Nanostructures for Electrical Energy Storage (NEES)

a DOE Energy Frontier Research Center

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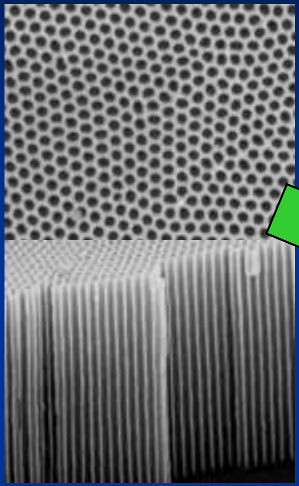
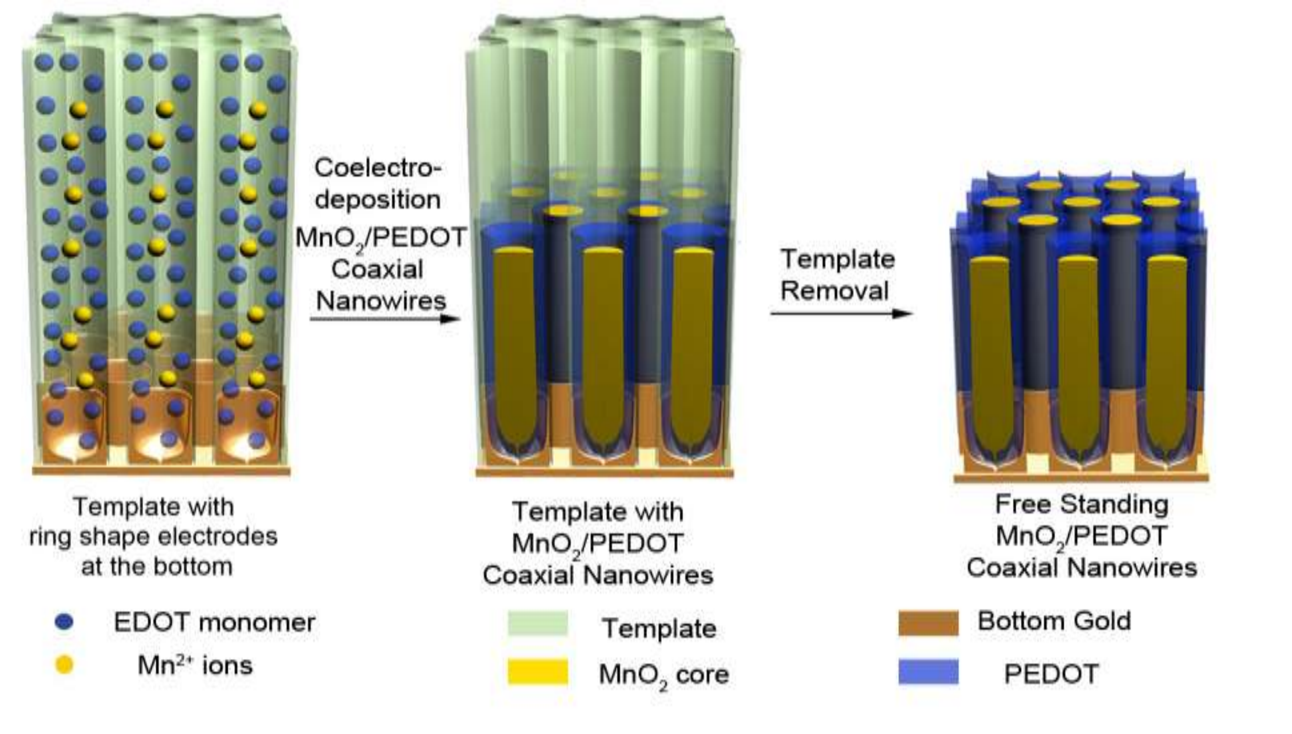
Director, DOE-EFRC Nanostructures for Electrical Energy Storage (NEES)

Dept of Materials Science & Engineering and Institute for Systems Research

Creating the EFRC

Electrodeposition into Nanopores → Coaxial Nanowires





AAO nanopores

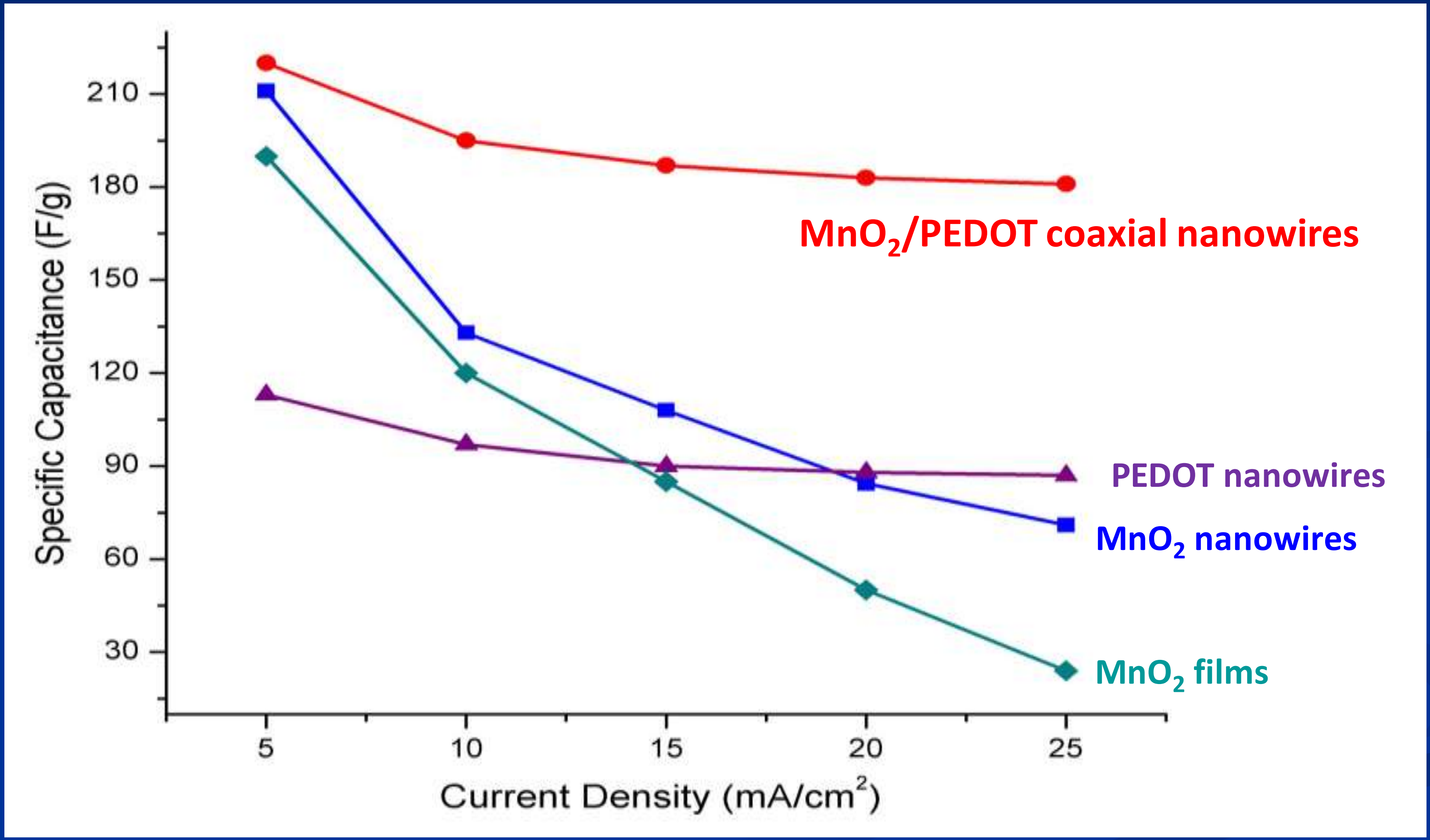
60nm dia, 1-30µm deep

Simultaneously electrodeposit:
MnO_2 charge storage material
Conducting polymer charge transport material

Liu & Lee, *J. Am. Chem. Soc.* (2008)

100 billion coaxial electrochemical nanowires per square inch

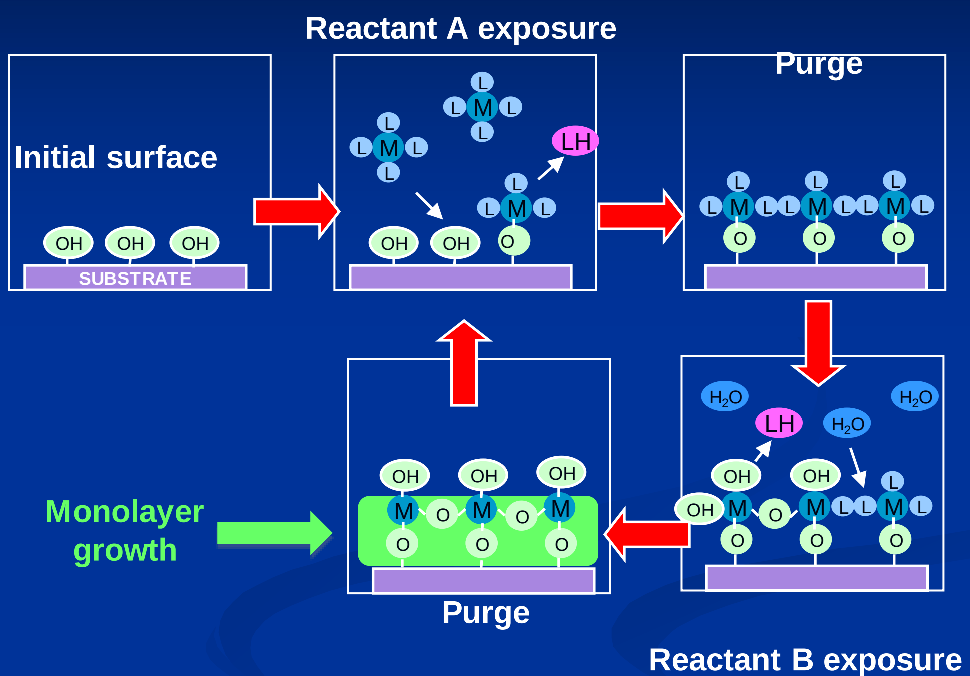
MnO_2/PEDOT Coaxial Nanowires for High Power & Energy



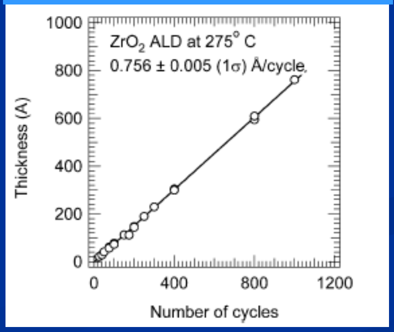
Liu & Lee, *J. Am. Chem. Soc.* (2008)

Atomic Layer Deposition (ALD)

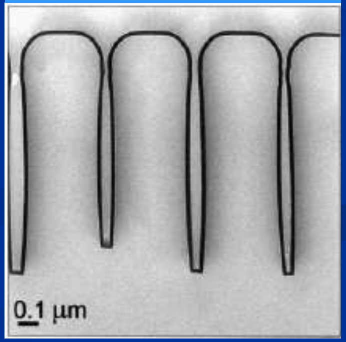
- Reactive CVD precursors alternately and separately exposed to surface
- Self-limiting adsorption/reaction
- Monolayer thickness control
- Superb conformality and uniformity



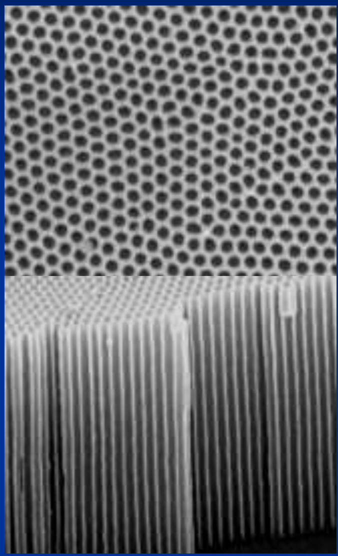
Thickness control



Conformality

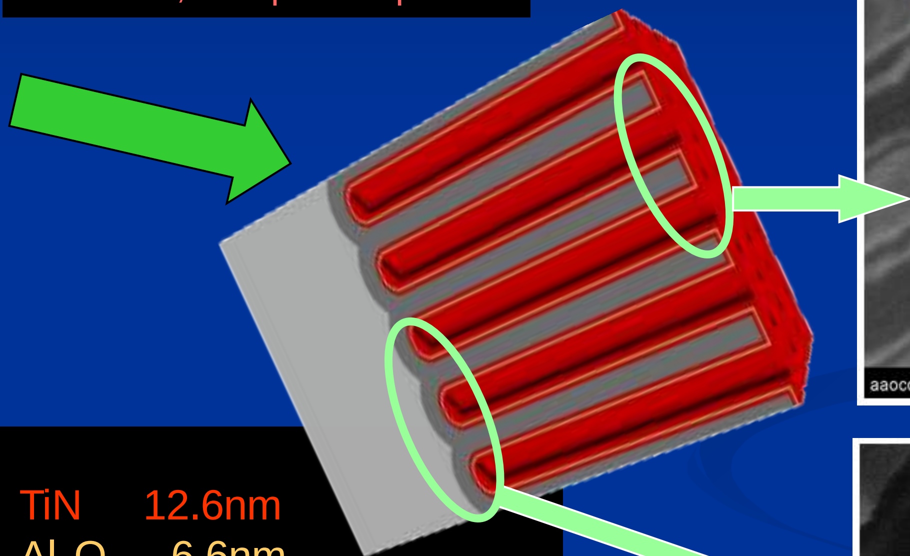


AAO-ALD for MIM Electrostatic Supercapacitor

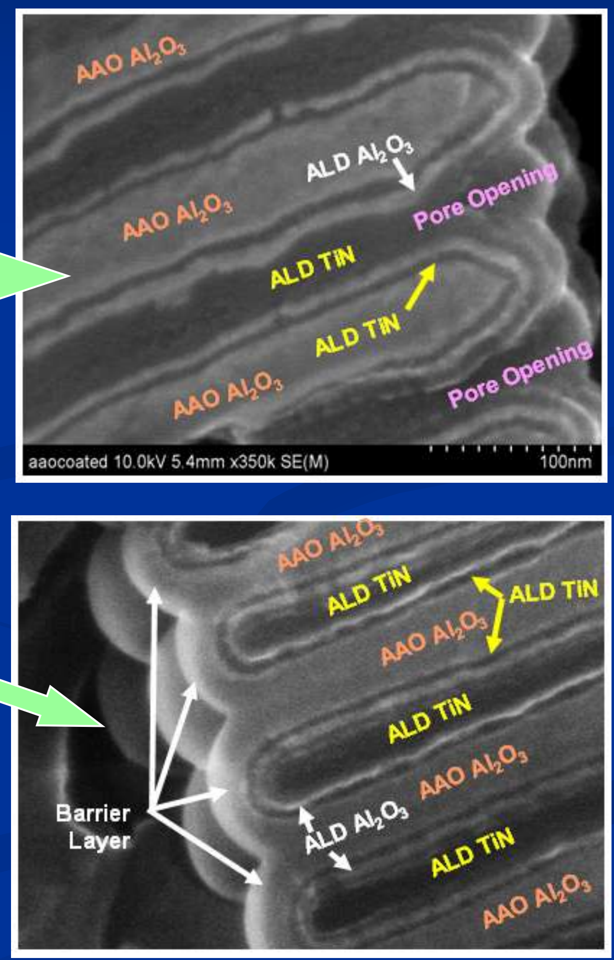


AAO nanopores

60nm dia, 1-10µm deep



SEM images



ALD MIM layers:

Top electrode: TiN 12.6nm

Dielectric: Al_2O_3 6.6nm

Bottom electrode: TiN 5.6nm

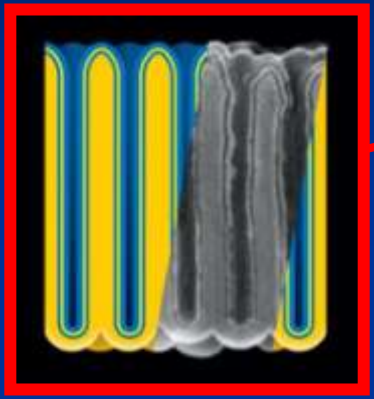
Aspect ratios 200-1000 (depth/width)

ALD conformality >93% in all layers

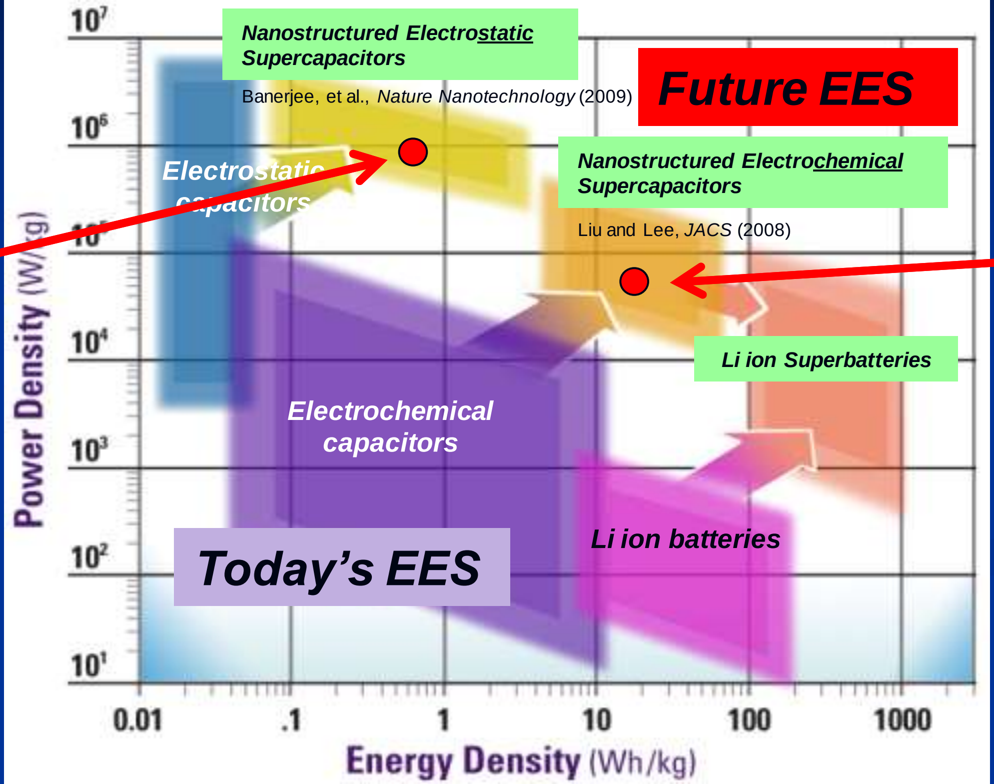
100 billion nanocapacitors per square inch

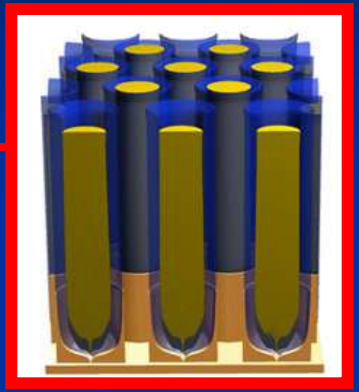
P. Banerjee et al, *Nature Nanotechnology* (2009)

Advances from Nanotechnology



AAO-ALD embedded metal-insulator-metal device





Free-standing MnO_2/PEDOT coaxial nanowires

1. Nanostructures for next-generation electrical energy storage

Massively parallel nanoengineered devices formed within nanopores

Much higher power and higher energy density

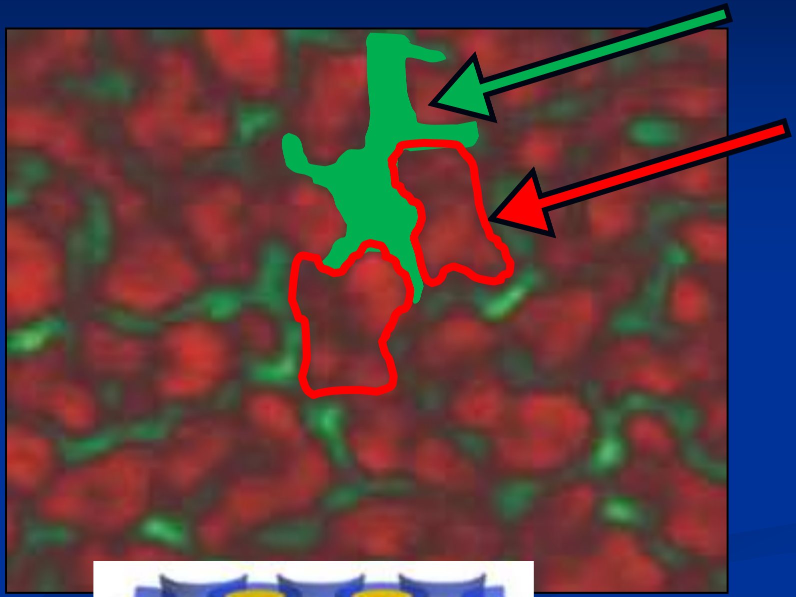
Nano-Enabled Energy Devices

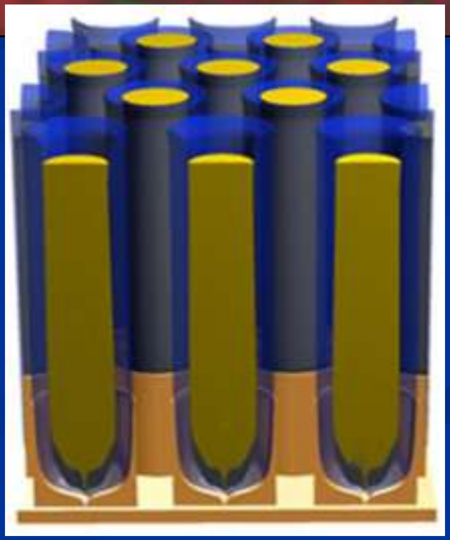
One material to do the basic job

- Store electricity
- Capture sunlight

At least a second material and/or interface to add other essential functions

- Move energy where it's needed
- Assist in energy conversion





2. Multiple, hetergeneous materials for multifunctional performance

"Designer nanomaterials & nanostructure systems" for efficient energy devices

Nanostructures – Regular or Random?

Regular (periodic)

Rapidly growing research activity

More amenable to characterization and understanding

Tighter distributions for manufacturing

Random (aperiodic)

Larger experience base

Easier, cheaper manufacturing processes

Potentially higher surface area

3. Focus on regular nanostructures

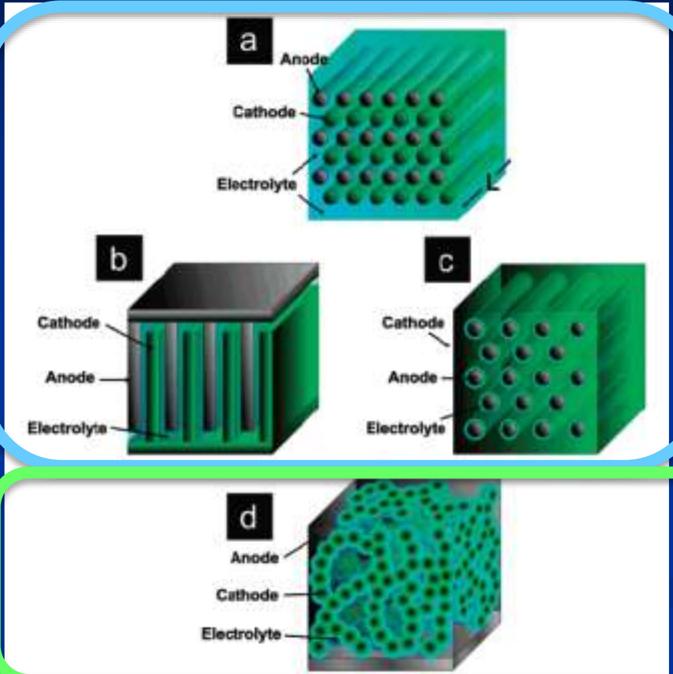


Figure 2. Examples of prospective 3-D architectures for charge-insertion batteries: (a) array of interdigitated cylindrical cathodes and anodes; (b) interdigitated plate array of cathodes and anodes; (c) rod array of cylindrical anodes coated with a thin layer of ion-conducting dielectric (electrolyte) with the remaining free volume filled with the cathode material; (d) aperiodic "sponge" architectures in which the solid network of the sponge serves as the charge-insertion cathode, which is coated with an ultrathin layer of ion-conducting dielectric (electrolyte), and the remaining free volume is filled with an interpenetrating, continuous anode.

J.W. Long, B. Dunn, D. R. Rolison and H. S. White, *Chem Rev* 104, 4463–4492 (2004)

Processes for Nanostructure Integration

4. Use the "3 self's"

- ***Self-assembly*** ➔ *massive arrays of nominally identical, regularly arranged nanostructures*

  let nature do the work

- ***Self-alignment*** ➔ *devices built upon/within the self-assembled templates*

  know where to go

- ***Self-limiting reaction*** ➔ *atomic scale control for thickness and conformality*

  stop when done

stated as mantras by P. Banerjee

Nucleating the EFRC

- **Initiate from small, familiar group**
- **Expand gradually as vision and strategy emerge**
- **Iterate themes, highlights, and expertise**
- **Exploit available resources (technical and administrative)**

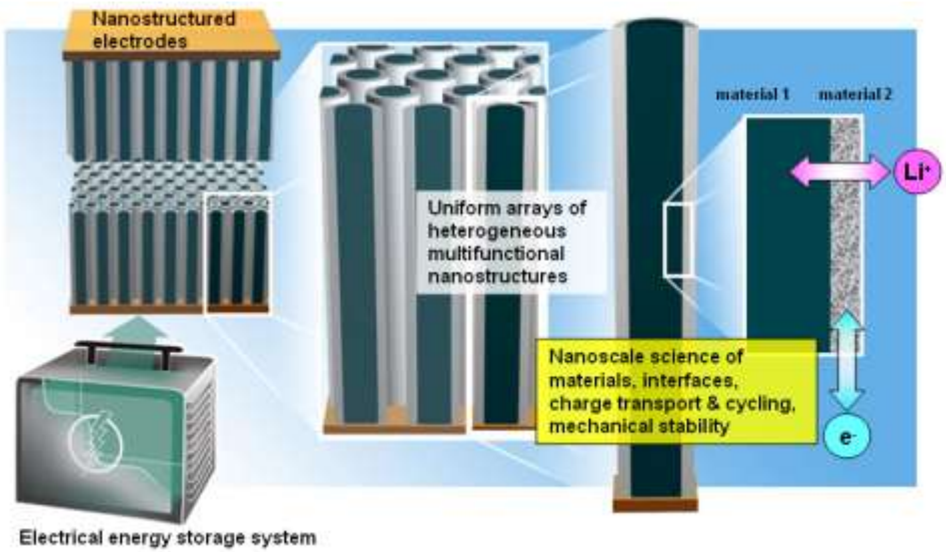
- **Seek:**
  - *Highly interwoven, synergistic program working through flexible thrust area organization*
  - *Coherent team and program through effective intellectual stimulation and communication*
  - *Program enrichment through outreach to broader technical community*
  - *Proactive management of program evolution*
  - *Strong support for important management and operations functions*

Center for Science of Precision Multifunctional Nanostructures for Electrical Energy Storage

Gary Rubloff (University of Maryland)

The EFRC will pursue multifunctional nanostructures as the basis for a next generation of high performance electrical energy storage to:

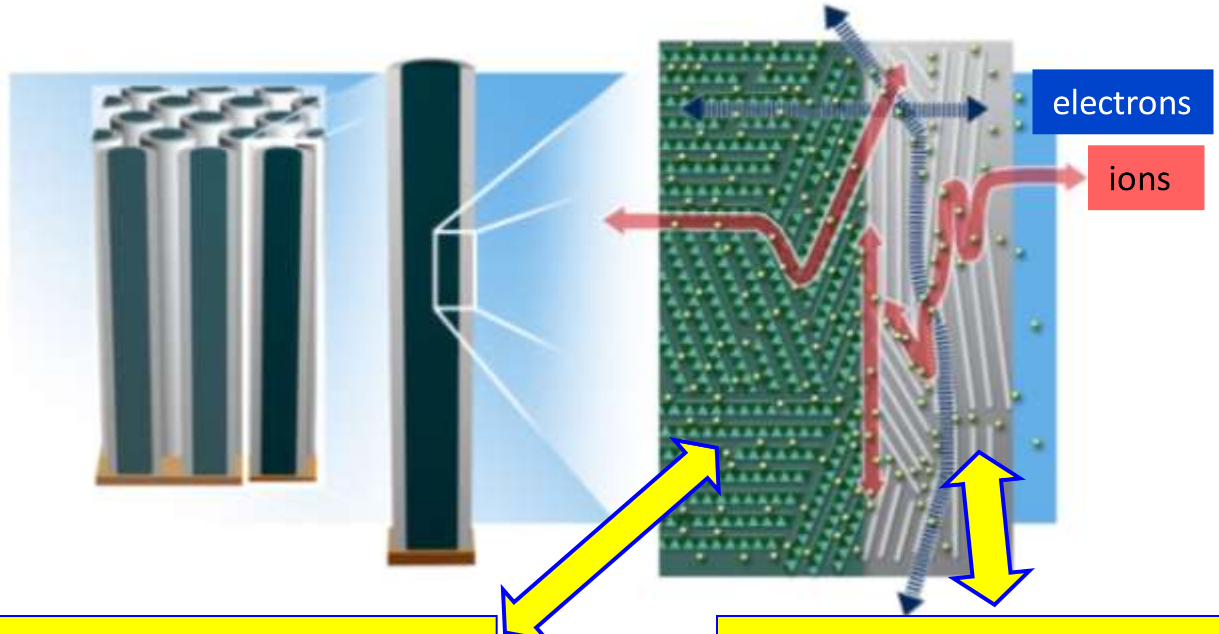
- power **electric vehicles** over long distances and recharge quickly, and
- capture, hold, and deliver energy from **renewable sources**.



EFRC features:

- **Metal oxide and silicon nanowires** to hold and cycle charge
- **Carbon-nanowire composite nanostructures** for faster charge transport and structural stability during charge cycling
- **Fundamental understanding** of nanostructure synthesis, properties, and electrochemical behavior, supported by novel instruments and theory
- **Uniform, predictable structures** for scientific analysis and as prototypes of massive arrays in future technology

Heterogeneous Multifunctional Nanostructures



Charge storage material

- High energy density
- Low electrical, ionic conductivity
- Low mechanical stability

Cathode: $LiMnO_2$, $LiFePO_4$, $LiCoO_2$

Anode: Si

Transport & support material

- High electrical conductivity
- High mechanical stability
- High ionic conductivity

Low-D carbon, conducting polymer

Center for Science of Precision Multifunctional Nanostructures for Electrical Energy Storage

A Department of Energy Energy Frontier Research Center

Initial $14M over 5 years

The EFRC will pursue multifunctional nanostructures as the basis for a next generation of high performance electrical energy storage to:

- **power electric vehicles over long distances and recharge quickly, and**
- **capture, hold, and deliver energy from renewable sources.**

Sandia National Laboratories · UNIVERSITY OF FLORIDA · YALE · Los Alamos NATIONAL LABORATORY · U.S. DEPARTMENT OF ENERGY · Office of Basic Energy Sciences

Research Strategy

… an integrated approach

Science thrust A →
Faster charge transport

Science thrust B →
Stability under charge cycling

Enabling thrust C →
Nanoscale dynamics

Enabling thrust D →
Nanostructure stability

Thrust C. Nanoscience of electrochemical interfaces

Electrochemical dynamics by scanning probe microscopy
Nanoprobe imaging and chemical spectroscopy of surface models for electrochemical systems
Density functional theory for Li transport in nanoscale heterostructures

UMD: Reutt-Robey (lead)
SNL: Zavadil (co-lead), Leung

Thrust A. Multifunctional nanostructures for fast ion transport

Oxide nanostructures for high-energy cathodes
Graphitic carbon for accelerated transport
Synthesis of nanoscale oxide-carbon heterostructures
Electrochemistry at nanowires surfaces and defects
Permselective membranes

UMD: Lee (co-lead), Fuhrer (co-lead)
U Florida: Martin
UC Irvine: Penner, Collins, Siwy

Thrust B. Self-healing nanostructures for electrodes

Silicon nanostructures for high-energy anodes
Graphitic carbon for mechanical stabilization
Synthesis of nanoscale silicon-carbon heterostructures
Nanostructure mechanics

UMD: Cumings (co-lead), CWang, YHWang
LANL: Picraux (co-lead)
Yale: Reed

Thrust D. Atomic scale mechanics and kinetics in heterogeneous nanostructures

Stimulus-response of heterogeneous nanostructures by electrochemical transmission electron microscopy
Mechanical and optical MEMS sensing of nanostructure response to actuation and cycling
Multilayer hetero-nano-structures for all-solid-state storage

UMD: Ghodssi (co-lead), Rubloff
SNL: Sullivan (co-lead), Huang, Hwang

Research Team Profile

		Nanotech	Mixed	Electrochemistry
4 universities	U Maryland (lead)	Gary Ruboff, Michael Fuhrer, Reza Ghodssi, Janice Reutt-Robey, YuHuang Wang, John Cumings	Sang Bok Lee	Chunsheng Wang
	UC Irvine		Phil Collins	Reg Penner, Zuzanna Siwy (new)
	U Florida			Charles Martin
	Yale U	Mark Reed		
2 nat'l labs	Sandia Nat'l Lab	Jianyu Huang, Bob Hwang	John Sullivan	Kevin Zavadil, Kevin Leung
	Los Alamos Nat'l Lab	Tom Picraux		

Intellectual and institutional mixes
➔ challenge and opportunity

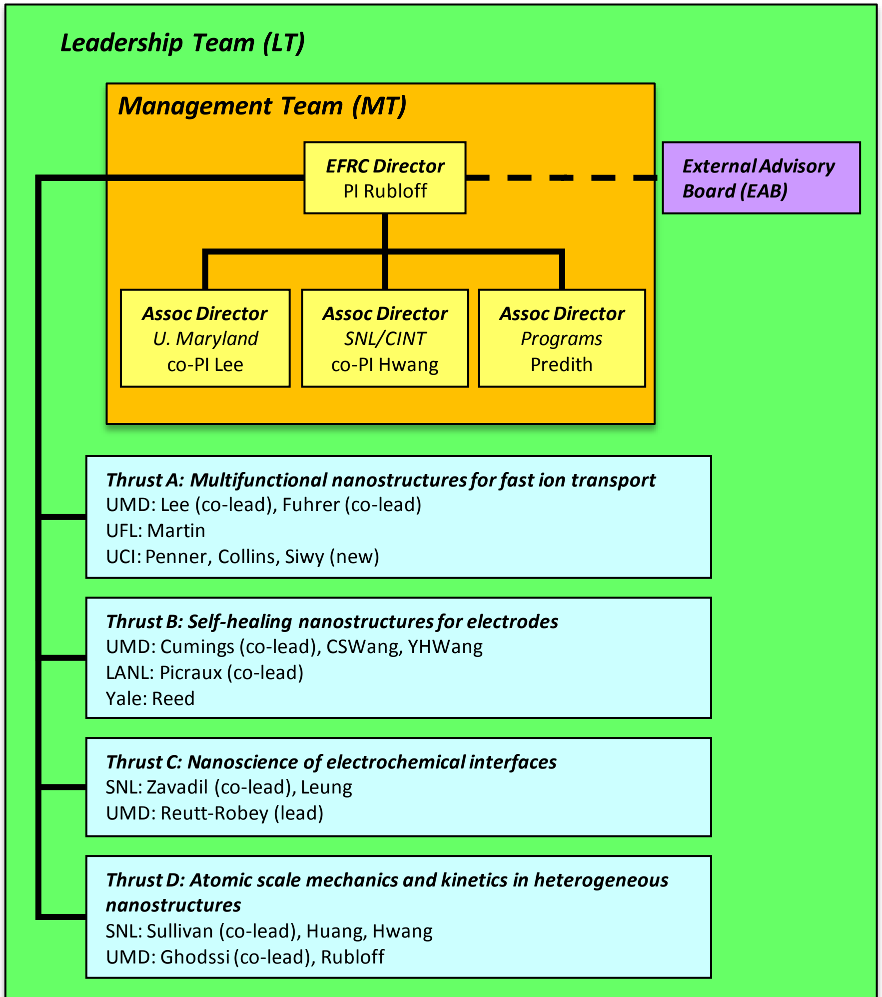
External Advisory Board (EAB)

	Name	Institution	Position
2 academia	Henry S. White	U. Utah	Distinguished Professor President, Soc. Electroanalytical Chemistry
	Wade Adams	Rice U.	Director, Richard E. Smalley Institute Chairman of Board, Nanotechnology Initiative
2 nat'l labs	Debra Rolison	Naval Res Lab	Head, Advanced Electrochemical Materials Section
	Martin Green	NIST	Electronic and Optoelectronic Group Leader
3 industry	Mike Wixom	A123	CTO and Vice-President for R&D
	Glen Merfeld	General Electric Global Research	Manager, Chemical Energy Systems Laboratory
	Tushar Shah (formerly Ned Allen)	Lockheed Martin	Energy Storage technology leader

Diverse technical and management experience

Operation of the EFRC

Organization to Achieve Strategy & Goals



Director

EFRC overall performance and management
Foster & express vision
Resource and people management to achieve vision
Direct interface to DOE, BES
Convey EFRC accomplishments to multiple audiences

Management Team (MT)

Confidant, sounding board to Director
Assist in identifying and resolving issues

Leadership Team (LT) – thrust leaders & MT

Coordinating respective thrust areas
Assisting overall EFRC goals, strategy, tactics

External Advisory Board (EAB)

Review and feedback on EFRC program, balance, consistency with goals
Suggest new opportunities and directions
Facilitate new collaborations, funding opportunities, and partnerships, particularly with their home institutions

Key Management Strategies

- **Stimulate scientific excitement**
  - *Integrating focus topics at NEES strategy meetings and teleconferences*
  - *Spring 2010 strategy: design of multifunctional nanostructured electrodes; electrochemistry at the nanoscale; frontiers of characterization*
- **Foster cross-EFRC collaborations**
  - *Support summer visits between sites*
- **Exploit existing resources**
  - *Maryland NanoCenter, SNL-LANL CINT*

- **Evolve the portfolio**
  - *Collaboration Initiation Grants*

- **Focus on highlights**
  - *Careful construction, iteration, and management review*

- **NEES self-assessment & management review**
  - *Science roadmap to focus and integrate projects*

A Shared Vision (2004)

Bringing world-class <u>scientists and engineers</u> as well as <u>fabrication and characterization infrastructure</u> together to drive technology and fundamental understanding in nano

INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

Engineering
A. James Clark School of Engineering

Physical Sciences
College of Computer, Mathematical and Physical Sciences

Life Sciences
College of Chemical and Life Sciences

MARYLAND NANOCENTER

Research
Faculty research groups
Partnerships
Collaborative research laboratories

Education
Nano educational programs
Outreach

Industry & govt
One-stop shopping
Partners' Program

Infrastructure
Initiatives
Shared user facilities
Operations – web, facilities, information

Nanofabrication
(FabLab)

Nanocharacterization
(NispLab)

Shared experimental facilities

80+ faculty groups
Top 10 rankings (Small Times)
www.nanocenter.umd.edu

Staffing

- **NEES staff**
  - ***Dr. Ashley Predith***

    Associate Director for Programs

    Supported by UMD matching funds

    PhD 2006, MIT, Materials Science, Computational Studies YSZ for fuel cells (advisor Gerbrand Ceder)

    Science policy and communications (NSF, MRS Bulletin, Natl Bureau Econ Res, ACS)

Ashley Predith

- **Maryland NanoCenter**
  - ***Ernie Cleveland***, *IT coordinator*
  - ***Alice Mobaidin***, *web update, events, etc.*

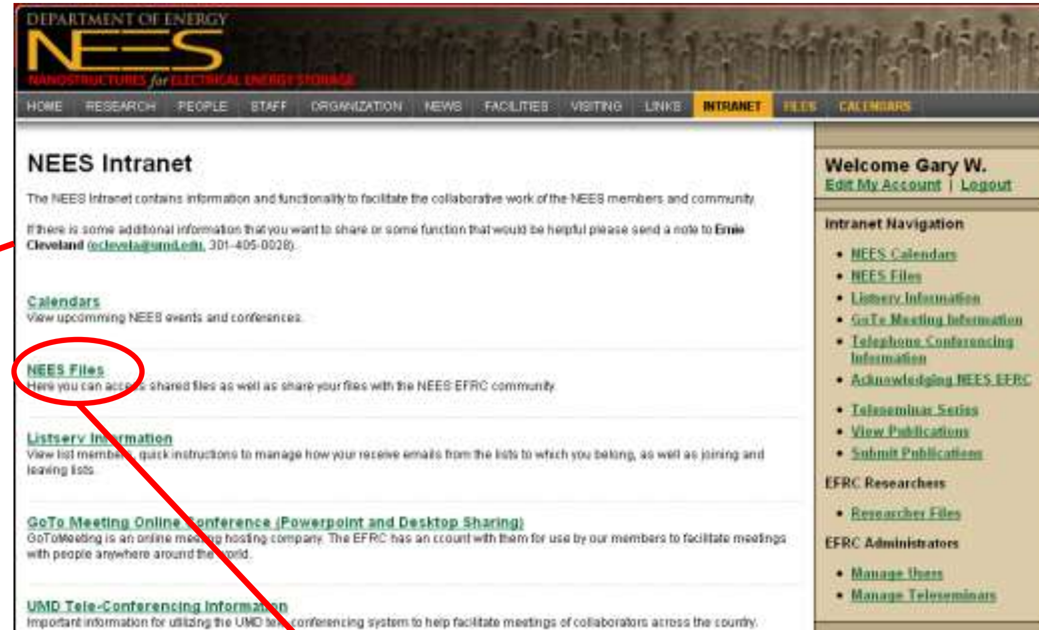
- **Institute for Systems Research**
  - ***Jason Strahan***, *Director of Finance*

Ernie Cleveland

Alice Mobaidin

Jason Strahan

NEES Website

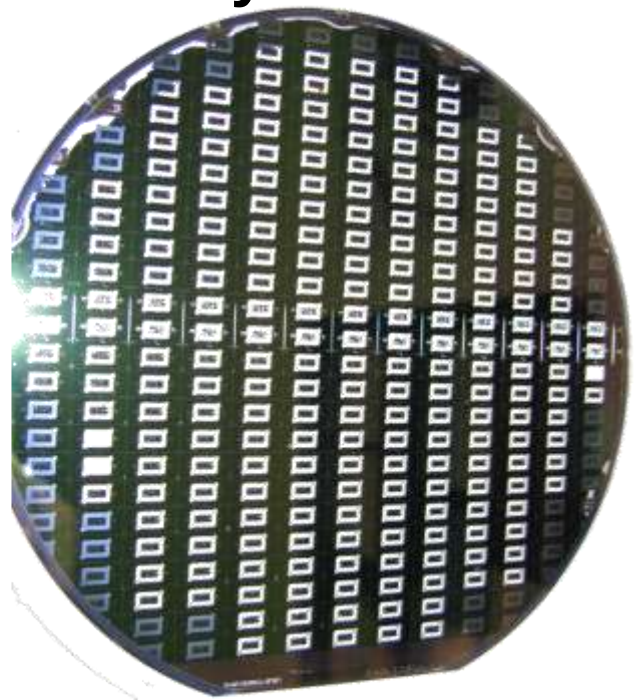


Center for Integrated Nanotechnologies

Core Facility in Albuquerque
96,000 sq. ft.

Gateway to Los Alamos
36,500 sq. ft.

Sandia MESA Facility – CINT Discovery Platforms



Microsystems and Engineering Sciences Applications (MESA) Complex

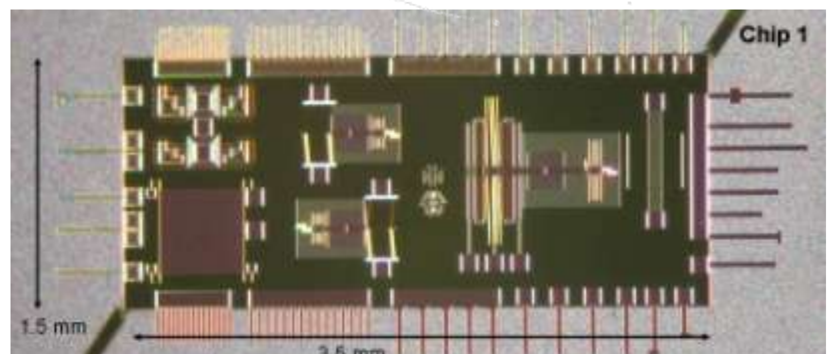
274 people, 131,000 GSF

16,600 ft^2 Class 10 and 100 cleanroom

<u>Discovery Platforms – User Facilities</u>

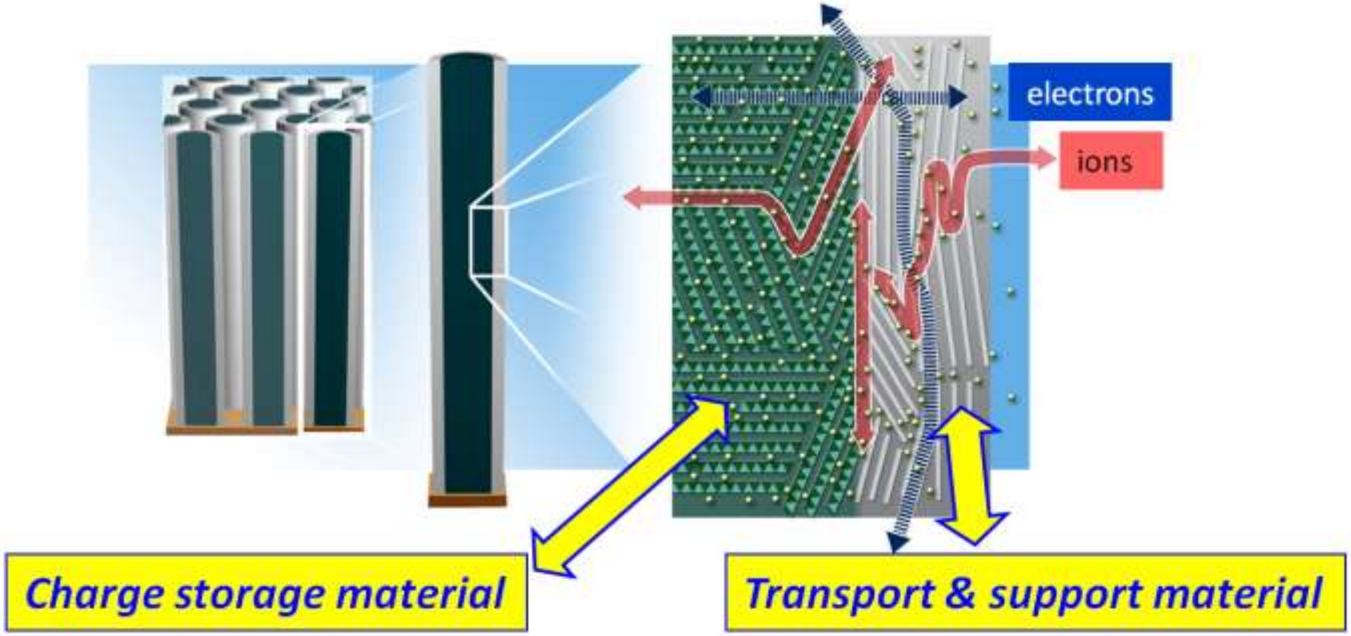
Cantilever – nanomechanics

In-situ TEM - nanoelectrochemistry



Vision, Mission, Expected Outcomes

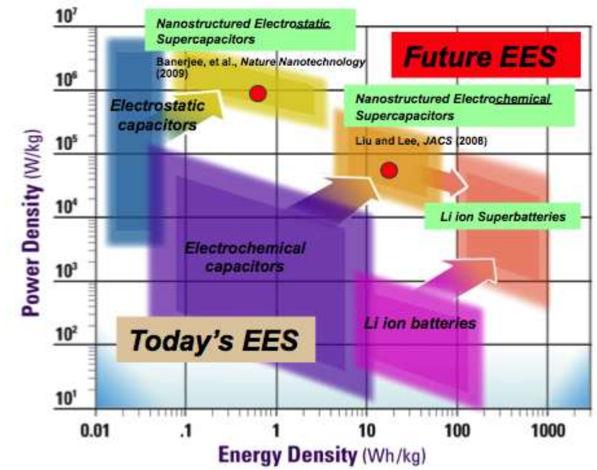
Vision



Inspire and guide a scientifically diverse group of research leaders to major advances in understanding and designing next-generation nanostructures for electrical energy storage

Nanostructures for Electrical Energy Storage

- Mission:
  - ➢ *provide scientific underpinnings for dramatically enhanced generation of EES devices*
    - ✓ 10-100X in power density
    - ✓ 10X in energy density

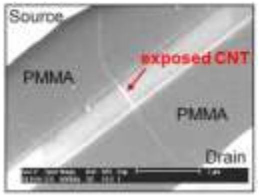


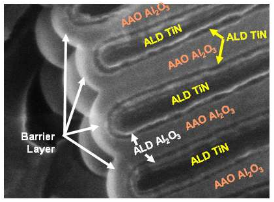
- Goals:
  - ➢ ***Understanding electrochemistry at the nanoscale***
  - ➢ ***Creating innovative nanostructure designs***
    - ✓ Large volume fraction for charge storage
    - ✓ Efficient charge transport to/from storage regions
    - ✓ Stability under charge cycling (volume change, stress/strain)

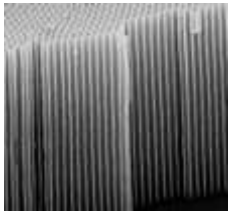
interdependent

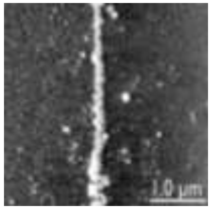
Research Approaches Which Distinguish NEES

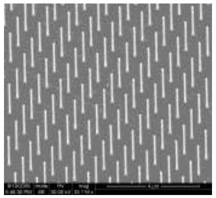
- **Multicomponent nanostructures**
  - *Heterogeneous, multifunctional*
  - *Well-defined, highly controlled*
- **Multiscale scope**
  - *Single defects and individual nanostructures to massive arrays*
- **New processes & combinations**
  - *Self-assembly, self-limiting, self-aligned*
- **Innovative experimental platforms**
  - *Imaging: in-situ TEM/MEMS, electrochemical SPM/Raman*

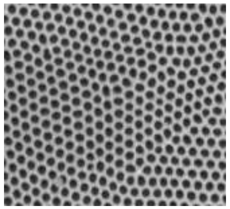


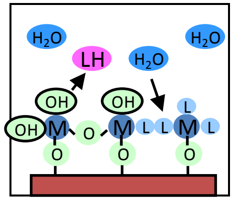


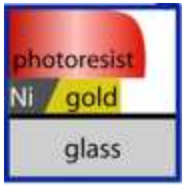


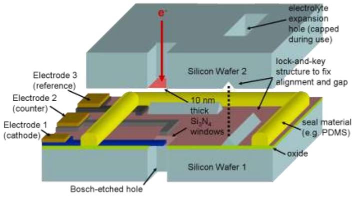


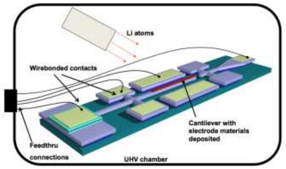


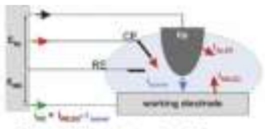






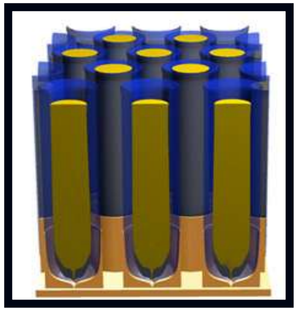






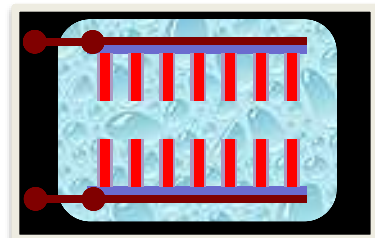
Schindler Electrochem Acta 05

Multicomponent Nanostructures



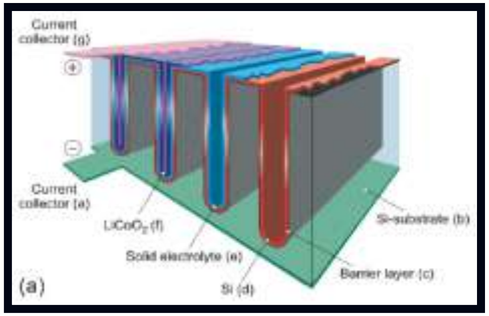
Nanowire electrochemical supercap
Liu & Lee
J Am Chem Soc 130, 2942 (2008)

Nanowire electrode supercap

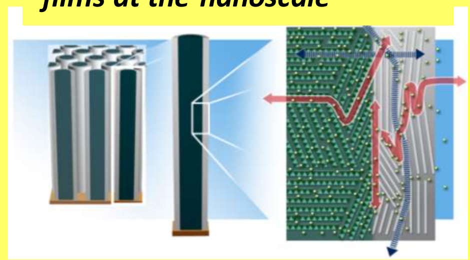


exposed nanostructures

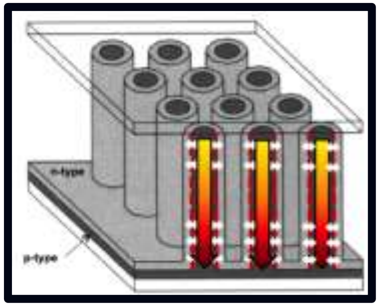
3-D solid state nanobattery
Roozeboom group
Adv Materials 19 (24), 4564 (2007)



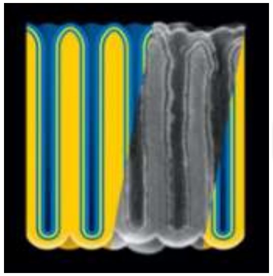
surfaces, interfaces, and thin films at the nanoscale



Nanorod solar cell modeling
Kayes, Atwater, Lewis
J Appl Phys 97, 114302 (2005)



Nanotube electrostatic supercap
Banerjee et al
Nature Nanotechnology 4, 292 (2009)

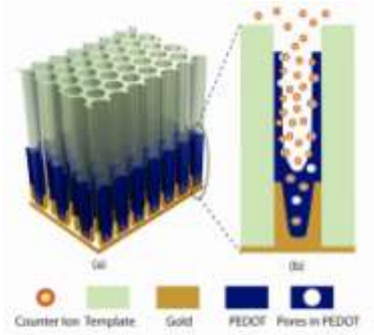


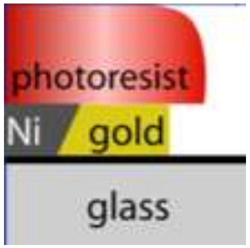
embedded nanostructures

Scientific Accomplishments

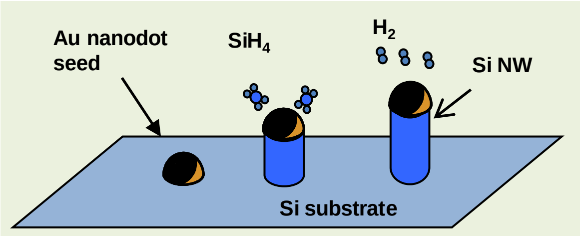
Nanomaterials Synthesis

- Electrochemical anodization and deposition

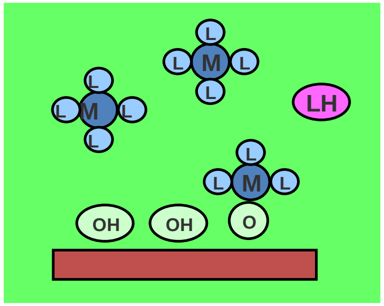




- Catalytic chemical vapor deposition



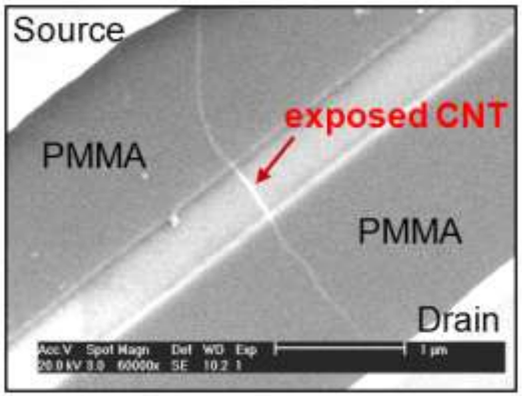
- Chemical vapor deposition

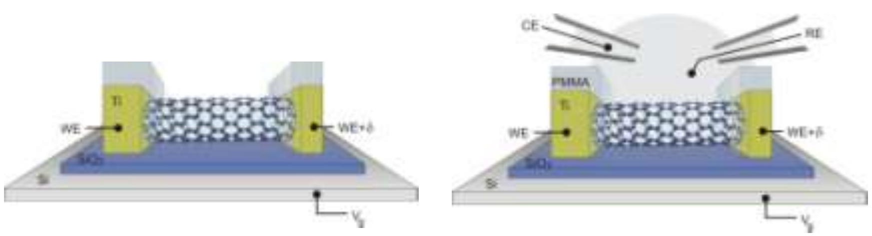


- Atomic layer deposition

Bridging Knowledge across Length and Aggregation Scales

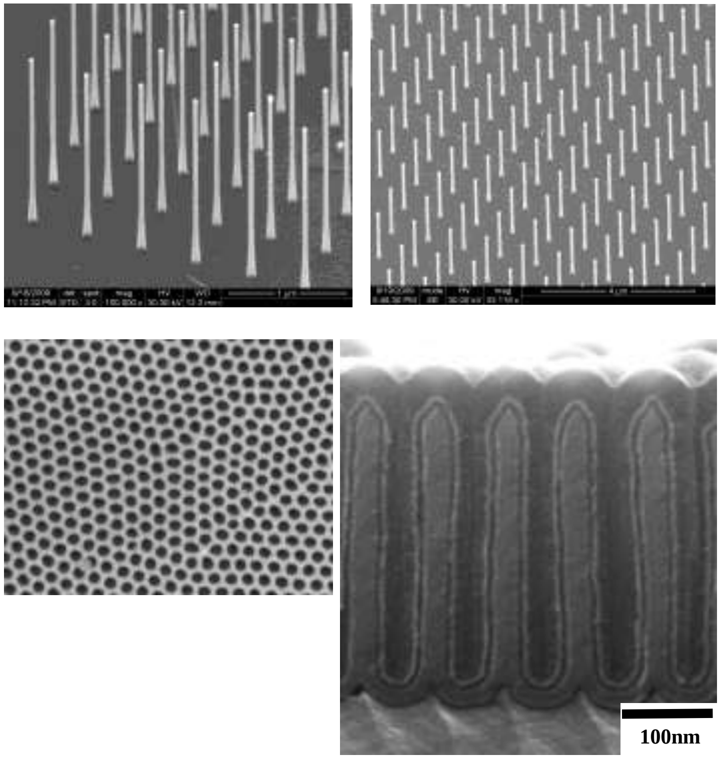
Single nanostructures and individual defects





Goldsmith et al, Nano Lett 8 (1) 189-194 (2008)

Massively parallel nanostructures



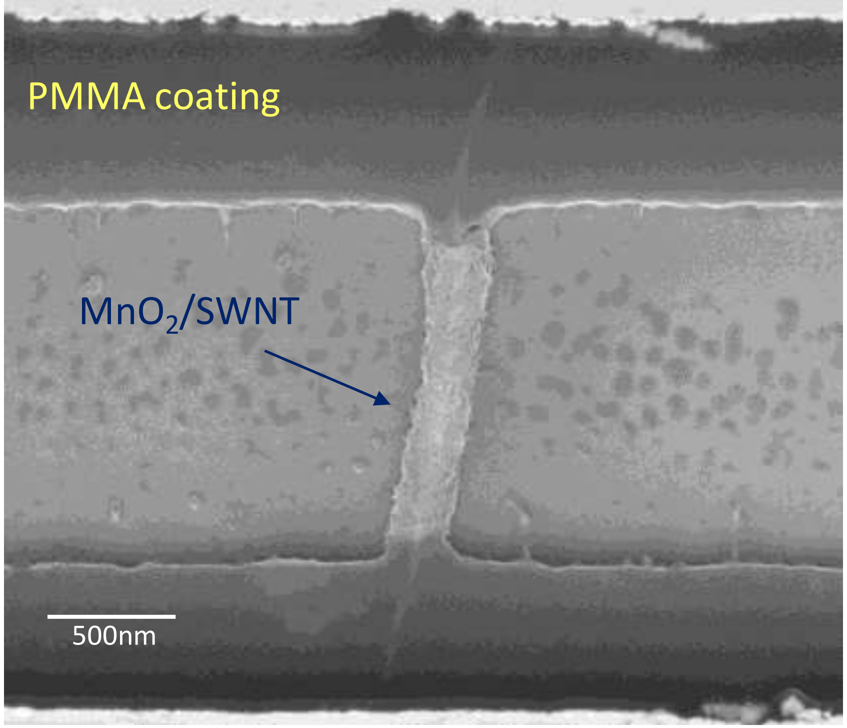
Carbon-MnO_2 Nanocomposites for High Power Cathodes

Accomplishment

Thin MnO_2-coated carbon nanotubes.
MnO_2 thickness of 4nm and higher are controlled with 1nm precision.
The Nanotubes (individual, single-walled conductors) are wired into 3-terminal transistors to exploit their sensitive electronic properties during charge-discharge cycles of the MnO_2.

Significance

This unique test structure allows us to study both electrochemical kinetics and degradation of the C-MnO_2 system in the absence of pre-existing graphitic edges or defects.



(source and drain connections not shown)

I. Perez, B. Corso, V. Khalap, P. Collins*, "Conformal MnO2 electrodeposition onto defect-free graphitic carbons", *Electrochemistry Communications* (accepted).

Collaborators: Israel Perez, Vaikunth Khalap, Brad Corso, Tatyana Sheps, and Profs. PG Collins and R. Penner

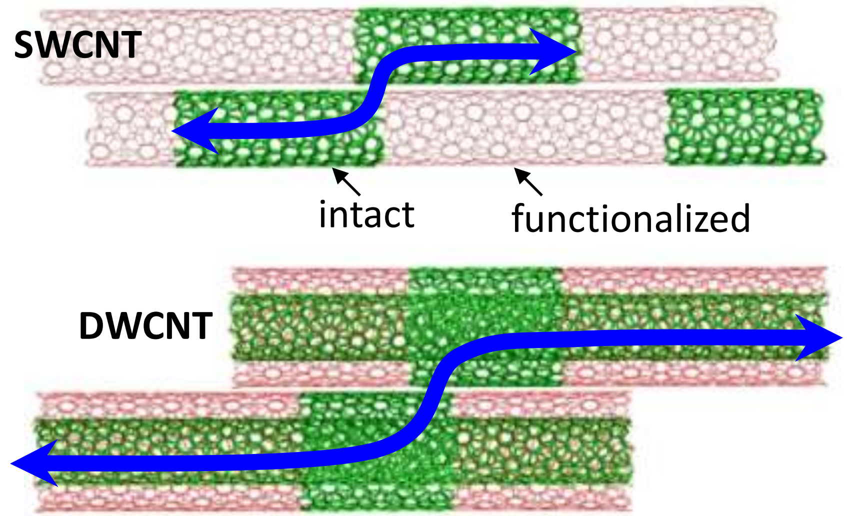
Simultaneous Conductivity and Solubility in Double-Wall CNTs

Accomplishment

Selective oxidation of the outer wall of double-wall carbon nanotubes (DWCNTs) by oleum and nitric acid made the CNTs water soluble.

Inner wall remains intact, preserving CNT electrical conductivity properties. Outer wall is mostly functionalized, but intact regions enable contacts to inner walls.

Thin film conductivity of functionalized DWCNTs is up to 65% better than for SWCNTS



Significance

CNT benefits in conductivity are normally compromised by the functionalization often needed for nanoassembly and use of the CNTs

Two walls of DW-CNTs allow outer wall to be functionalized, providing for flexible design, assembly and use of CNT's in nanostructures, while retaining unique conductivity properties of CNTs in the inner wall

Collaborators

A.H. Brozena, J. Moskowitz, B. Shao, S.-L. Deng, H.W. Liao, K.J. Gaskell, Y.H. Wang
UMD Chemistry

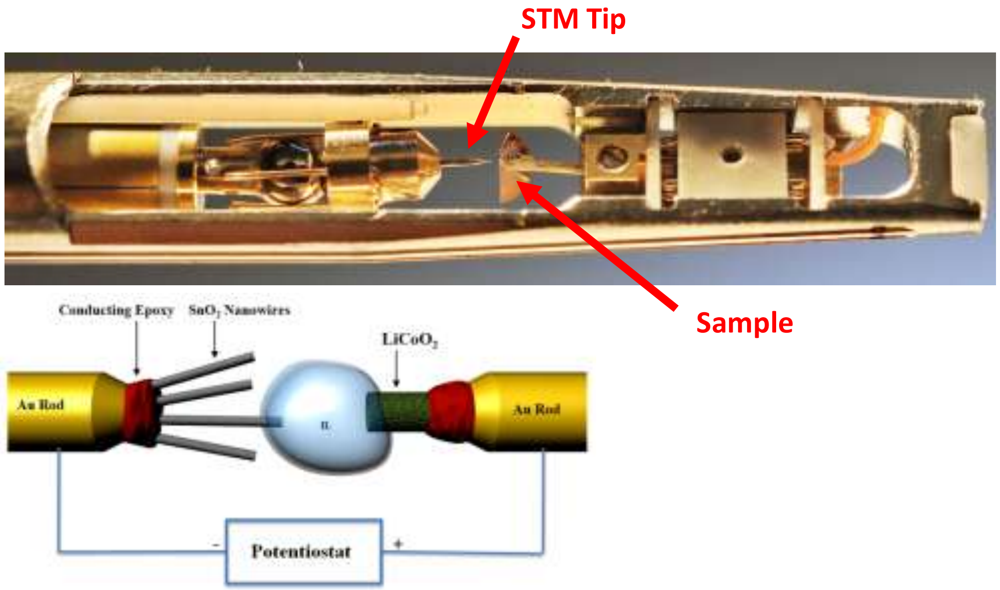
Supporting material

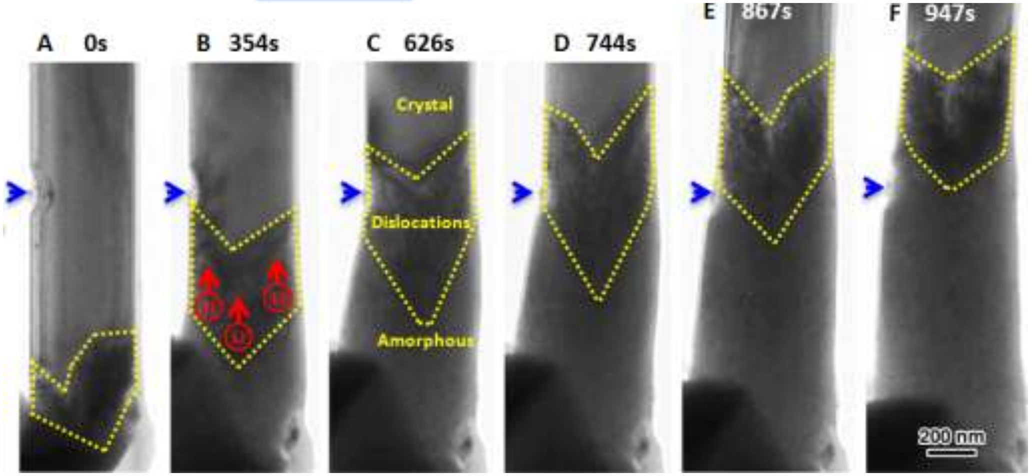
A.H. Brozena et al, J. Am. Chem. Soc. ***2010,*** *132*, pp 3932–3938.

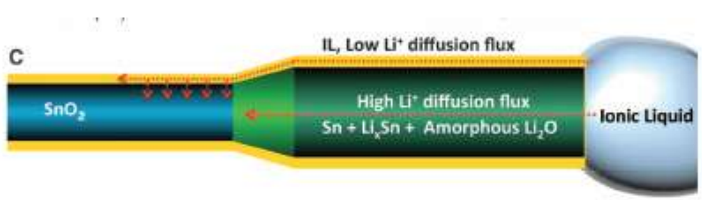
Lithiation of SnO_2 Nanowire in TEM

Science AAAS

- **In-situ TEM imaging of nanowire transformation during lithiation**
  - *Nanowire SnO_2 anode*
  - *Bulk $LiCoO_2$ cathode*
  - *Ionic liquid (IL) electrolyte to enable open electrochemical nanocell within TEM vacuum*
- **Precursor to Sandia MEMS/TEM platform**
- **SnO_2 crystal → Li_2O glass with Li_xSn (0≤x≤4.4) nanocrystalline precipitates**
- **Moving dislocation cloud accompanies major volume change and structural distortion**







Jianyu Huang et al (SNL)
Science 330, 1515-20 (10 Dec 2010)
with Perspective by Yet-Ming Chiang

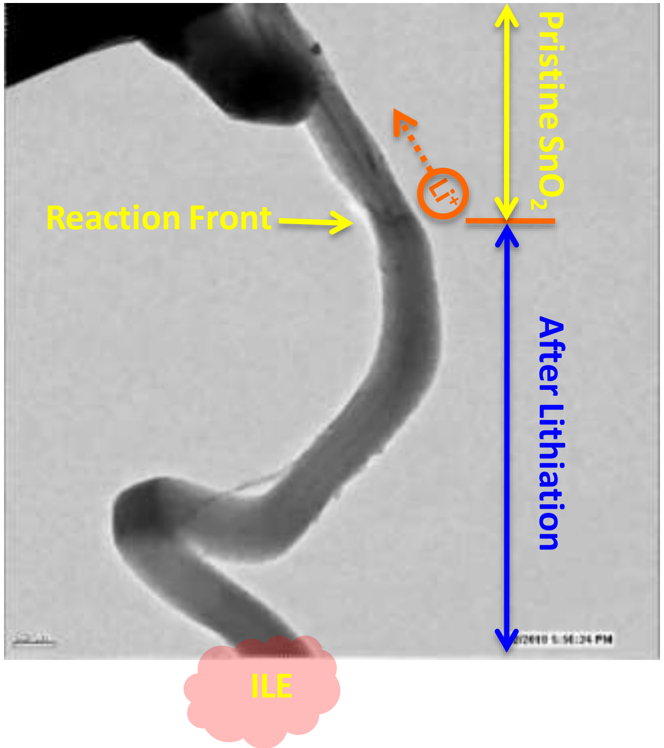
Real-time observation of the charging process of a single SnO_2 nanowire anode

Accomplishment

- Direct real-time structural evolution and phase transformation of a SnO_2 nanowire anode during electrochemical lithiation by transmission electron microscope
- SnO_2 nanowire was placed in contact with an ionic liquid electrolyte loaded with Li salt that was in contact with a $LiCoO_2$ cathode.
- Li moves primarily through bulk diffusion into SnO_2, reacting to form Li_2O and initiating mechanical changes observed as nanowire bending and distortion.

Significance

- First definitive experiments of monitoring an electrochemically-induced reaction in Li-ion battery materials with atomic-scale resolution inside a TEM.
- The approach is general and may be applied to most any Li-ion battery material of suitable thin cross-section or even to other electrochemical phenomena, such as electrodeposition.
- Major advance in methodology to identify fundamental mechanisms of Li-ion battery reactions.

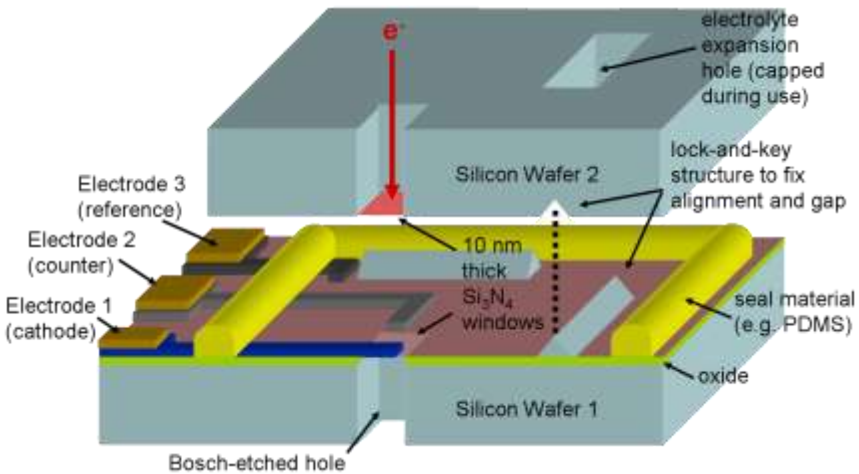


Jianyu Huang et al (SNL)
Science 330, 1515-20 (10 Dec 2010)
with Perspective by Yet-Ming Chiang

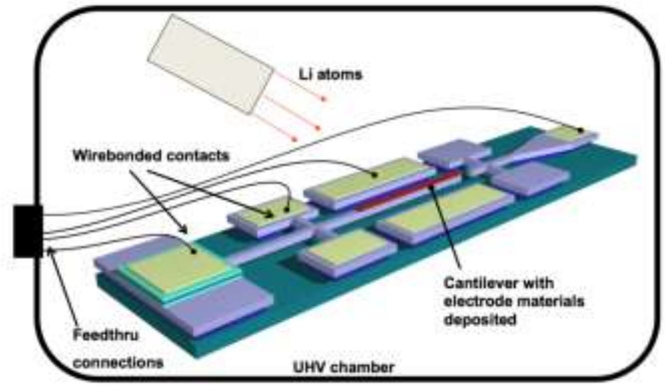
Collaborators
Jianyu Huang, John P. Sullivan (Sandia)
Chongmin Wang (Pacific Northwest Lab)
Scott Mao (Univ. Pittsburg)
Ju Li (Univ. Pennsylvania)

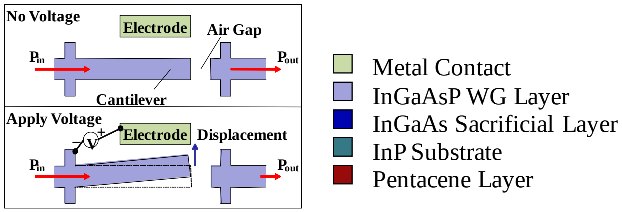
Microsystems for Characterization

In-situ TEM Discovery Platform



Optical waveguide cantilever

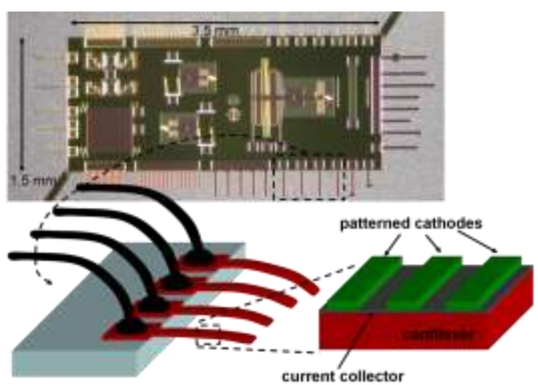




Nathan Siwak, et al. Journal of Microelectromechanical Systems, Vol. 18, No. 1, pp. 103-110, February 2009.

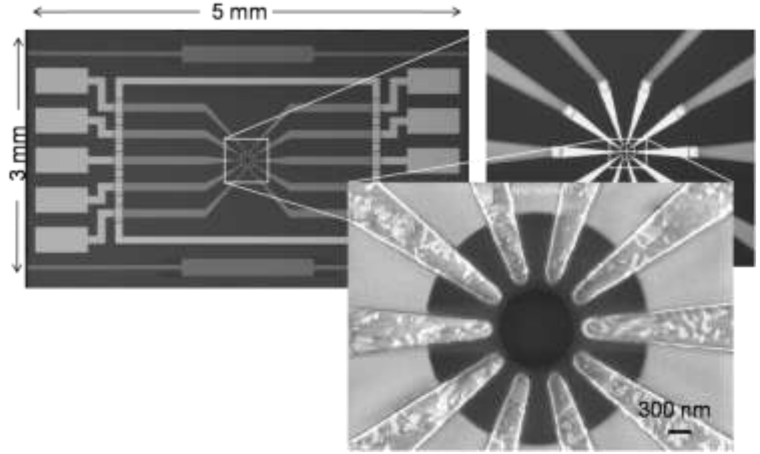
Ghodssi group (UMD)

Cantilever Array Discovery Platform



SNL/CINT group

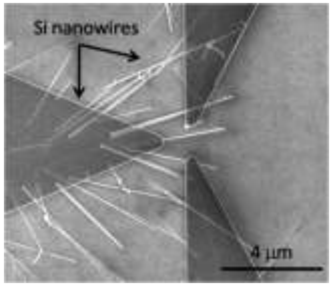
Development of platforms for understanding Li-ion battery processes at the atomic to nano-scale



Optical microscope image (upper left) and scanning electron microscope (SEM) images of the bottom chip showing one of the twenty electrode configurations.

Accomplishment

- The development of a suite of platforms and techniques for the in situ characterization of Li-ion battery materials.
- MEMS-based platform for in situ TEM characterization of Li-ion battery materials
- Initial experiments in isolating nanowires and measuring the electrochemical behavior of MnO_2 nanowires.



SEM image showing the assembly of silicon nanowires on to one of the electrode configurations of the platform.

Significance

- Probes with atomic to nano-scale spatial resolution and the capability to follow changes in real-time.
- Understanding the structural changes that occur with the lithiation and delithiation of Li-ion battery materials
- Electrochemical investigations inside a TEM using liquid electrolytes.

Collaborators

J. P. Sullivan, J. Huang, M. J. Shaw, A. Subramanian, N. Hudak (Sandia) & J. Lou, Y. Zhan (Rice U.)

Supporting material

J. P. Sullivan, J. Huang, M. J. Shaw, A. Subramanian, N. Hudak, Y. Zhan, and J. Lou, Proc. SPIE 7683, 76830B-1 (2010).

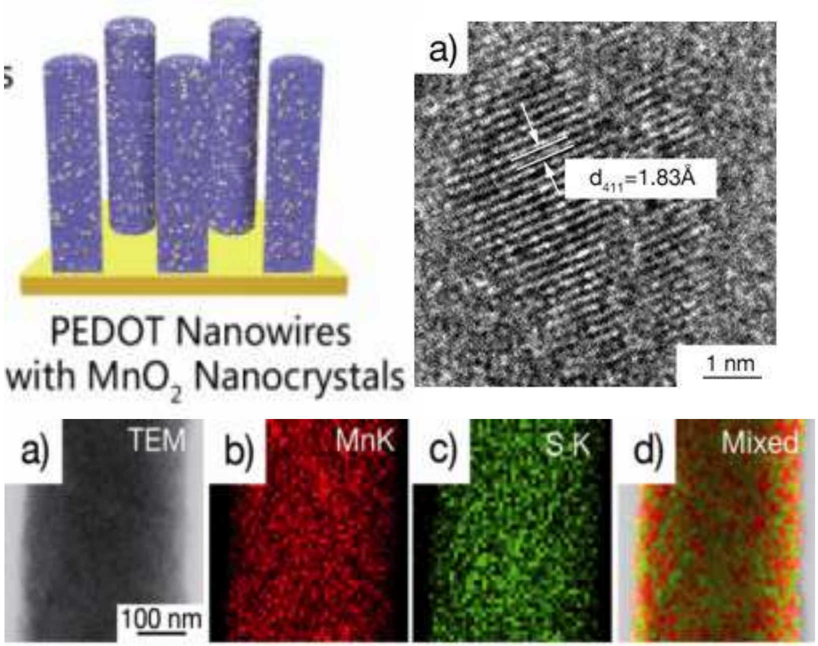
Redox Exchange Induced MnO_2-Nanoparticle Enrichment in PEDOT Nanowires

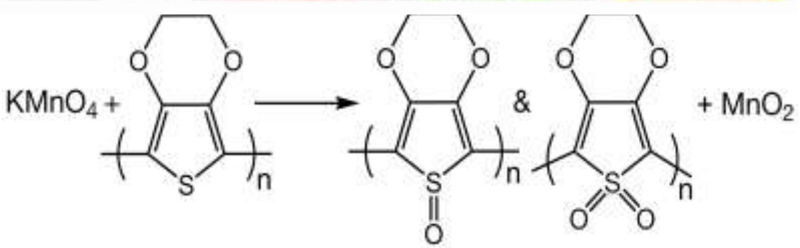
Accomplishment

- Synthesis of MnO_2 nanoparticles (likely alpha) in PEDOT conductive polymer matrix, with control over nanoparticle size and ability to achieve uniform distribution in the PEDOT
- High electrochemical performance: very high specific capacitance (410 F/g) as the supercapacitor electrode materials as well as high Li ion storage capacity (300 mAh/g) as cathode materials of Li ion battery with good cyclability.
- Revealed the mechanism of MnO_2 nanoparticle formation in the PEDOT: triggered by the reduction of $KMnO_4$ via the redox exchange of permanganate ions with the functional group 'S' on PEDOT.

Significance

- Identified a new reaction pathway model to synthesize metal oxide nanoparticles in conductive polymer and graphitic carbon matrices.
- Determined that the reaction primarily involves the S group on PEDOT, rather than the oxidized polymer backbone as previously believed
- This synthesis route offers design flexibility to control and optimize MnO2 nanoparticle size for Li storage (insertion/desertion)



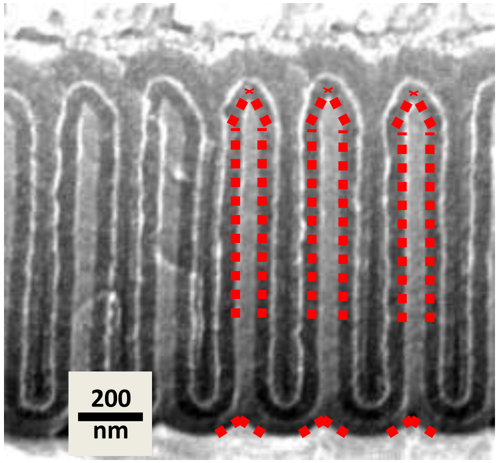


R. Liu, J. Duay, S.B. Lee. *ACS Nano*, **2010**, *4* (7), pp 4299-4307 **DOI:** 10.1021/nn1010182

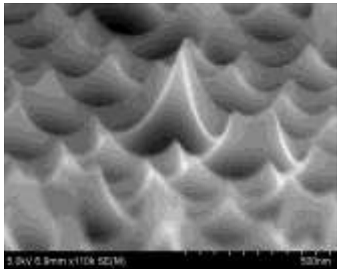
Collaborators: *Ran Liu, Jonathon Duay, Zhe Gui, Stefanie Sherrill, Sung Kyoung Kim*

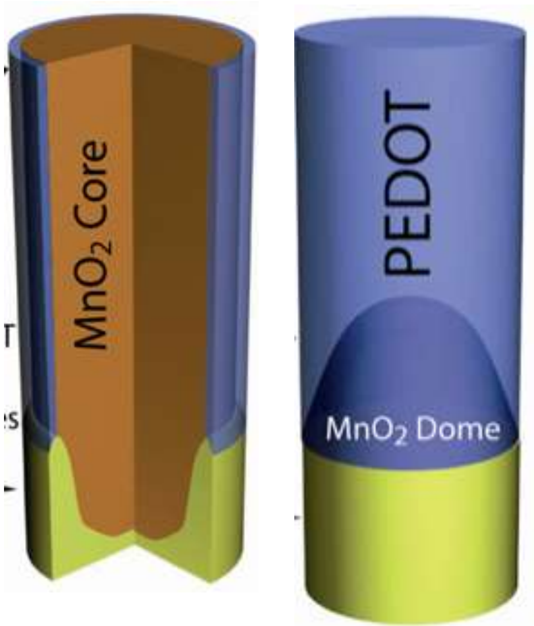
Engineering 3-D Structures at the Nanoscale

- **Specific processes and process sequences to form**
  - *heterogeneous multifunctional nanostructures*
  - *specific 3-D shapes*
- **3-D geometry, material properties, and interfaces determine performance**

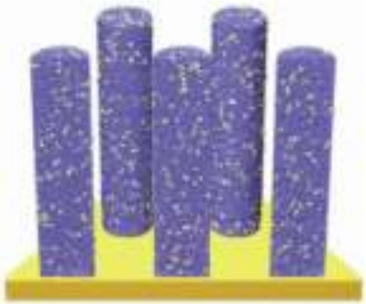


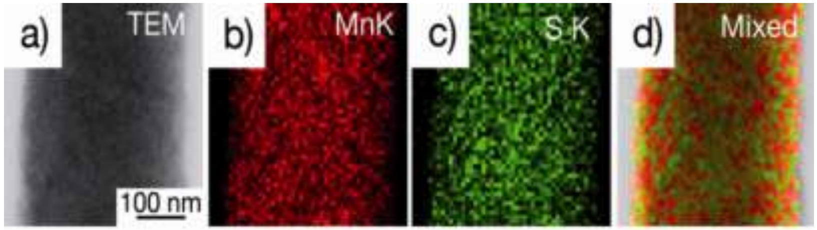
embedded nanostructures





exposed nanostructures





Virus-Templated Silicon Anode for Li Ion Batteries

Accomplishment

- Assembly of a novel Si nanowire anode from *Tobacco Mosaic Virus* (TMV1cys) template
  - TMV's are identical nanotubes 300nm long, 4 nm ID, 18 nm OD
  - Self-assemble TMV on stainless steel through TMV 3' thiol group
  - Electroless deposition Ni current collector, then Si sputter deposition, onto TMV
- High capacities (3300mAh/g), nearly 10x capacity of graphite
- Excellent charge-discharge cycling stability (0.20% loss per cycle at 1C), and consistent rate capabilities (46.4% at 4C) between 0 and 1.5 V.

Significance

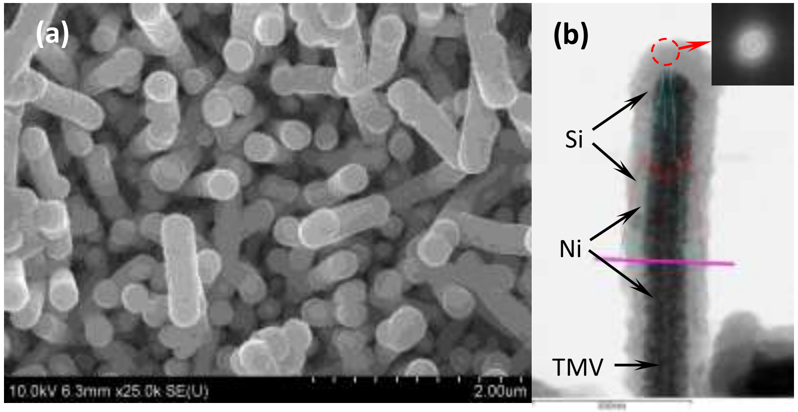
- TMV provides precisely reproducible template for a nanostructured electrode, ideal for assessing the benefits of highly regular nanostructures
- High capacity, comparable to other silicon nanostructured electrodes, demonstrates viability for TMV, biologically based nanoassembly strategy
- TMV offers technology advantages: very lost cost, easily self-assembled on surfaces, highly reproducible nanostructures, in room temperature, neutral pH processes

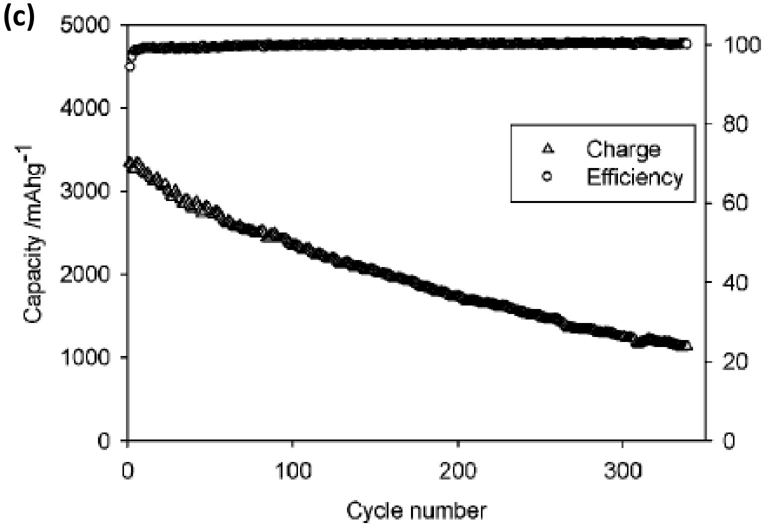
Collaborators

Xilin Chen, Konstantinos Gerasopoulos, Juchen Guo, Adam Brown, Chunsheng Wang, Reza Ghodssi, James N. Culver, *UMD*

Supporting material

Xilin Chen et al, "Virus-Enabled Silicon Anode for Lithium-Ion Batteries", *ACS Nano,* Article ASAP (Aug. 13, 2010); DOI:10.1021/nn100963.



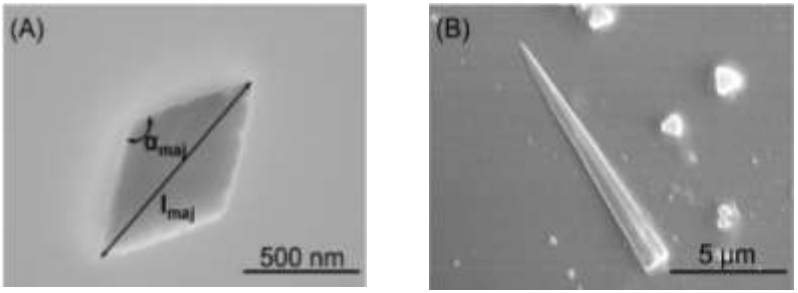


Si/Ni/TMV1cys nano wire (insert: Fast Fourier Transform image of silicon) (c) Cyclic performance of the 3-D TMV1cys/Ni/Si anode at 1C (2000mA/g)

Electro-osmotic Flow Rectification in Pyramidal-Pore Mica Membranes

Accomplishment

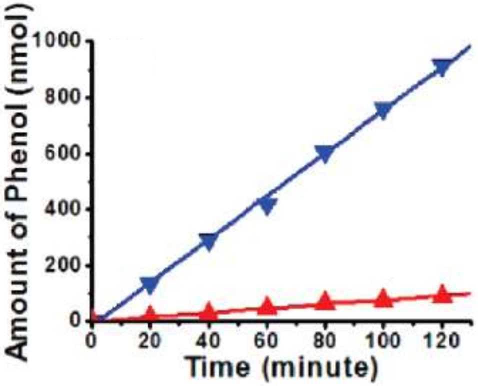
- Electro-osmotic flow (EOF) rectification has been demonstrated in membranes containing pyramidal nanopores, using phenol transport to decorate the flow rectification.
- EOF velocities are larger when phenol is transported from base-to-tip than from tip-to-base.
- EOF rectification in tapered pores complements our prior findings on ion transport rectification.



Electron micrographs of (A) the base opening of a pore in a mica membrane and (B) a carbon replica of a pyramidal mica pore.

Significance

- Nano-engineering of pore design offers opportunity to control electro-osmotic flow phenomena.
- Understanding of these ion and fluid transport processes at the nanoscale may prove important for electrochemical performance in high density nanowire forests, the focus of next-generation nanostructure-based electrodes.



Amount of transported phenol vs. time from EOF experiments on a pyramidal-pore mica membrane.
(   ) Transport from base to tip
(   ) transport from tip to base

Collaborators

Jin, P.; Mukaibo, H.; Horne, L. P.; Bishop, G. W.; Martin, C. R.,

Supporting material

J. Am. Chem. Soc. 2010, 132 (7), 2118-2119.