EFRC: NANOSTRUCTURES FOR ELECTRICAL ENERGY STORAGE (NEES)

UPDATED: AUGUST 2016

AWARDS: $14.0M (August 2009 – July 2014); $11.2M (August 2014 – July 2018)

WEBSITES: http://science.energy.gov/bes/efrc/centers/nees/; http://www.efrc.umd.edu/

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SCIENTIFIC MISSION AND APPROACH

The NEES mission is to reveal scientific insights and design principles that enable a next-generation electrical energy storage technology based on dense mesoscale architectures of multifunctional, heterogeneous nanostructures. Nanotechnology provides the control essential to build such structures and to form them in the highly aggregated, dense arrays to achieve high power and extended cyclability at high energy density. The Center's research is pursued in four thrusts:

1) **Transport in Electrochemical Interphases**: To reveal interfacial mechanisms and interphase properties – charge transport, electrochemical reactions and structural changes – and their consequences in battery electrochemistry.

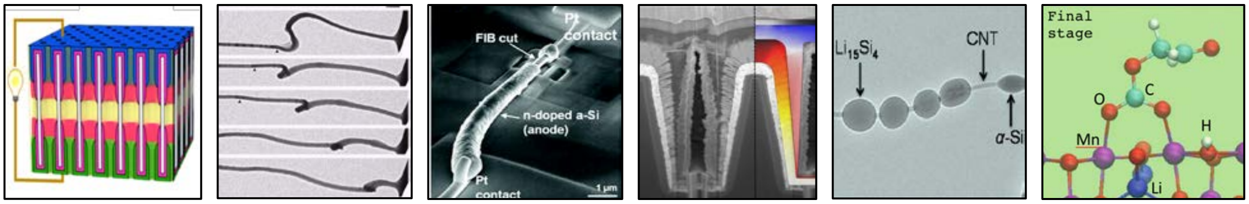
2) **Mesoscale Architectures**: To understand ion and electron transport in mesoscale assemblies of storage nanostructures, and to compare performance and cycle stability of architectures assembled in regular and pseudo-random configurations.

3) **Nanostructure Degradation Science**: To identify, quantify, & understand key degradation and failure mechanisms that lead to capacity loss with cycling in nanostructured energy storage structures.

4) **Solid State Energy Storage**: To directly confront the 3D structure challenges presented by thin film solid electrolyte materials and processes compatible with nanostructure topography and interfaces, and to seek mechanistic insights informed by multiscale modeling.

SELECTED SCIENTIFIC ACCOMPLISHMENTS

- Pioneered real-time transmission electron microscopy (TEM) to observe lithiation, delithiation, and degradation in single nanowire structures, along with TEM liquid cell for organic electrolytes.
- Identified multi-component nanostructure configurations and chemical mechanisms to stabilize nanoelectrodes against stress-induced degradation associated with ion insertion/deinsertion.
- In both isolated and densely packed nanostructures, demonstrated that high performance storage requires intimately integrated electron and ion transport components, the latter involving length scales less than ~50nm from the electrolyte interface to achieve high power.
- Exploited computational methods (DFT, etc.) to understand degradation and stability at the nanoscale, including electrolyte degradation, formation and mitigation of the solid-electrolyte interphase at electrode surfaces.
- Developed means to enable Li-S batteries – entrapping S in carbon nano/micro structures; thermally modifying polysulfide distributions; using ultrathin protective layers to prevent Li anode degradation.
- Demonstrated first single-nanowire solid state Li ion battery and synthesis of solid electrolytes as needed for advanced 3-D solid state nanobatteries and metal anode protection layers.



NEES research, from left: precision nanostructured batteries; lithiation reaction front observed in TEM; miniature all-solid-state nanowire lithium-ion battery; multiphysics modeling of non-uniform Li^+ transport in all-solid-state Li-ion batteries; a structurally stable silicon-carbon nanotube; a tunable, air-stable electrical conductive metal organic frameworks.

IMPACT

- NEES has led new conceptual research directions based on precision nanostructures as model science platforms, as exemplified by the world's smallest Li ion battery (over 1 million in grain of sand), achieving record-setting capacity retention at high power and cycle stability, demonstrating that ion transport in highly confined electrolyte volumes is not limiting. The work was featured in > 36 media coverage including *The Times* and *National Geographic*, reaching a broad range of public audience.
- NEES has published > 20 invited perspectives and review articles on key scientific concepts involved in using nanostructures and architectures for next generation energy storage.
- In collaboration with DOE Center for Integrated Nanotechnologies (CINT), NEES PIs developed a novel Discovery Platform – a microfabricated sealed liquid cell that allows imaging and control of battery electrochemical processes in an atomic-resolution transmission electron microscope (TEM).
- NEES co-sponsors 2016 CINT Users Meeting Symposium, titled "Electrochemical Nanostructures: Mesoscale Architectures and Integration", Santa Fe, NM, Sept 2016, highlighting scientific research in nano- materials and structure characterization at the CINT 10 Years of Innovation.
- With K. Xu (ARL), NEES PI C. Wang has co-founded the Center for Research in Extreme Batteries (CREB) to capitalize on battery expertise in NEES, ARL and NIST, promoting open access to facilities and collaborative research in advanced battery materials and technologies.
- Over $8M follow-on funding from ARPA-E, EERE, NSF and JHU-APL has been awarded to NEES PIs to take nanostructure designs to technology, including the DELTA, RANGE and IDEAS programs in ARPA-E and the CMMI-Nanomanufacturing in NSF.
- **Saft Groupe SA** has been collaborating and supporting NEES PIs, including C. Wang on Li-S and other battery chemistries, and recently G. Rubloff on electrode protection layers. saftbatteries.com

PUBLICATIONS AND INTELLECTUAL PROPERTY

As of May 2016, NEES had published 187 peer-reviewed publications cited over 8,500 times and filed 12 disclosures, 9 US patent applications, and 1 foreign patent application. 2 patents have been issued. The following is a selection of impactful papers:

- Huang, J. et al. *In Situ* Observation of the Electrochemical Lithiation of a Single SnO_2 Nanowire Electrode. *Science* **330**, p1515-p1520, doi: 10.1126/science.1195628 (2010). [**576 citations**]
- Guo, J., Xu, Y., Wang, C. Sulfur-Impregnated Disordered Carbon Nanotubes Cathode for Lithium-Sulfur Batteries. *Nano Letters* **11**, p4288-p4294, doi: 10.1021/nl202297p (2011). [**476 citations**]
- Liu, R., Duay, J., Lee, S.B. Heterogeneous nanostructured electrode materials for electrochemical energy storage. *Chemical Communications* **47**, p1384-p1404, doi: 10.1039/c0cc03158e (2011). [**281 citations**]
- Liu, X.H. et al. Anisotropic Swelling and Fracture of Silicon Nanowires during Lithiation. *Nano Letters* **11**, p3312-p3318, doi: 10.1021/nl201684d (2011). [**280 citations**]
- Liu, C. et al. An all-in-one nanopore battery array. *Nature Nanotechnology* **9**, p1031-p1039, doi: 10.1038/NNANO.2014.247 (2014). [**39 citations**]
- Kozen, A.C. et al. Next-Generation Lithium Metal Anode Engineering via Atomic Layer Deposition. *ACS Nano* **9**, p5884-p5892, doi: 10.1021/acsnano.5b02166 (2015). [**33 citations**]