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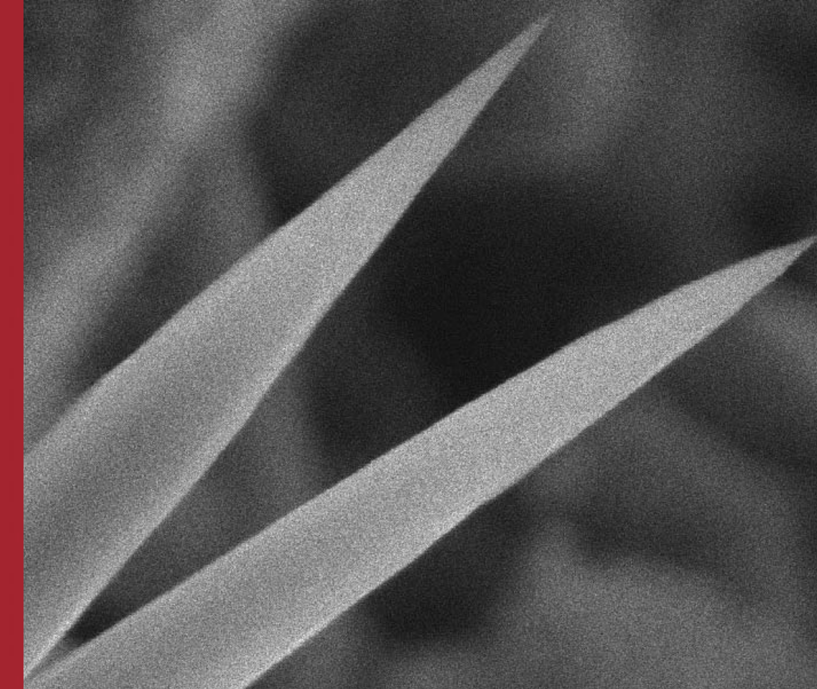

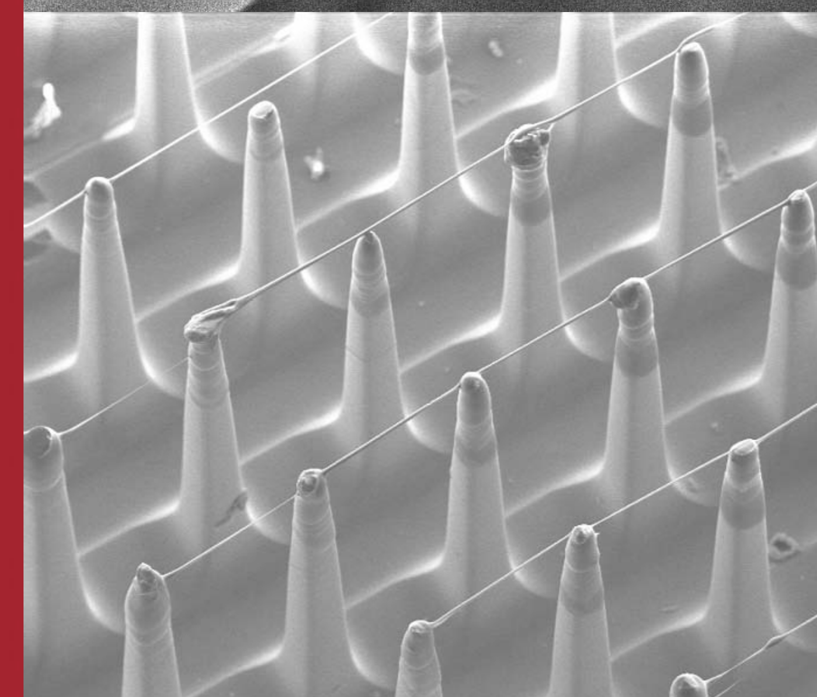

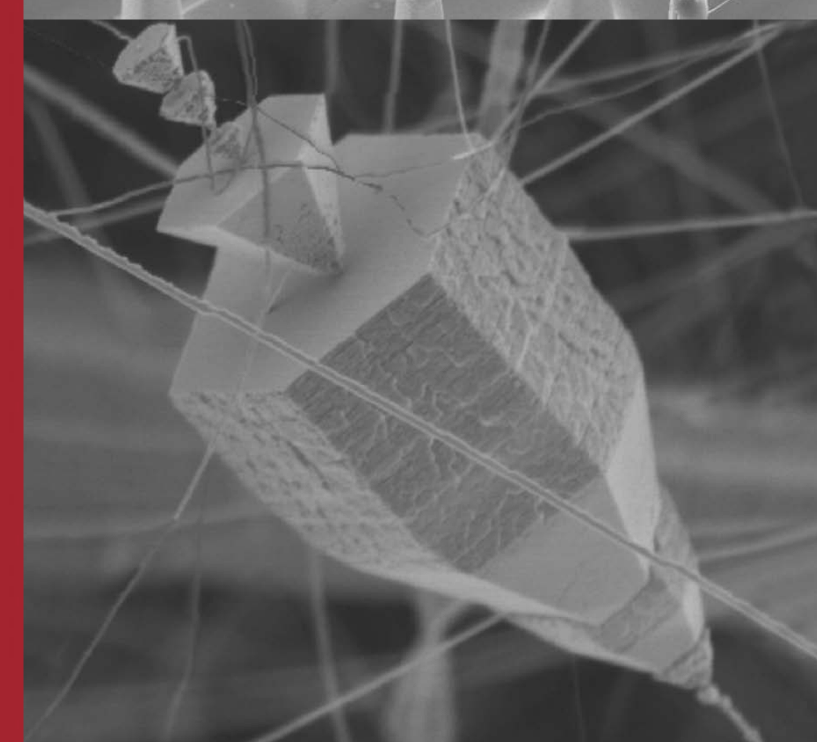

Nanomaterials and Devices R&D at ERINC

The ElectroOptics Research Institute & Nanotechnology Center

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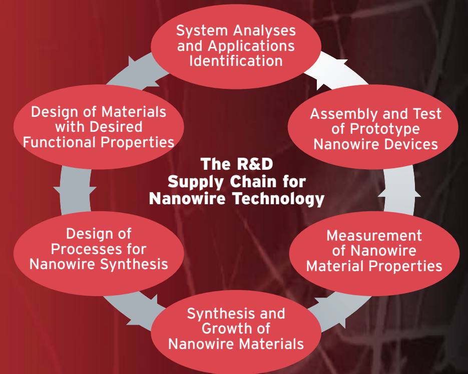


The University of Louisville (UofL) provides extensive R&D capabilities and services for federal agencies, industry, and other academic institutions in nanotechnology, microsystems technology, bio-device technology, and advanced materials. A major portion of these activities are being co-located in the center of campus in Lutz Hall and the new Belknap Research Building. The nanotechnology faculty from the ElectroOptics Research Institute and Nanotechnology Center (ERINC) share over 40,000 sq. ft. of space in these centralized facilities, including a new seven-bay 10,000 sq. ft. class 100 microfabrication cleanroom, 5,000 sq. ft. of core facilities devoted to advanced materials analysis, and parallel computer systems devoted exclusively to computational materials analysis. A major focus of the nanotechnology faculty is nanowire technology, including computational and experimental studies of functional properties and growth processes, production scale-up, integration-fabrication, and selected growth of nanowires into demonstration devices and systems studies, as well as identification of novel applications of nanowire materials.

This brochure provides a further introduction to our capabilities. The ERINC faculty and researchers would be pleased to assist you in your research and development activities. We can support your organization through research, service or consulting contracts, joint collaborative studies, material transfer agreements, and assistance with proposal development.

On the Cover:

a. Carbon nanopipettes that are hollow with a 1 nm inner diameter and tapered to a sharp point of a few nanometers tip radius.
b. Suspended PMMA polymer fibers that were self-assembled by a manual brush-on procedure. Fibers as small as 30 nm have been formed this way.
c. Gallium nitride crystallite grown on the end of a GaN nanowire that provides microscale handles for simpler contacting and manipulation of nanowires.

ERINC's Nanotechnology Focus

- Modeling, design, synthesis, and measurement of enhanced physical properties of 1 to 100 nanometer materials.
- Synthesis of novel nanowires and other unique nanostructured materials.
- Development of nanowire growth processes that can be scaled up for industrial applications.
- Design, assemble, and demonstrate novel micro and nanosystems and multifunctional devices enabled by nanowire materials; e.g., nanoelectronic, optical (MOEMS), mechanical (MEMS/NEMS), and microfluidic (MicroFlips) devices.
- System analysis, applications identification, and prototype development for government and industry.

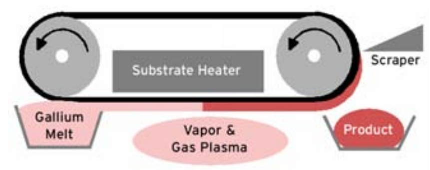
Nanomaterials

Nanowires
Nanowires, due to their nanometer-scale diameter and microns to millimeters of length, provide properties of nanoparticles (e.g., quantum confinement) together with improved control over diameter, crystal perfection, and greatly simplified attachment into macroscopic systems. The unique patented processes of the University of Louisville ERINC are especially notable for their control of diameter, diameter taper, length, crystalline orientation, and degree of perfection during synthesis. These characteristics permit us to tailor the properties of these materials for your specific applications. Our nanowire growth methods have been used to synthesize a variety of nanowire materials, including elemental metals, semiconductors, oxides, nitrides, phosphides, sulphides, arsenides, and antimonides (see table below).

Nanowires grown by UofL - patented processes:

Elemental	Si, Ge, Ni, Fe, Bi, W
Nitrides	GaN, InN, AlN, Si_xN_y, WN_x
Phosphides & Sulphides	GaP, InP, Ga_2S_3, In_2S_3
SiGe & Antimonides	Si_xGey, InSb, GaSb
Oxides	SiO_x, GeO_x, In_2O_3, Al_2O_3, Ga_2O_3, SnO_2, TiO_2, Nb_2O_5, V_2O_5, Ta_2O_5, Bi_2O_3, Fe_2O_3, NiO

Many other compositions are feasible and can be grown on request. Both crystalline and amorphous wires can be grown.



Planned nanowire production reactor (kgs/day) that has rapid reaction capability.

Carbon Nanomaterials
- Single-walled, multi-walled, and double-walled carbon nanotubes.
- Carbon nanotubes functionalized and/or filled with C_{60} buckyball, lithium, etc.
- Tapered carbon pipettes, large diameter carbon tubes, tapered carbon funnel shapes.

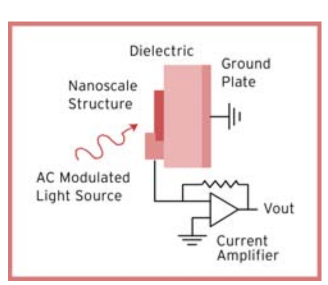
Nanostructured Materials
Shape and structure of directly grown materials, as well as of composites, provide enhanced or new functions. Examples of various structures grown at UofL include:

- Tapered carbon pipettes and needles, inorganic ribbons and tubes, heterostructured/hybrid wires, webs, mats, carpets, ropes and bundles of ropes.
- Growth of large tapered crystals on the ends of nanowires ("handles").
- Well dispersed and well suspended solvent and liquid polymer solutions of nanowires.
- Electrospun and/or self-assembled polymer, sol-gel, and composite polymer/nanowire fibers.

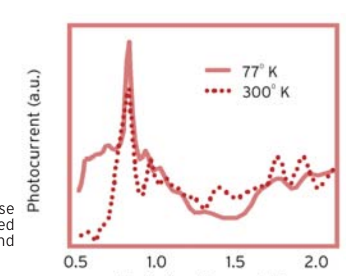
Nanomaterials Growth Capabilities
- A variety of reactors, including combined microwave/ECR/thermal CVD, hot wire filament CVD, and fluidized bed reactors which provide a range of processing conditions, the ability to study issues related to production scale up, and the establishment of uniform growth conditions across entire semiconductor wafers (i.e., wafer-level processing).
- In addition to our patented nanowire growth processes, we routinely use conventional methods of chemical vapor deposition, arc growth, and pulsed laser vaporization for the growth of carbon nanotubes (single, double and multiwalled) and nanowires (GaAs, GaP, Si, $GaAs_xP_{1-x}$, Ga_2O_3, MgB_2, CdS).

Advanced Materials Analysis Tools

UofL has over 5,000 sq. ft. of core user facilities dedicated to structure and composition analysis of nanomaterials. The facilities provide substantial capabilities to characterize materials in-house enabling rapid feedback of the analyses into the optimization of material growth processes. A brief list of our principal assets include high resolution electron microscopes (field-emission SEMs and TEMs), composition analyses (EDS, EELS, XRD), surface analytical tools (ESCA: XPS, LEED, Auger, STM/AFM), optical spectroscopy (Raman/PL, tunable wavelength femtosecond laser), electronic measurements to 30 milliKelvin and 9 Tesla, and several surface profiling/atomic force microscopes, with a number of options (e.g., conductive, near-field optical, thermal, electrochemical, nano-indentation, nanomanipulation).



UofL's femtosecond spectroscopy method for single nanowires.



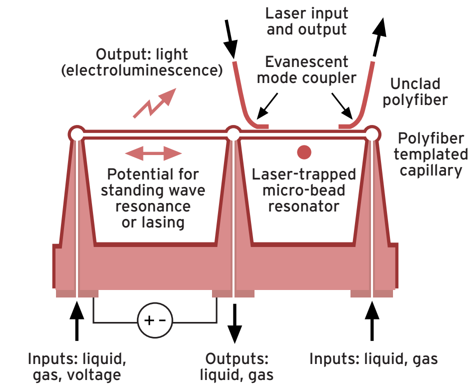
Resulting photoresponse of InN nanowire measured using UofL's femtosecond spectroscopy method.

MicroElectronics Fabrication and Design

The 10,000 sq. ft. microfabrication cleanroom facility and service center (with an additional 10,000 sq. ft. of support laboratory space) focuses on standard microfabrication processing, with an emphasis on MEMS fabrication by photolithographic processing, deep etching, back-to-front side aligned patterns and glass-silicon wafer bonding. The facility includes rapid turnaround photomask fabrication using a submicron resolution Heidelberg Instruments laser pattern generator.

In addition to these standard services, the nanotechnology group at UofL can provide custom nanofabrication R&D services including:

- E-beam fabrication of single nanotube, nanowire, and break junction devices.
- Thermal and UV nanoimprinting and nanoimprint lithography with an Obducat nanoprinter.
- Man-in-the-loop nanofabrication by nano-manipulation inside an SEM.
- Nanolithography via AFM surface modification (e.g., oxidation, electron exposure of PMMA).
- Tapered fiber/pipette puller down to 60 nm tapers.
- Brush-on and self-assembly of air-suspended polymer nanofiber bridges.
- Selected growth and placement of individual freestanding metal nanowires.
- Suspended MEMS device release using critical point dryer.
- Electronic devices of conductors, semiconductors, and dielectrics templated from colloidal crystals.



A multifunctional microsystem device concept configured around the ability to make suspended polymer fibers in one step.

Computational Modeling

UofL's Computational Materials Group models the properties and growth of nanoscale materials using quantum mechanics-based molecular dynamics (MD). While first-principles MD can only handle ~500 atoms, UofL's computational models use our custom-developed semi-empirical Hamiltonians to simulate upwards of 20,000 atoms with reasonable computation speeds and accuracy comparable to using the rigorously correct Hamiltonian. This Hamiltonian includes electron screening and charge transfer effects in many-body systems through explicit considerations of environment-dependency and charge self-consistency. This model together with a new 242 CPU Opteron-based Linux cluster enables the group to move from studies of low number of atom systems, such as carbon nanotubes with periodic constraints, to nanowires with low or no symmetry, nanowire growth, and even the structure and dynamics of large biological molecules. Additionally, algorithms for long-term time-evolving simulations of dynamic phenomena, such as growth and self-assembly, can be integrated into this method.

A few representative computational studies recently performed by UofL using these models include:

- Conductance changes in carbon nanotubes due to mechanical deformation.
- Conductance changes of carbon nantubes as a function of gas adsorption.
- Colossal paramagnetic moments in toroidal metallic carbon nanotubes.
- Quantum interference and ballistic transmission in nanotube electron waveguides.
- Relative stabilities of silicon nanorods of different orientations.
- Electronic properties of silicon, carbon and $Si_{1-x}Ge_x$ clusters.
- Strain relaxation effects in $Si_{1-x}Ge_x$ clusters, thins films and heterostructures.

Additional computational tools include:

Kinetic Monte-Carlo simulations of nanowire growth (UofL developed)
- Models the VLS (vapor, liquid, solid phase) and VS growth of nanowires.

Finite Difference Time Domain E&M Modeling Packages (RSOFT, Lumerical)
- Rigorous electromagnetic calculations of guided wave and free space optics (licensed for both single processor PC and unlimited multi-processor PC clusters).

Current and Potential Application Development

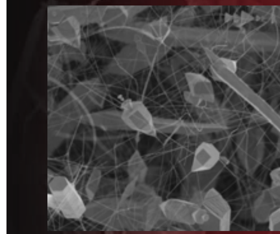
NEMS/MEMS/Nanomechanics/Fluidics
- Mechanical resonators with piezoresistive readout.
- E-Field actuated metal nanoneedles.
- Electro and chemo-mechanical actuated/sensing suspended optical fiber couplers.
- Micro/nano-capillaries templated on suspended polymer fibers.
- Laser trapping for manipulation, construction and transport of particles.
- Micro/nanofluidic capillary networks for fluid delivery and gas mixing.

Medical and Life Sciences
- Carbon nanopipette arrays for controlled drug delivery system.
- Carbon nanopipette arrays and porous platinum electrodes for neurotransmitter detection.
- Near-field scanning microscopy of live cells.
- Fluorescence redistribution after photo bleaching (FRAP) studies of protein dynamics.
- Polymer/Nanowire composites for AR coating of plastic ophthalmologic lenses.

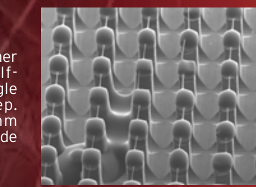
Power Electronics
- Nanomaterial-based battery electrode materials (both cathode and anode) for Li-ion battery.
- Li-Ion battery electrodes using tubular carbon and silicon/tubular carbon composites.
- Nanotube/polymer composite electrodes for supercapacitors.
- Colloidal crystal (synthetic opal) based p-n junction arrays for super junction diodes.

Photonics
- Photodetectors built from nanowires and nanowire carpets.
- Photoluminescent materials.
- Electroluminescent fibers and electro-luminescent liquid filled microcapillaries.

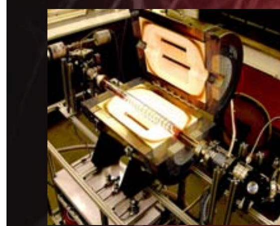
Reaction Engineering/Catalysis/Chemical Sensing
- Nanowires as catalyst supports.
- Nanowires as catalysts (e.g., photocatalysis for water splitting).
- Superporous metal and oxide thin films for catalysts and sensors.
- Vapor/gas adsorption sensors made from nanomaterials.



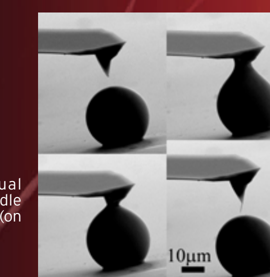
Handles on GaN nanowires. Tapered GaN crystals that were grown onto existing GaN nanowires.



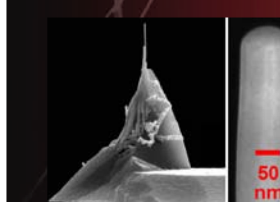
Suspended PVAC polymer fiber array that self-assembled after a single manual brush-on step. Fibers down to 30nm diameter have been made this way.



An experimental reactor for evaluating principles for the bulk production of nanowires.

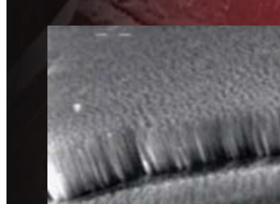


Growth of individual metal alloy nanoneedle at a selected location (on an AFM tip).



Closeups of the resulting nanoneedle from the figure above.

While commercial WO_3 nanoparticles fall from solution in 4 hours (top), our WO_3 nanowires (bottom left) and nanowire bundles (bottom right) stay in suspension for 10 days.



Carpet of vertical freestanding silicon nanowires of 90 nm diameter.

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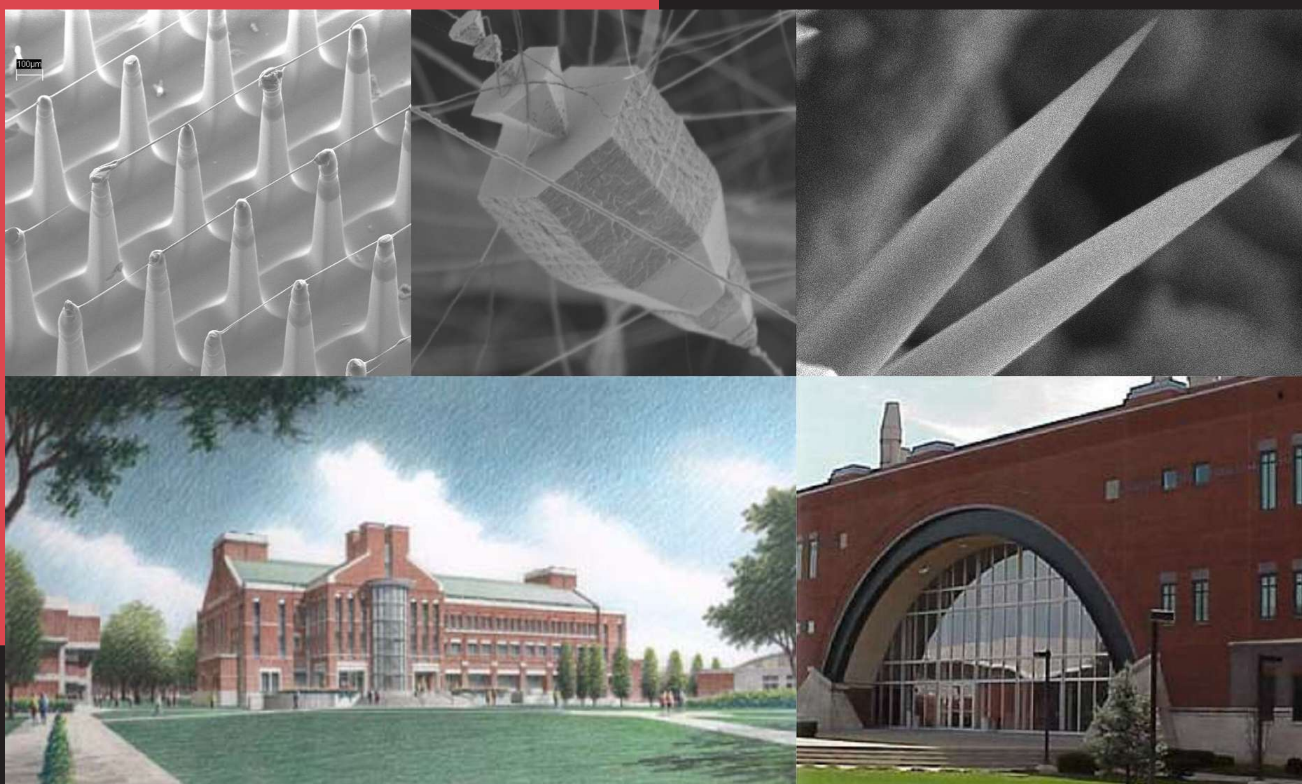

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