SAND2016-4283PE

Thrust Overview

Nanoscale Electronics and Mechanics

Brian Swartzentruber (TL)
Nate Mara (PSL)

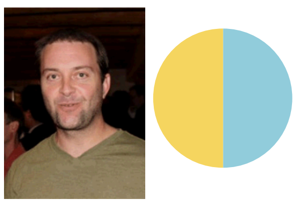
SAND2016-xxxx

NEM scientists have a broad range of expertise

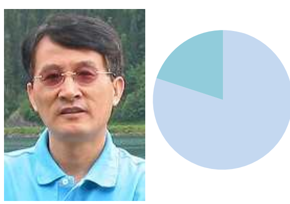
Synthesis | Fabrication | Characterization | Theory

B. Swartzentruber, TL
0.75 FTE
Nanomanipulation, scanning tunneling microscopy

N. Mara, PSL
0.6 FTE
Nanomechanics / nanocomposite synthesis



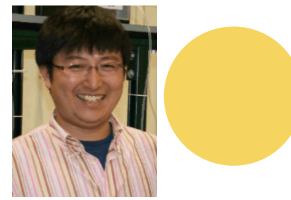
T. Harris
0.5 FTE
Transport in nanoscale structures



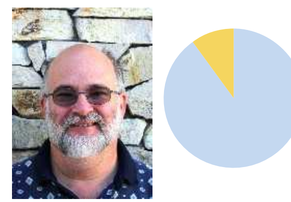
Q. Jia, Director
0.0 FTE
Complex oxides

K. Jungjohann
0.5 FTE
In-situ TEM techniques

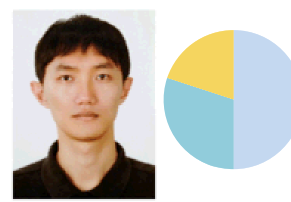
M. Lilly
0.5 FTE
Single e^- transport in 2d systems



T. Ohta
0.5 FTE
Low-energy electron and photoemission microscopy



J. Reno
0.5 FTE
III-V molecular beam epitaxy of high-mobility structures



J. Yoo
0.5 FTE
CVD nanowire and thin-film growth

J. Nogan
1.0 FTE

Integration Lab

NEM staff includes technologists, post docs, and students

Technologists, 8.5 FTE

J. Baldwin
A. Coley
P. Dowden
T. Hargett
T. James
J. Lucero
D. Pete
C. Sheehan
D. Webb

Post Docs, 0.75 FTE

U. Carvajal Nunez
D. Kim

Contracted Staff, 2.0 FTE

W. Mook
W. Ross

Students

J. Gutierrez-Kolar
S. Maldonado

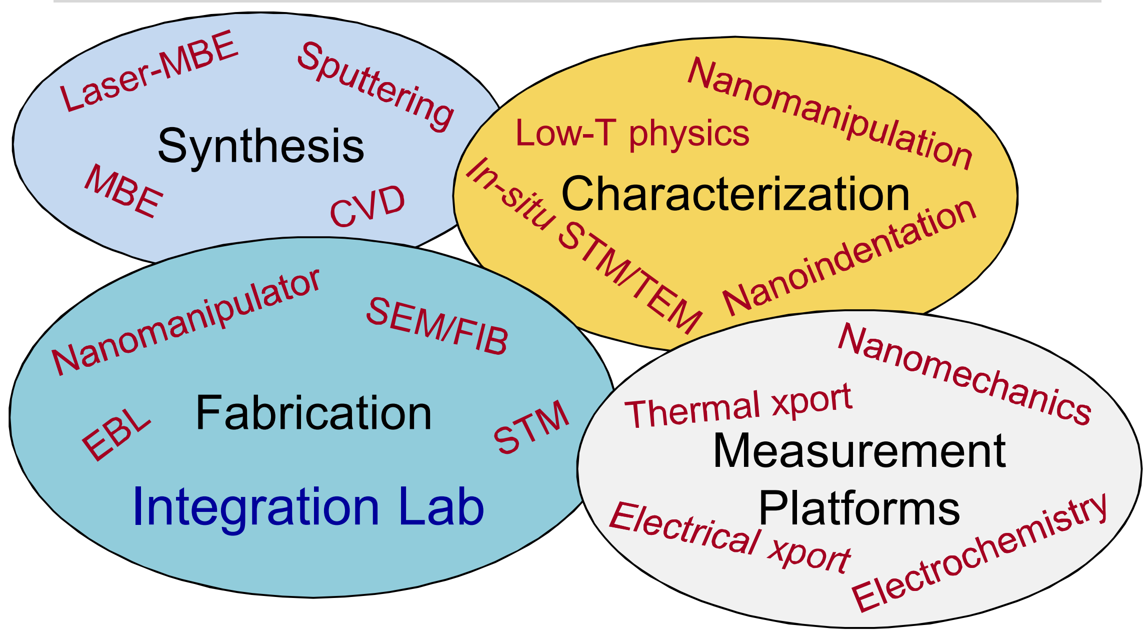
NEM Vision

The NEM vision is to understand and control electronic transport and wave functions, and mechanical coupling and properties using nanomaterials and integrated structures.

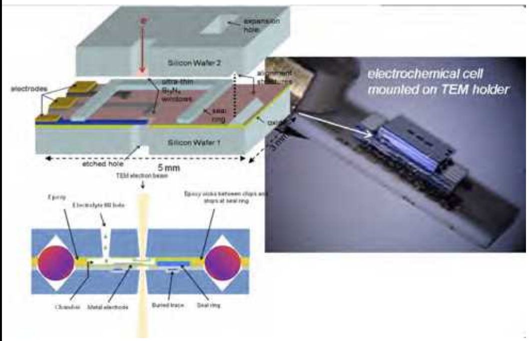
Scientific challenges

- How do defects and crystal distortions alter the electronic and/or mechanical properties in nanostructured materials?
- How does coupling between electronic and mechanical behaviors affect the functionalities of integrated nanostructures?
- How can we understand and control energy transfer across interfaces and over multiple length scales?

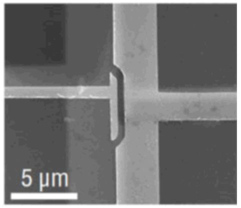
We address these questions through a combination of synthesis, fabrication, and characterization techniques that include a suite of foundational and differentiating capabilities.

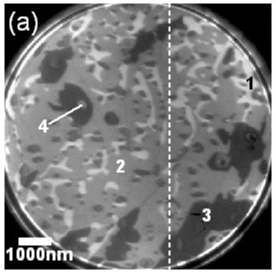


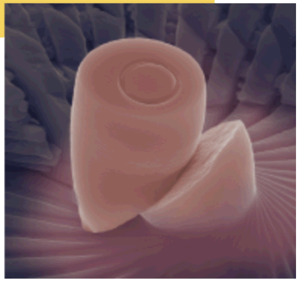
NEM supports a host of differentiating capabilities

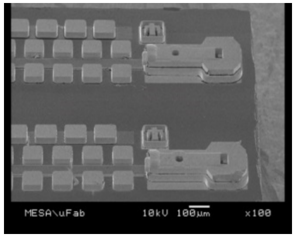


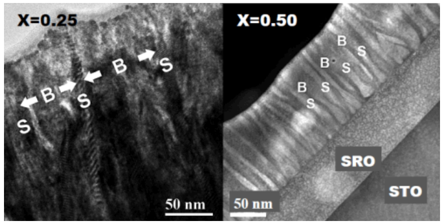
- *In situ* TEM Measurements
- Discovery Platforms
- Quantum Xport / Low-T Physics
- Low-Energy Electron Microscopy
- *in situ* Nanomechanics



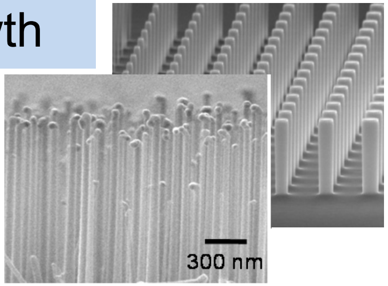




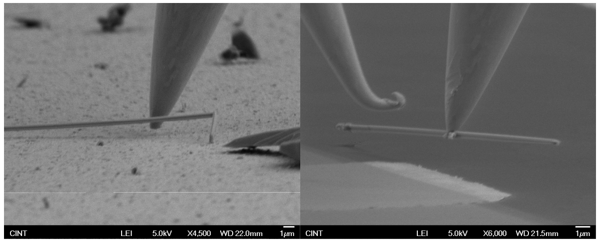


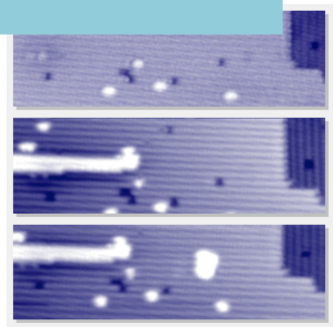


- Ultra-High Mobility MBE
- Complex Oxide PLD
- CVD Nanowire Growth



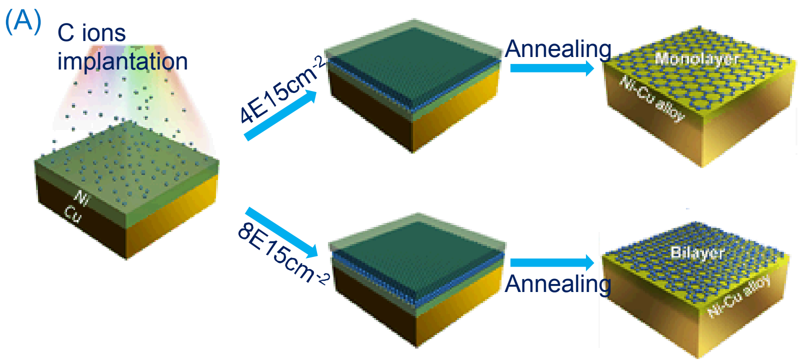
- Atomic-Precision Lithography
- Nanomanipulator

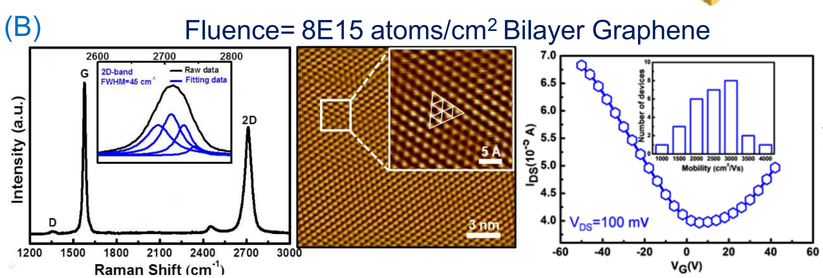




Selected Highlights of Accomplishments

Synthesizing Graphene by Ion Implantation

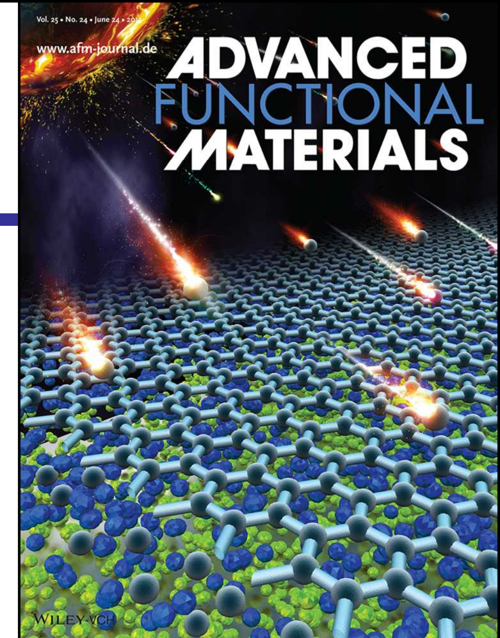




(A) Schematic diagrams of monolayer and bilayer graphene synthesized by C ion implant into the Ni/Cu bilayer substrate.

(B) Characterization of bilayer graphene by Raman, STM and electrical measurement.

Shanghai Institute of Microsystem And Information Technology, Chinese Academy of Sciences



Scientific Achievement

Precise control of graphene layer thickness is achieved by implanting carbon in Ni-coated Cu foils.

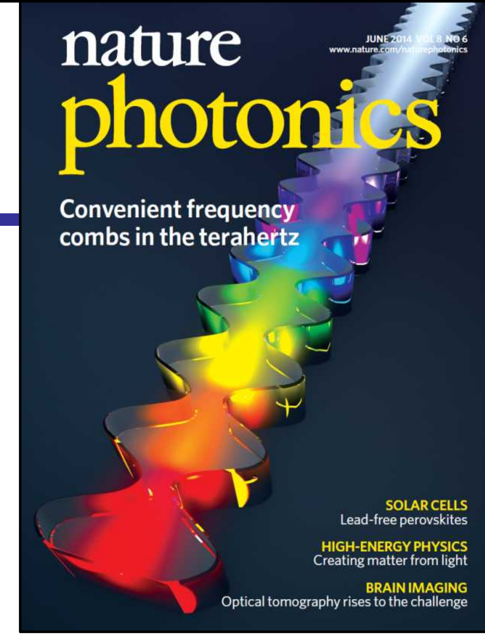
Significance and Impact

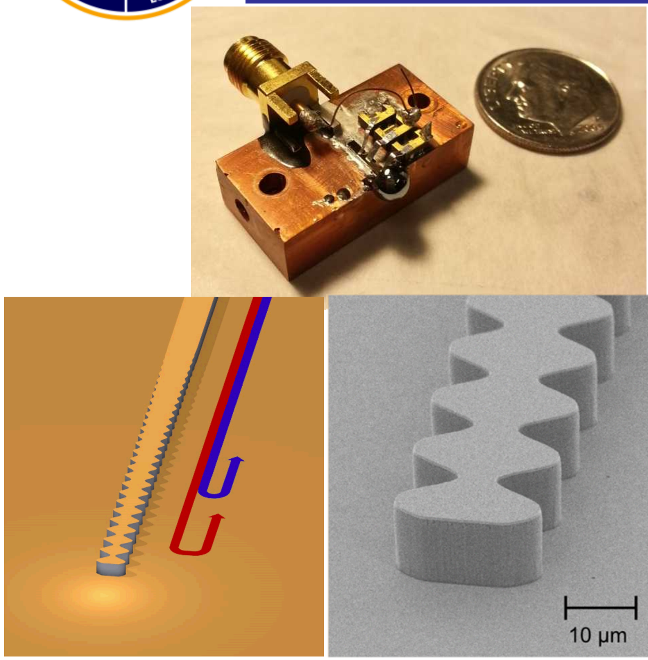
Graphene is a promising material in nanoelectronics and flexible electronic devices due to its unique 2D hexagonal lattice. However, synthesis of layer-tunable graphene by using traditional chemical vapor deposition method still remains a great challenge. Since our technique is compatible with large-scale microelectronics processing, it is expected that this approach will expedite the application of high-quality graphene to graphene-based nanoelectronic devices.

Wang, G., Zhang, M., Liu, S., Xie, X.M., Ding, G.Q., Wang, Y.Q., Chu, P.K., Heng, G., Ren, W., Yuan, Q.H., Zhang, P.H., Wang, X., Di, Z.F (2015) “Synthesis of layer-tunable graphene: A combined kinetic implantation and thermal ejection approach” Advanced Functional Materials: 25, 3666-3675 U2014A0013

Carbon implanted at Ion Beam Materials Laboratory (Leveraged capability at LANL)

Compact Terahertz Laser Frequency Combs Using THz QCL





Top: Picture of actual device
Bottom: Cartoon of double-chirped mirrors used and SEM of them.

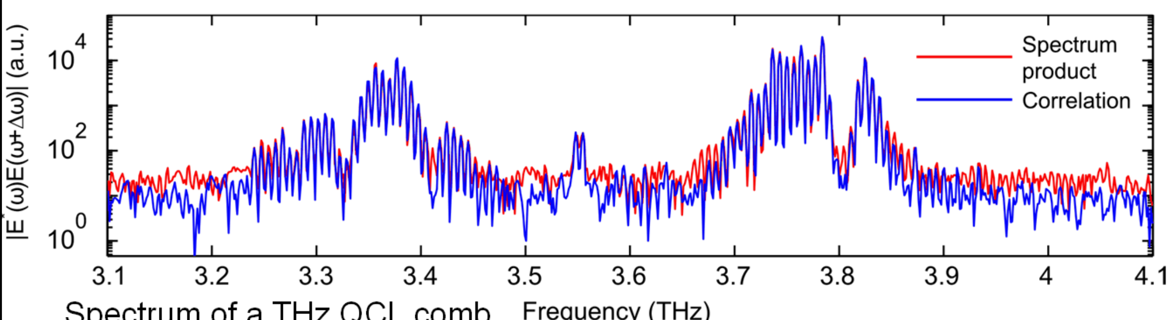
Scientific Achievement

Demonstrated compact terahertz laser frequency combs based on terahertz quantum cascade laser (QCL).

Significance and Impact

Frequency combs are powerful tools for high-precision metrology and spectroscopy (2005 Nobel Prize in physics).

- The comb spans over 550 GHz with ~70 equally spaced lines (total power of 5mW).
- Linewidth is 1.8 MHz – much narrow than needed for high-precision spectroscopy.

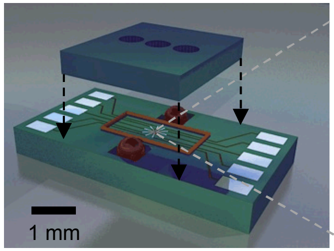


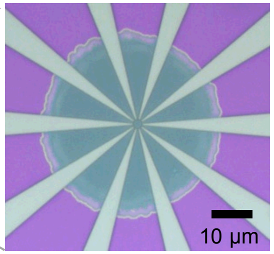
Spectrum of a THz QCL comb.

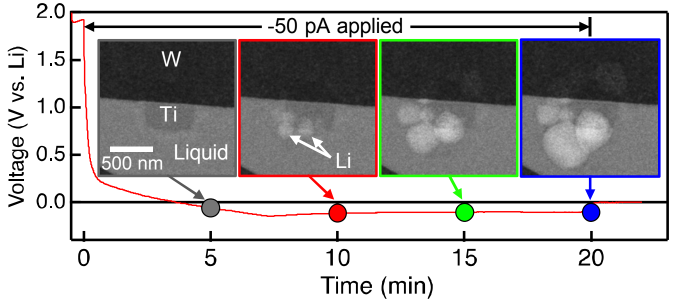
Burghoff, D., Kao, T.Y., Han, N.R., Chan, C.W.I., Cai, X.W., Yang, Y., Hayton, D.J., Gao, J.R., Reno, J.L., Hu, Q. (2014) "Terahertz laser frequency combs" Nature Photonics: 8, 6 C2013A0020D.

Lithium Electrodeposition Dynamics in Aprotic Electrolyte Observed *in Situ via* Transmission Electron Microscopy (TEM)

Custom TEM cell encapsulates a thin liquid layer between electron transparent membranes with multiple electrodes.

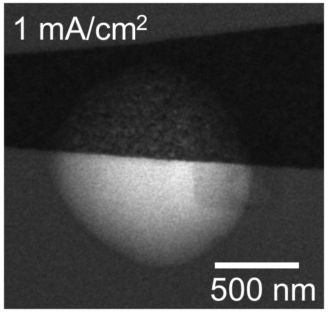


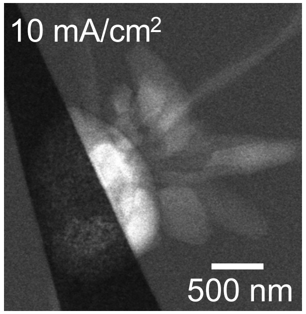




Time series of Li microstructures formed during quantitative, current-controlled electrodeposition.

Dendritic Li formation occurs depending on the applied current density.





Scientific Achievement

We show the first *in-situ* observations at sub-μm resolution of controlled-rate Li electrodeposition & dissolution in standard battery electrolyte.

Significance and Impact

For high-capacity Li metal battery electrodes, the microstructure evolution during cycling reveals critical degradation mechanisms that are governed by passivating interfacial layers.

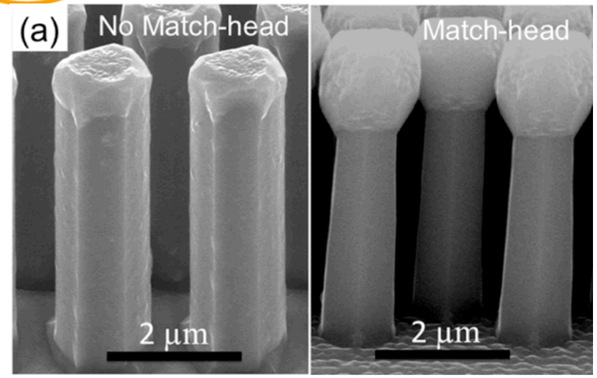
Such understanding can lead to increased battery cycle performance.

- TEM liquid cell with multiple electrodes enabled multiple experiments under identical chemical conditions.
- Interfacial films on the Li led to more pronounced dendrite formation, and electron-beam exposure altered surface film properties.

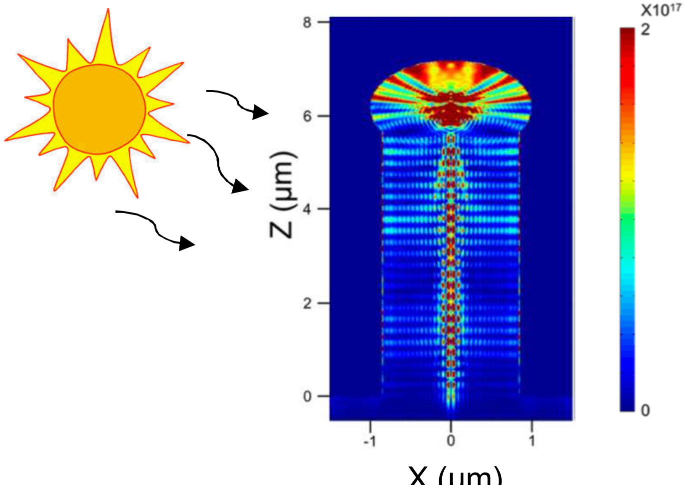
Leenheer, A.J., Jungjohann, K.L., Zavadil, K.R., Sullivan, J.P., Harris, C.T. (2015) "Lithium electrodeposition dynamics in aprotic electrolyte observed in situ via transmission electron microscopy" ACS Nano: 9, 4

NEES III NANOSTRUCTURES *for* ELECTRICAL ENERGY STORAGE

Tiny "match-head" wires boost solar energy efficiency at nanoscale and microscale levels



Cylindrical silicon wires without a match-head structure and with a match-head structure



Light absorption cross-section profile of silicon match-head wire at 476 nm

Scientific Achievement

The match-head acts as a light concentrator and creates a new architecture for controlling light-energy properties. Radiant-light absorbance was increased by 36%, and photovoltaic efficiency was increased by 20% over no-match-head wires.

Significance and Impact

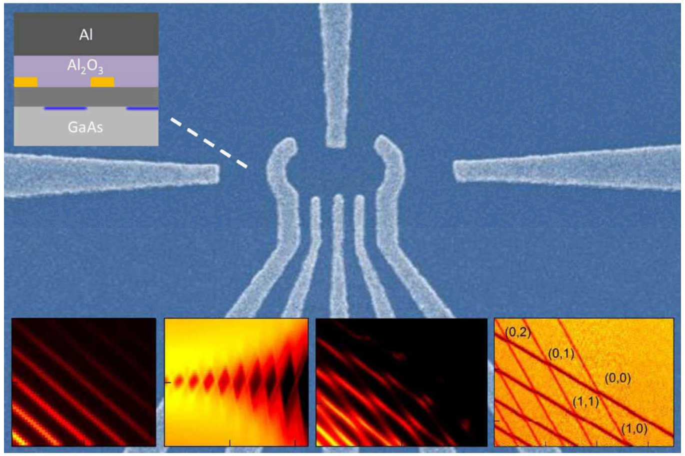
Do not require construction of a light-concentrator system.

Match-head nanowires are attractive candidates for next-generation semiconductor devices such as photodetectors and light emitters

- Surface energy minimization causes layered crystal growth of silicon at the tips of nanowires.
- The match-head structure improves light absorption of silicon when measured in a photovoltaic cell – match-head acts as a built-in light concentrator.
- Smaller-diameter nanowires that are densely packed optimize photovoltaic performance.

Yoo, J., Nguyen, B.M., Campbell, I.H., Dayeh, S.A., Schuele, P., Evans, D., Picraux, S.T. (2015) "Si radial p-i-n junction arrays for photovoltaics with built-in light concentrators" ACS Nano: 9, 5 U2013B0062

Coupled Hole Quantum Dots in GaAs/AlGaAs

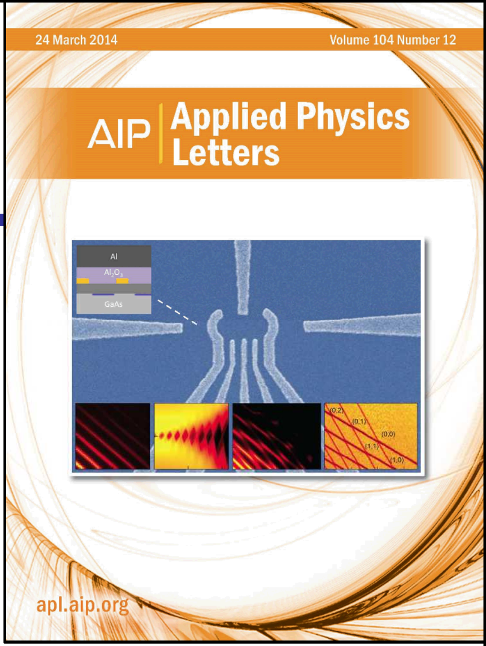


Top: An SEM micrograph along with a sketch of the cross-section of the device showing the metallic control gates.

Bottom: On the left, charge conductance through the device operating as a large single dot. On the right, demonstration of of the device working as two separate dots and the control of the number of holes on each dot.

Scientific Achievement

Coupled hole quantum dots in a GaAs/AlGaAs heterostructure were demonstrated with an interdot coupling that can be tuned from a large single dot to two well-isolated quantum dots.



Significance and Impact

The device should allow for control of individual hole location, number, and spin. This device is a promising candidate for a solid-state quantum bit due to the increased coherence time of hole spins over electron spins.

- Charge sensing was used to detect and control the charge occupation of the dots
- The number of holes in the dots was controlled from completely empty to the few-hole regime
- The holes were obtained using Coulomb attraction to a negatively charged gate

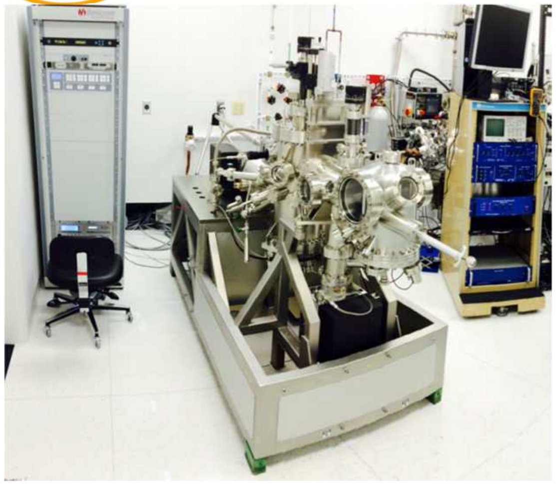
Tracy, L.A., Hargett, T.W., Reno, J.L. (2014) “Few-hole double quantum dot in an undoped GaAs/AlGaAs heterostructure” Applied Physics Letters: 104, 123101

U2011A1019

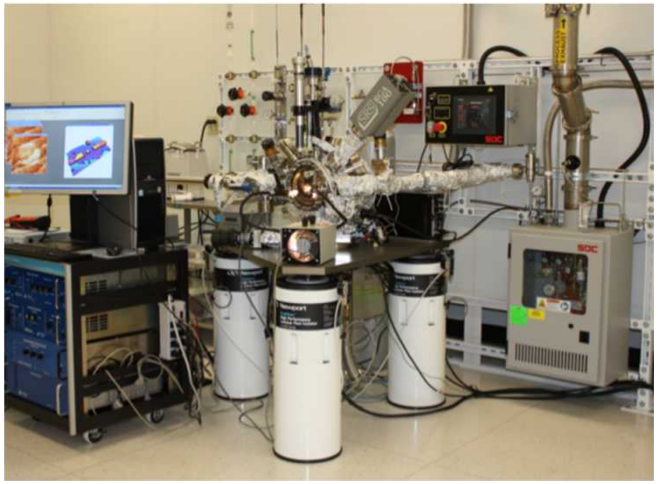
New Capabilities

- Atomic-precision lithography
- LANL electron microscopy adoption

Atomic-precision lithography via STM is a collaboration with Quantum Information Science (Partner User)



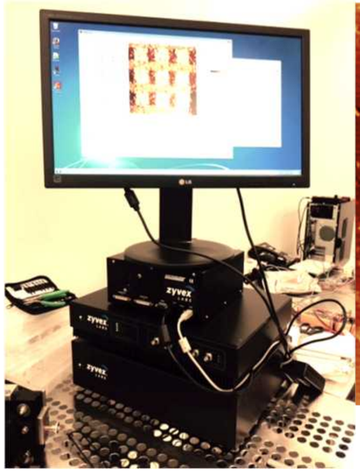
Omicron MBE + STM (1/2015)

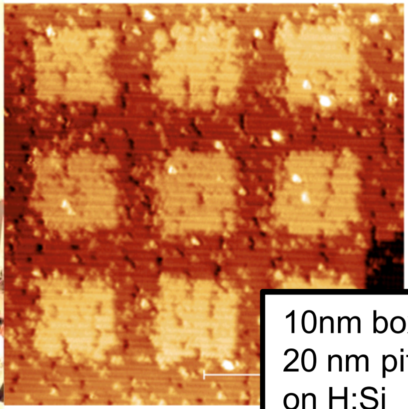


Custom STM w PH_3 Gas

Omicron MBE + STM (9/2014)

Automated STM lithography controller (Zyvex Inc, 12/2014)





10nm boxes
20 nm pitch
on H:Si

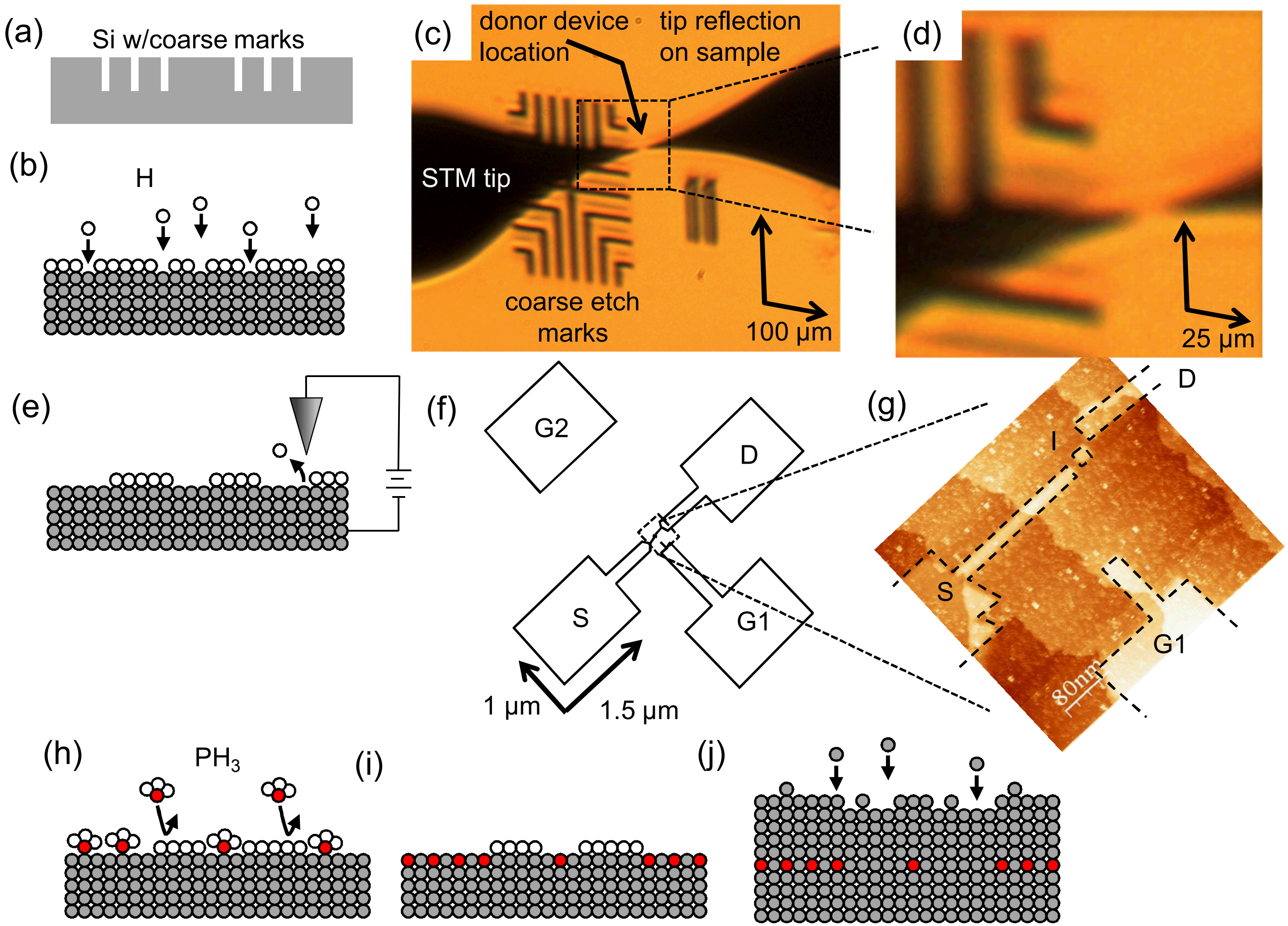
Important capabilities of STM fab lab

- Automated atomic-precision lithography and doping of Si
- Si and Ge molecular beam epitaxy

Other critical tools

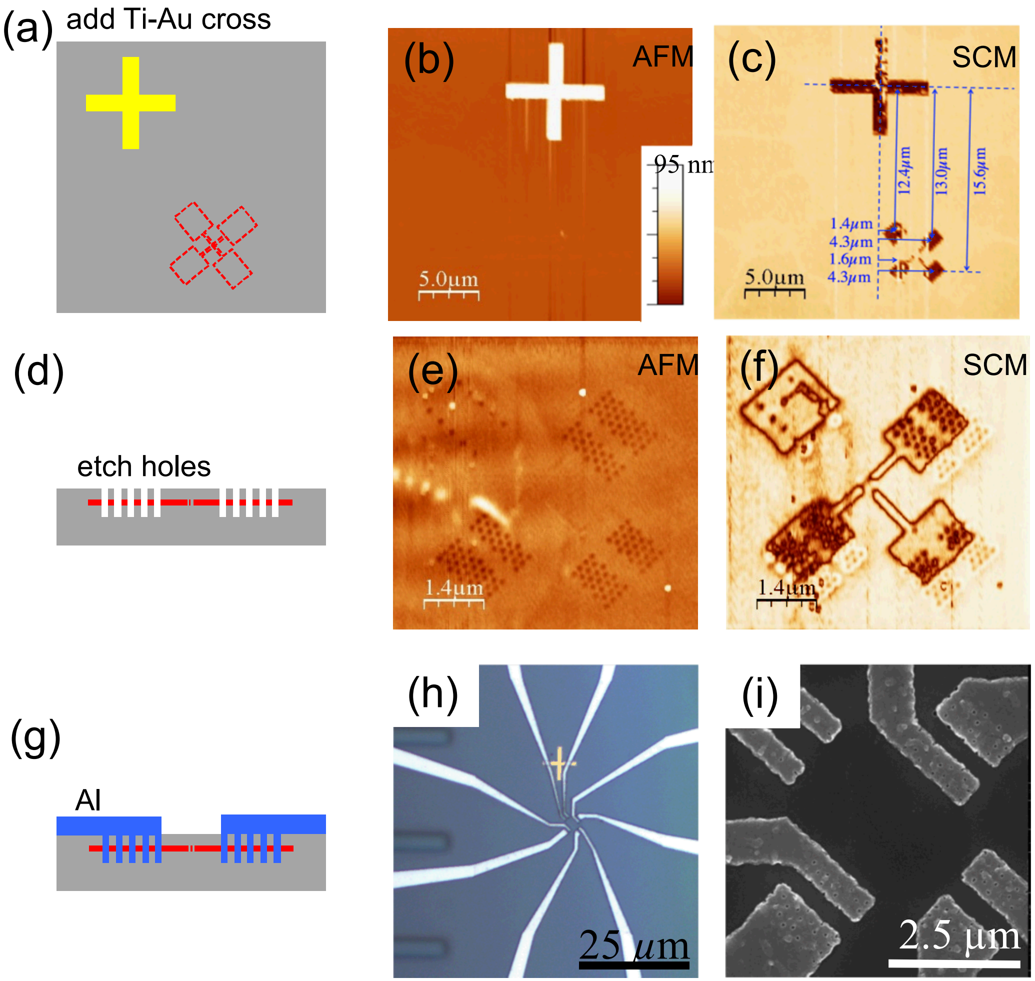
- Scanning capacitance microscope
- Si foundry processing in-house

STM qubit fabrication involves hydrogen depassivation and P dopant incorporation



Single Electron Transistor device

Subsequent processing is done in the CINT Integration Lab



Scanning capacitance microscopy reveals buried dopant features.

Future:

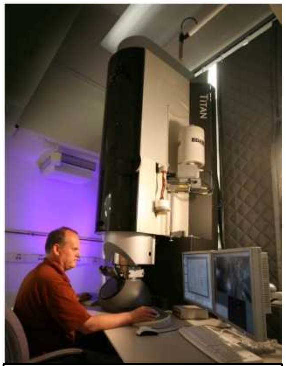
- Upgrade all STMs with auto-lithography capability
- Use CINT-developed scripting capability
- Demonstrate quantum bit device
- Scale to two and more devices

$$ Financial resources largely through SNL QIST program

Partner User investment ($1.5 – $2M to date)

Leveraging LANL electron microscopy will add unique “Lab-in-a-Gap” capabilities

Tecnai F30 TEM



Titan 80-300 TEM

Helios Nanolab 600 DualBeam SEM/FIB

FEI Tecnai F30 TEM - *analytical TEM/STEM*

- Chemical Analysis: energy dispersive spectrometry (EDS)
- Electron Energy Loss (EELS) imaging and analysis.
- ***Compatible with in-situ holders @ CINT Core***

FEI Titan 80-300 TEM - *monochromated, aberration-corrected imaging, and analytical TEM*

- EDS and EELS imaging and analysis
- including sub-Å TEM, 1.4 Å STEM
- TEM and STEM tomography
- ***Compatible with in-situ holders @ CINT Core***

FEI Helios 600 FIB/SEM – *Dual-Beam FIB*

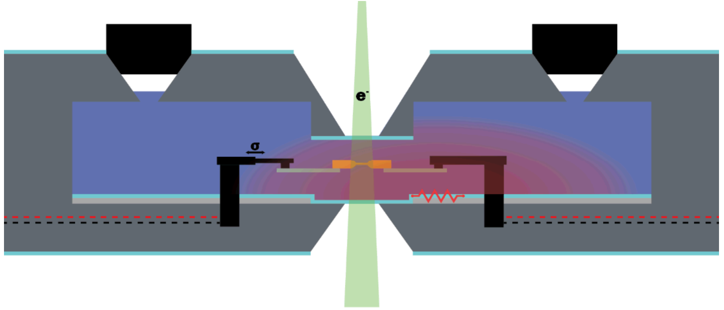
- FIB nanofabrication
- milling of TEM and micromechanical test specimens
- EDS and ESBD detectors
- 2D and 3D chemical and crystallographic imaging

Nanomechanics and high-T at Gateway
Electrochemistry, liquid cell, and low-T at Core

Future Directions

- Liquid-nanomechanics TEM Discovery Platform
- Core–shell nanowires and 1D–2D integration
- New functionalities in epitaxial nanoscaffolding films

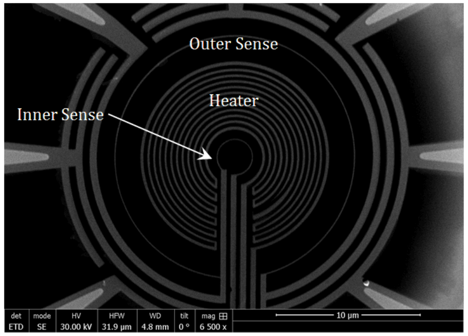
Liquid–nanomechanics TEM Discovery Platform



Advance "Lab-in-a-Gap" capabilities…

Adding heater to the liquid cell.

A



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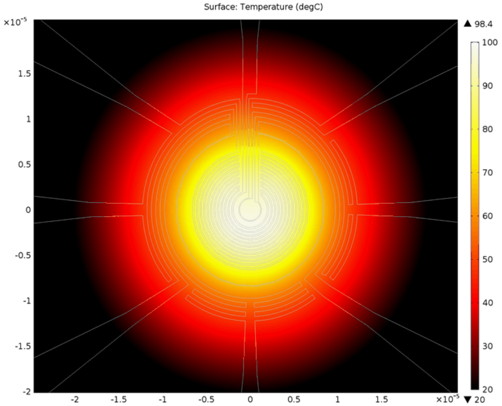
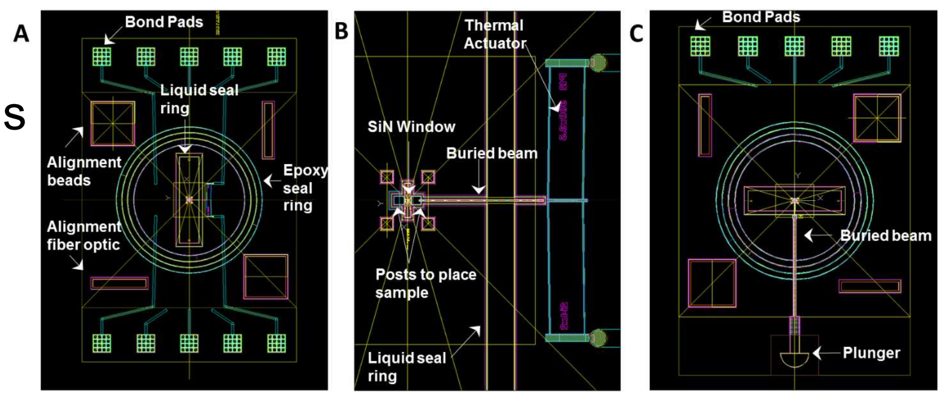
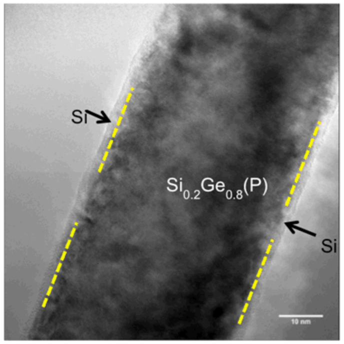


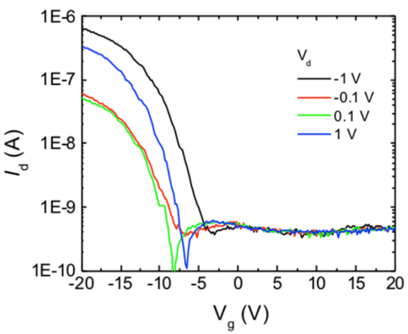
Integrating mechanical control for quantitative loading in liquid environment using integrated MEMS actuation or movable rod for external actuation.

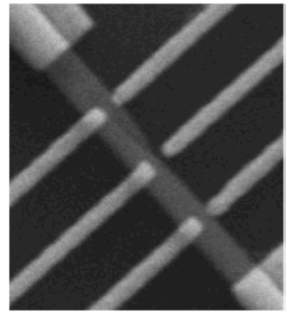
Holders will be produced to lend stages and platforms to users at their institutions.



Core–shell nanowires and 1D–2D integration







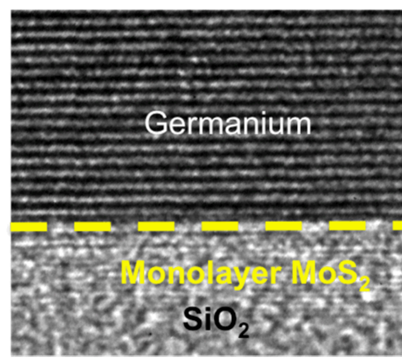
TEM image (left) and FET characteristic curve (middle) of n-type SiGe/p-type Si core/shell heterostructure. Hall bar fabrication on a single SiGe/Si/SiGe core/multi-shell nanowire for magnetotransport measurement (right).

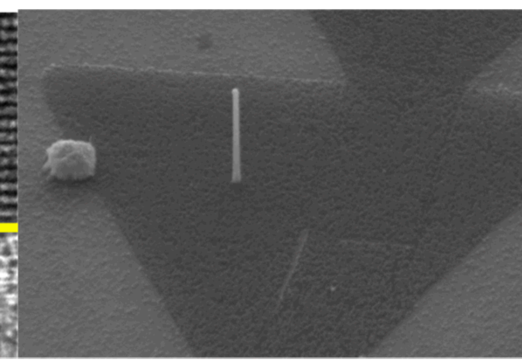
Core/multi-shell nanowire heterostructures can confine carriers in tubular conduction channels.

Focus: Understand the size-dependent, ring-topological aspects of carrier transport from nano- to micro-scale.

Focus: Understand the novel functionality of semiconductors on 2D material heterostructures in integrated devices.

Observation: Ge/MoS_2 heterostructure is metallic though both are semiconducting. Mechanistic study with TSMP (poster)



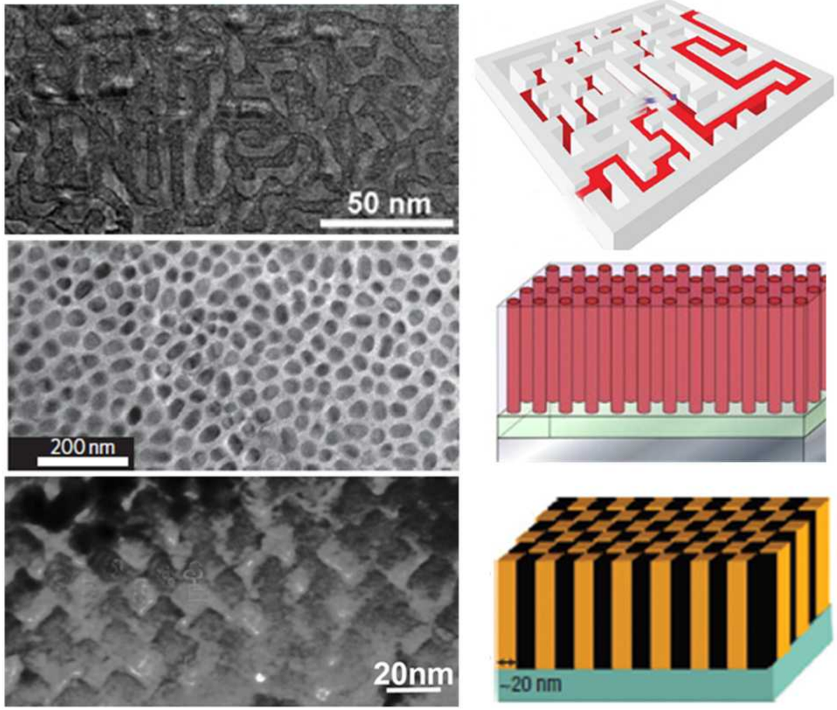


CINT 2020: Integrate various materials and dimensionalities – understand transport at nanoscale interfaces

New functionalities in epitaxial nanoscaffolding films

Lattice-strained epi-NSFs provide a new paradigm to tune functionalities not found in individual constituents.

- Function can be induced through vertical interfacing.
- Thickness limitations can be circumvented (x10).
- Function of active phase can be tuned by the passive phase.



Maze, pillar, and checkboard patterns

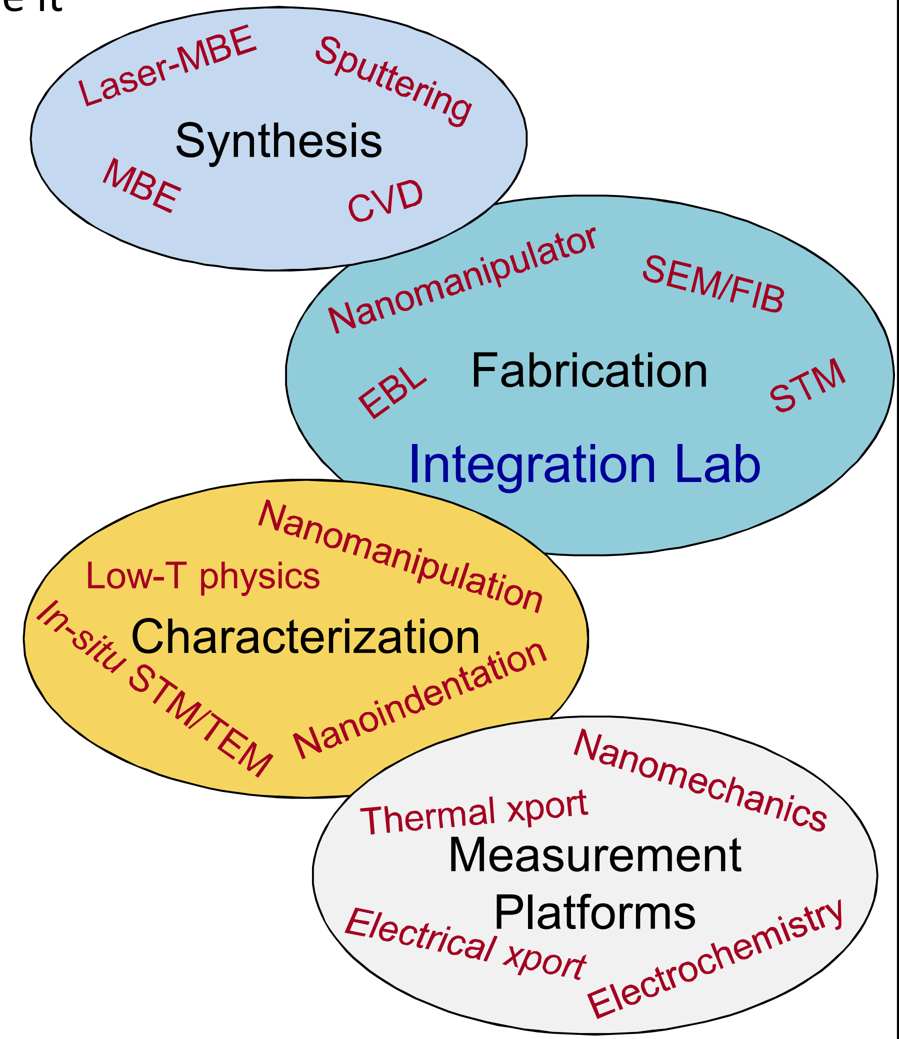
Our advanced synthesis, unique characterization, and well-established modeling capabilities enable us to understand the emergent behavior arising from surface morphology, vertical interface strain, and interface chemistry.

User talk: Haiyan Wang

Nanoscale Electronics and Mechanics (NEM)

- Our expertise and unique capabilities have made it possible for us to effectively support our user community and successfully accomplish our scientific and technological goals in
  - Platforms for study of nanostructured materials
  - Semiconductor single spin devices
  - Nanomechanics
  - Nanocomposite films
  - Nanowires for new energy concepts

- NEM Thrust strives to continue
  - Leading in the cutting edge of science and technology of nanoscale electronics and mechanics through development of new capabilities
  - Attracting high profile users, and
  - Training the future workforce in the field



Talks and Posters

Talks

- **Haiyan Wang:** "Self-assembled Nanocomposite Thin Films for Multifunctionalities – Current and Future"
- **Guillaume Gervais:** "Alternative Processing for Quantum Devices"

Posters

- **Shadi Dayeh:** "Interfacing with Human Neurons: From Single Cells to Intact Brains"
- **David Mitlin:** "Coupling in-situ TEM and ex-situ analysis to understand sodiation of Sb"
- **Rachel Liontas:** "Effect of Irradiation on Metallic Glasses Nanopillars and Nanolattices"
- **Ezra Bussmann:** "Atomic-precision silicon nanoelectronics by scanning tunneling microscopy (STM)"