A simple processing step to define a structure of 30 atoms across, such as the gate of a small electronic transistor, requires:

- An understanding, through chemistry and materials science, of the growth of oxides and semiconductors
- Formation of a pattern in an organic layer through advanced tools, such as electron-beam lithography, that were derived from electrophysics and chemistry
- Transfer of this pattern into the semiconductor through a gaseous etching process that came about from efforts in chemical engineering and plasma physics

J.P. Krusius

Cornell Nanofabrication Facility

Providing the Core of Interdisciplinary Research That Is Revolutionizing Nanoscale Science and Technology

Any research in verifying predictions of theories, discovering new phenomena, or creating prototypes for engineering structures, devices, circuits, and systems requires a complex effort in fabrication of the experimental apparatus. In the case of experiments at the nanoscale, this fabrication, which is performed at the Cornell Nanofabrication Facility (CNF), takes advantage of techniques (or fabrication processes as engineers like to call them due to their background in the semiconductor industry) from a multitude of disciplines. The structural form of the end result is applicable to research in electronics, physics, chemistry, biology, materials science, and mechanical engineering.

Interdisciplinarity of the research and its techniques are central to work at the nanoscale. Research at these dimensions requires extensive knowledge of the interactions between the fabrication process steps and the use of a large number of very complex and expensive tools. The most advanced, state-of-the-art tools and a technical staff who keeps the tools functional are critical to the success of experiments. Experiments themselves can have a variety of characteristics. An investigation to study the electronic property of a single molecule may involve an experiment at the limits of capability in defining the smallest dimensions and requires a careful orchestration of 15 to 20 processing steps. On the other hand, an experiment to demonstrate a new circuit technique utilizing an electronic device at small dimensions may require 150 to 200 processing steps, and place a premium on reproducibility rather than the limits of dimension. All of these efforts must be executed in an environment where a large number of users (nearly 600 in 2001 at CNF) can accomplish their research at a desirable pace. Research, safety, and accommodation must all be achieved at their best simultaneously. This intricate juggling of demands, disciplined use, knowledge, and an expensive tool set are the characteristics of a successful nanostructure fabrication facility.

"Research at these dimensions requires extensive knowledge of the interactions between the fabrication process steps and the use of a large number of very complex tools."

CU

CNF came into existence 25 years ago when a group of faculty members from electrical engineering, applied physics, and materials science came together under the leadership of Joseph M. Ballantyne, Electrical and Computer Engineering, to win the first NSF competition for the establishment of the National Research and Resource Facility in Sub-Micron Structures. Under Edward D. Wolf, Electrical and Computer Engineering, the first centralized cleanroom facility on a U.S. university campus was established as the Lester B. Knight Laboratory (1981). The commitment

Charles Harrington/CU

Joseph Ballantyne, Electrical and Computer Engineering

Joseph Ballantyne won the first NSF competition in 1977... Edward Wolf established the first centralized clean-room facility, the Lester B. Knight Laboratory (1981)

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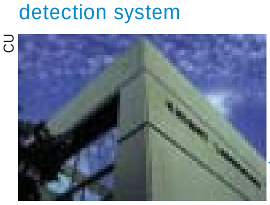
The Stepper

Y. H. Lo

▲ MEMS coherent optical detection system

Zimmer Gunsul Fransca Partnership

▲Duffield Hall, a commitment to Cornell's continued success in nanoscience and technology



CU

◂ Knight Laboratory housed the first centralized cleanroom facility on an U.S. university campus

M. Morgan/Edtek

to this laboratory building, similar to the commitment today to Duffield Hall, is the clearest indicator of the value that Cornell places on nanotechnology and interdisciplinary research.

Two decades ago, CNF was the leader in high frequency and optoelectronic devices, superconductivity and Josephson junctions, and e-beam (electron-beam) lithography. Today, CNF is the leader in three-dimensional nanoelectronic integration, nanomagnetics, observations of unique spin effects, resists, and nanobiotechnology. The Nanobiotechnology Center and the Center for Nanoscale Systems are two recent examples of Cornell's success made possible by the research performed in CNF. Research in the Cornell Center for Materials Research also takes advantage of the fabrication capabilities of CNF.

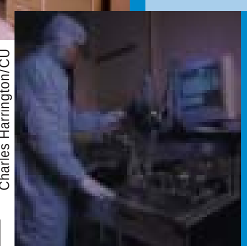

Charles Harrington/CU


Charles Harrington/CU

CNF is open to Cornell and outside users, and nearly half from academia and industry come from outside, bringing with them new ideas and augmenting the intellectual fermentation that makes CNF a special place. This intellectuality also leads to industrial outgrowths. Work performed at CNF has led to the formation of several start-up companies. Recent examples include Kionix, Agave, BinOptics, Quantera, and Galayor.

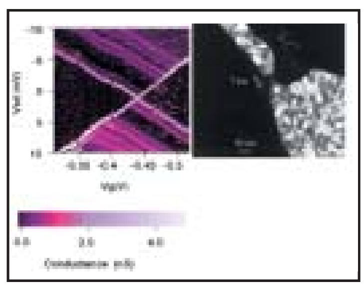

Charles Harrington/CU

The following examples highlight current research at CNF with a focus on the phenomena of small dimensions and use of the phenomena in a variety of fields.

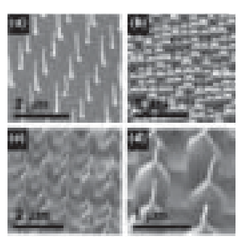

Charles Harrington/CU

Nanoscale Chemistry, Physics, and Materials

Daniel C. Ralph and Paul L. McEuen, Physics, Cornell, study charge transport with proximal probes. They are developing several techniques for incorporating nanometer-scale materials into functional electronic devices. They have pioneered measurements of the quantum transport properties of metal and semiconductor nanoparticles and also carbon nanotubes. They have fabricated single-electron transistors in which charge flow occurs through electronic states on a single ion within one molecule. The crucial fabrication steps that make these devices possible are e-beam lithography on oxidized silicon at near 10 nm dimensions, the formation of molecular-length gaps using electromigration, and the placement of synthesized molecules using self-assembly.


Quantum resonances in single-molecule transistor and a nm junction.

Michael L. Simpson, University of Tennessee-Knoxville / Oak Ridge National Laboratory, develops microfabricated field emission devices using carbon nanofibers. His group uses CNF to fabricate defect-free arrays of robust field emitters with low turn-on field and stable operating characteristics in moderate vacuum. They have fabricated a prototype array of Vertically Aligned Carbon Nanofibers (VACNF) with very attractive physical and electronic properties. The e-beam emitted by VACNF is well focused, demonstrating the promise of this approach for making arrays of programmable parallel electron emitters.


Array of vertically aligned carbon nanofibers

Optics and NanoPhotonics

Nanofabrication plays an important part in advanced photonic structures that support optical communications and computing technologies. Advanced device structures (lasers, gratings, detectors, waveguides) can be fabricated, as well as novel, artificially structured materials. Advanced e-beam lithography is central to this effort.


Charles Harrington/CU

Photonic bandgap structure

Pallab Bhattacharya, Electrical Engineering and Computer Science, University of Michigan, uses CNF to fabricate InP-based photonic crystals. The goal of this project is to use photonic bandgap structures to develop novel light sources for use in future optical communications with high-power efficiency, single-mode operation, narrow spectral line–width, and directional output. In this work, InP-based devices were fabricated for the first time at CNF utilizing a unique nanofabrication approach developed at the facility. The fabrication of the structures, using patterning, dry-etching, and lift-off techniques, has allowed the demonstration of the unique properties of photonic bandgap structures and their use in semiconductor lasers.

Trench detector

Sandip Tiwari, Electrical and Computer Engineering, Cornell, and graduate student Jeremy Wahl study novel silicon optoelectronic integration. Silicon is the common platform for most of the large-scale integration electronics. However, it is an optically poor material and is difficult to use in implementations involving photonic communication. Tiwari and Wahl have developed a new vertical diode structure that allows efficient detection of optical communication signals while providing for compatibility with electronic integration. They demonstrated ultra-high responses and low-power operation for this structure, and they are utilizing it for optoelectronic applications in wavelength detection multiplexing and in biological applications involving fluorescence signal detection.

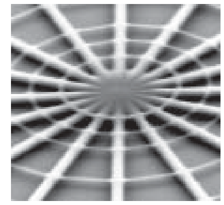
Nanoscale Electronics

Polysilicon gate

Sanjay Banerjee, Electrical and Computer Engineering, University of Texas-Austin, addresses scaling challenges in nanoelectronics by using higher electron mobility materials on silicon substrates, as compared to those used currently. CNF helped this group to fabricate nanometer-scale polysilicon gates and to demonstrate attractive electronic properties suitable for circuits with massive integration levels well beyond what is possible today.

MEMS and NEMS

Micromechanical structures (MEMS) and devices emerged as a significant technology in the 1990s. CNF made significant contributions to this field, as researchers sought open facilities with the flexibility to try new processes, materials, and designs outside the scope of traditional microelectronics. MEMS continue to have a strong presence in CNF with both academic research and strong commercial exploitation. While initially a strictly “micro” technology, mechanical structures with nanometer dimensions are becoming increasingly important for applications in biology. As the technology matures, research in nanomechanical systems will continue to grow.



Nanomechanical oscillator

David Tanenbaum, Physics and Astronomy, Pomona College, studies novel fabrication processes for nanomechanical devices. He has developed a major new technique, called the DEGLaSS (Dual Exposure Glass Layer Suspended Structure) process, for fabricating nanomechanical systems. This technique has been successfully applied to fabricating very high quality oscillators with a quality factor between 10^3 to 10^4 at frequencies of 7 to 30 MHz. The process is very versatile and is capable of producing more complex structures with higher resolution instrumentation. This would nearly double the frequencies and Quality Factor. These novel nanomechanical systems open an exciting avenue of basic and applied research in nano-oscillators to be used in signal processing and biological studies.

Biosystems at the Nanoscale

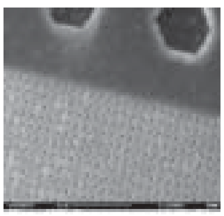
Lois Pollack, Applied and Engineering Physics, Cornell, studies macromolecular folding. She investigates the macromolecular scattering capabilities of the Cornell High Energy Synchrotron Source (CHESS) with the advanced fabrication capabilities of CNF. Pollack builds flow cells at CNF to study the folding process with high time resolution. (See also NBTC, page 8.)

Michael S. Isaacson, Applied and Engineering Physics, Cornell, explores insect neural networks using microfabricated electrode arrays. He studies how groups of neurons compute by simultaneously recording the electrical activity of the neurons that constitute the network. This requires fabrication of multiple recording sites with high spatial resolution, which needs to be compatible with the biological environment in which they are placed. Andrew Spence, a graduate student at Cornell, has fabricated such arrays and is studying the cricket ventral nerve cord and the stalk-eyed fly larva.

Harold G. Craighead, Applied and Engineering Physics, Cornell, researches nanofluidic devices for molecular separation and detection. Craighead has fabricated nanostructures that can perform common tasks of molecular biology in improved ways. E-beam lithography is used to fabricate molecular-sized features that can contain, sort, and characterize single biological molecules. Several methods are used to

"Today, CNF is the leader in three-dimensional nanoelectronic integration, nanomagnetics, observations of unique spin effects, resists, and nanobiotechnology."

achieve this: the use of nanochannels to guide and contain single biological molecules, the use of near-field apertures that are fabricated in thin aluminum films using e-beam lithography, and the use of sharp metal tips for field enhancement during characterization. Excitation volumes as small as 30 zeptoliters (30×10^{-21} liters) have been demonstrated by this approach. Single molecules have been observed at concentrations as high as 100 micromoles.



Entropic traps

Another aspect of this project is the fabrication, using e-beam lithography, of an array of entropic traps that can be used to separate long DNA molecules ranging from 10 to 100 kilobase pairs (kbp). The entropic traps consist of microscopic reservoirs connected to arrays of nanochannels under a pulsed electric field. The novel device fabricated at CNF allowed successful analysis of DNA molecules ranging from 5 to 160 kbp, with much greater efficiency than conventional pulsed field gel electrophoresis. This research aims to make further improvements in resolution in order to make this technique applicable to longer DNA chains. (See also NBTC, page 9.)

These projects illustrate CNF's leadership in nanotechnology, the immense contribution CNF makes to Cornell's leadership in nanotechnology, and the importance of CNF to the nation, to science and engineering, and ultimately to the well-being of humans.

Sandip Tiwari
Lester B. Knight Director of the Cornell Nanofabrication Facility and Professor of Electrical and Computer Engineering

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Doug Hicks

- Daniel Ralph and Paul McEuen, Physics
  Develop techniques for incorporating nanoscale materials into functional electronic devices

CU

- Sandip Tiwari, Director, CNF; Electrical and Computer Engineering
  Studies novel silicon optoelectronic integration

Nicola Kountoupes/CU

- Lois Pollack, Applied and Engineering Physics
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