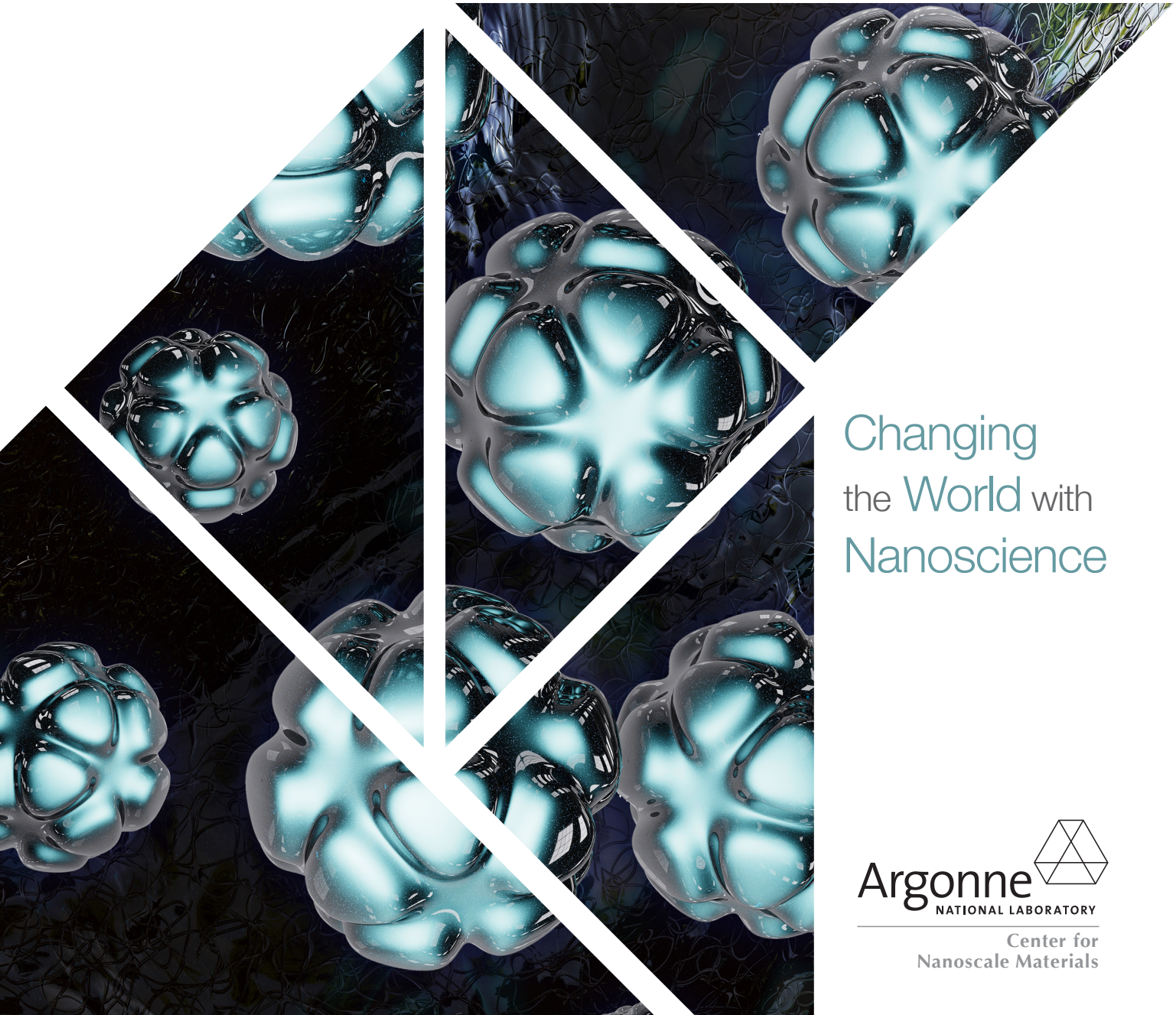
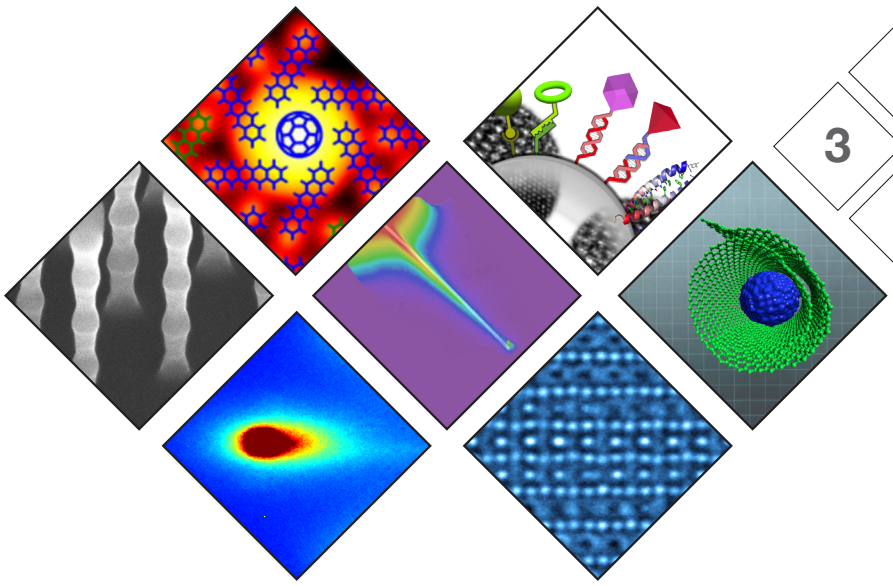
The **Center for Nanoscale Materials** at Argonne National Laboratory

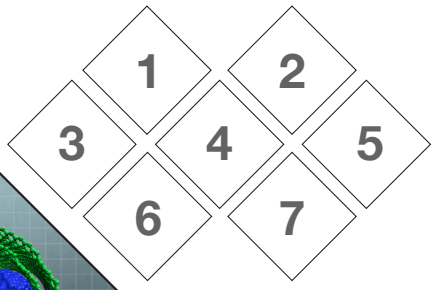


Changing the World with Nanoscience

Argonne NATIONAL LABORATORY

Center for Nanoscale Materials





1. Electronic & Magnetic Materials & Devices
2. Nanobio Interfaces
3. Nanofabrication & Devices
4. Nanophotonics
5. Theory & Modeling
6. X-Ray Microscopy
7. Electron Microscopy Center

Overview

The ability to create, visualize, and manipulate materials at the nanoscale is changing the world of science—leading to many technological breakthroughs that will benefit society from light harvesting for energy to quantum computing.

The Center for Nanoscale Materials (CNM) at Argonne National Laboratory is a premier user facility whose mission is to provide expertise, instrumentation, and infrastructure for interdisciplinary nanoscience and nanotechnology research. Academic, industrial, and international researchers can apply to use CNM for both nonproprietary and proprietary research.

The Center's goal is to support basic research and instrumentation development that explores ways to create functional hybrid nanomaterials and to tailor nanoscale interactions for energy-related research and development programs. Both Argonne staff and outside users carry out research within the Center's primary theme of "Energy and Information Transduction at the Nanoscale." This cross-cutting theme addresses grand challenges in energy and information conversion and transport (transduction), while furthering the Department of Energy (DOE) missions in energy generation, storage, and efficiency.

The CNM is one of the DOE Office of Science Nanoscale Science Research Centers. It was constructed under a joint partnership between DOE and the State of Illinois. Along with Argonne's Advanced Photon Source (APS), CNM shares a Hard X-ray Nanoprobe beamline, which allows unprecedented views deep within nanomaterials. Other premier capabilities include world-class nanofabrication and scanning probe research facilities, an oxide molecular beam epitaxy system, aberration-corrected transmission electron microscopy, ultrafast optical probes, and many other state-of-the-art instruments.

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User Community

The CNM welcomes outside users, both as independent investigators and as collaborators, from a wide range of scientific fields, on the basis of peer-reviewed proposals. The cross-disciplinary approach to nano-related research at CNM enables ideas and activities to cross-pollinate, mature, and evolve over time into the pathways of scientific investigation and discovery that will help shape the future of our society. An external Proposal Evaluation Board reviews user proposals. If allocated, proposals are active for one year or until the allocation allotment has been expended, whichever occurs first. Access is available at no charge for work that is intended for publication or the public domain. Access is also available on a cost-recovery basis for proprietary research that is not intended for the public domain. Safety is an essential part of all work done at the CNM, and users are required to be properly trained before working in its facilities. A Users Executive Committee acts as a liaison between the user community and CNM management, and also organizes the technical program for the annual Users Meetings.

"I consider CNM to be similar to the cultural centers in Renaissance Europe where artists met to push the boundaries of art. Today, scientists from around the world are meeting at CNM to push the boundaries of nanoscience."

Ralu Divan/ Chemist

400-500
users per year

22
countries

40
states

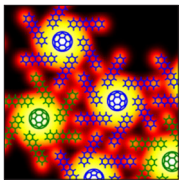
50%
from academia

11,000
square feet of cleanroom space

3
proposal calls per year

30
nanometer resolution of x-ray microscope

>7000
citations per year



Electronic & Magnetic Materials & Devices

The CNM's Electronic and Magnetic Materials and Devices (EMMD) Group seeks to take control of materials at the atomic and molecular scale to better understand and utilize their behavior and properties. By doing so, we aim to pave the way for breakthroughs in new energy conversion and power-efficient energy technologies. Our research consists of several key areas:

- low-dimensional materials such as graphene and heterostructures formed by stacked two-dimensional materials,
- next-generation photovoltaics,
- polymer molecular engineering,
- hybrid magnetic nanoparticles,
- molecular self-assembly,
- single-molecule studies on surfaces,
- atomic-scale investigations of structural, electronic, magnetic, and optical properties of nanostructured surfaces, and
- atomic and molecular manipulation.

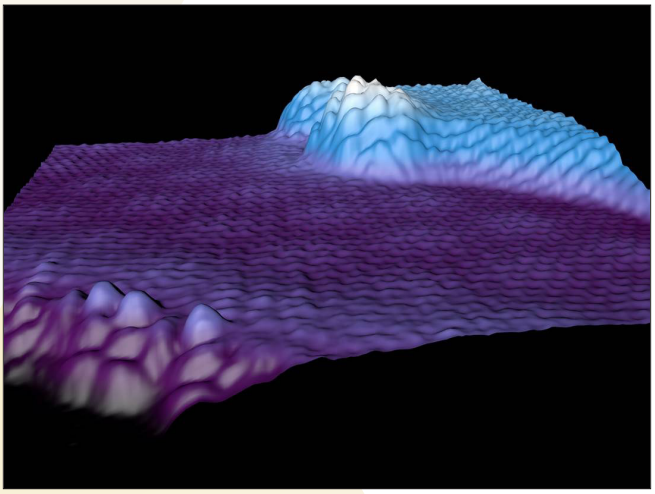
Investigation of nanoscale phenomena often requires experimental approaches that extend beyond conventional techniques. To that end, EMMD exploits highly advanced instrumentation such as ultrahigh vacuum scanning probe microscopy, single-particle laser spectroscopy, molecular beam epitaxy, and novel approaches for hybrid, organic and nanoparticle materials synthesis.

Research Activities

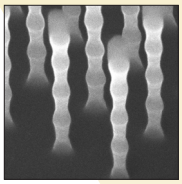
- Synthesis and characterization of low-dimensional materials
- Tailoring of interactions at the nanoscale
- Development of hybrid nanoparticles and nanomaterials for energy applications, novel hybrid organic solar cells, and molecular electronic and spintronic devices
- Atomistic investigations of engineered interfaces
- Nanomechanics of nanofabricated and self-assembled systems

Key Capabilities

- Scanning tunneling microscope operating at varying temperature and ultrahigh vacuum (Omicron VT-AFM/STM and UHV VT-STM)
- Scanning probe microscope (Veeco MultiMode 8)
- Ultrahigh vacuum nanoprobe (4-tip SEM Omicron UHV Nanoprobe)
- Colloidal chemistry and self-assembly techniques
- Complex oxide molecular beam epitaxy (DCA R450 Custom)
- Physical vapor deposition (Lesker CMS 18 and PVD 250)
- Photovoltaics suite: integrated glovebox system, solar simulator, quantum efficiency measurement system



Graphene is a single-atom-thick honeycomb lattice of carbon atoms with many potential applications, including photovoltaics and energy storage. Above is a three-dimensional rendering of graphene showing continuous growth on a platform.



Nanofabrication and Devices

The Nanofabrication and Devices Group is advancing the state-of-the-art in nanofabrication and the fundamental science of nanoscale systems. We seek to achieve unprecedented control in the creation, integration, and manipulation of nanostructures that will form the foundation of functional nanoscale devices. Our main areas of research fall into the following topics:

- Integration of hybrid materials and nanostructures
- Manipulation of nanoscale interactions
- Research on nonlinear phenomena at the nanoscale

We are developing new processes capable of creating features smaller than 10 nanometers through large-area patterning, as well as micro- and nano-electromechanical systems that serve as platforms for manipulation and control of nanostructures.

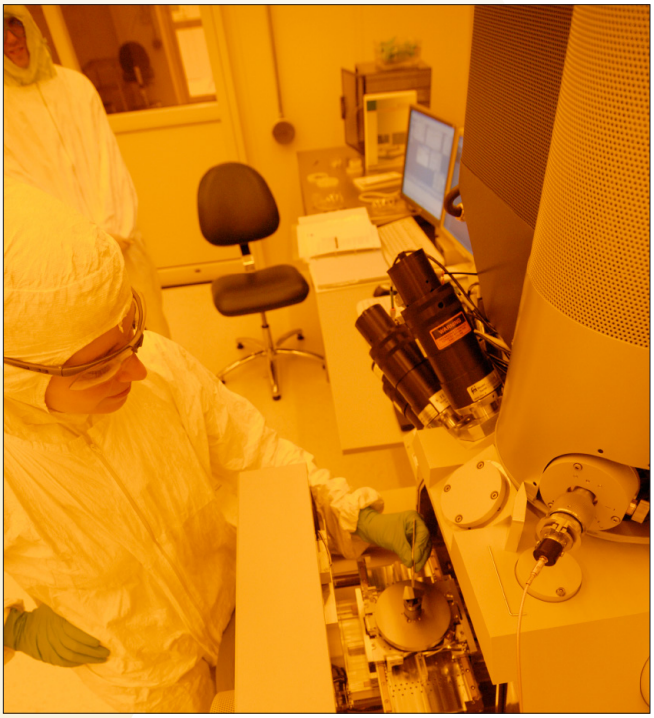
Our research helps to meet the scientific demands of our user community, which requires expertise in nanofabrication and nanodevices and access to state-of-the-art nanofabrication capabilities. A large part of our effort is oriented toward development of novel instrumentation and materials that the user community can exploit to advance its own research programs.

Research Activities

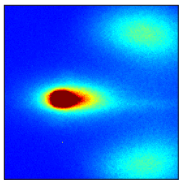
- Processes for achieving sub-10-nanometer critical dimensions with large area patterning
- Development of micro- and nano-electromechanical systems for manipulation and control of nanostructures and for microenergy harvesting
- Integration of novel nanomaterials into devices
- Manipulation of nanoscale interactions
- Nonlinear phenomena at the nanoscale
- Development of novel instrumentation for the CNM user community to advance its own research programs

Key Capabilities

- High- and low-voltage electron beam lithography (JEOL 9300 FS and Raith 150)
- Optical lithography (Karl Suss MA6 and Microtech Laser-Writer 405)
- Nanoimprint lithography (Nanonex NX-3000)
- Focused ion beam patterning/scanning electron microscopy (FEI Nova 600 NanoLab Dual Beam)
- Microwave plasma chemical vapor deposition of nanocrystalline diamond (Lambda Technologies)
- Plasma-enhanced chemical vapor deposition of carbon nanotubes and graphene (Atomate)
- Wide variety of deposition, etching, and metrology techniques



Cleanroom researcher preparing a nanofabrication process via focused ion beam lithography.



X-ray Microscopy

The X-ray Microscopy Group works to apply high-resolution X-ray microscopy to nanoscience. X-ray microscopy is an especially useful tool for examining the structures and defects of materials that often define their properties and behaviors.

We employ Argonne's Hard X-ray Nanoprobe, which uses X-rays produced by Argonne's Advanced Photon Source, to study the structure and characteristics of nanomaterials with embedded or buried features.

The spatial resolution of the nanoprobe can reach 30 nanometers. This tool is also being developed to probe materials *in situ* – under actual working conditions. Such conditions can include high or low temperatures, for example.

One of our main research areas is the investigation of nanoscale critical phenomena, which involves looking at the behavior of structures that affect the function of a material in conditions in which the material undergoes a phase change. These kinds of materials have potential applications for low-power electronics and high-density computer memory.

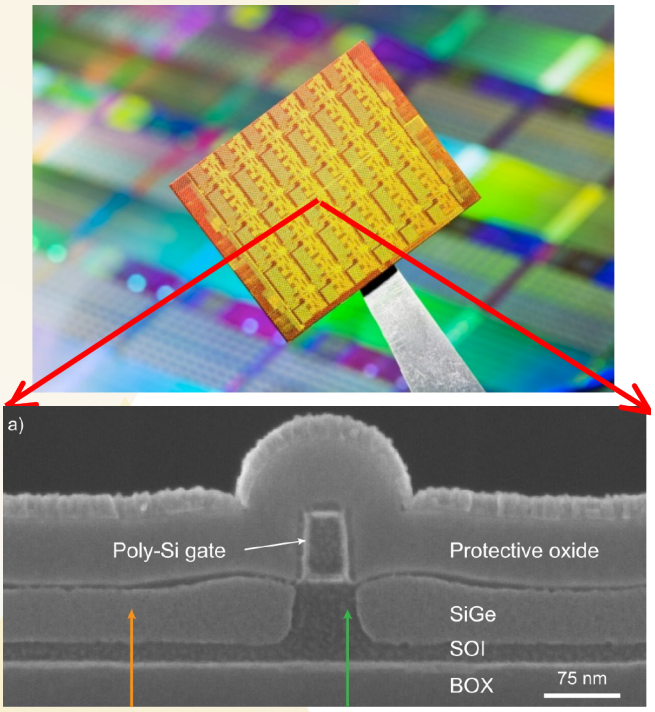
Additionally, researchers in the group are investigating new materials for energy storage by examining changes in the internal structure of batteries undergoing charging and discharging to understand why battery electrodes degrade with use.

Research Activities

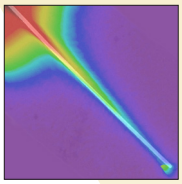
- Nanoscale critical phenomena at phase transitions
- New nanomaterials for energy science
- Nanoscale magnetic ordering and interactions
- Ultrathin and ultradilute systems
- User science that is aimed at understanding strain in systems such as silicon-based devices and resistive RAM systems, distribution of matrix elements in geopolymers and novel nanocomposites, and nanocomposites in tissues and cells

Key Capabilities

- Full-field transmission imaging and nanotomography
- Scanning nanodiffraction and Bragg ptychography
- Scanning fluorescence X-ray microscopy
- *In situ, in operando* experiments



Looking inside "stressed-out" nano-sized objects. Computers depend on tiny transistors that work better when squeezed. New research looks inside individual nanoscale silicon channels, using nano-focused X-ray beams, to see exactly how they respond to pressure. This discovery could lead to better high-performance nanoscale engineered materials for energy applications in general.



Nanophotonics

The objective of the Nanophotonics Group is to understand the fundamental behaviors that govern light-matter interactions and energy flow in nanomaterials. Our research encompasses the prediction, design, creation, and characterization of nanoscale optical materials, with a particular emphasis on energy flow in hybrid nanoparticle systems. For instance, the coupling of nanoparticles with normally disparate properties, such as a metal and semiconductor to form a hybrid nanostructure, can produce completely new optical and electronic properties that otherwise would not be possible.

Nanophotonics research involves acquiring a detailed understanding of the interaction of light with isolated nanostructures. Through the use of advanced spectroscopies and microscopies, with an emphasis on ultrafast time-resolution experiments, Argonne researchers can understand the critical factors that influence the flow of energy following photoexcitation.

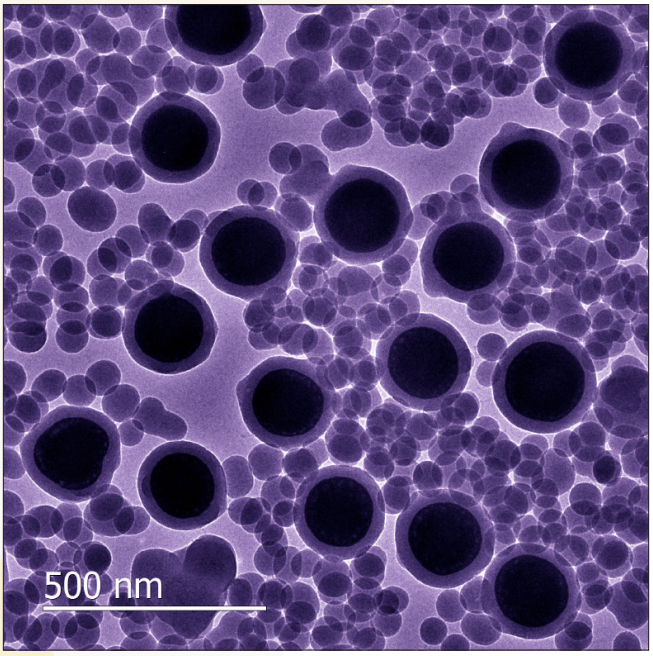
Understanding, managing, and utilizing energy flow when light interacts with single nanostructures are critical for then exploring the optical behavior of coupled hybrid nanoparticles. The ability to realize these nanostructures is at the limit of current technology due to the nanoscale spatial precision that is required. We are thus developing important new approaches to fabricate, characterize, and manipulate nanoparticle hybrid structures with controllable optical properties. This will produce opportunities for new developments, such as photoinduced catalytic processes, novel ultrafast optical switching mechanisms, and energy conversion processes.

Research Activities

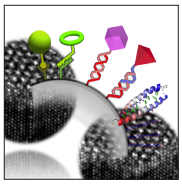
- Energy dissipation and transduction in nanostructures
- Hybrid optical states in coupled nanoparticle systems
- Understanding of light harvesting and charge separation in nanoscale systems

Key Capabilities

- Femtosecond to microsecond transient absorption spectroscopy
- Ultrafast photoluminescence spectroscopy and microscopy
- Confocal Raman microscopy and mapping
- Optically-coupled scanning probe microscopies
- Nanophotonics nanoparticle synthesis laboratory
- Size-selected clusters and cluster-based nanomaterials



Transmission electron microscopy image of hybrid nanoparticles consisting of a silver chloride and platinum core encased in a shell of silica. The surrounding smaller nanoparticles are made of mesoporous silica. These nanostructures are being studied for advanced photocatalysis.



Nanobio Interfaces

The Nanobio Interfaces Group seeks to develop and utilize hybrid nanomaterials that are not found in nature, but that are inspired by nature's principles. Natural systems adopt a large degree of inhomogeneity and disorder to evolve and achieve resilience by harnessing environmental fluctuations. In analogy to nature, our goal is to create artificial materials that adapt and evolve as they are exposed to the environment. With advances in the synthesis of nanoscale materials, we are in position to introduce structural, compositional, and interfacial inhomogeneity that assists materials to evolve and develop desired functionality. By controlling the order in engineered nanomaterials, we can create better solutions for catalysis, solar energy conversion, energy storage, and even cancer therapies.

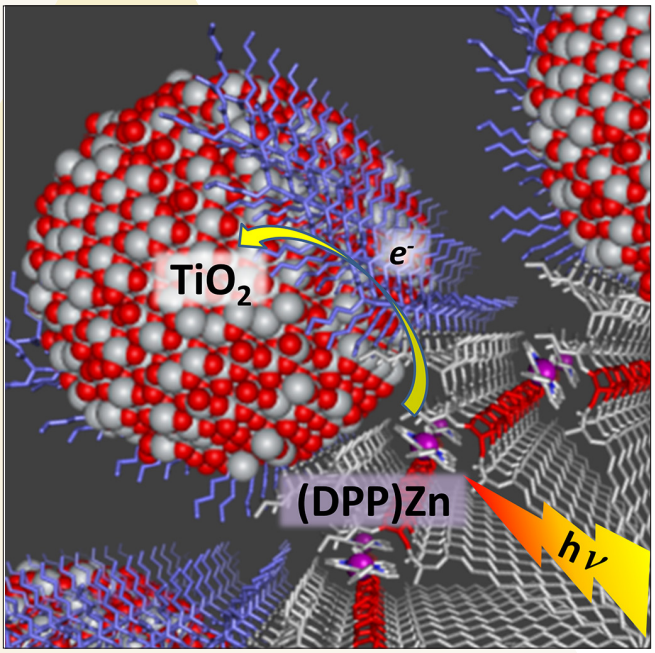
In pursuing the above goal, we use physics-based scaling laws, chemical control (precision), and biological selectivity to develop structures with emergent magnetic, electronic, and optical behavior. The ability to correlate and synchronize interactions of individual constituents enables the design of atom-efficient catalysts and photocatalysts with high selectivity and activity, as well as electrochemical materials with exquisitely controlled ion and electron transport properties. Stimuli-responsive biohybrid materials, guided by the same principles, will provide highly selective and efficient advanced medical therapies.

Research Activities

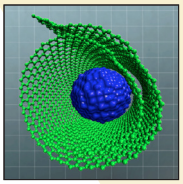
- *Hybrid Systems* – to build new forms of matter with tailored functionalities. Chemical synthetic methods are employed to coax atoms into new spatial arrangements that improve energy transport, charge separation, and chemical reactivity.
- *Visualization of nanoparticle interactions* – to understand, predict, and design physical and chemical interactions that lead to hierarchical architectures capable of energy transduction.
- *Evolution of nanostructures under external stimuli* – to understand dynamic mechanisms of material transformation to achieve correlated (synchronized) interactions of individual constituents that regulate energy and information transduction on the nanoscale.

Key Capabilities

- Specialized synthesis of high-quality metallic, semiconductor, and metal oxide nanoparticles; biomolecule, inorganic, and bio-inorganic composites; and self-assembled hierarchical nanoarchitectures
- Catalysis and photo-initiated catalysis in hybrid organic-inorganic and biomolecule-inorganic materials
- Electrochemical characterization of nanomaterials relevant for energy conversion and storage
- Imaging of dynamic processes using high-resolution transmission electron microscopy, electron paramagnetic resonance, and laser scanning confocal optical microscopy
- Analysis of nanomaterials using field emission scanning electron microscopy and transmission electron microscopy
- Characterization of catalytic and photocatalytic properties of nanomaterials using gas chromatography coupled to mass spectrometry



Interface of a self-assembled array of peptide/Zn porphyrin/titania micelle capable of photo-initiated charge separation with possible photovoltaic applications.



Theory and Modeling

While theory and modeling are essential to most scientific endeavors, they are especially relevant and necessary for nanoscience. This is because of the wealth of information and exciting possibilities that continue to be provided by the many experimental advances in the field. The Theory and Modeling Group develops and applies theoretical methods to better understand the interrelationship between theory and experiment. Recognizing that energy and information transduction occur via many conduits (for example, electrons and ions, atoms and phonons, photons and plasmons), we organize our efforts into the following areas, which we are especially well-positioned to study.

Molecular conversion and transport at interfaces: Our first goal is to understand energy and information transduction through movements of electrons and ions at nanoscale interfaces. Understanding interface physics and chemistry (including nanoparticle catalysis, oxide growth, ionic transport on and across interfaces, hydrophobic and hydrophilic interactions, and numerous other phenomena) is key to the successful exploitation of a wide variety of nanoscale materials and devices.

Atomistic origins of the physical properties of nanoscale material: We also focus on understanding the effects that atomistic arrangements have on measurable physical quantities in the nanoscale (i.e., the role of atoms and phonons). Nanoscale materials can exhibit very different physical properties, such as thermal conductivity, phase transitions, and tribological and mechanical properties, from their bulk counterparts.

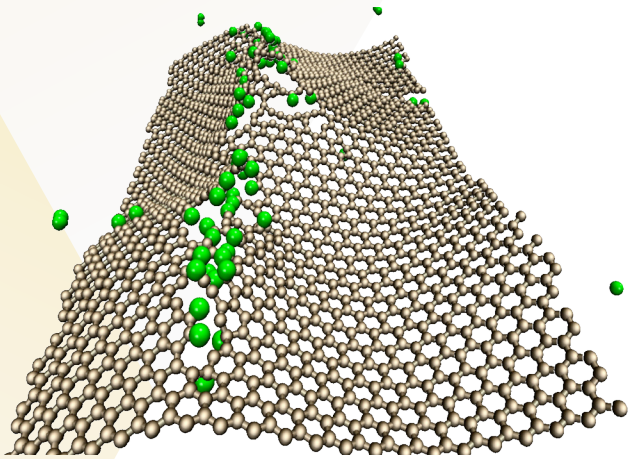
Optical and plasmonic phenomena in nanoscale materials and devices: Finally, we are exploring energy and information transduction processes involving photons and plasmons. The dimensions of metal nanoparticles are such that, even at a classical level, sub-wavelength focusing and other novel optical phenomena can occur. As ever-smaller components are considered in nanoscale materials and devices, quantum mechanical effects can become important, such as in the case of hybrid plasmonic materials that include semiconductor quantum dots.

Research Activities

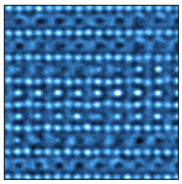
- Electronic structure calculations of catalysis by nanoparticles and other nanomaterials for energy applications, including energy storage, catalysis, photovoltaics, and thermoelectrics.
- Atomistic studies of oxide formation, transport, and nanotribology
- Electrodynamics modeling of light interactions with nanostructures
- Methods and software development, including multiscale approaches to assembly

Key Capabilities

- High-performance computing cluster (2800 cores, 30 TFlops) and development tools (GNU, intel compilers, math libraries)
- Electronic structure (including Dacapo, GPAW, Siesta, VASP, Q-Chem) and molecular dynamics (including LAMMPS and NAMD) software
- Electrodynamics software (including MEEP and Lumerical) and specialized software developed by group members



Computational simulations elucidate the origin of extraordinary wear resistance of one-atom-thick graphene coatings. Reactive molecular dynamics simulations show that hydrogen (shown in green) passivation of the dangling bonds in a ruptured graphene (shown in tan) leads to significant improvement in the stability and lifetime of the graphene protection layer. Tuning the atomistic-scale chemical interactionst may hold the promise of realizing extraordinary tribological properties of monolayer graphene coatings.



Electron Microscopy Center

The Electron Microscopy Center (EMC) develops and maintains unique capabilities for electron beam characterization and applies those capabilities to solve materials challenges. The EMC emphasizes three major areas: materials research, experimental technique and instrumentation development, and operation of unique and state-of-the-art instrumentation.

The goals of the materials research are closely aligned with those of our user community. To achieve those aims, the EMC offers unique capabilities and expertise in imaging and spectroscopy, with particular emphasis on analysis of complex oxides and energy-related materials. Research to develop new capabilities focuses on enhancing detection efficiency for electron beam spectroscopies and developing *in situ* and *operando* microscopy. One of the signature capabilities in the EMC is a chromatic aberration-corrected transmission electron microscope, one of only three such instruments currently operating worldwide.

State-of-the-art support facilities are also available. Specimen preparation is an important part of electron microscopy, and EMC thus has an array of standard specimen preparation facilities. In addition, an Image Analysis Laboratory provides resources for image processing and analysis. The laboratory includes computers and workstations with commercial software for image simulation, modeling, manipulation, and analysis together with input and output devices for image handling.

Key Capabilities

- Argonne Chromatic Aberration-corrected TEM (ACAT): This transmission electron microscope (TEM) has a corrector on the imaging side of the column that corrects both spherical and chromatic aberrations. The corrector also provides greatly improved resolution and signal for energy filtered imaging and electron energy-loss spectroscopy.
- FEI Tecnai F20ST TEM/STEM: This premier analytical transmission electron microscope has specialized accessories that include an X-ray energy-dispersive spectrometer (XEDS), a rotatable biprism for electron holography, and a post-column electron filter for both electron energy-loss spectroscopy (EELS) and energy-filtered imaging. The scanning transmission electron microscopy (STEM) capability enables high-angle annular dark field imaging and XEDS/EELS spectrum imaging, among others. Specimen cooling and heating holders are available.
- Zeiss 1540XB FIB-SEM: This platform accommodates site-specific TEM sample preparation, 3D data acquisition, nanofabrication and manipulation, and other advanced uses. Simultaneous electron and ion scanning offers unique imaging and fabrication opportunities.

Core Instruments

- Analytical transmission electron microscope (FEI CM30T)
- High-resolution, high-vacuum scanning electron microscope (Hitachi S-4700-II)
- High-resolution environmental and variable-pressure scanning electron microscope (FEI Quanta 400F)

Scanning electron microscopy image of graphene-forming crystals when grown on copper; this "snowflake" is about 75 micrometers in size.

Cleanroom Nanofabrication Facilities

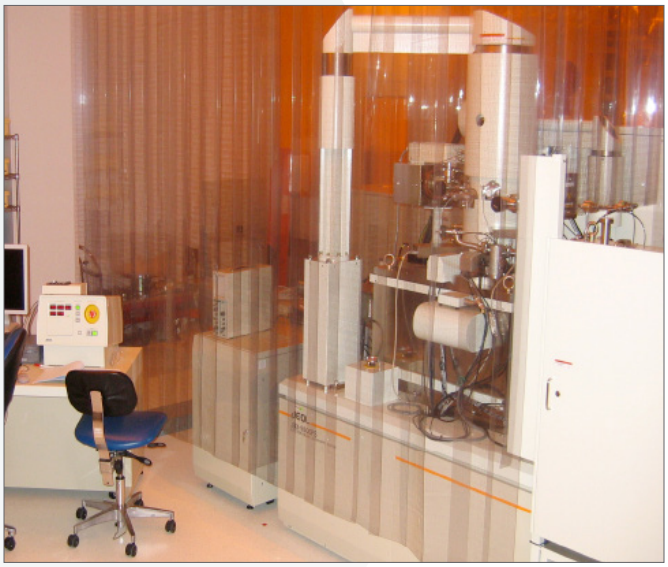
The CNM's ability to fabricate complex nanostructures and devices is based on the advanced tool set housed within the clean room of the Nanofabrication and Devices Group. The clean room spans over 11,500 square feet and contains a remarkable depth and breadth of nanofabrication equipment. Clean room staff has over 100 combined years of relevant experience.

Lithography Suite: Electron beam, ion beam, direct write optical, nanoimprint, and holographic lithography capabilities, as well as contact printing with back-side alignment.

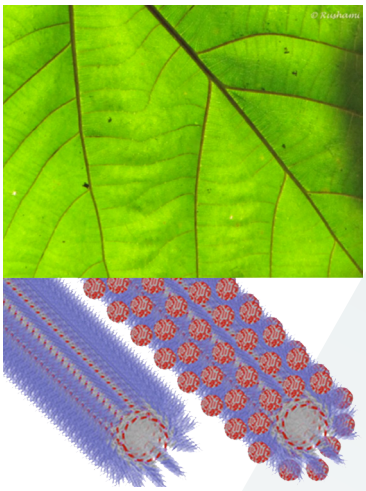
Deposition Suite: Multi-chamber sputtering tools, electron beam evaporation, and plasma-enhanced chemical vapor deposition for production of dielectric and metal films. Also, microwave-plasma chemical vapor deposition for production of diamond films and an Atomate system for production of carbon nanotubes and graphene.

Wet Etch Bay: Electroplating, an electrochemical workstation, and supercritical drying capability for post-processing, including a dual-chamber Oxford Instruments Plasmalab 100 and two tabletop March Plasma reactive ion etchers. Also, various metrology tools, including profilometers, a spectroscopic ellipsometer, and an atomic force microscope.

Biohazard Level-2 Biobay: Functionalization of surfaces with biomolecules without breaking device cleanliness protocol.

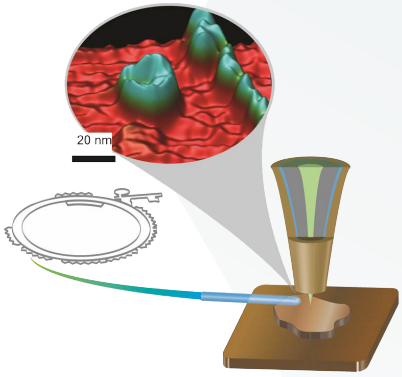


Success Stories



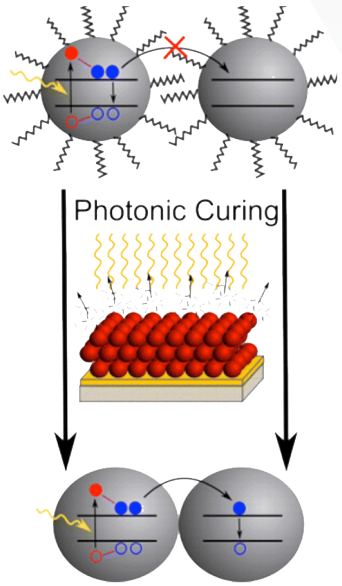
Learning from Mother Nature

In natural systems, electron flow is assisted by proteins that organize donor and acceptor molecules with great precision. Researchers in CNM have created the first self-assembled organic fibers, specifically peptides, that organize electron flow and charge separation in a way similar to the photosynthetic process in a leaf, for example. The degree of charge separation can be finely controlled through variations in the peptide sequence. This is the first example of a complex peptide assembled from simple starting precursors to yield an organized and functional, dye-sensitized semiconducting material. The new approach offers an elegant means to spatially control components artificially. Achieving a guided, directional flow of electrons is a desirable feature for photovoltaic applications.



Elemental Fingerprinting of Materials with Sensitivity at the Atomic Limit

Scanning tunneling microscopy (STM) offers a finer degree of spatial resolution than virtually any other imaging technique, although it has one significant drawback: it does not provide direct information about the chemistry or the magnetic properties of the material. Overcoming this “chemical blindness” has proved challenging. A new technique of synchrotron X-ray scanning tunneling microscopy unites STM with the synchrotron X-rays provided by the Advanced Photon Source. As illustrated by the adjacent image, researchers in CNM achieved chemical fingerprinting of individual nickel clusters on a copper surface at lateral resolution of 2 nanometers, along with height sensitivity of a single atom. Moreover, they measured the photoionization cross sections of a single Ni nanocluster. This new technique opens exciting opportunities for the chemical imaging of nanoscale materials.



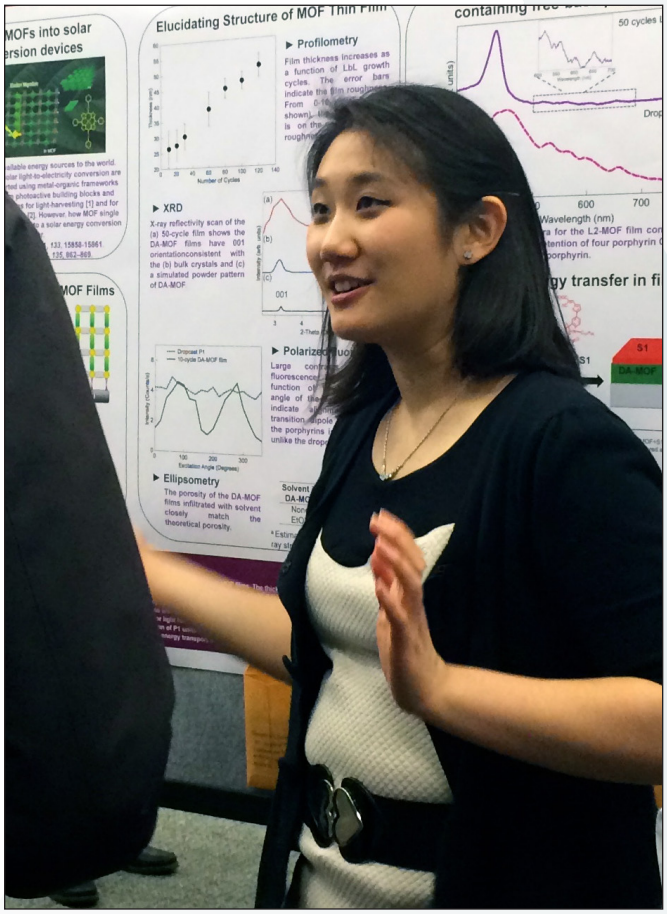
When Getting the Blues is Good for Solar Cells

A new, inexpensive nanomaterial using a process dubbed “photonic curing” was developed for solar cells by a user team led by B. Korgel at the University of Texas at Austin. This material is capable of generating multiexcitons, which help to increase the amount of electricity generated. This new technology has the potential to capture and convert solar energy – especially from the bluer part of the spectrum – more efficiently than ever before. An exciton is a mobile concentration of energy in a crystal formed by an excited electron and an associated hole. Specialized spectroscopic equipment at the CNM has detected these multiexcitons. An inexpensive thin-film semiconductor, nanocrystalline $CuInSe_2$, was created by photonic curing to vaporize organic molecules that inhibit multiple exciton extraction. The accompanying image illustrates the removal of capping ligands from the area where multiexciton transport occurs.

Outreach Programs and Activities

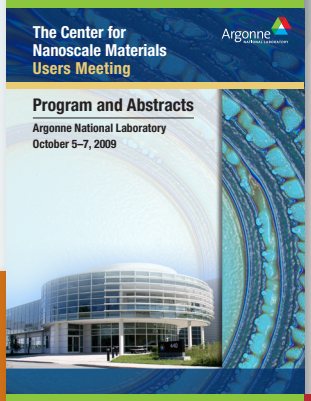
The CNM's outreach programs raise awareness about the unique features, capabilities, and expertise that keep our center on the cutting edge of nanoscience and nanotechnology research. They also provide an avenue for CNM staff scientists to interact with the general public.

- Annual Users Meeting with plenary sessions, workshops, poster sessions, and a vendor expo
- Technical workshops on various scientific topics in nanoscience and nanotechnology
- Short courses that offer tutorials and hands-on training on various instruments and capabilities
- Facility tours
- Triannual newsletters
- Facebook page
- Educational outreach and public awareness events



Timeline

The CNM facility was completed in October 2006, and much of the staffing took place during the next year when it reached full operations mode. The CNM continually adds capabilities and expertise that keep pace with nanotechnology advancements and that address the desires of our diverse user community.

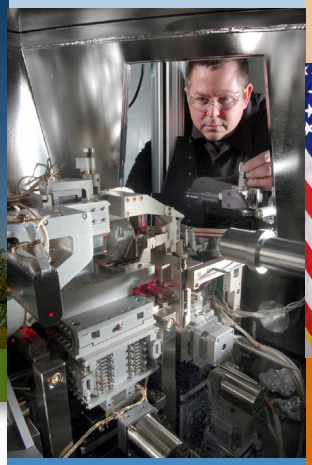


2006

- October, CNM opens Building 440
- Inaugural Users Executive Committee is formed

2007

- Hard X-ray Nanoprobe at APS Sector 26 commissioned
- High Performance Computing Cluster Carbon makes "Top 500" world's fastest computers

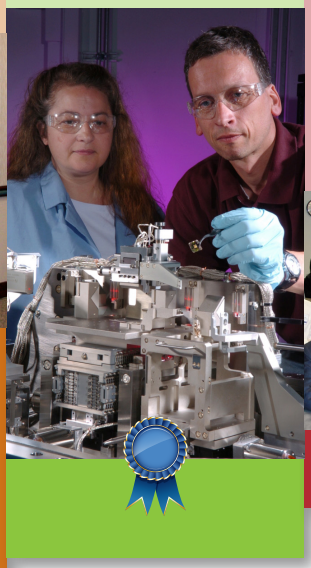


2008

- Safe Handling of Nanoscale Materials Workshop
- Yugang Sun wins Presidential Early Career Award for Scientists and Engineers

2009

- A CNM-only users meeting is held
- Scanning Probe Microscopy facility (Building 441) is built
- R&D100 Award for Hard X-ray Nanoprobe

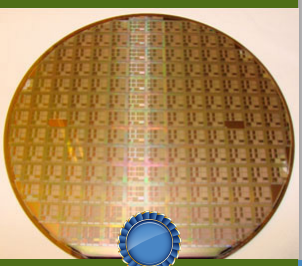


2010

- Joint meeting for CNM/APS/EMC users held annually from this year
- High School Talent Fellowship Program started
- Magnetism in Micro- and Nano-electromechanical Systems Workshop
- Raman Microscopy in Nanoscience Workshop

"By understanding the properties of nanomaterials, we can not only understand the fundamental phenomena, but also there may be opportunities to apply them to the good of human kind."

Saw Wai Hla/ Physicist

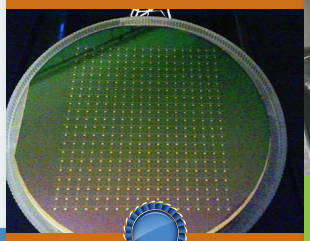


2011

- R&D100 Award for Radiofrequency Micro-mechanical System Switch
- Greeley wins DOE early career award
- Shevchenko wins Distinguished Performance Award and Presidential Early Career Award
- Chemical Synthesis of Nanoparticles and Catalysis Workshop

2012

- Rose wins DOE early career award
- Carbon for Micro- and Nano-electromechanical Systems Workshop
- NSRC Workshop on Nanoparticle Science



2013

- R&D100 Award for Miraj Diamond
- Wiederrecht and Rozhkova win Distinguished Performance Awards
- Wood wins Outstanding Service Award
- User Facilities for Industry Workshop
- National User Facility Organization Exhibition on Capitol Hill

NATIONAL USER FACILITY ORGANIZATION

2014

- October, EMC joins CNM
- R&D100 Award for Nanofab Lab in a Box
- R&D100 Award for Sequential Infiltration Synthesis Lithography
- International Workshop on Nanoscale Spectroscopy and Nanotechnology

2015

- APS/CNM Users Meeting in May
- New scanning probe microscopy and electron paramagnetic resonance (EPR) capabilities become available

"Science is actually a team sport. You cannot win a football game with just a quarterback. You really need a team of people interacting together, and we at CNM have that team."

Volker Rose/Physicist

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On the cover:
Cartoon representation of temperature-responsive magnetic nanomicelles that can serve as thermal energy sources and cargo carriers for controlled drug release (Vitol et al., Advanced Materials Interfaces, DOI: 10.1002/admi.201400182)

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