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NANOTECHNOLOGIES FOR ADVANCED MICROSYSTEMS

COMS 2009 – Copenhagen, Denmark

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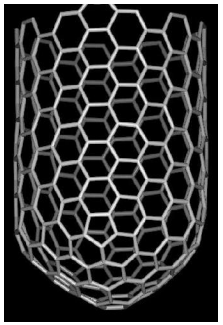
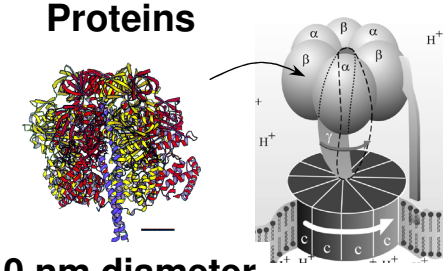
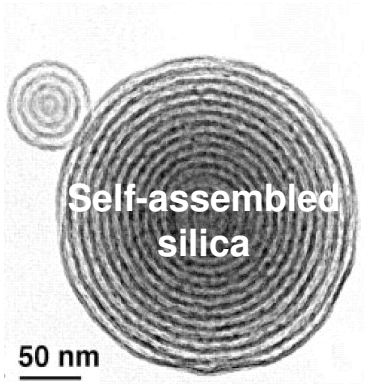
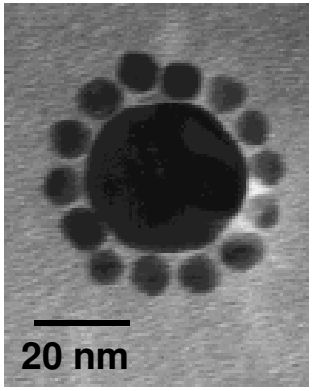


Carbon nanotube
~2 nm diameter







Colloidal assembly

The Nanoworld

Matter structured at a scale of ~ 5 – 100 nm

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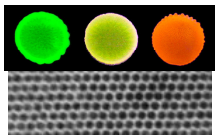
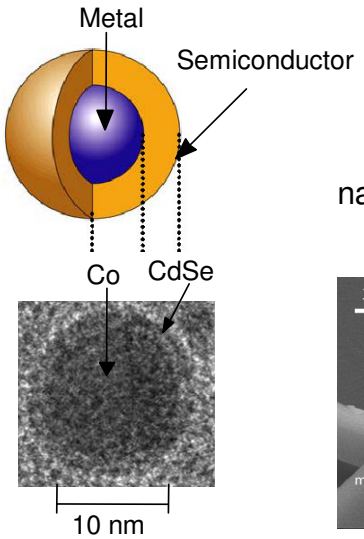
Theme: *From Complex Functional Material Synthesis & Assembly to Integration & Application*

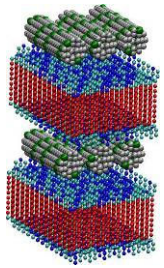
Nanoscale material synthesis



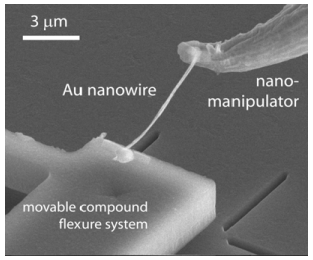


Combining ferromagnetic & semiconducting behavior

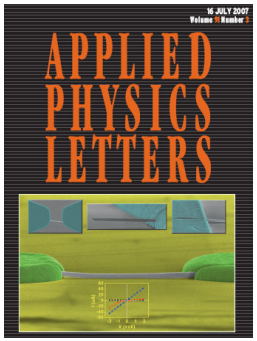
Nanomaterial assembly

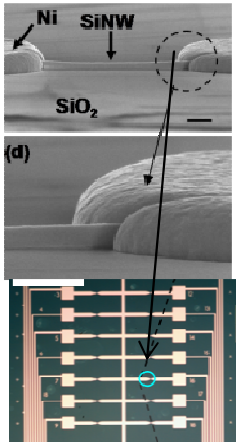


Engineered nanocomposites

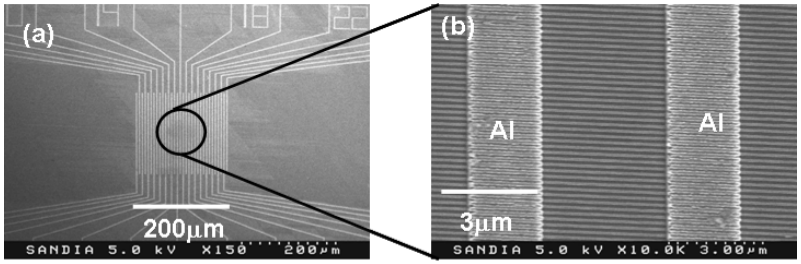


Integration

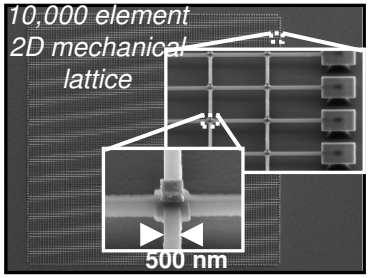




Application



Nanowire arrays



Nanomechanical arrays

Length scale

Nano → **Micro**

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Applications of Nanomaterials for Microsystems

Nano: Unique performance that cannot be achieved otherwise

1. Size-dependent and collective optical, electric, and magnetic properties: tuning refractive index for optical coatings, tuning dielectric constant, quantum dots for solar cells, electron transport/conductance, magnetic memory, etc.

(CdSe) Semiconductor size increase

Conductors: Au, Ag, …

Semiconductors: Ge, CdSe, …

Dielectrics: TiO_2, ZrO_2, …

Magnetics: FePt, $FeMnO_4$

2. Chemical Sensors: chemically selective interactions, fast/stable/reproducible

3. Nanowire electronics: novel response, unique size effects

4. Energy applications: high surface area, structured porosity

5. Next generation lithography: high resolution, low defect density structures

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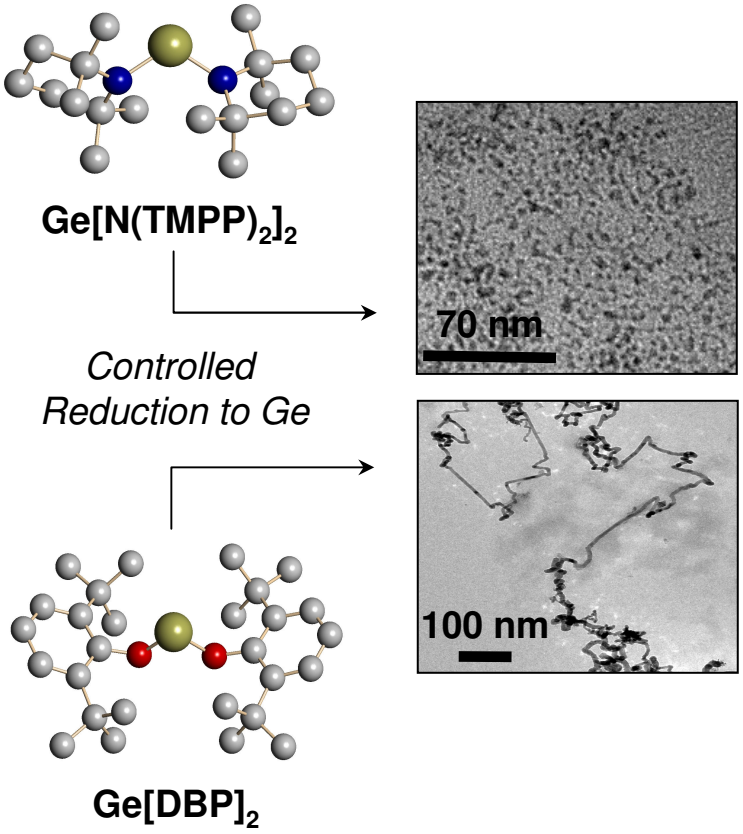
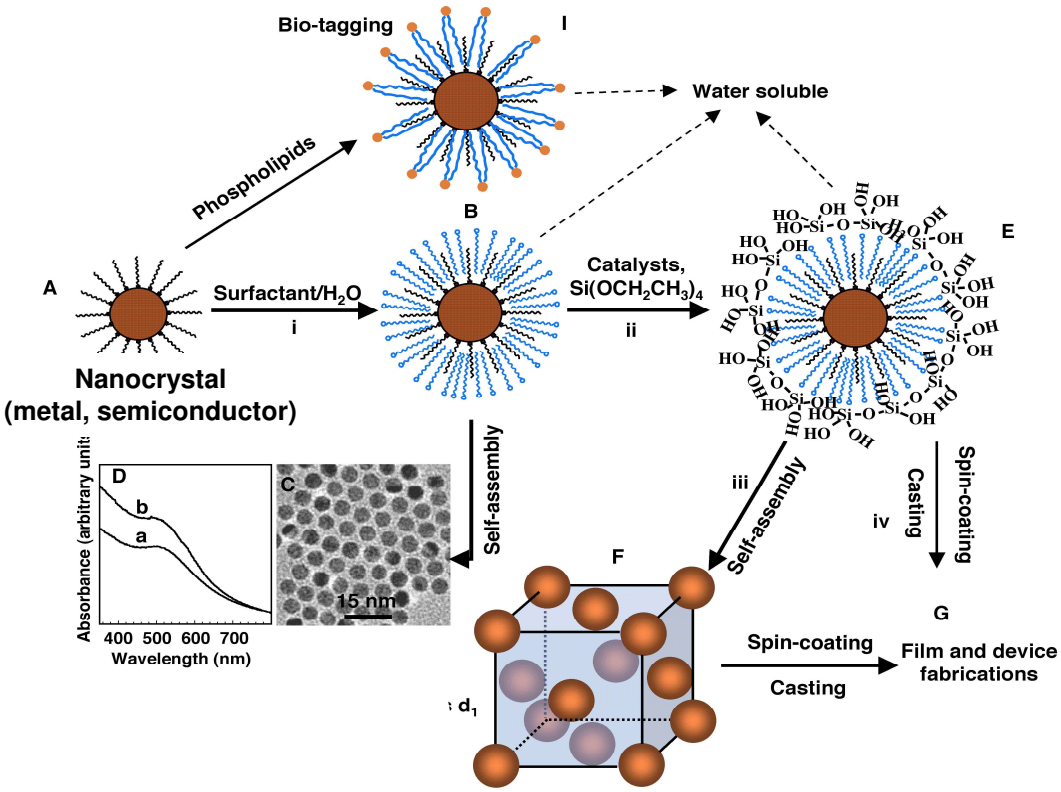
Fabrication: Building Block Synthesis & Assembly

Building Block Synthesis → Assembly





Precursor structure - control of nanocrystal/nanowire formation
(ligand-metal bond strength, ligand size).

Gerung, H et al. *J. Am. Chem. Soc.* **2006** *128*, 5244.

Nanocrystal functionalization - control of self-assembly
(surfactants, phospholipids).

Fan et al. *Science* **2004**, 304, 567-571.

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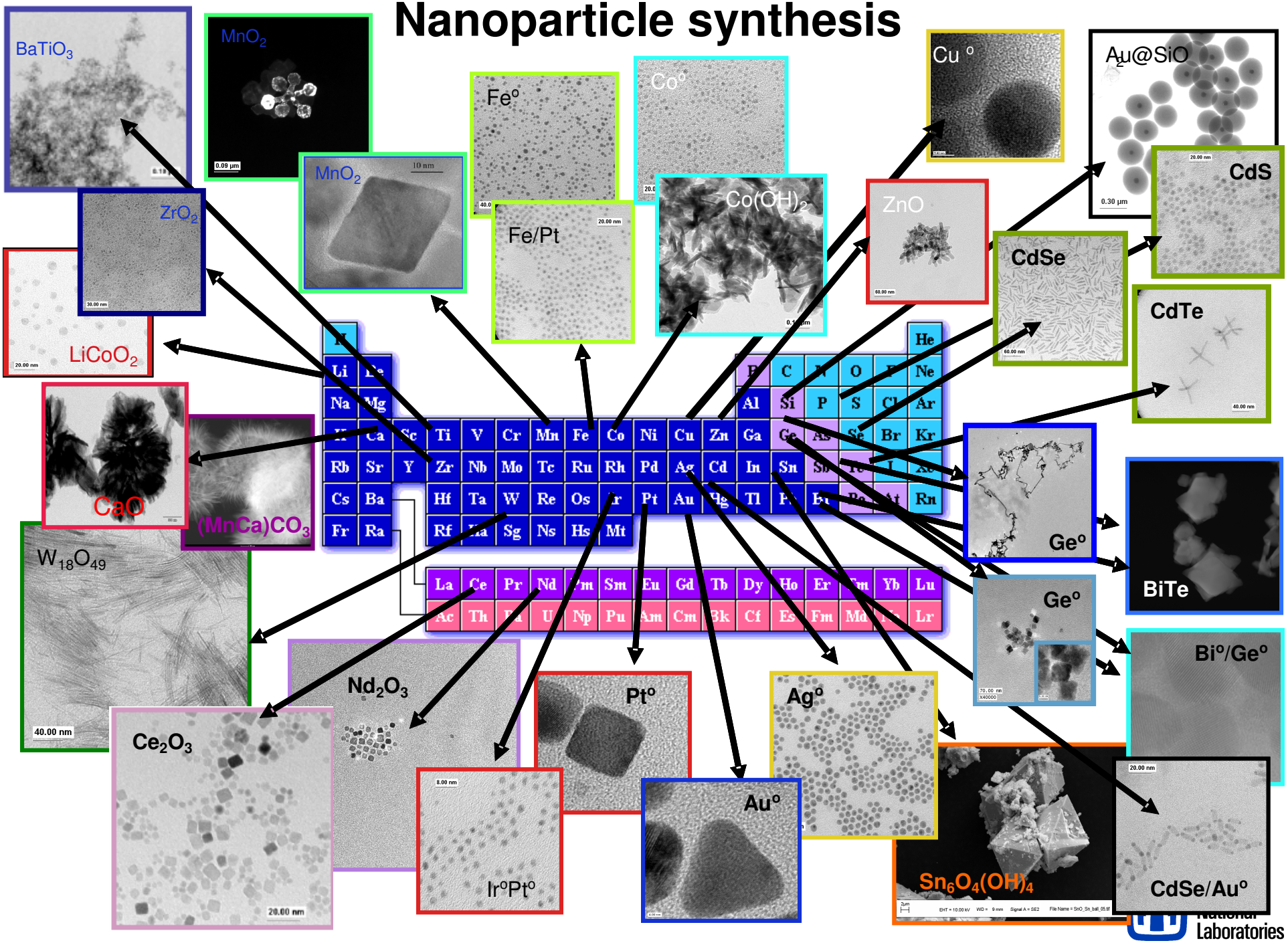
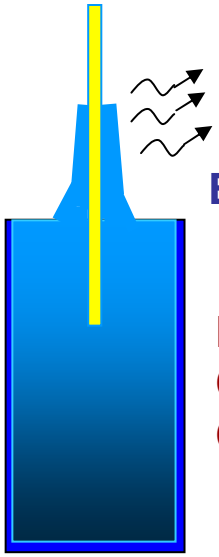
Nanoparticle synthesis



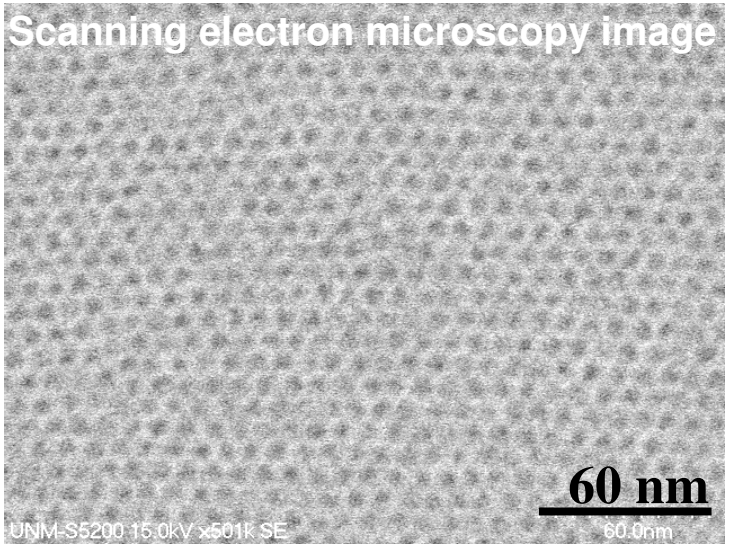
Evaporation induced self-assembly of highly-ordered thin films

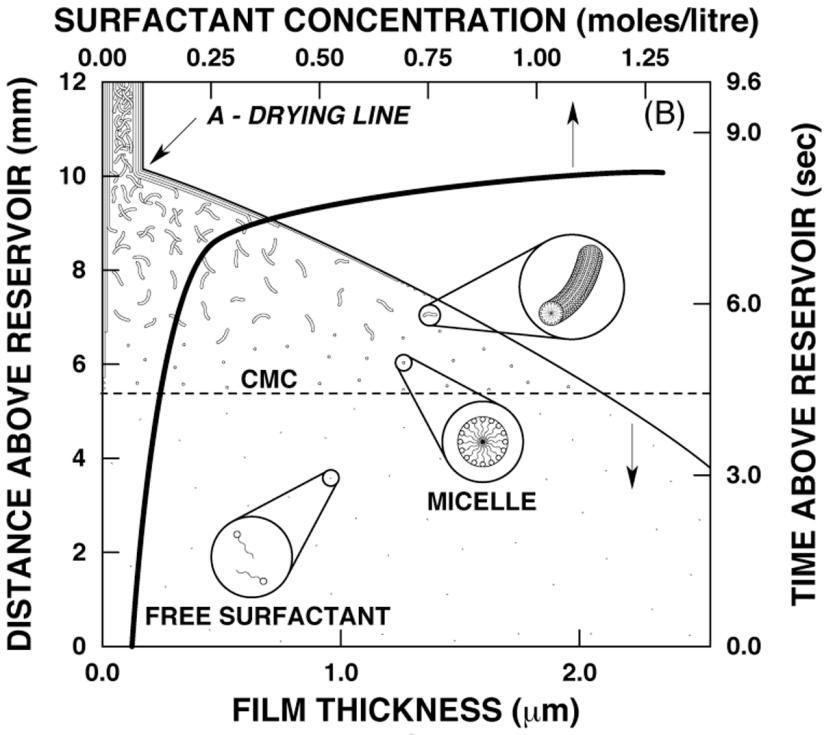
Dip-coating

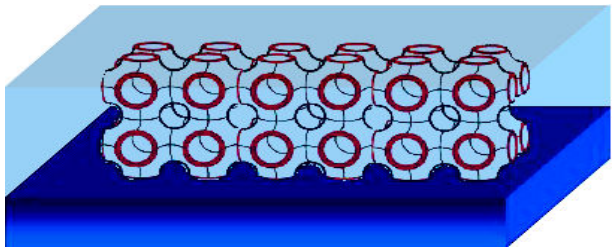


Solvent Evaporation

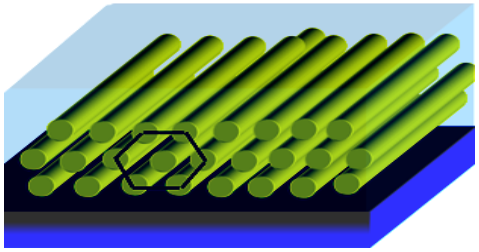
Fast (few seconds)
Continuous self-assembly
Controlled structure







Cubic



1-d Hexagonal

Fan *et al. Adv. Funct. Maters.*, 2006; *Chem. Mater.* 2006

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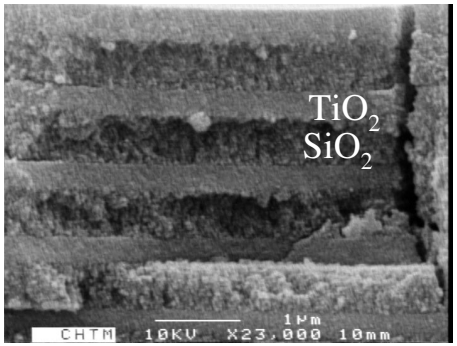
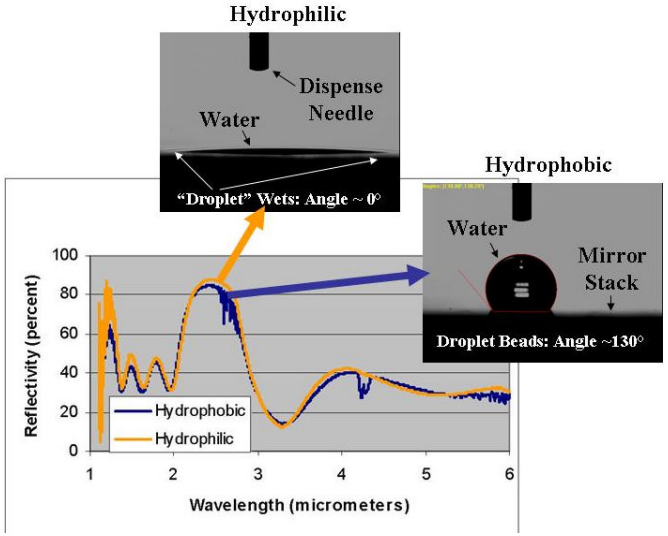
Near infrared reflectors w/layered nanoparticle coatings

Quarter wave stacking of self-assembled nanoparticle films for near infrared reflectors, overcomes the harsh conditions from conventional processing (CVD, sputtering, etc) with improved functionality.

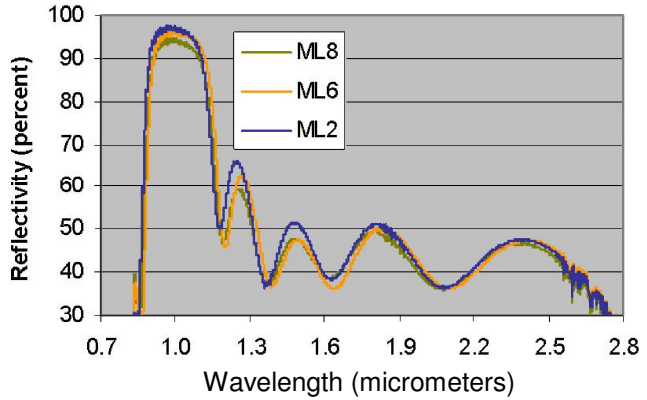
SEM image of quarter wave stacking of TiO_2 and SiO_2 reflector

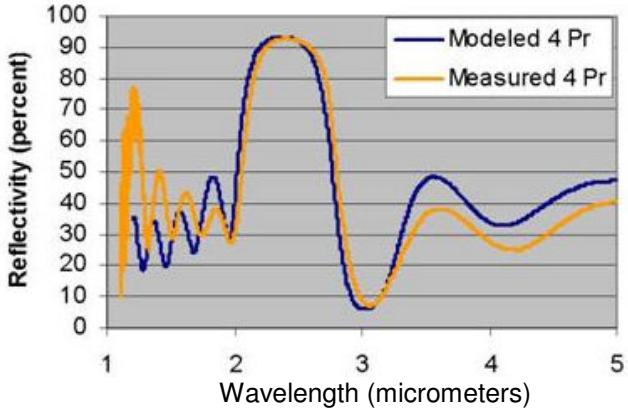


Functionalization of optical coatings



Reflectivity studies show high and reproducible reflectivity over controlled wavelength windows





LOCKHEED MARTIN

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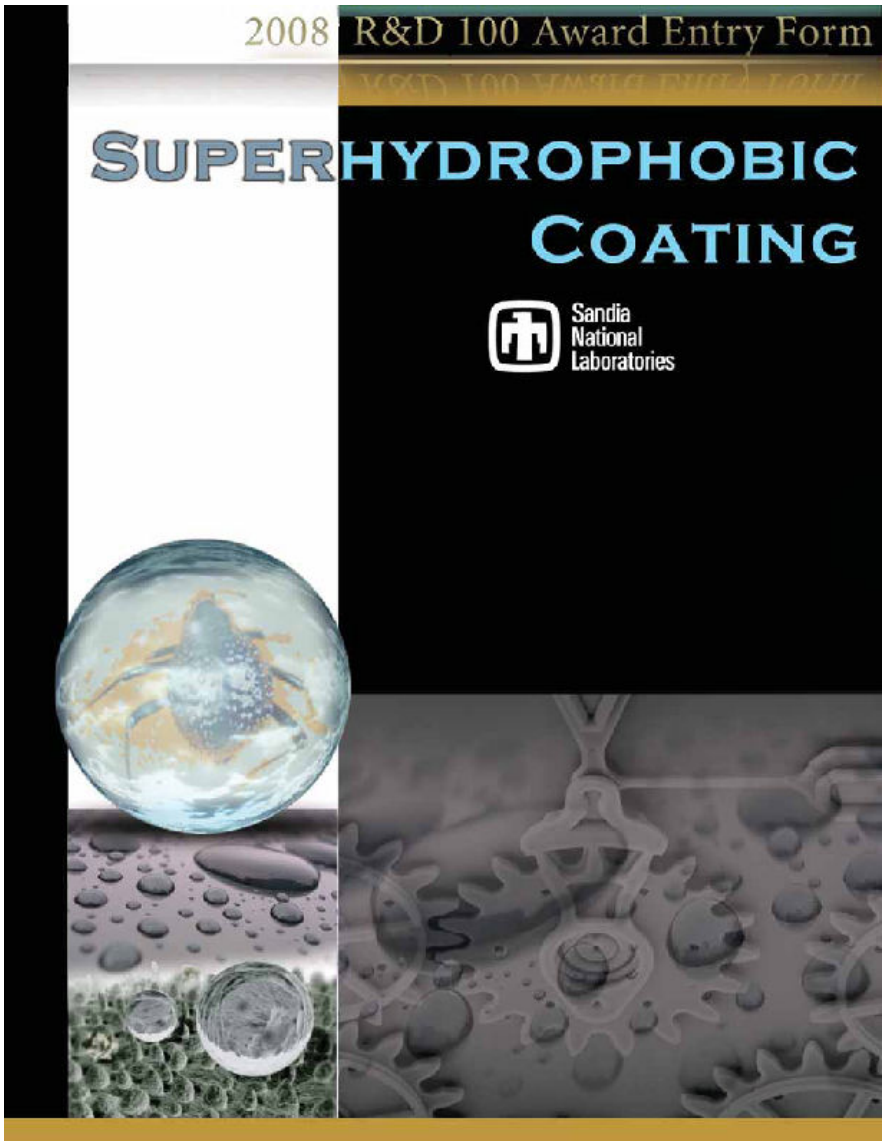
Self-assembly work has been award winning



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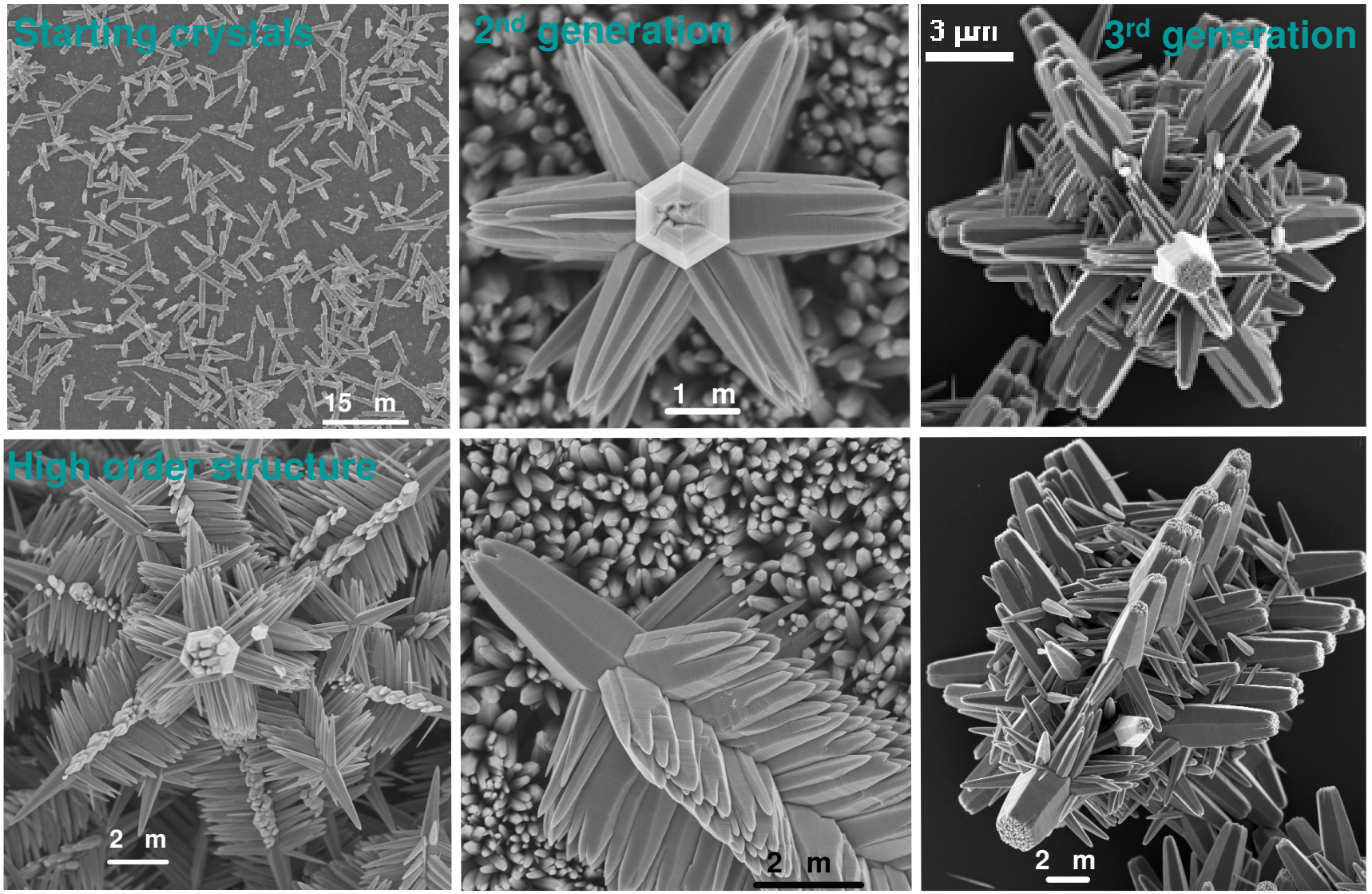
Stepwise Growth of Complex Nanostructures (ZnO)



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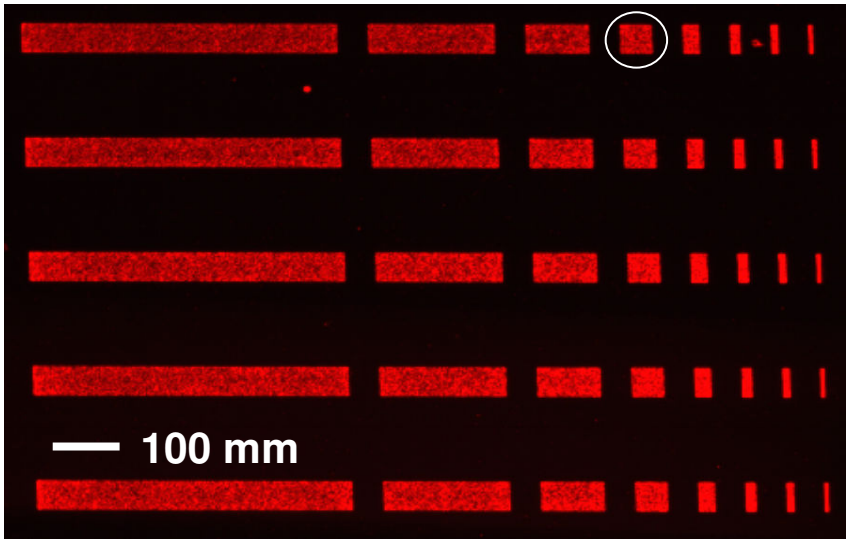
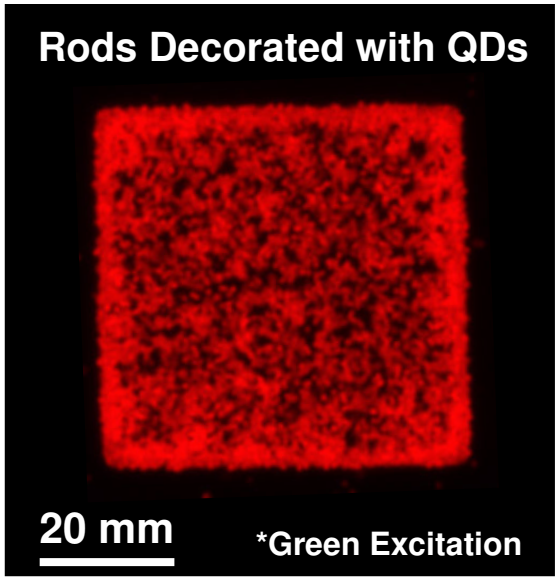
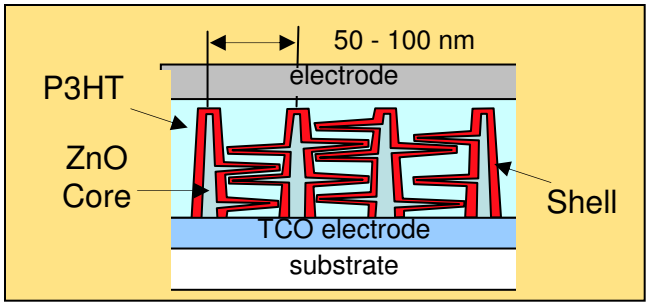
Nanostructured composites enable new microdevices

Optical ‘devices’ w/functionalized surfaces for assembly

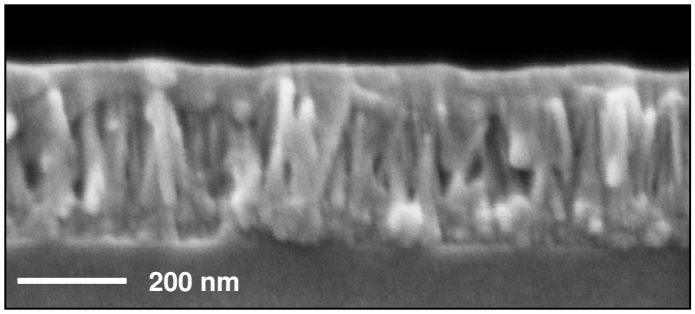




Hybrid organic-inorganic nanoscale photovoltaic cell



Schematic of hybrid solar cell under development.



P3HT filled ZnO Nanorod Array
(2% efficiency demonstrated)

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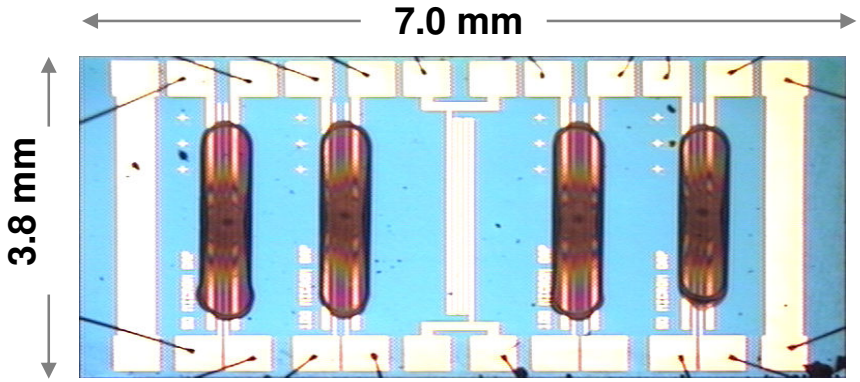
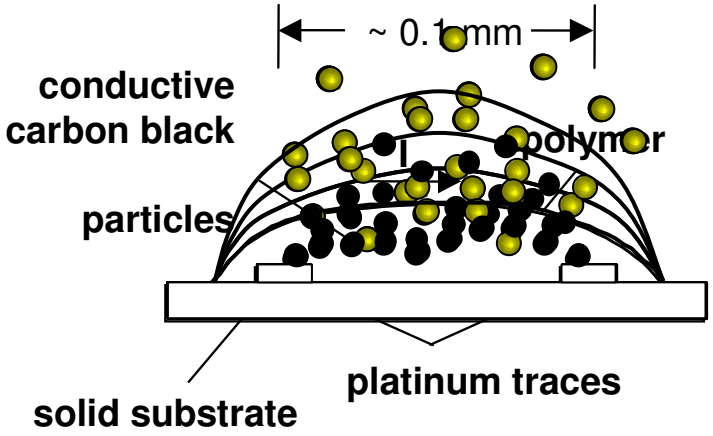
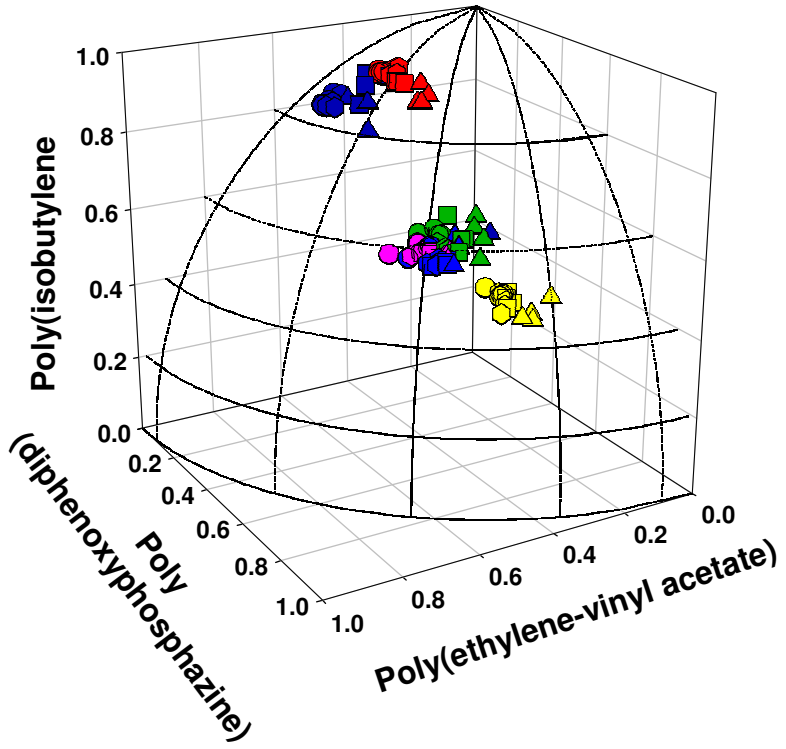
Chemiresistor sensors for monitoring volatile organics

***In-situ*, continuous monitoring of volatile organic compounds in air, soil & water**







- **Polymer-carbon black film is a percolative conductor with high sensitivity to swelling**
- **Extremely small, low-power system with no pumps, valves, or moving parts**
- **Chemiresistor arrays act as a 'nose'**

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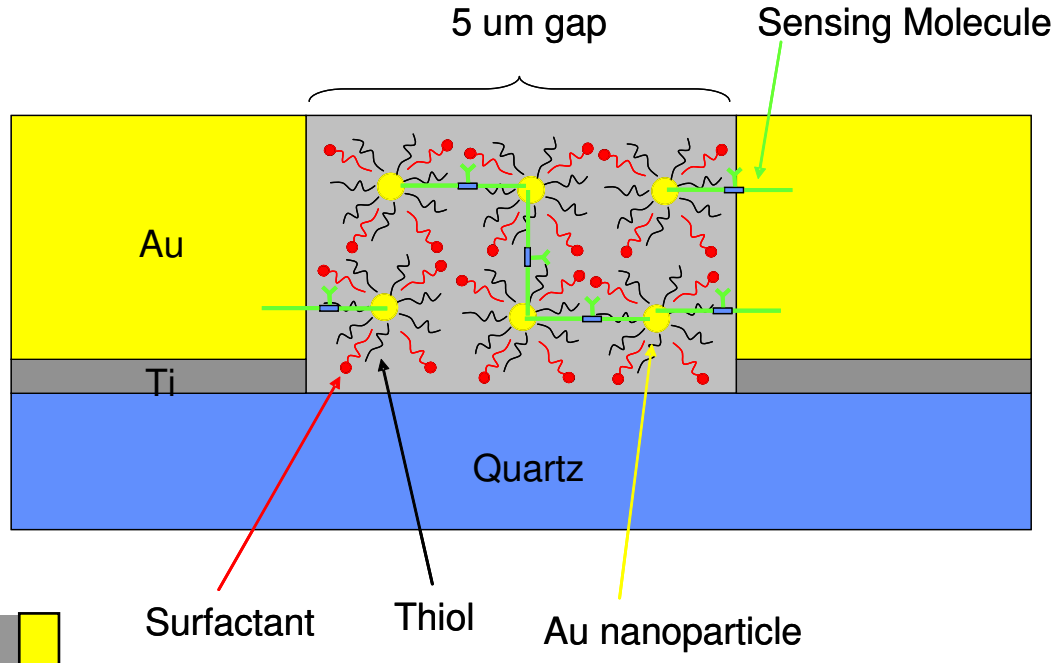
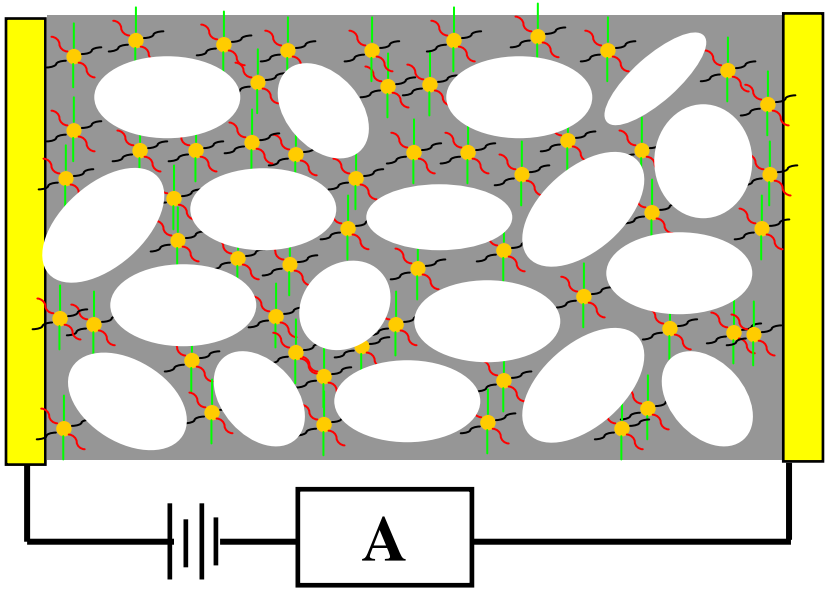
Nanoporous chemiresistors offer improved performance

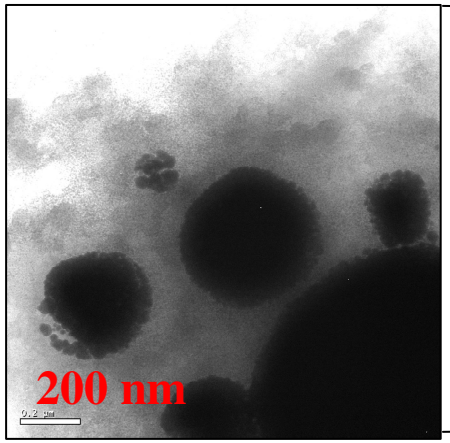
Chemoselective sensor coating is prepared by combining:

- A solution of Au nanoparticles (~5 nm) and surfactant
- Silica precursor
- Acetate protected cross-linking phenylene ethynylene compounds
- Catalyst to initiate cross-linking and silica condensation



Porous Silica Matrix





TEM of sensor coating material (silica, Au nanoparticles, crosslinkers)

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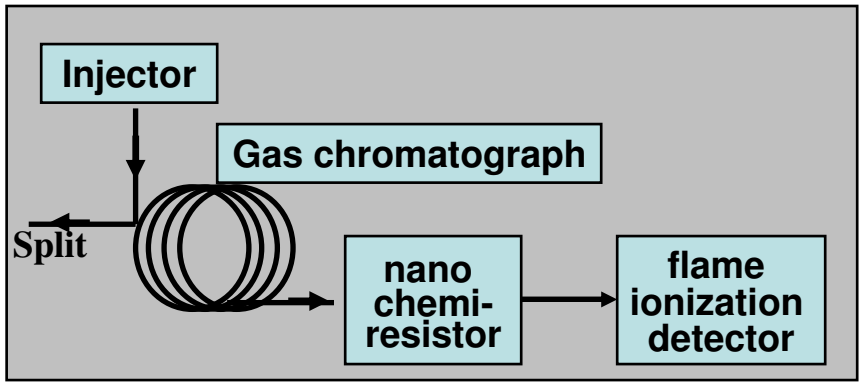
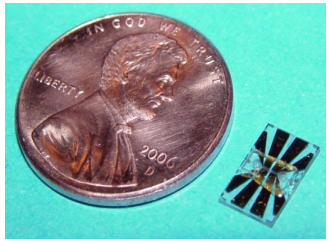
Au nanoparticle chemiresistors exhibit good response





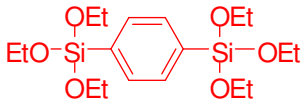
4 devices

Silica to Au ratio: Crucial to minimizing effect of swelling mechanism & maximizing the analyte response

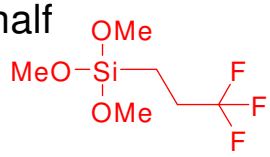
- Too much glassy silica, response amplitude low
- Not enough silica, swelling mechanism dominates
- Just enough silica, increased amplitude

Modification of silica precursor to change chemoselectivity

- 1,4-Bistriethoxysilyl)benzene
  - Increase phenyl character of the sensing film



- 1,1,1-trifluoropropyl(trimethoxy)silane
  - Lower surface energy of the sensing film, useful for half mustards and mustards



S. M. Dirk, S. W. Howell, B. K. Price and e. al., "Vapor Sensing Using Conjugated Molecule-Linked Au Nanoparticles in a Silica Matrix," Journal of Nanomaterials, vol. 2009, doi: 10.1155/2009/481270, 2009.

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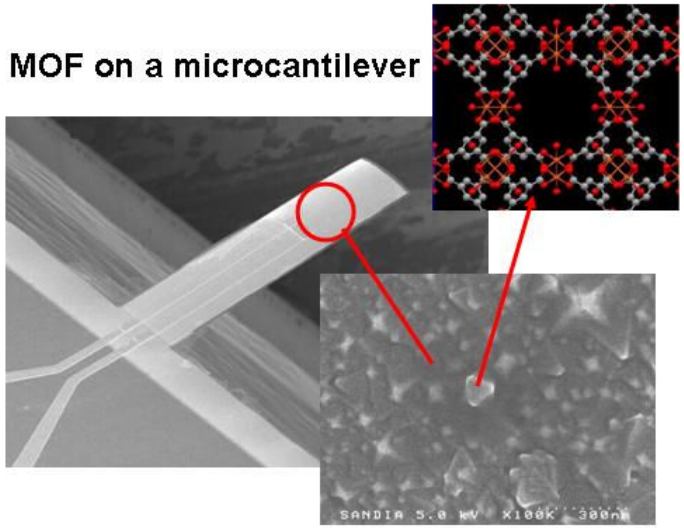
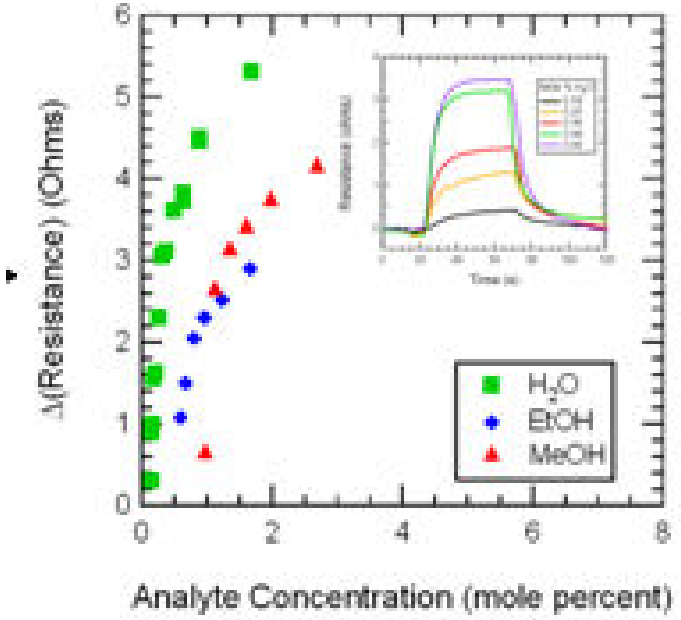
Nanomaterials can be precisely tailored for chemical specificity

Metal-Organic Frameworks: Tailorable nanoporous materials

- MOF structural change upon adsorption induces measurable stress in Si microcantilever
- Specificity by controlling the occupancy of exchangeable coordination sites
- Detection of H_2O, CO_2, alcohols demonstrated





Allendorf et al. *J. Amer. Chem. Soc.* ***130*** (2008)***,*** 14404, **Patent pending**

Collaboration with Prof. P. Hesketh, Georgia Tech School of Mechanical Engineering

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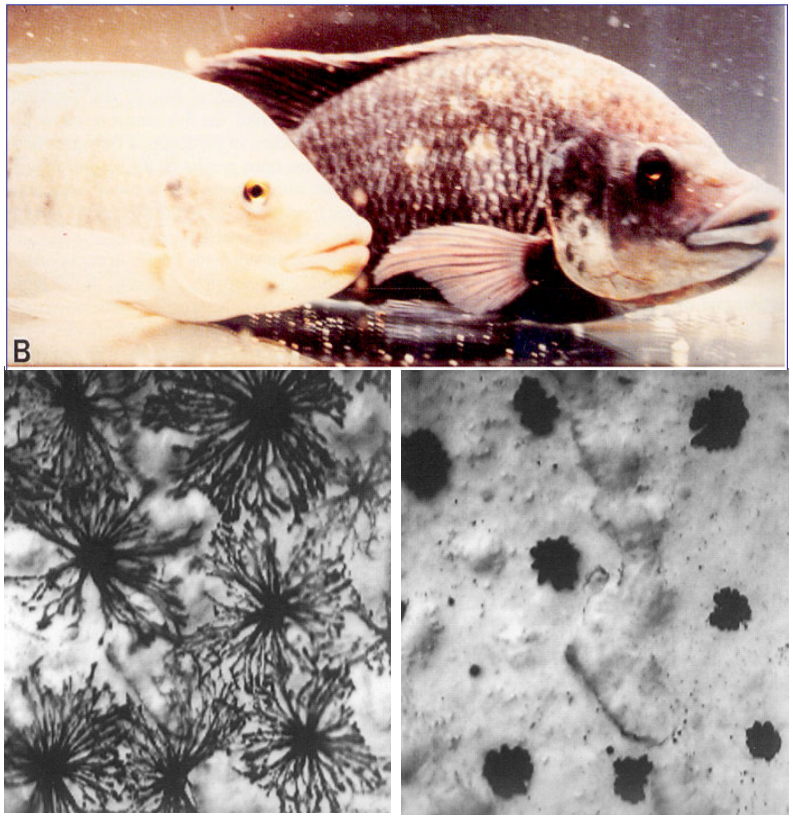
We are exploring active biomolecules for materials and devices.

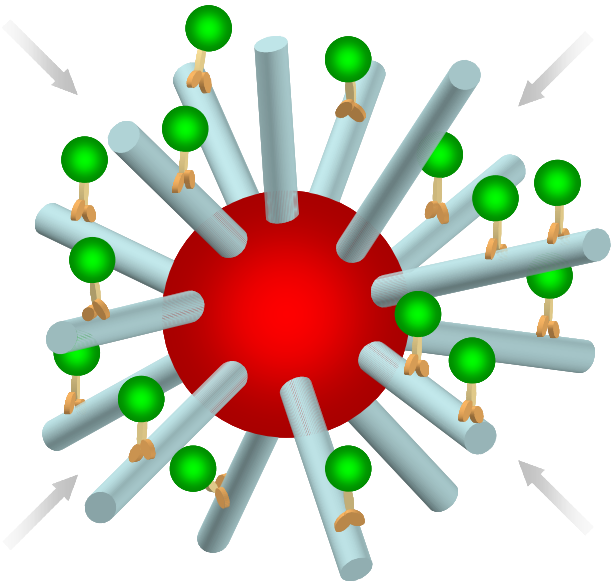
Living systems utilize energy-driven, non-equilibrium processes to assemble and organize nanoscale materials in a dynamic and adaptive manner.

Adaptive reorganization



Color change due to adaptive reorganization of melanophores

Can such processes be exploited for creating artificial, dynamic, and adaptive nano-materials and devices?



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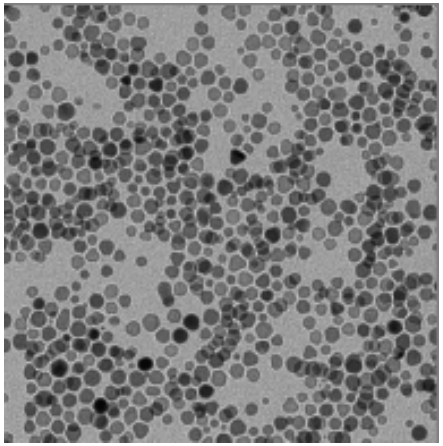
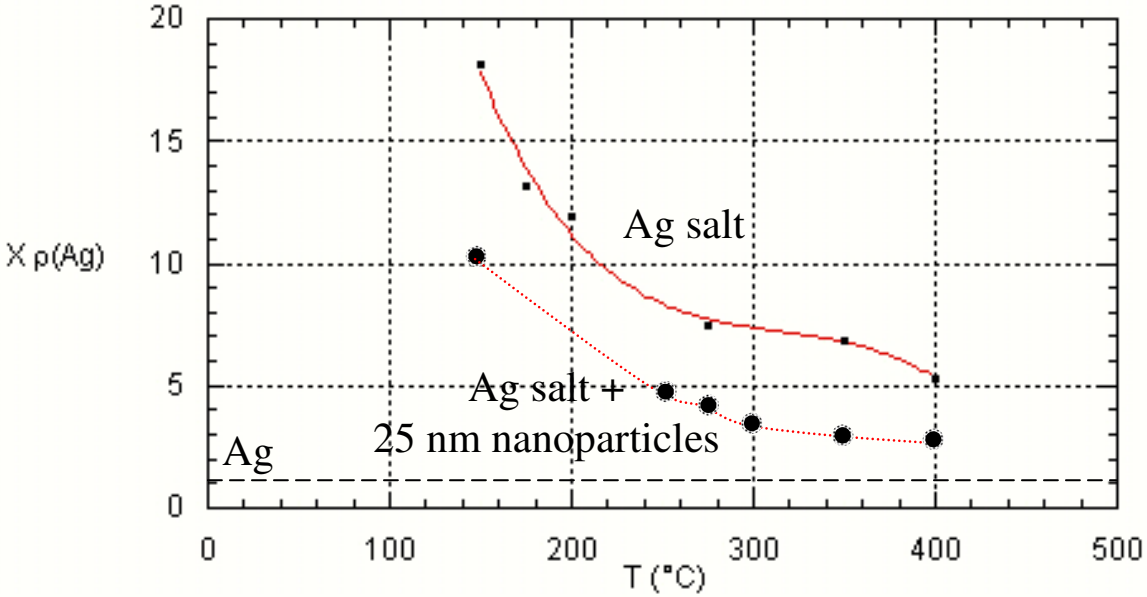
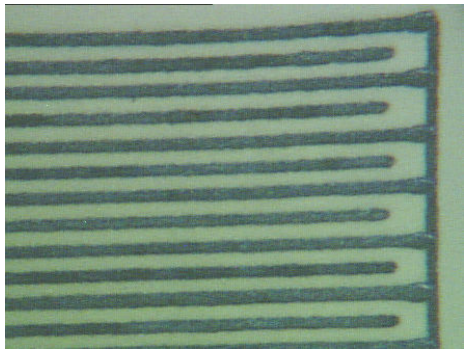
Nanoparticles provide reduced processing temperatures for improved integration

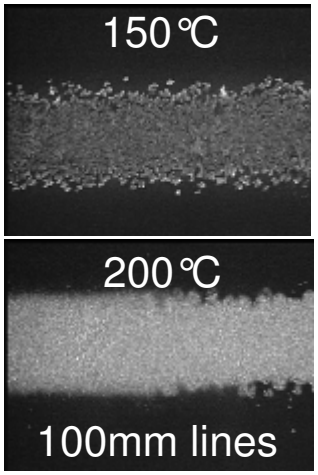
Ag Nanoparticle ink
(5-25 nm particles)

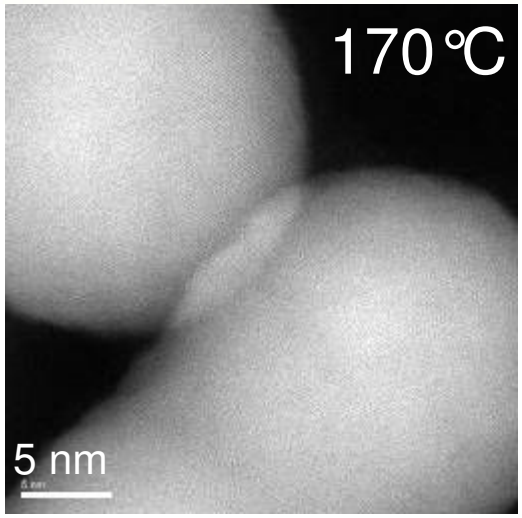






100 m Ag line/space





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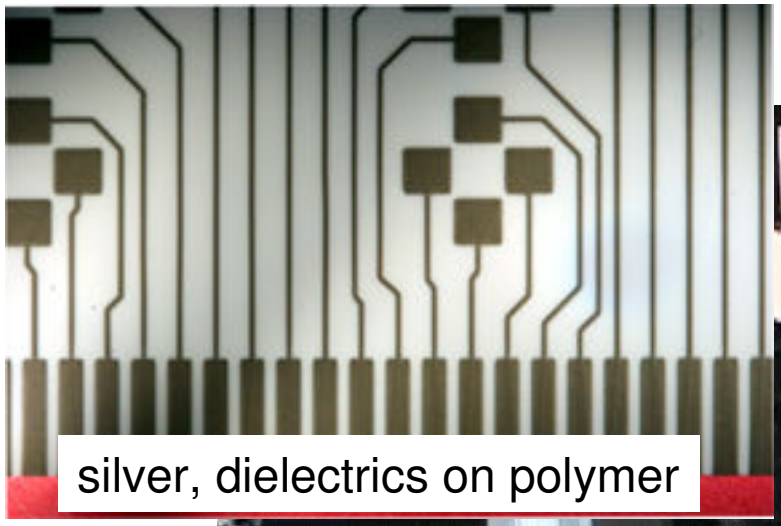
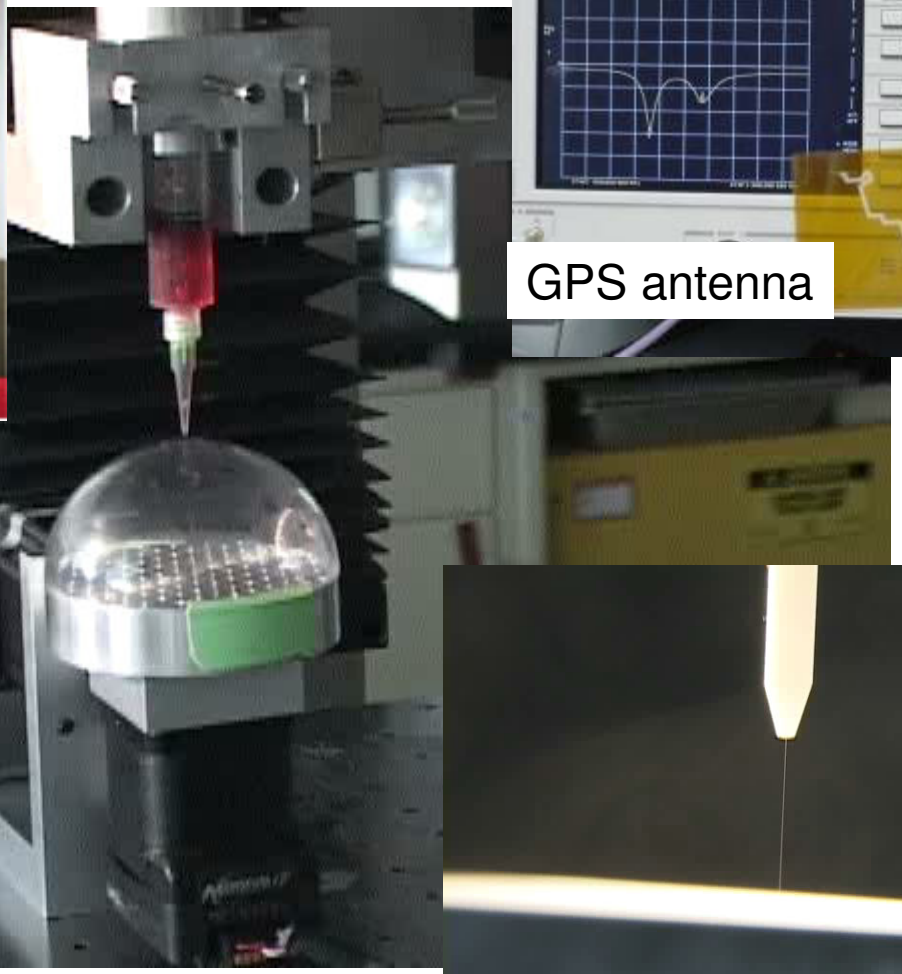
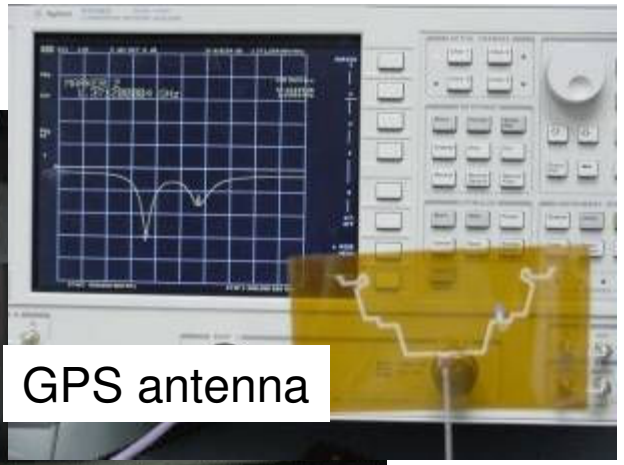
Nanoparticles provide new options for 3-D direct write electronics designs

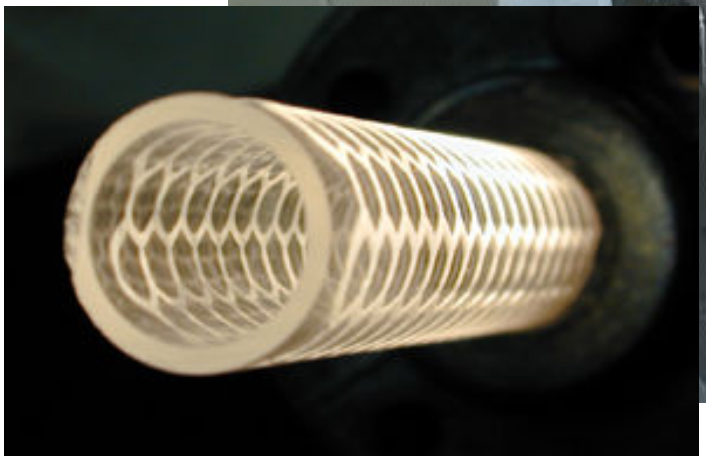


silver, dielectrics on polymer





GPS antenna



3D metal antenna on plastic

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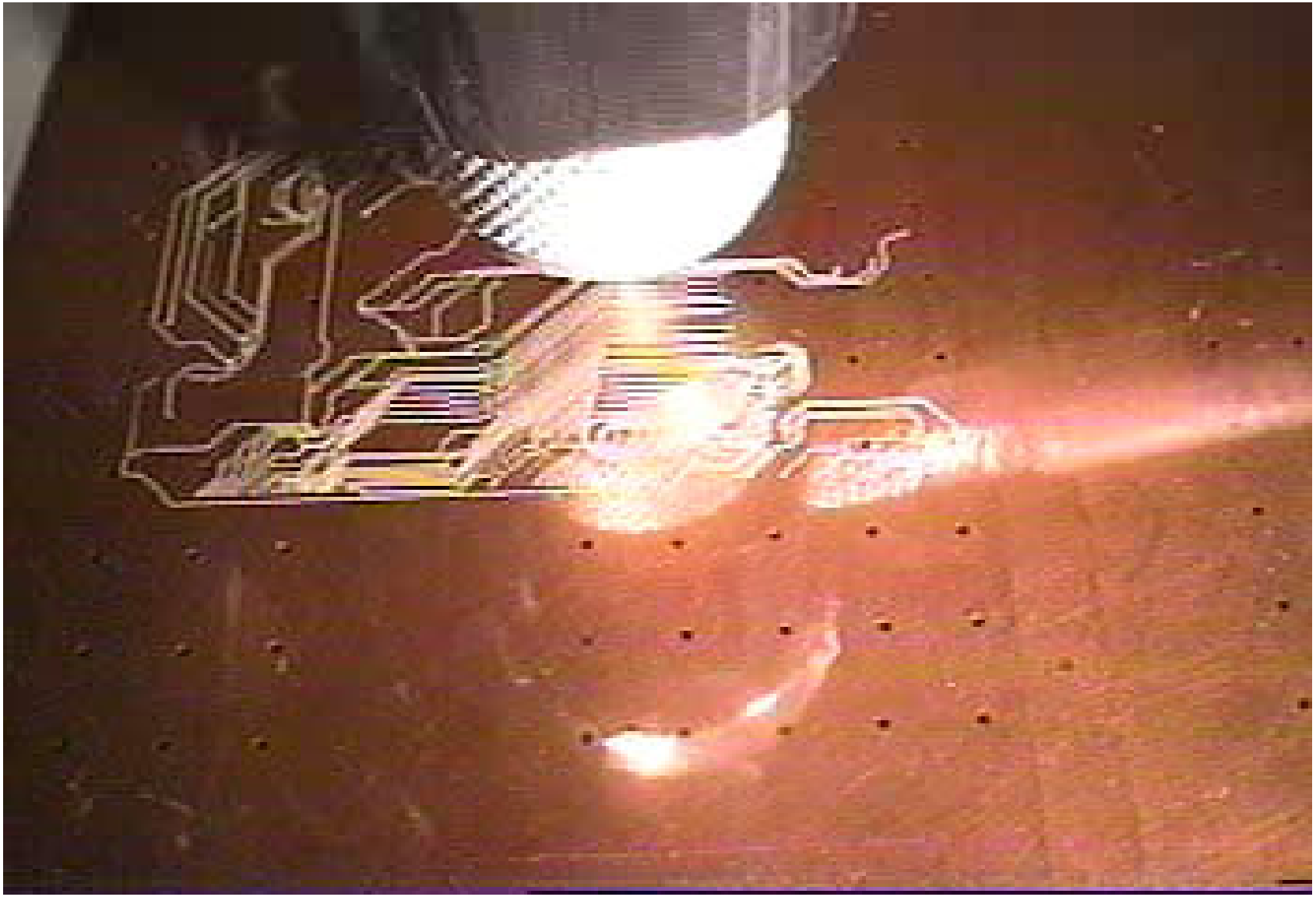
Direct write fabrication for device customization



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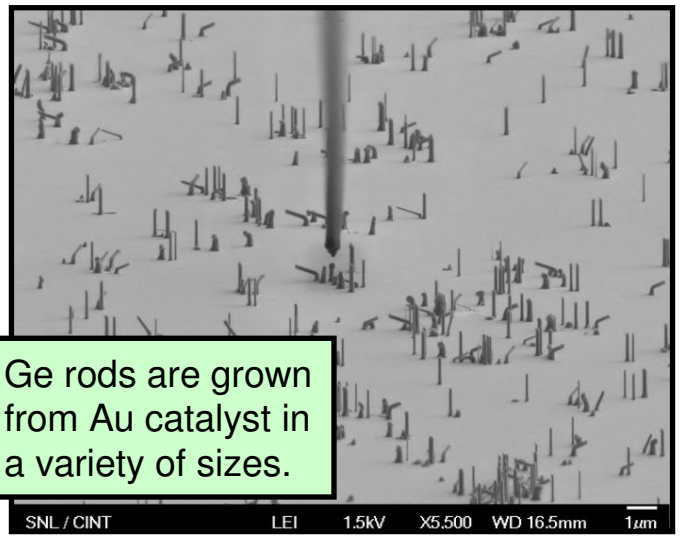
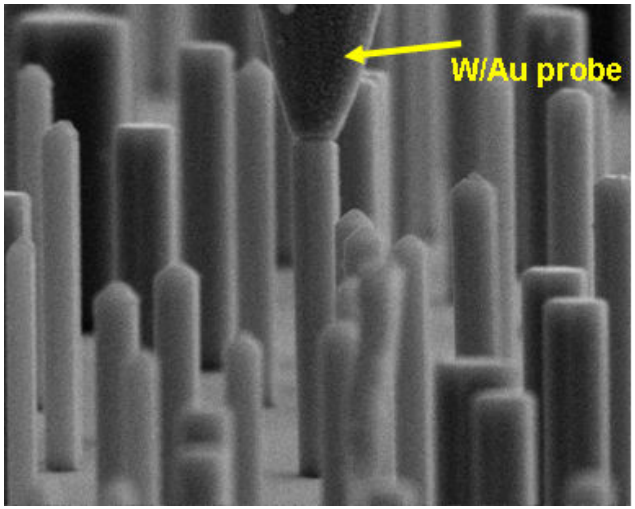
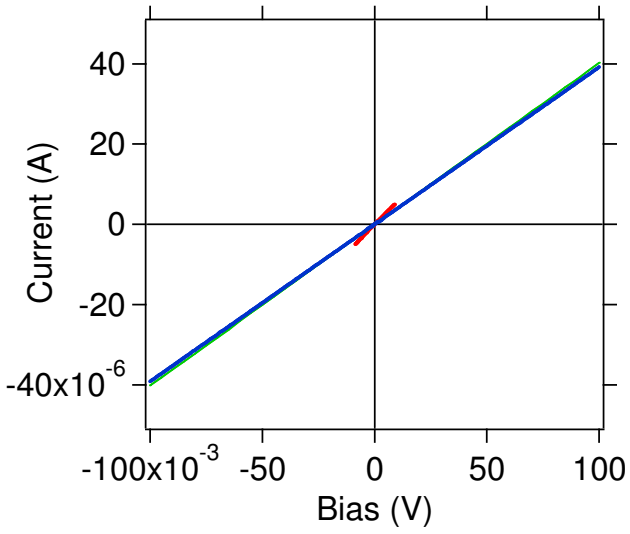
In-situ nanoprobes for direct nanowire characterization

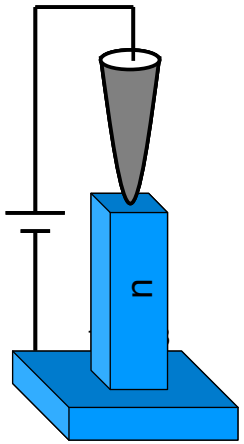


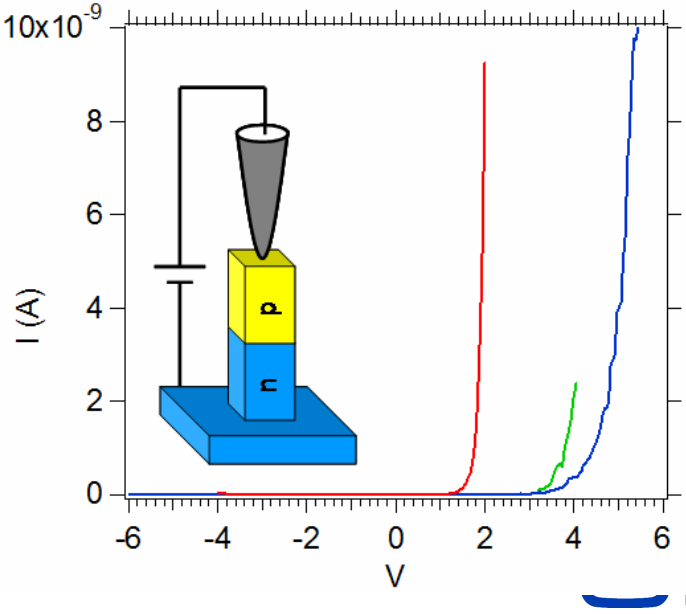
Ge rods are grown from Au catalyst in a variety of sizes.



- n-doped nanowires show Ohmic I/V
- pn-doped nanowires show diode I/V (and electroluminescence!)







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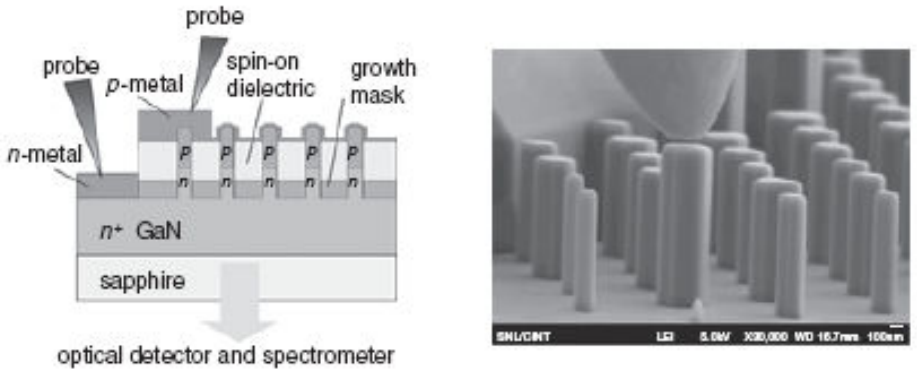
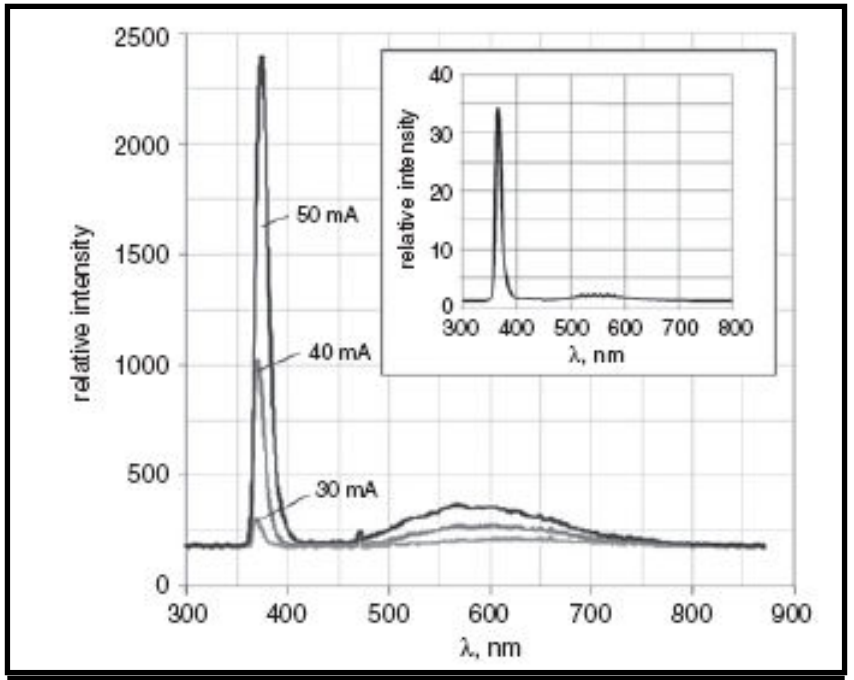
GaN nanowire Light Emitting Diodes based on templated and scalable nanowire growth process

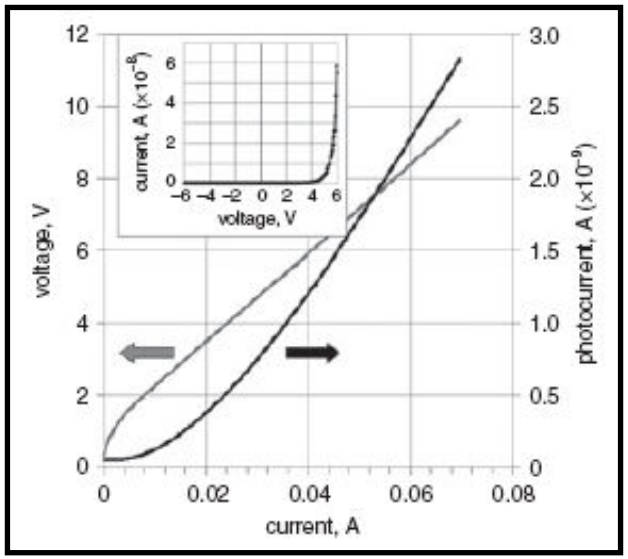


Schematic showing cross-section of nanowire array LED (EL intensity and spectrum measured through sapphire substrate) and SEM image showing electrical probing of individual pn-nanowire diodes.

Hersee, Talin, et al., Electronics Letters 45, 1 2009



Peak wavelength red-shifts with increasing current owing to heating. Inset: PL spectrum of single nanowire, pn-diode.



EL intensity grew super-linearly over this current range. Inset: I-V curve for single nanowire, pn-diode.

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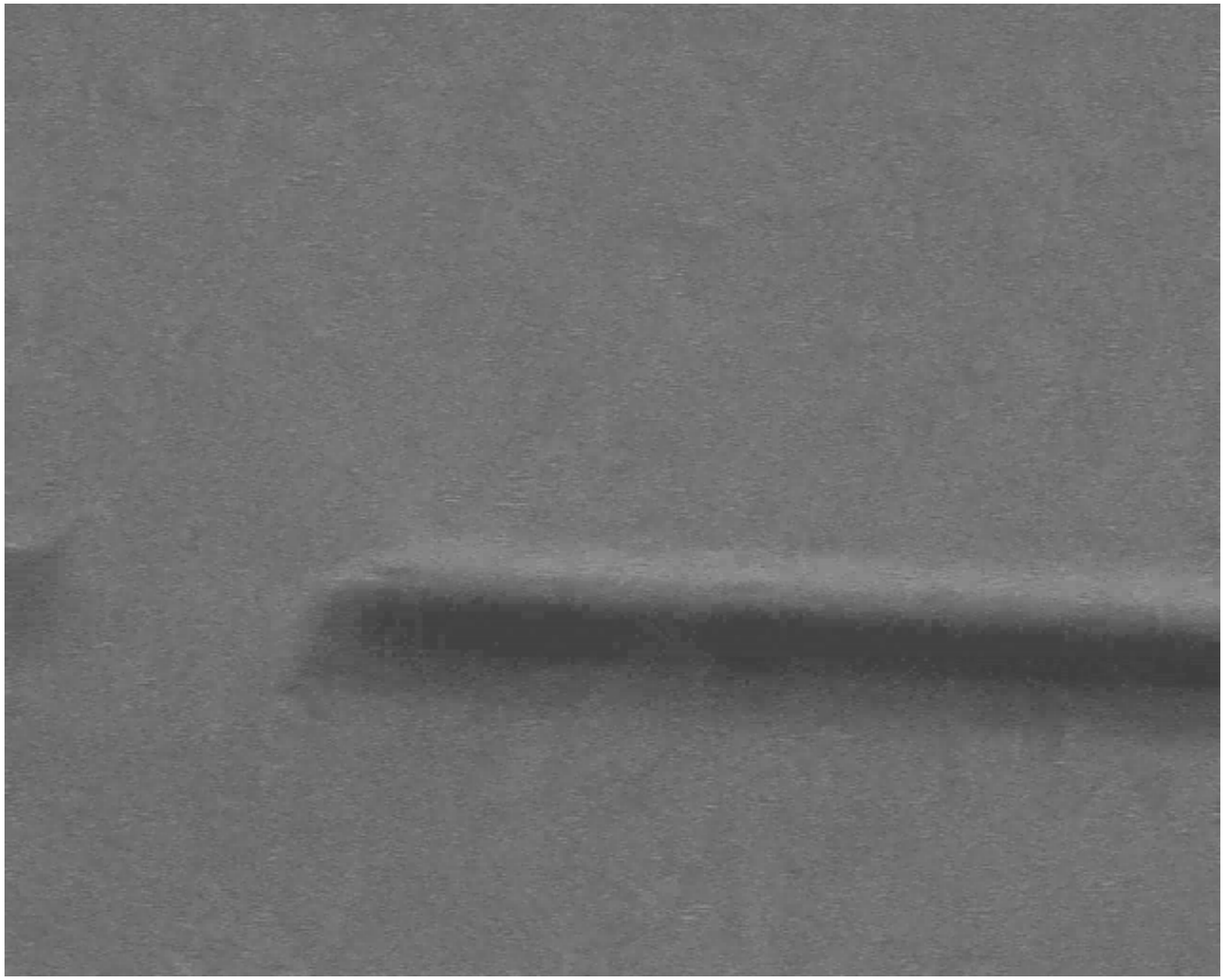
Individual nanowires can be manipulated



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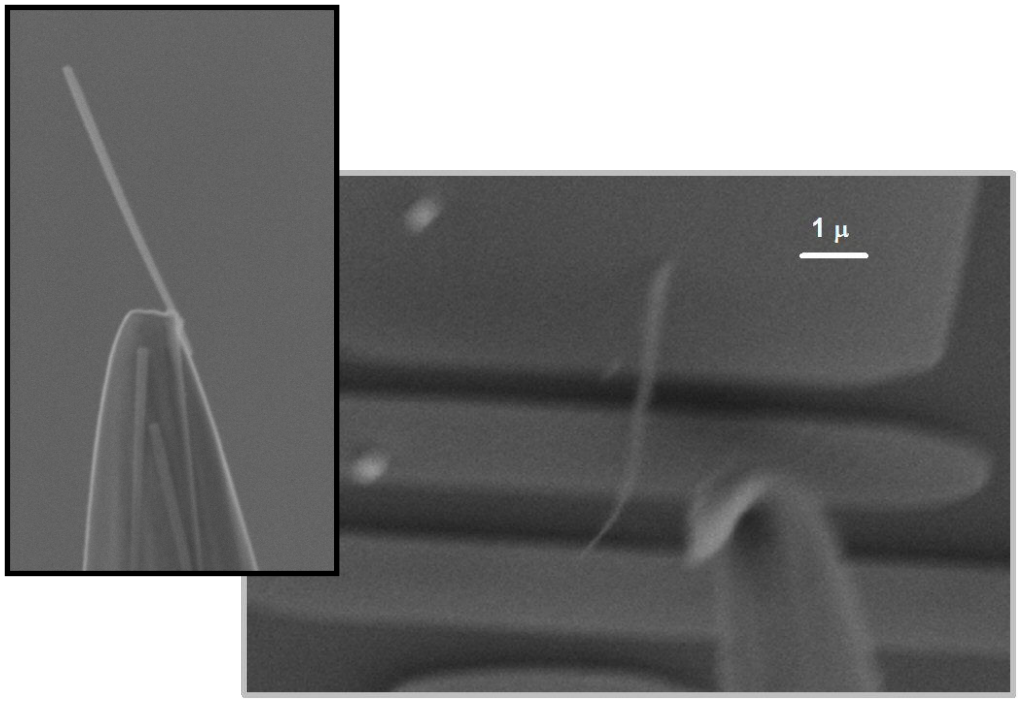
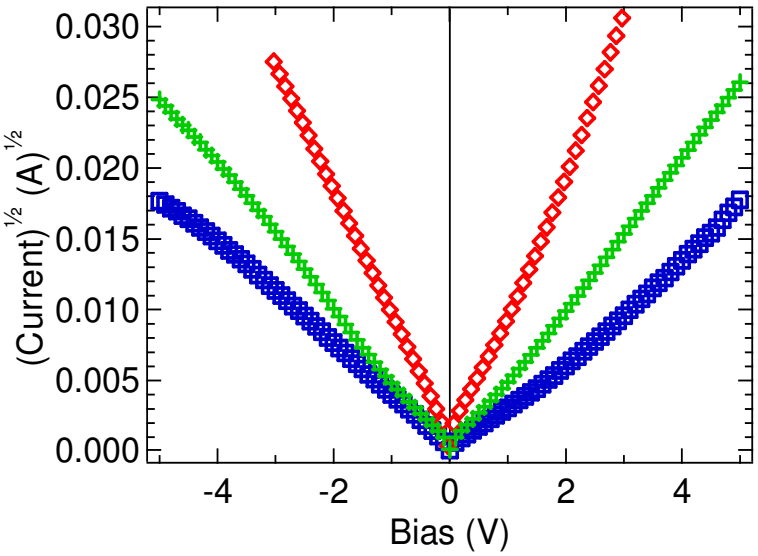
Nanowires with low doping show space-charge limited conduction, with geometric scaling different from bulk!



Ge nanowire placed across Au contacts



$$I_{sc}(nanowire) \left(\frac{R}{L}\right)^2 \frac{A}{L^3} V^2$$

Talin, Leonard, Swartzentruber, Wang, Hersee Phys. Rev. Lett. 101, 076802 2008

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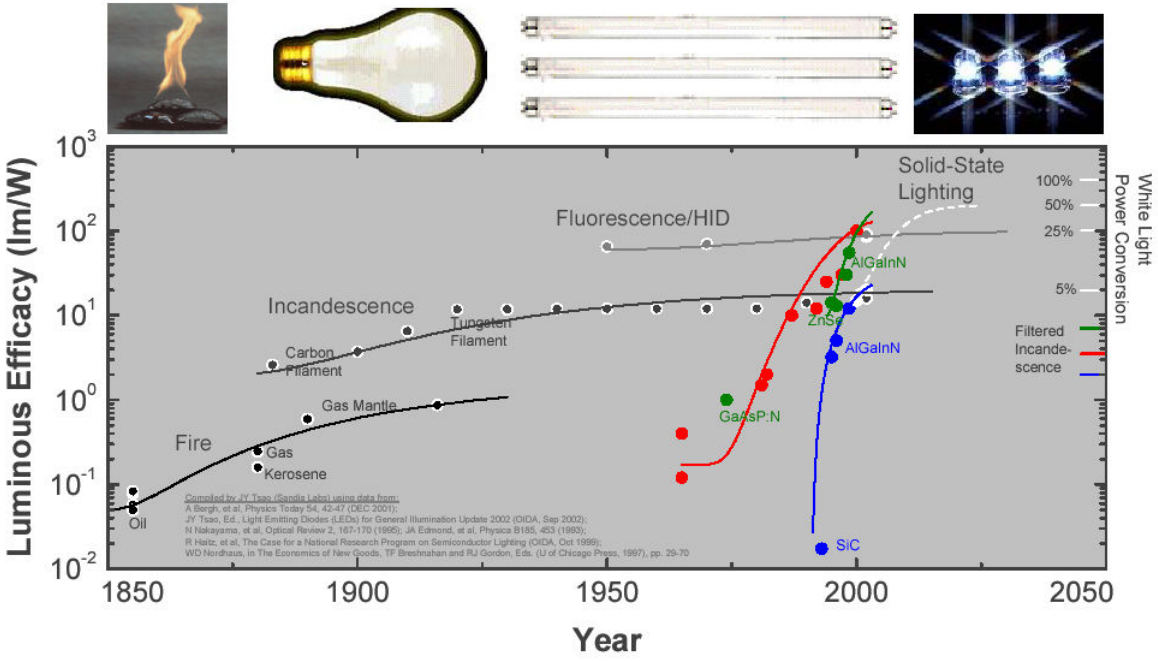
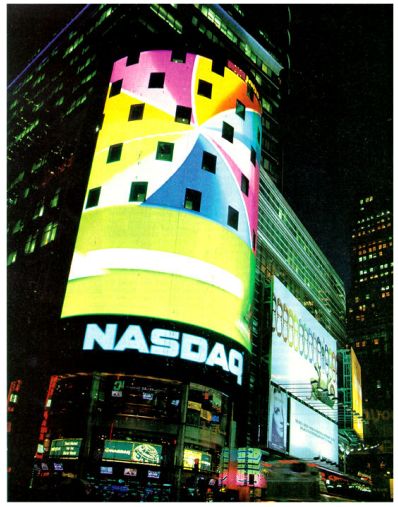
Solid State Lighting: an important technology for energy efficiency

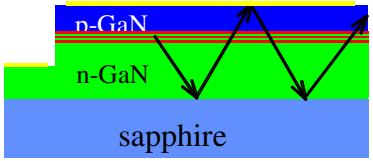
- **Red LEDs are 10X more efficient than red- filtered incandescents**
- **Today, 1/3 of US traffic lights are LED-based (Payback time ~ 1 yr)**



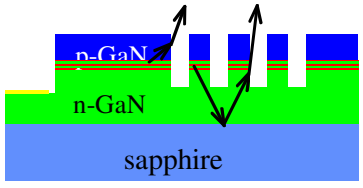


Getting the Light Out: Innovative Photon Management

Regular LED:
traps light inside



Photonic Lattice LED:
light escapes at surface



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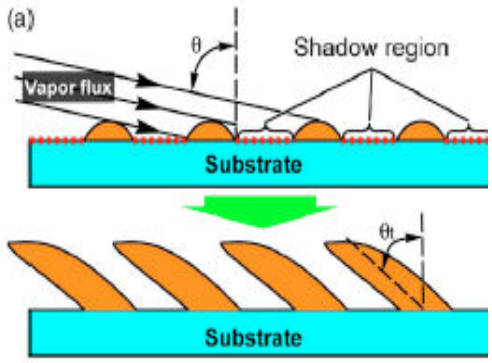
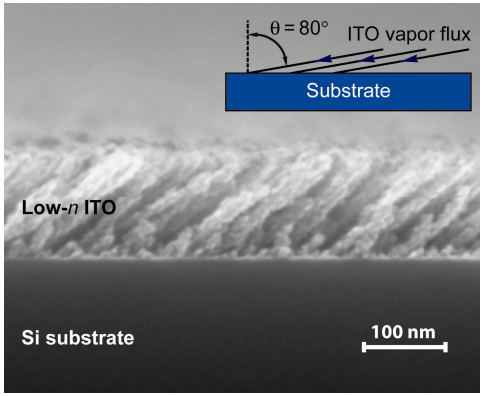
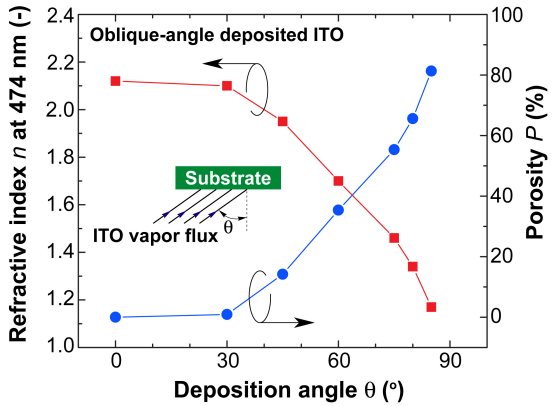
Novel Graded Refractive Index (GRIN) structures for improved light extraction in LEDs

Nanorod GRIN structures: Indium Tin Oxide (ITO)

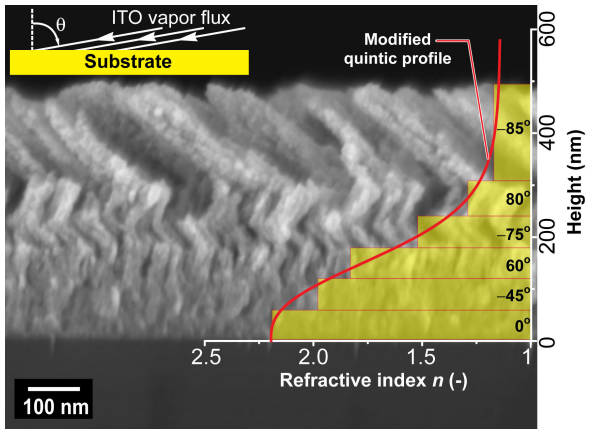




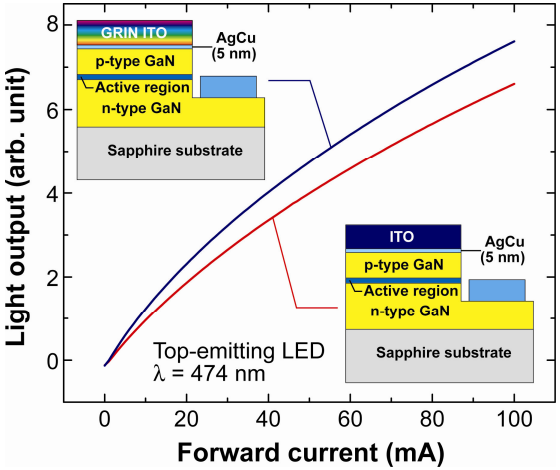


- Oblique angle deposition (e-beam evaporation) enables nanorod coatings
- Deposition angle defines porosity and refractive index of nanorod coating
- Refractive indices continuously tunable between ~1.14 and 2.19 for ITO nanorods

6 layer ITO Nanorod GRIN coating



Light Output Characteristics of LEDs



→ 24% enhanced light output with GRIN ITO coating

J. K. Kim et al., Advanced Materials, 2008

RPI: Group of Prof. E. F. Schubert

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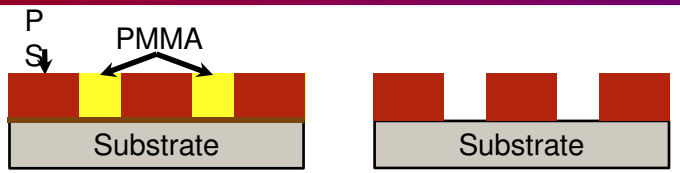
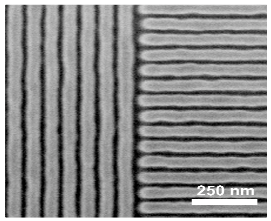
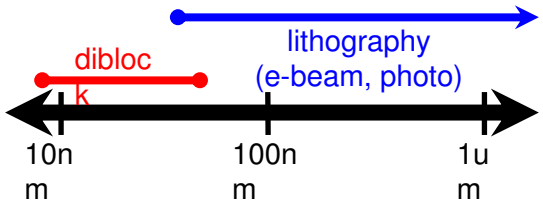
Self-assembled diblock copolymer mask



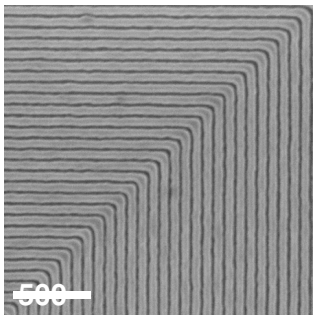
Periodic Lines



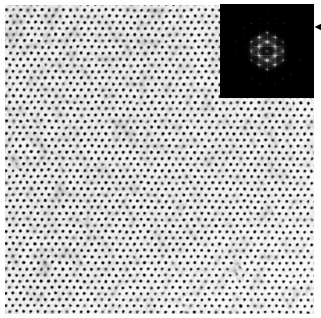
T-junctions



Bends



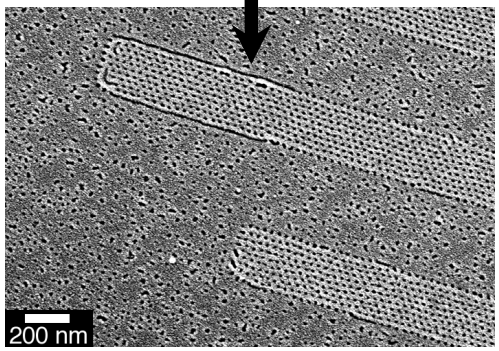
Spots



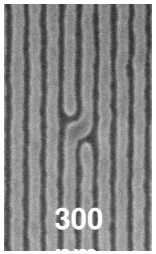
Canonical set of features for integrated circuits demonstrated

Improved line edge roughness and resolution doubling at limit of exposure tool

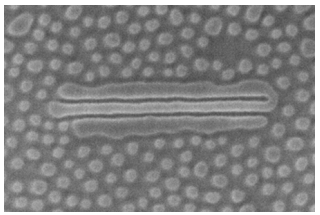
Bi-level patterning when combined with lithography



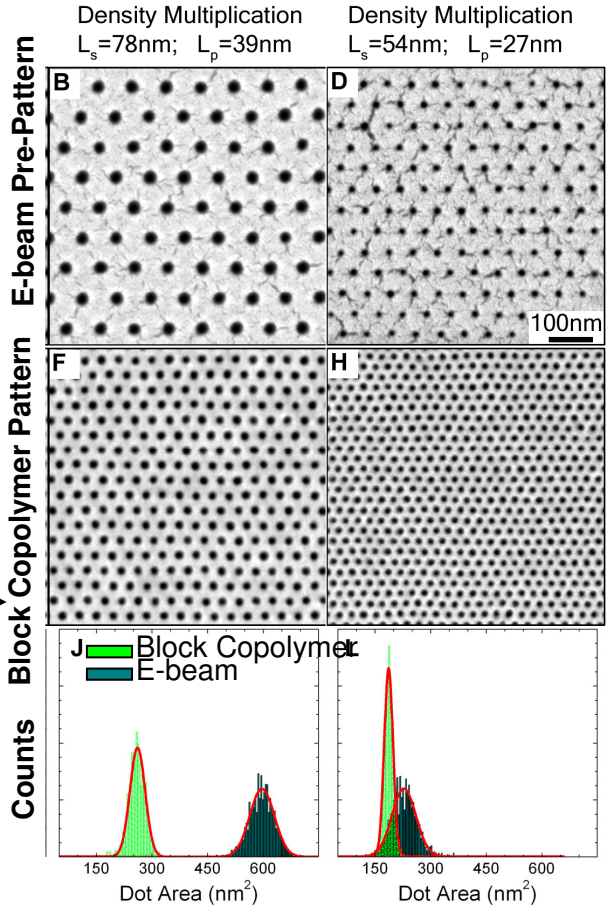
Jog



Isolated Lines



Stoykovich et al. *ACS Nano*, 2007, *Science* 2005



Ruiz, Nealey, de Pablo et al. *Science*, 2008

Collaboration: Sandia, the University of Texas-Austin, & he University of Wisconsin

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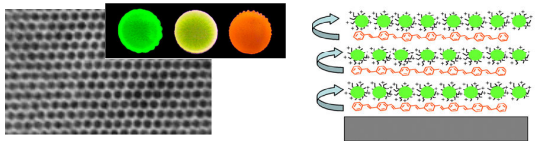
Center for Integrated Nanotechnologies (CINT): A national user facility for integration science

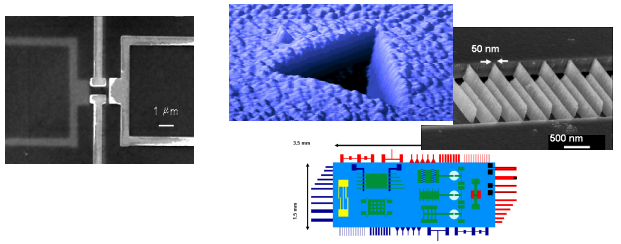
Nanophotonics & Optical Nanomaterials

Synthesis, excitation and energy transformations of optically active nanomaterials and collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices)



Nanoscale Electronics, Mechanics & Systems

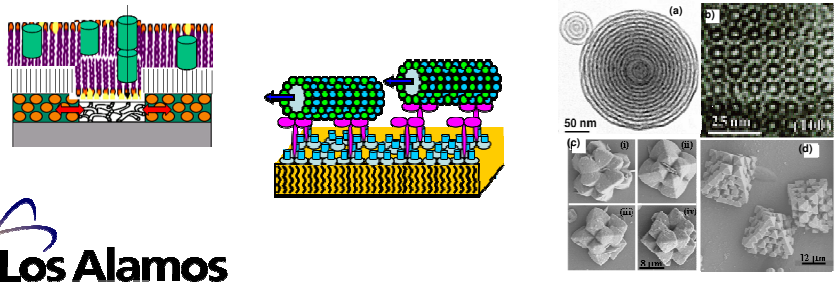
Control of electronic transport and wavefunctions, and mechanical coupling and properties using nanomaterials and integrated nanosystems



Center for Integrated Nanotechnologies
DISCOVERY
PERFORMANCE
CINT
EDUCATION
INTEGRATION
Sandia
Los Alamos

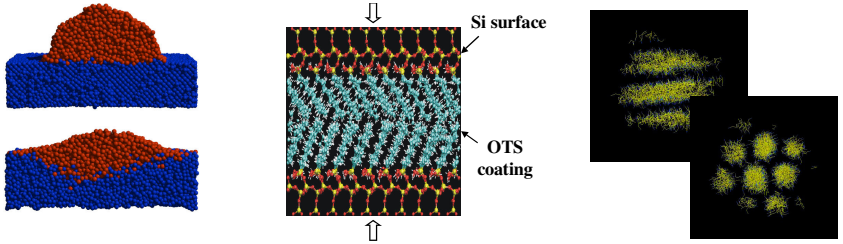
Soft, Biological, & Composite Nanomaterials

Solution-based materials synthesis and assembly of soft, composite and artificial bio-mimetic nanosystems



Theory & Simulation of Nanoscale Phenomena

Assembly, interfacial interactions, and emergent properties of nanoscale systems, including their electronic, magnetic, and optical properties



Los Alamos NATIONAL LABORATORY

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Acknowledgements

Outstanding colleagues from Sandia National Laboratories

Mark Allendorf – metal organic framework materials

Kate Bogart – advanced Lithography

Tim Boyle – nanomaterial synthesis

Geoff Brennecka – dielectrics, advanced lithography

Paul Clem – direct write

Mary Crawford – solid state lighting

Shawn Dirk - chemiresistors

Hongyou Fan – nanomaterial and thin-film fabrication

Robert Hwang – Director, Center for Integrated Nanotechnologies

Brian Swartzentruber – nanowire synthesis and characterization

Alec Talin - nanowire synthesis and characterization

Jim Voigt – oxide crystal growth & functionalization

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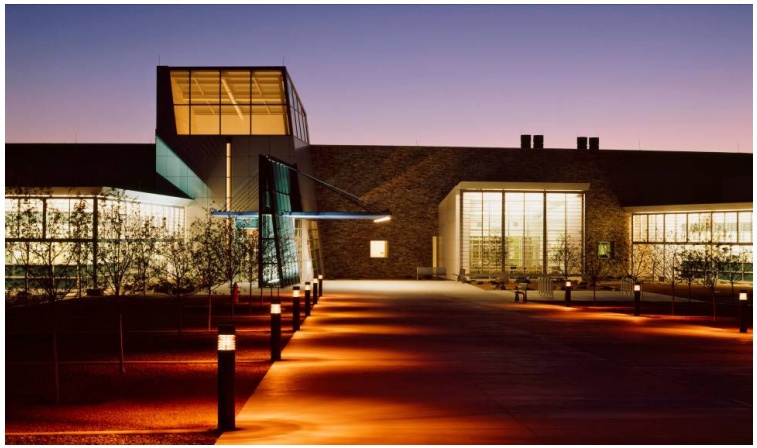
Please visit us!



Center for Integrated Nanotechnologies

See you at COMS 2009

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