

Operando Electron Microscopy for Energy Generation, Use, and Storage

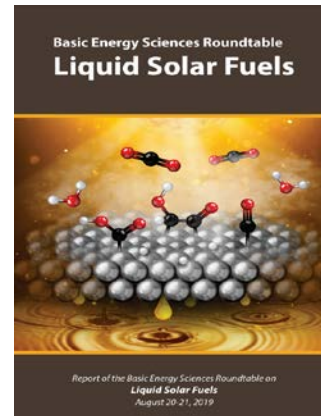
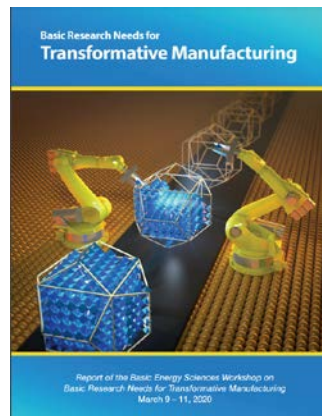
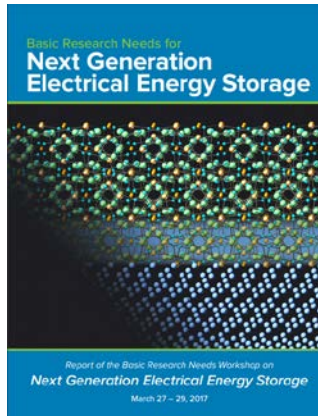
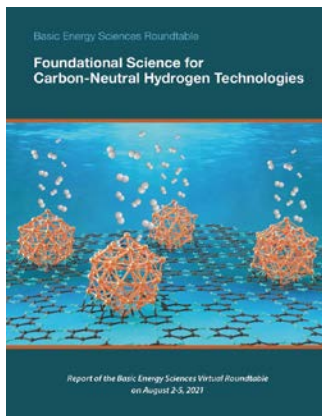


Katherine Jungjohann

Group Manager, Analytical Microscopy and Imaging Sciences

BESAC Virtual Meeting
July 14th, 2022

Atomic Scale Foundational Energy Phenomena



Interfaces

Impurities

Transient
States

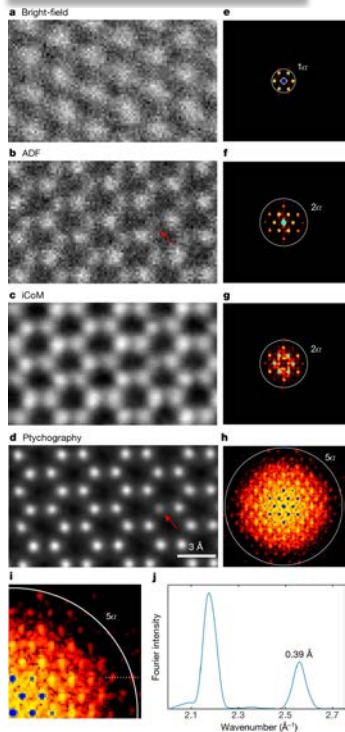
Reaction
Mechanisms

Degradation
Pathways

Why Electron Microscopy?

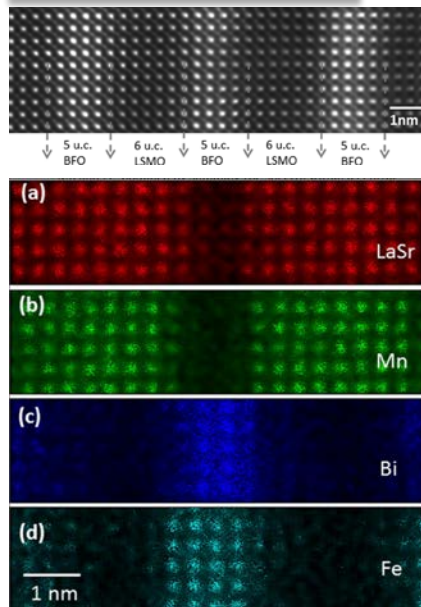
Atomic Scale Detail

Imaging at 0.39 Å



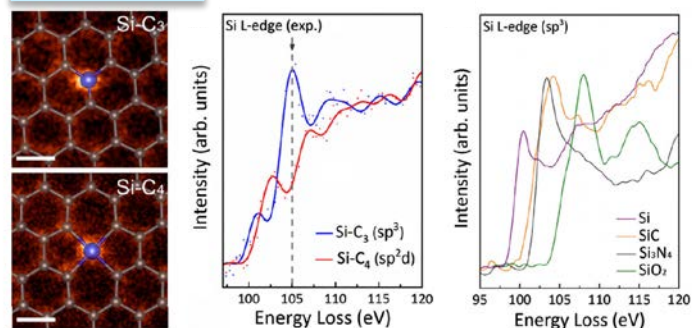
Jiang et al. Nature 559, 343 (2018)

Composition Maps



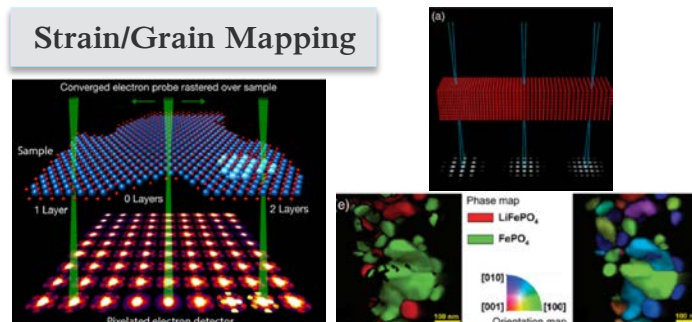
Lu et al. Appl. Phys. Lett. 102, 17311 (2013)

Bonding



Zhou et al. Phys. Rev. Lett. 109, 206803 (2012)

Strain/Grain Mapping



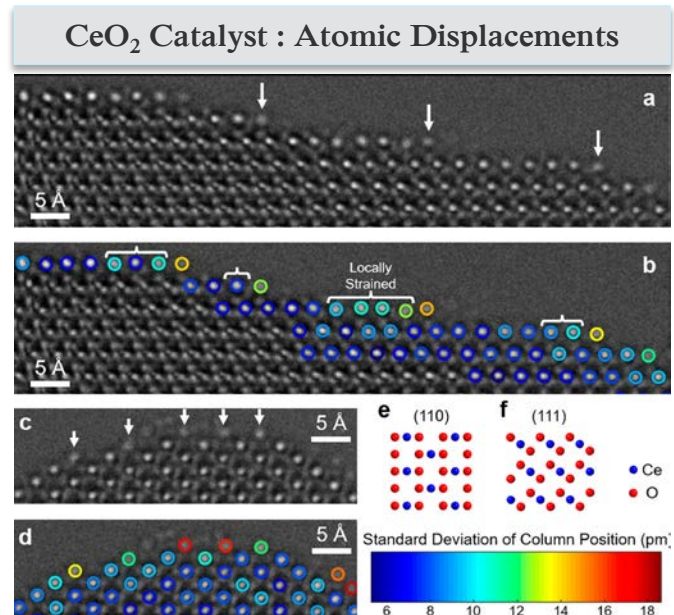
Ophus et al. Microsc. Microanal. 25, 563 (2019)

Obtain this information for *operando* phenomena in energy systems?

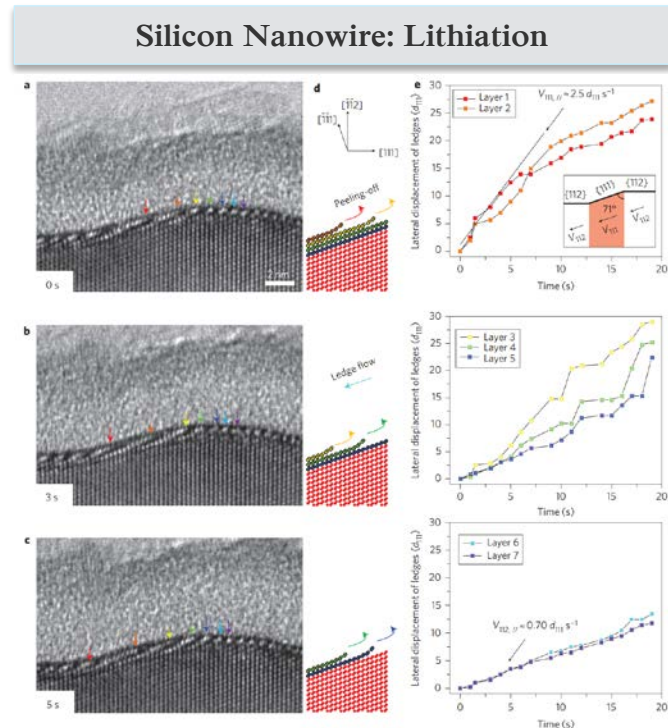
Operando Electron Microscopy



Atomic Scale *Operando* Electron Microscopy



Lawrence et al. ACS Nano 15, 2624 (2021)



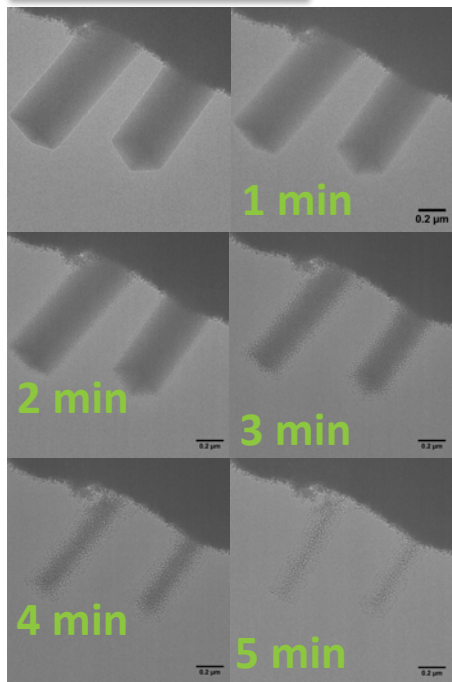
Liu et al. Nature Nanotech. 7, 749 (2012)

Atomic-scale *operando* imaging is simpler with electron beam resistant materials/interfaces

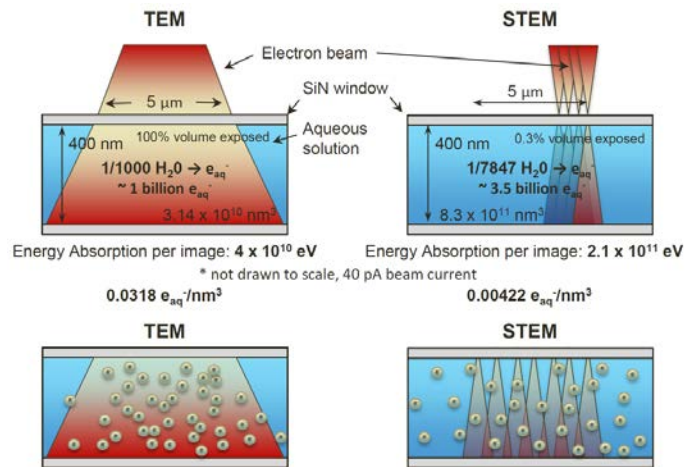
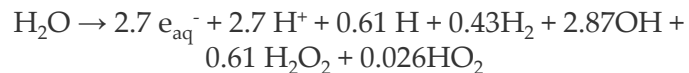
Limitations with Atomic Scale *Operando* EM

Beam Effects

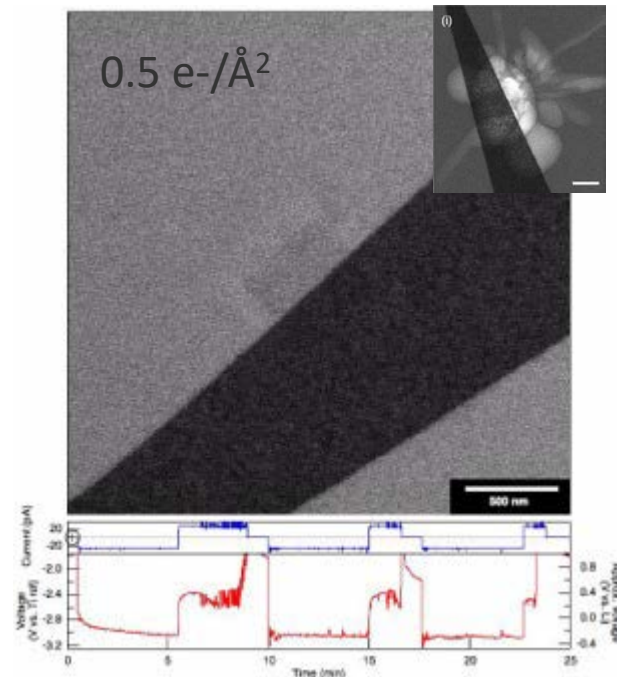
Lithium Metal



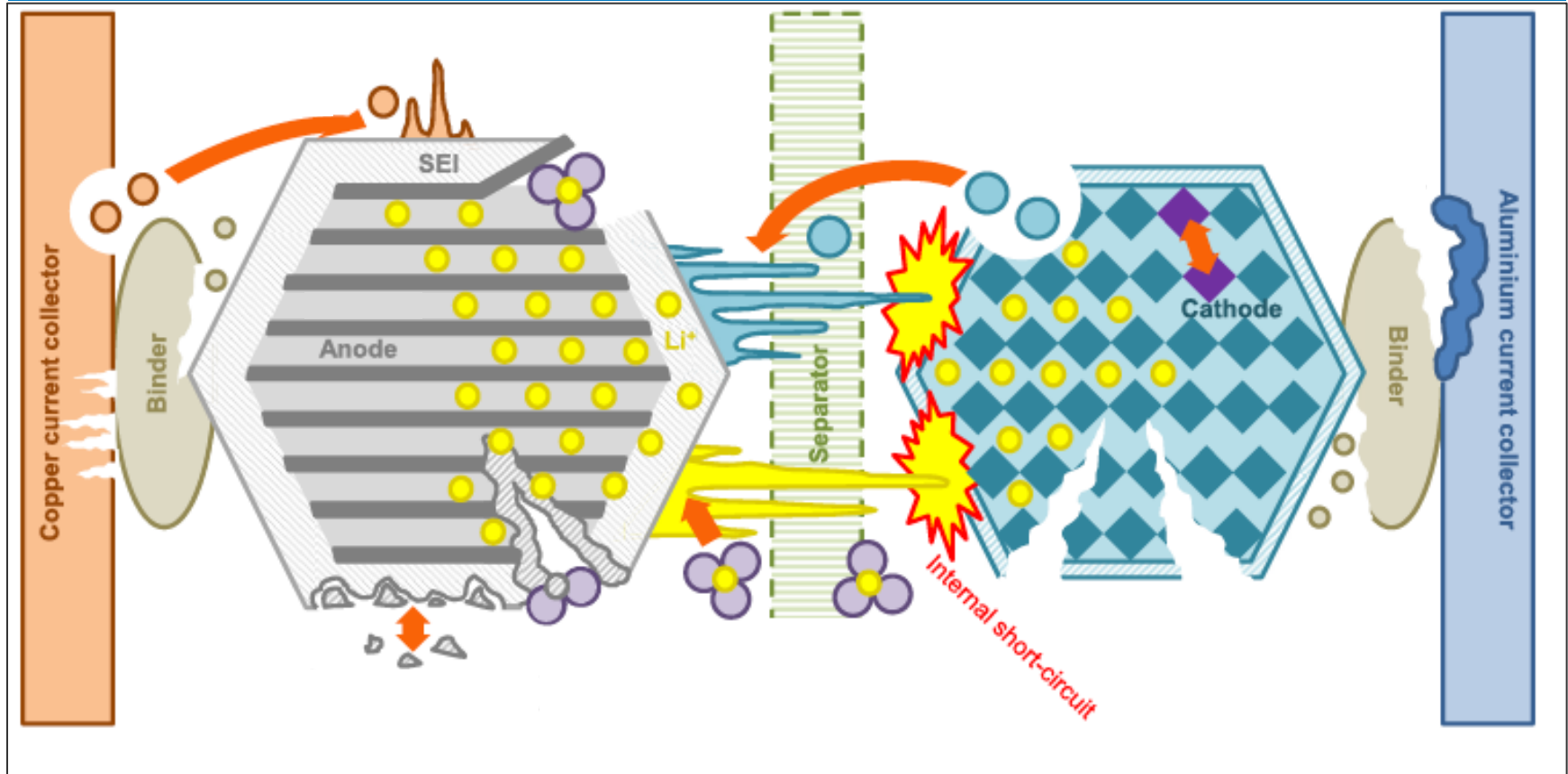
Radiolysis of Liquids



Li Electrodeposition Structure

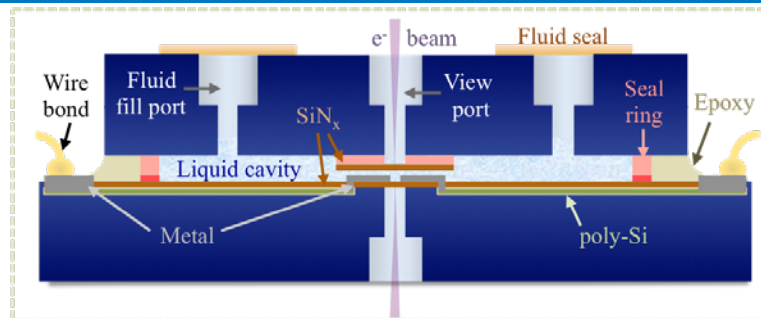
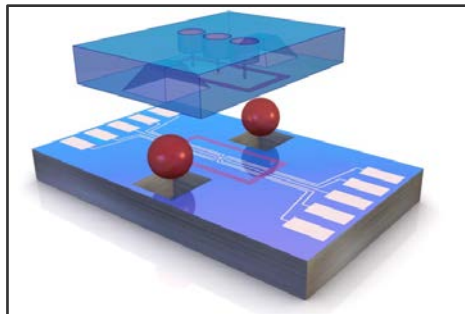
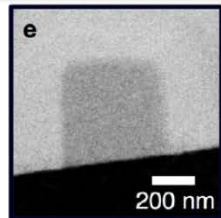


Battery Degradation Pathways

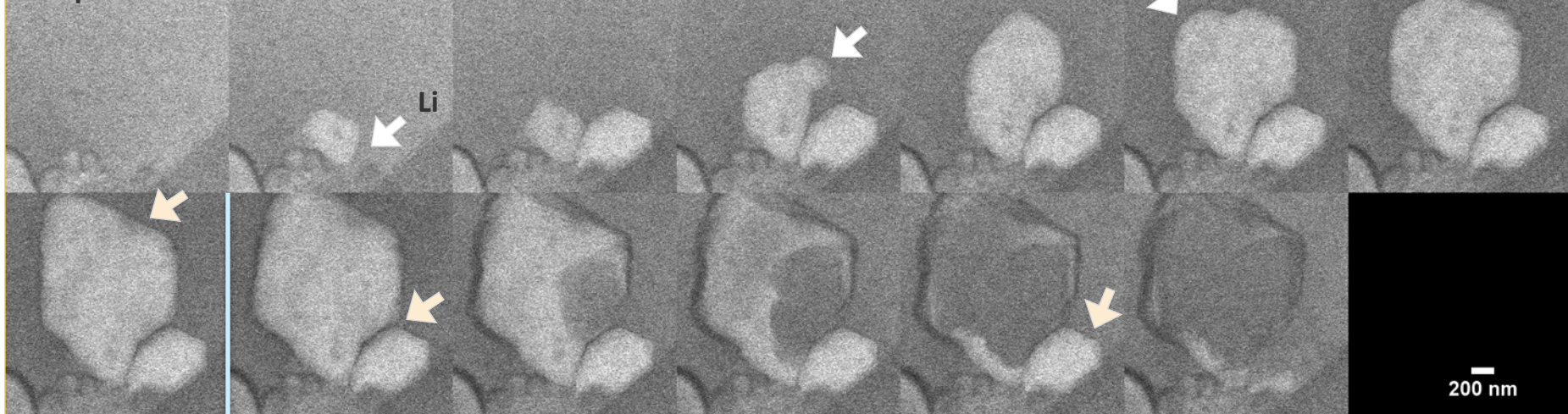


Operando Information Unlocks Pathways

Lithium Metal Batteries



Li Deposition

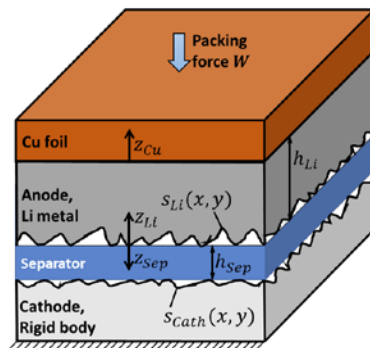
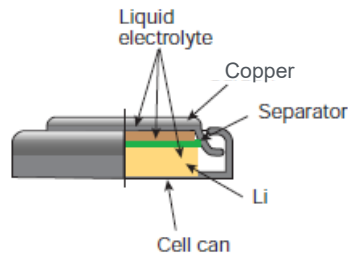
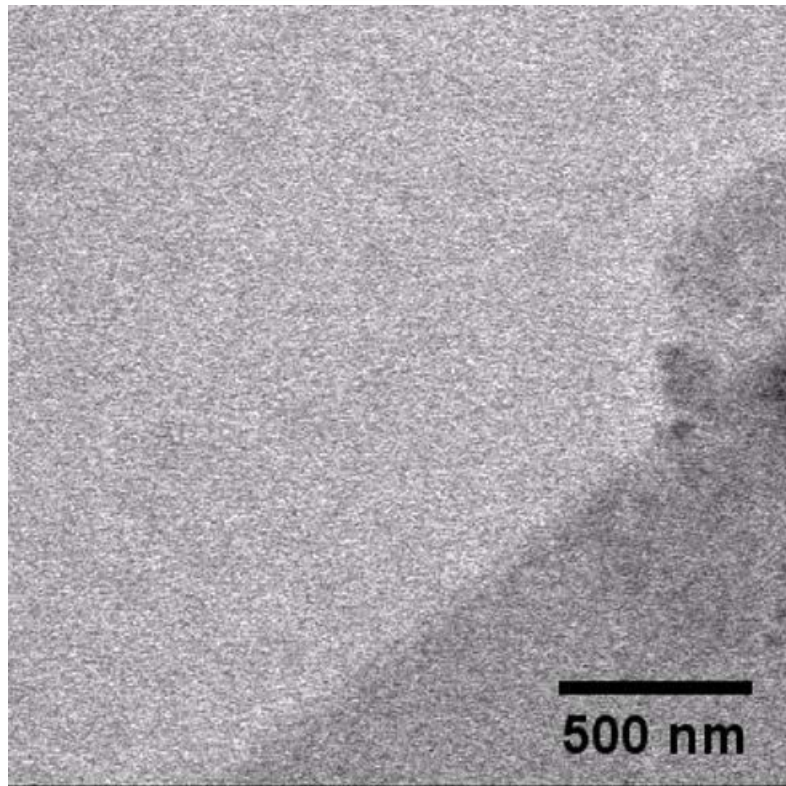


Li Stripping

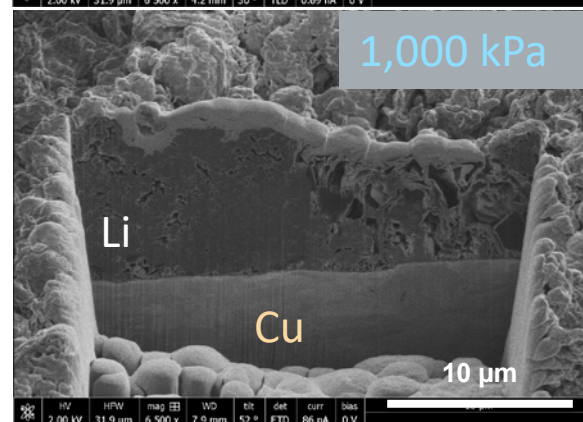
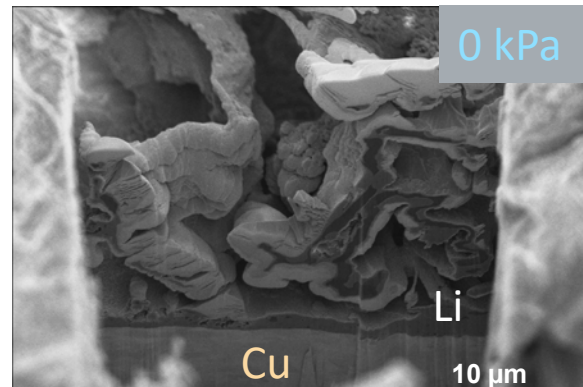
Operando Information Unlocks Pathways



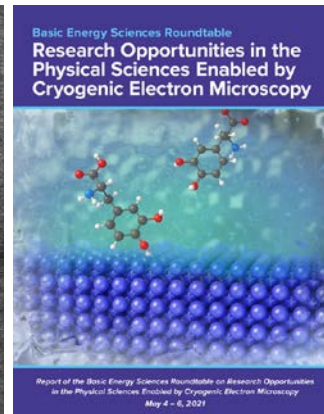
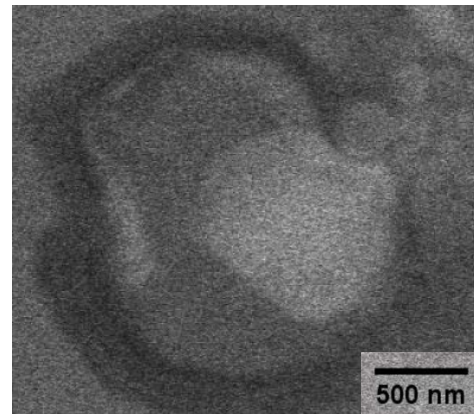
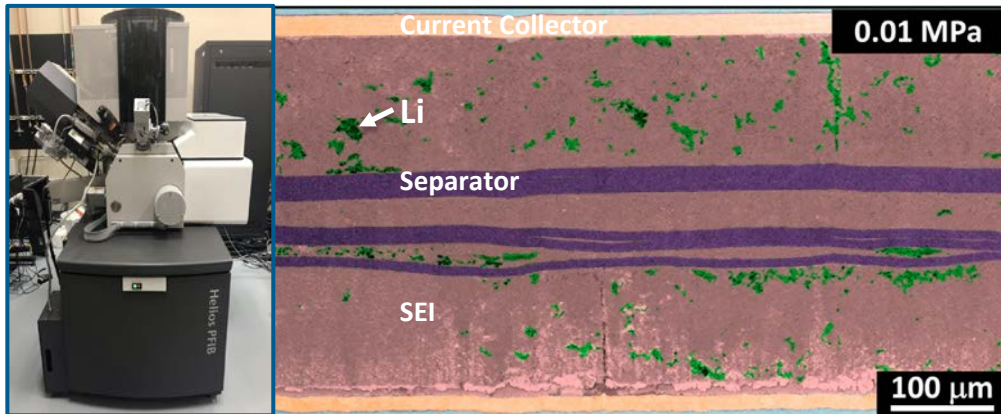
Lithium Metal Batteries



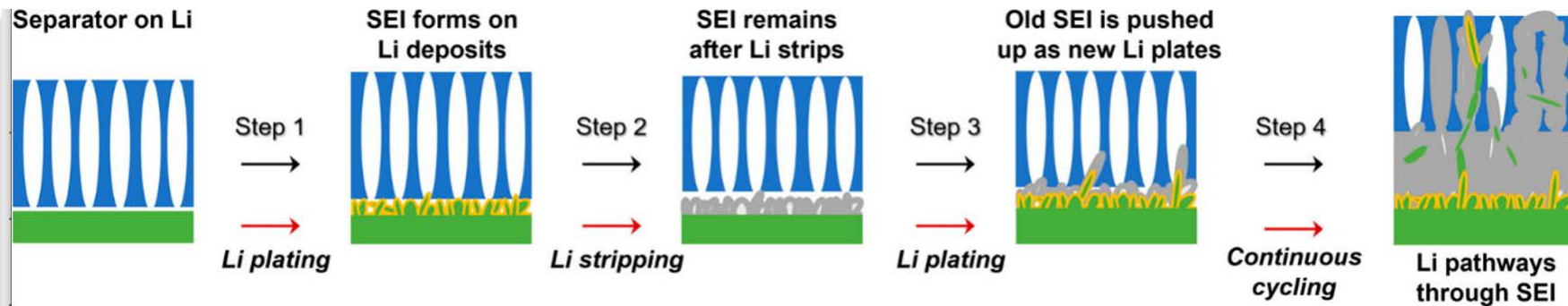
Zhang et al. J. Electrochem. Soc. 166, A3639 (2019)



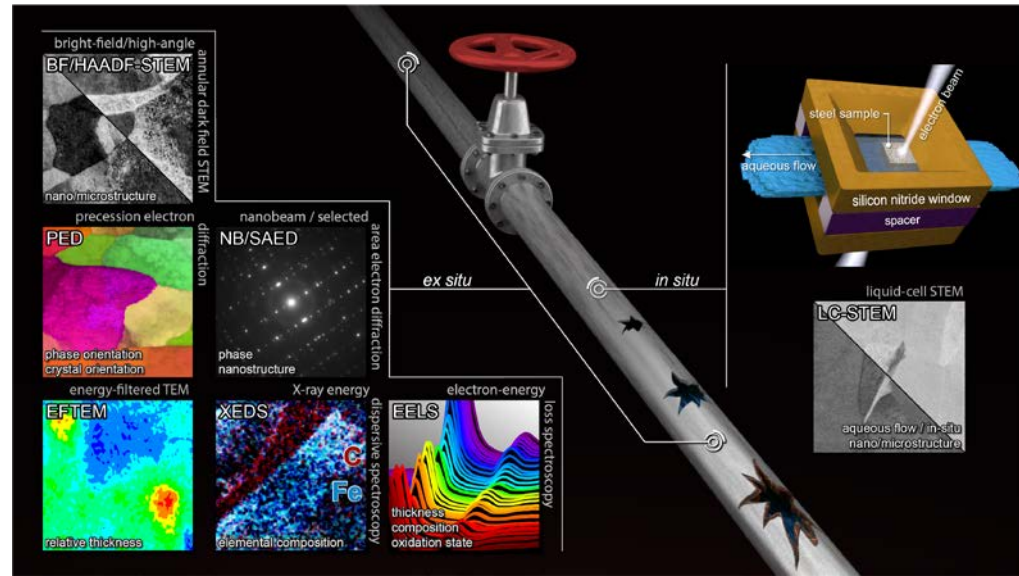
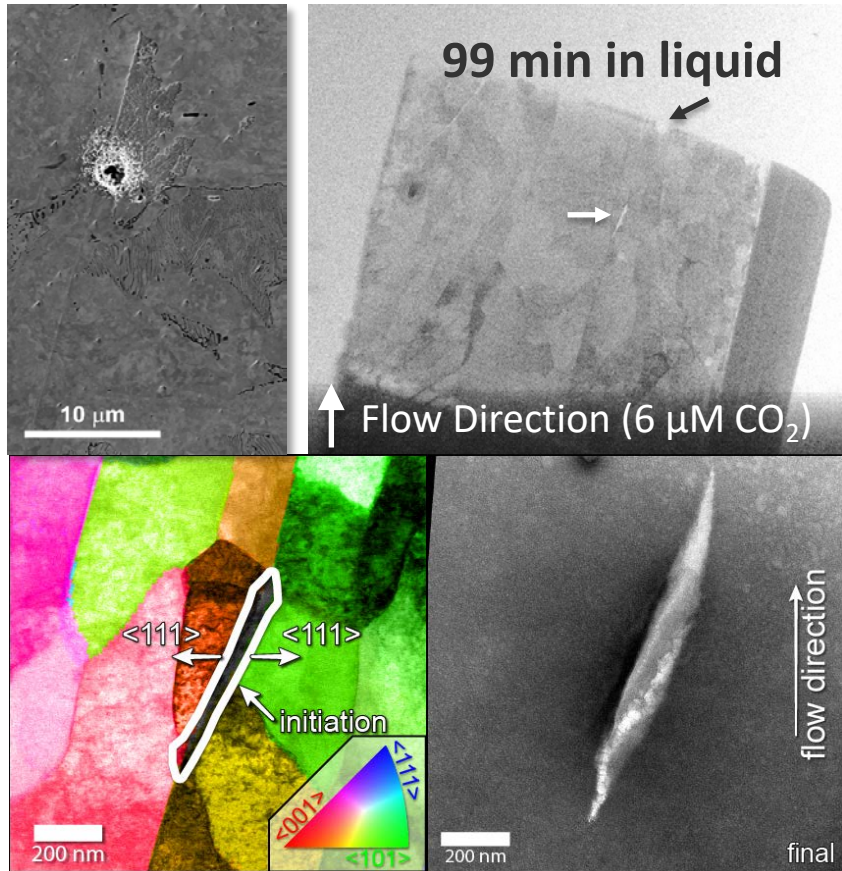
Operando EM Supported by Cryo EM



Harrison et al., iScience 24, 103394 (2021)



Often Need Capabilities of Many Optimized EMs



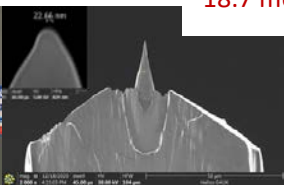
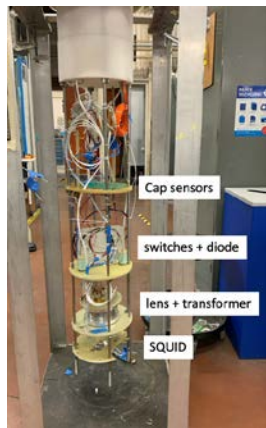
Hayden et al., npj Materials Degradation 3, 17 (2019)

Needed analytical characterization to properly identify *operando* corrosion mechanism

Data were collected from three electron microscopes at SNL and a fourth at INL

Operando Electron Microscopy at NSRCs

1K TEM



18.7 meV



Molecular Foundry
Lawrence Berkeley National Laboratory

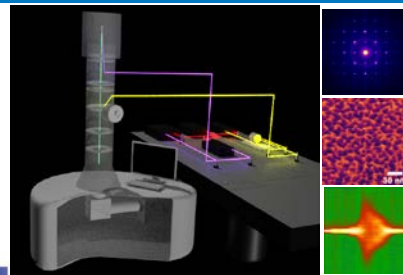


Operando UEM

Center for Nanoscale Materials
Argonne National Laboratory



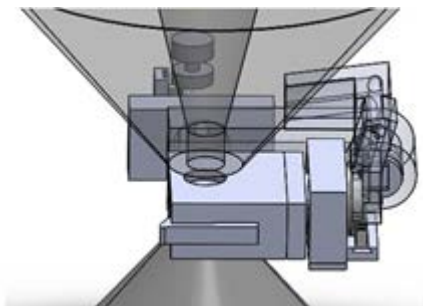
Center for Functional Nanomaterials
Brookhaven National Laboratory



Paired EM and X-Ray



Extreme Environment TEM



Center for Integrated Nanotechnologies
Sandia National Laboratories
Los Alamos National Laboratory

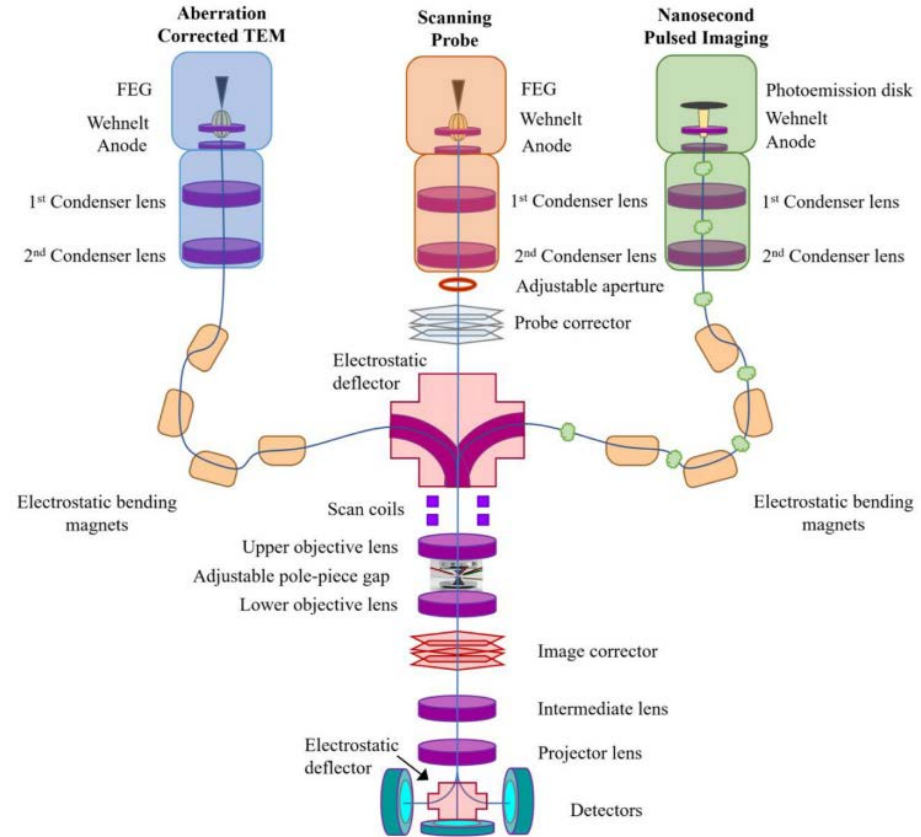
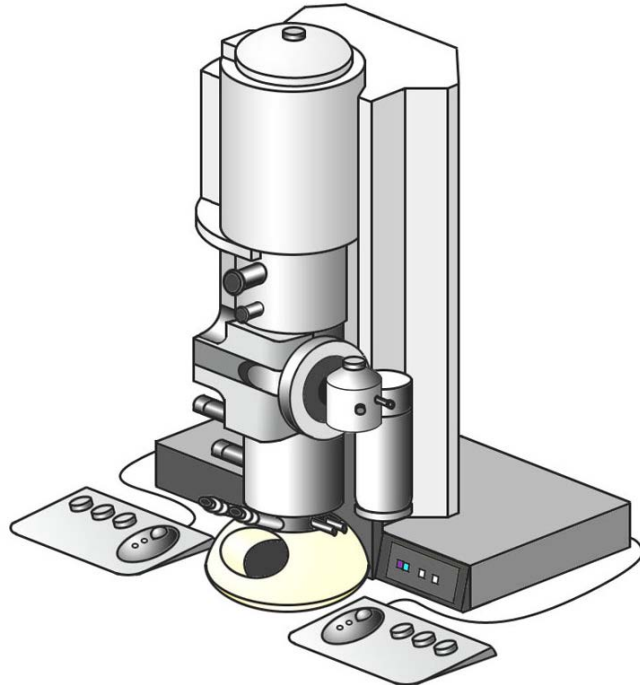


Center for Nanophase Materials Sciences
Oak Ridge National Laboratory

Liquid-He MAC-STEM



Optimized *Operando* Electron Microscope



Concluding Remarks

Solar



Hydrogen



Batteries



Electronics



Future Needs

- Workforce development: Need time for training to gain the expertise in *operando*, analytical, and cryogenic EM
- State-of-the-art capabilities on single instruments available within DOE's NSRCs

Interfaces

Impurities

Transient States

Reaction Mechanisms

Degradation Pathways

ThermoFisher
SCIENTIFIC

Renaë Gannon



Dave Johnson



Steven Randolph

Thank You BES!



Daniel Long

www.nrel.gov

NREL/PR-5K00-83483



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Laura Merrill

Kevin Zavadil

Khalid Hattar

Andrew Leenheer



Steven Hayden

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Los Alamos National Laboratory (Contract 89233218CNA000001) and Sandia National Laboratories (Contract DE-NA-0003525). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

