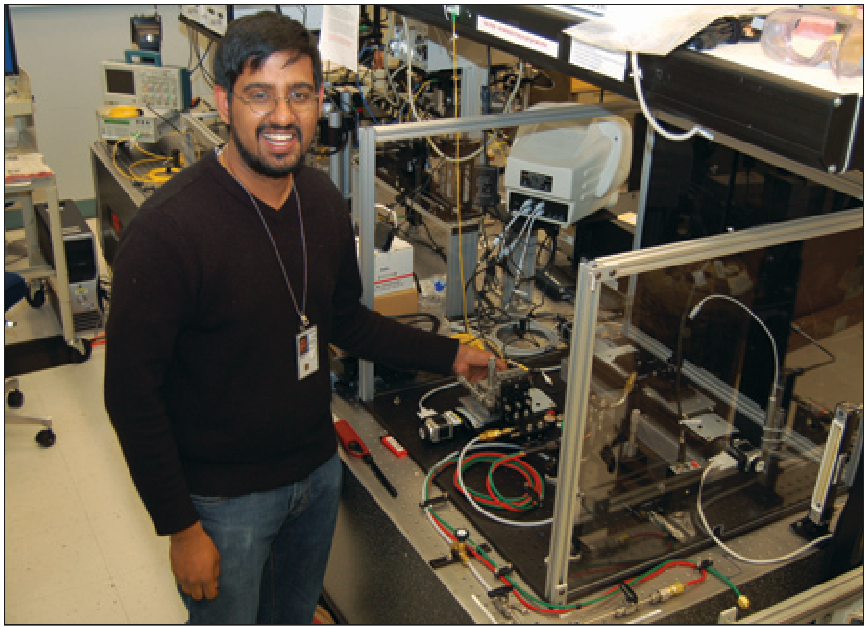
Kartik Srinivasan, Project Leader



Kartik Srinivasan is a Project Leader in the Nanofabrication Research Group. He received B.S., M.S., and Ph.D. degrees in Applied Physics from the California Institute of Technology, where his graduate research was supported by a Fannie and John Hertz Foundation Fellowship. After receiving his B.S., he worked for one year at XPonent Photonics, a startup company based in Monrovia, CA. After completing his Ph.D., he continued at Caltech as a Postdoctoral Fellow at the Center for the Physics of Information. In September 2007, he joined the CNST, where he is leading projects in the field of nanophotonics. Kartik has published over 30 peer-reviewed papers in journals such as *Applied Physics Letters*, *Physical Review*, *Nature*, and *Science*, on topics including microcavity lasers, chip-based cavity quantum electrodynamics, near-field optical probing and the electromagnetic design and nanofabrication of photonic crystal devices.

Selected Publications:

- Linear and Nonlinear Optical Spectroscopy of a Strongly-Coupled Microdisk-Quantum Dot System, K. Srinivasan, and O. Painter, *Nature* **450**, 862-865 (2007).
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- Optical-Fiber-Based Measurement of an Ultrasmall Volume High-Q Photonic Crystal Microcavity, K. Srinivasan, P. E. Barclay, M. Borselli, and O. Painter, *Physical Review B* **70**, 081306(R) (2004).
- Quantum Cascade Surface-Emitting Photonic Crystal Laser, R. Colombelli, K. Srinivasan, M. Troccoli, O. Painter, C. Gmachl, D. M. Tennant, A. M. Sergent, D. L. Sivco, A. Y. Cho, and F. Capasso, *Science* **302**, 1374-1377 (2003).
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- Momentum Space Design of High-Q Photonic Crystal Optical Cavities, K. Srinivasan and O. Painter, *Optics Express* **10**, 670-684 (2002).

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John Unguris, Project Leader

John Unguris is a Project Leader in the Electron Physics Research Group. He received a B.S. in Physics from Carnegie Mellon University, and a Ph.D. in Physics from the University of Wisconsin. John initially joined NIST as an NRC Postdoctoral Research Associate investigating the application of electron spin measurements to various surface sensitive spectroscopies. Since then his research at NIST has focused on the development of techniques to measure the properties of magnetic nanostructures; in particular, spin sensitive electron microscopy. John has over 80 publications, is a frequent invited speaker at international meetings, and has helped organize numerous workshops and conferences on magnetism. He is a Fellow of the American Physical Society, and has been awarded a Bronze Medal from the U.S. Department of Commerce. John currently leads multiple projects investigating the fundamental physics of magnetic nanostructures.

Selected Publications:

- Size Dependent Transition from Shape to Exchange Dominated Magnetic Nanostructures in Patterned Zigzags, W. C. Uhlig, and J. Unguris, *Journal of Applied Physics* **99**, 08G302 (2006).
- Direct Observation of Spin Configurations and Classification of Switching Processes in Mesoscopic Ferromagnetic Rings, M. Kläui, C. A. F. Vaz, J. A. C. Bland, T. L. Monchesky, J. Unguris, L. J. Heyderman, and Z. Cui, *Physical Review B* **68**, 134426 (2003).
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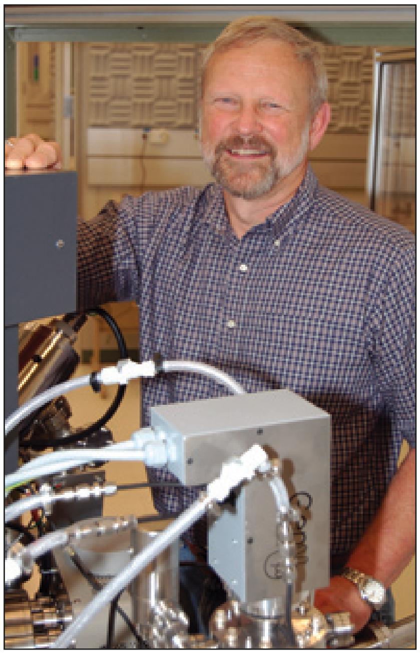

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- Spin and Energy Analyzed Secondary Electron Emission from a Ferromagnet, J. Unguris, D. T. Pierce, A. Galejs, and R .J. Celotta, *Physical Review Letters* **49**, 72-76 (1982).

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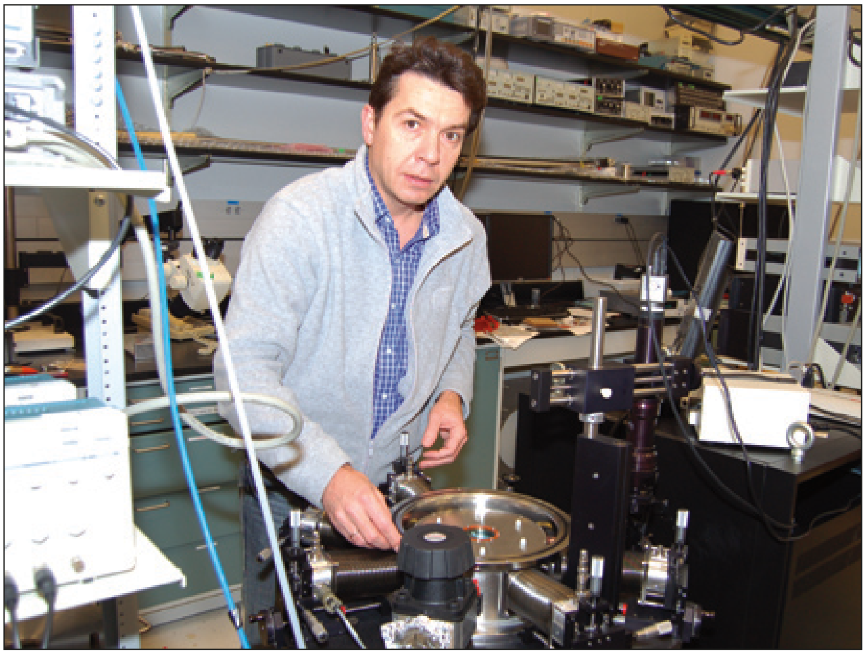
Nikolai Zhitenev, Project Leader

Nikolai Zhitenev is a Project Leader in the Nanofabrication Research group. He received a M.Sc. degree in Physics from the Moscow Institute of Physics and Technology, Russia, and a Ph.D. degree in Condensed Matter Physics from the Institute of Solid State Physics, Russia. After receiving his Ph.D., he was an Alexander von Humboldt Fellow at the Max-Planck Institute for Solid State Physics, Stuttgart, Germany, and then a Postdoctoral Fellow at the Massachusetts Institute of Technology. He then became a staff member at Bell Laboratories, Lucent Technologies, where his research focused on electronic transport in different physical systems, ranging from two-dimensional electron gas in Si, Ge and GaAs, to semiconductor and metal quantum dots, to nanoscale molecular and polymer devices. Nikolai has over 45 publications in high-profile journals including *Science*, *Nature* and *Physical Review Letters*. As a staff member in the CNST, Nikolai leads multiple projects related to the measurement of electronic properties of novel materials patterned into nanoscale devices, and to the development of local electrical measurements using quantum and classical on-probe circuitry.



Selected Publications:

- Chemical Modifications of the Electronic Conducting States in Polymer Nanodevices, N. B. Zhitenev, A. Sidorenko, D. M Tennant, and R. A Cirelli, *Nature Nanotechnology* **2**, 237-242 (2007).
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- Dynamic Excitations of Fractional Edge Channels, G. Ernst, N. B. Zhitenev, R. G. Haug, and K. von Klitzing, *Physical Review Letters* **79**, 3748-3751 (1997).

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Publications, Honors and Awards

Publications: 2007-2008

Imaging the Interface of Epitaxial Graphene with Silicon Carbide via Scanning Tunneling Microscopy, G. M. Rutter, N. P. Guisinger, J. N. Crain, E. A. A. Jarvis, M. D. Stiles, T. Li, P. N. First, and J. A. Stroscio, *Physical Review B* **76**, 235416 (2007).

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Identification of the Dominant Precession Damping Mechanism in Fe, Co, and Ni by First-Principles Calculations, K. Gilmore, Y. Idzerda, and M. D. Stiles, *Physical Review Letters* **99**, 027204 (2007).

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Honors and Awards

In order to highlight the level of excellence of our staff, here we list recognition they have received in 2007 and 2008, including for accomplishments achieved prior to joining the CNST. Although it is too soon for CNST research to be so recognized, we expect great things from our staff.

Amit Agrawal, DJ Lovell Scholarship, SPIE - The International Society for Optical Engineering, August 2007.

Amit Agrawal, LEOS Graduate Student Fellowship, IEEE Lasers and Electro-Optics Society, October 2007.

Robert Celotta, Presidential Distinguished Rank Award, 2007.

Kenneth Chau, Andrew Stewart Memorial Award, April 2007

Kenneth Chau, Optical Society of America New Focus Bookham Award Grand Prize Winner, May 2007.

Kenneth Chau, SPIE Educational Award, September 2007.

Keith Gilmore, 2007 Outstanding Dissertation in Magnetism from the American Physical Society's Topical Group on Magnetism, March 2008.

Young Kuk, Inchon "Academy" Prize, one of South Korea's most prestigious prizes for academic achievement, October 2008.

Joseph Stroscio, NIST Fellow, August 2007.

Daniel Pierce, Inducted into the NIST Portrait Gallery, November 7, 2008.

Gregory Rutter, AVS Dorothy M. and Earl S. Hoffman Award, for continuing excellence in graduate studies in the sciences and technologies of interest to AVS, October 2008.

Lloyd Whitman, Biosensors & Bioelectronics Best Paper Award, 2008 World Congress on Biosensors, May 2008.

Lloyd Whitman, Navy Meritorious Civilian Service Award, April 2008.

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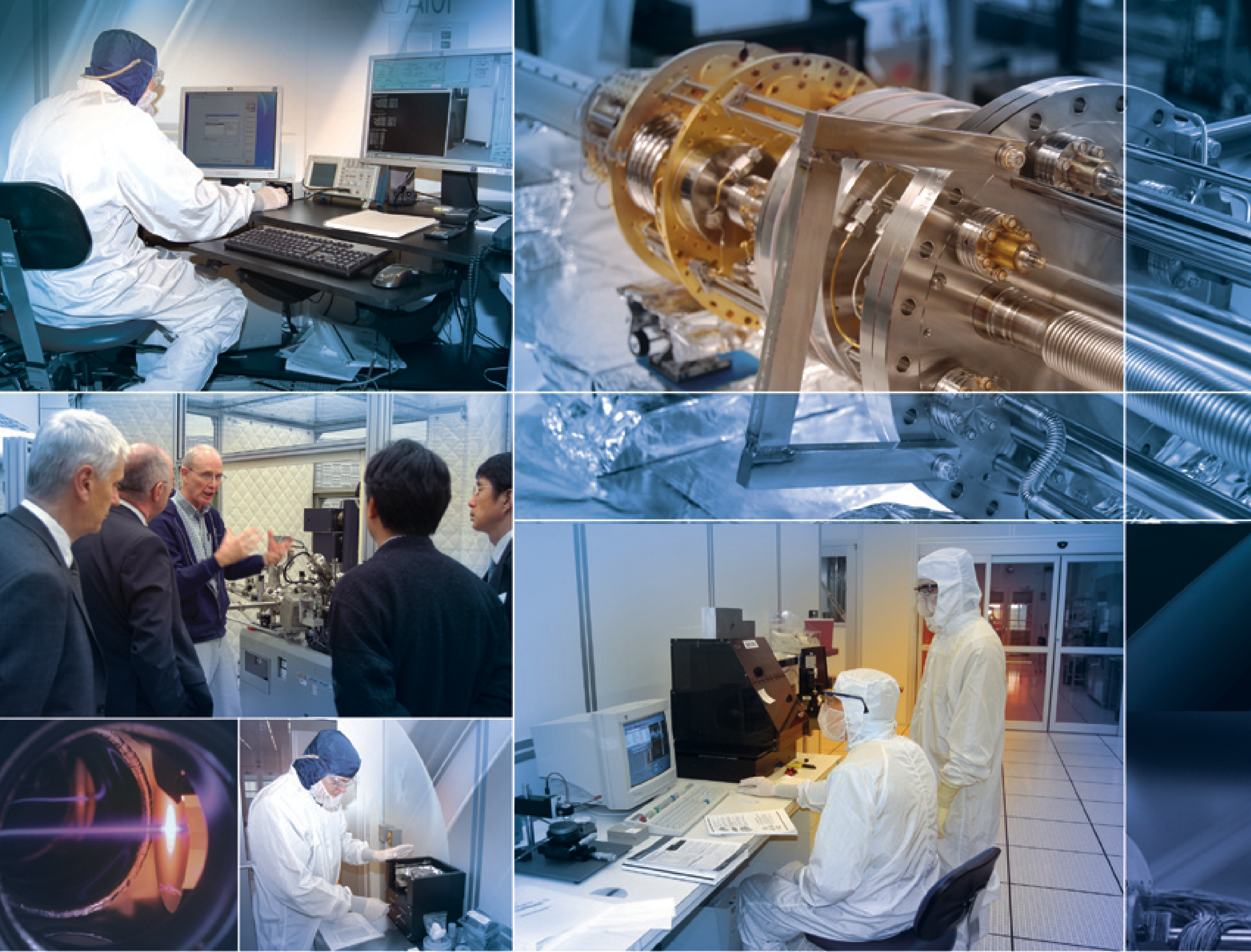

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