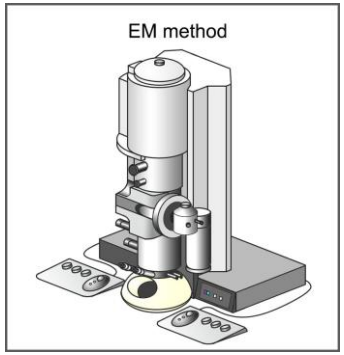


Operando Electron Microscopy for Energy Generation, Use, and Storage

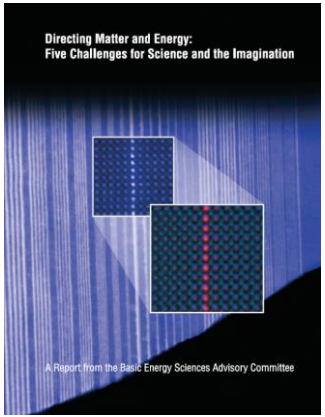
Katherine Jungjohann

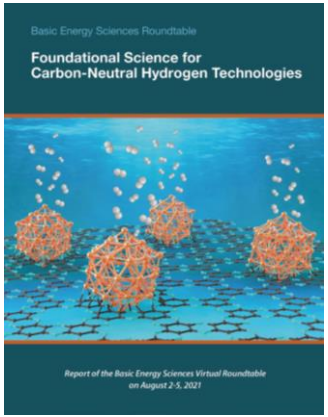
Group Manager, Analytical Microscopy and Imaging Sciences

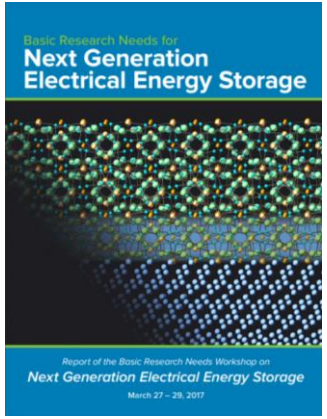
BESAC Virtual Meeting

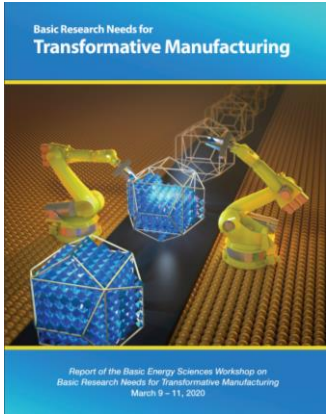
July 14th, 2022

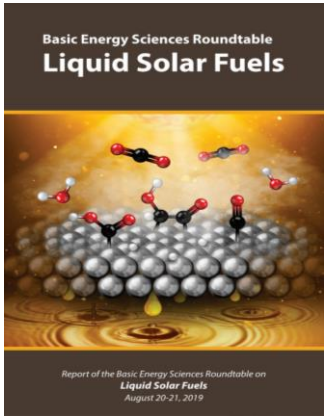
Atomic Scale Foundational Energy Phenomena

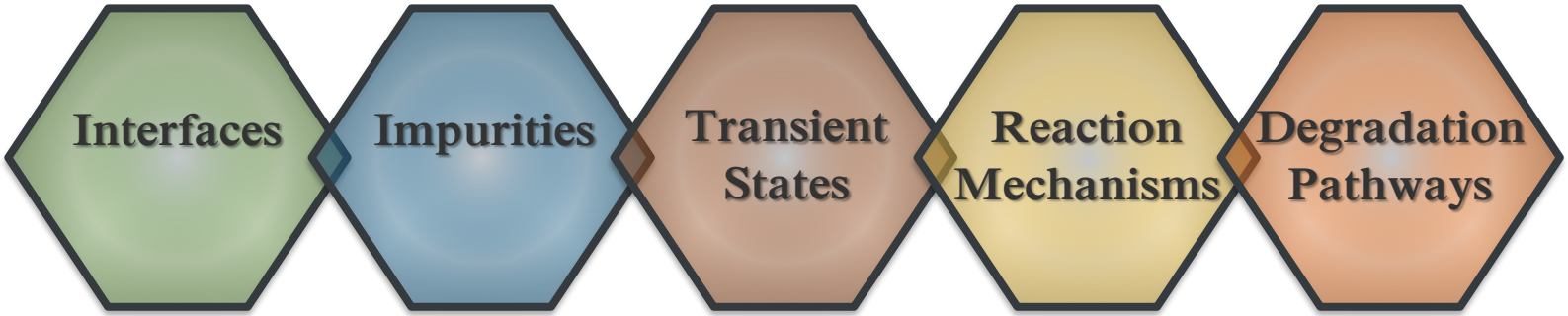






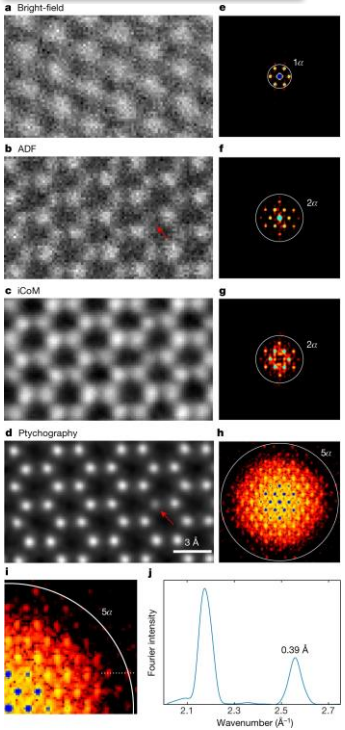






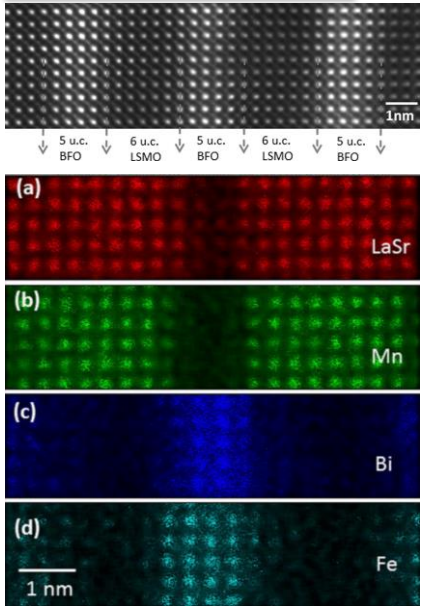
Why Electron Microscopy? Atomic Scale Detail

Imaging at 0.39 Å



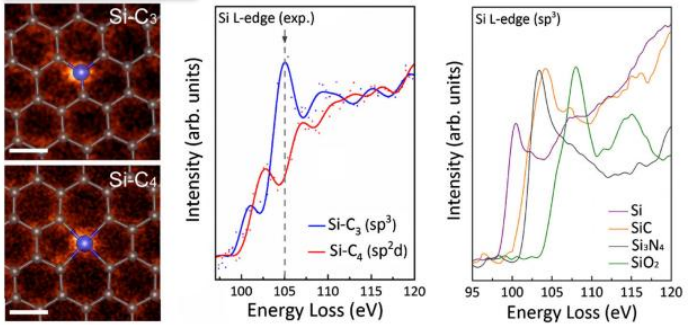
Jiang et al. Nature 559, 343 (2018)

Composition Maps



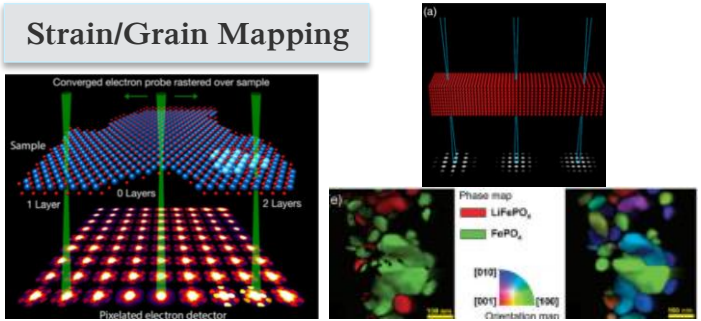
Lu et al. Appl. Phys. Lett. 102, 17311 (2013)

Bonding



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

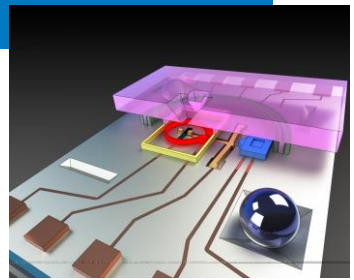
Strain/Grain Mapping

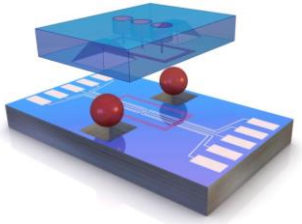


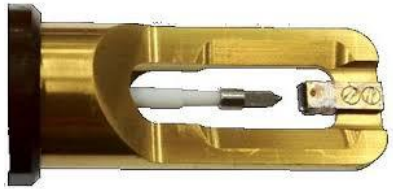
Ophus et al. Microsc. Microanal. 25, 563 (2019)

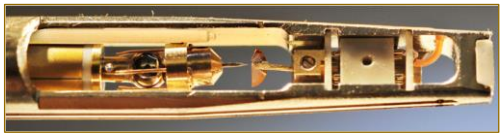
Obtain this information for *operando* phenomena in energy systems?

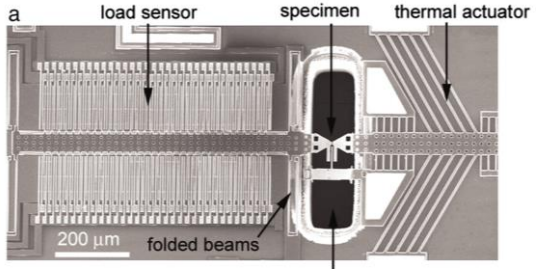
Operando Electron Microscopy





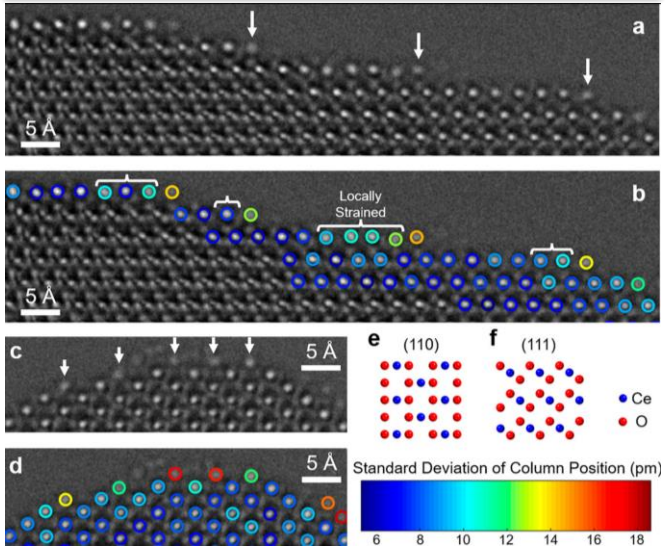






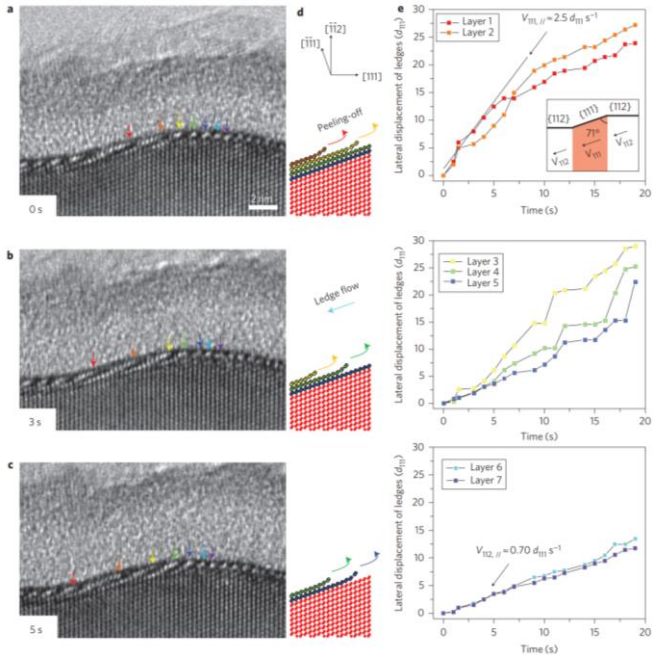
Atomic Scale *Operando* Electron Microscopy

CeO_2 Catalyst : Atomic Displacements



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

Silicon Nanowire: Lithiation



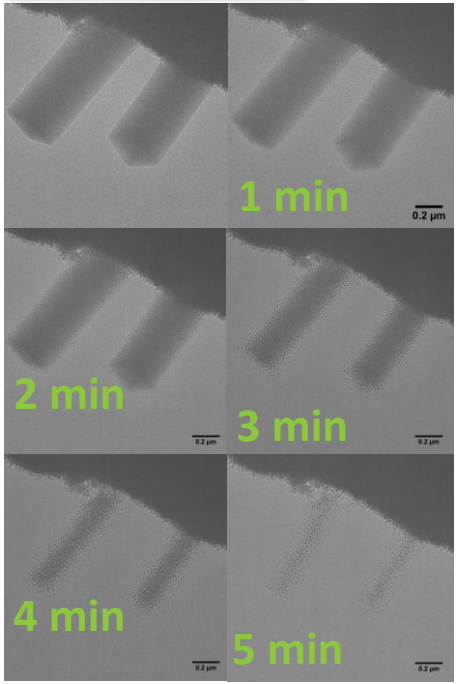
Liu et al. Nature Nanotech. 7, 749 (2012)

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

Limitations with Atomic Scale *Operando* EM

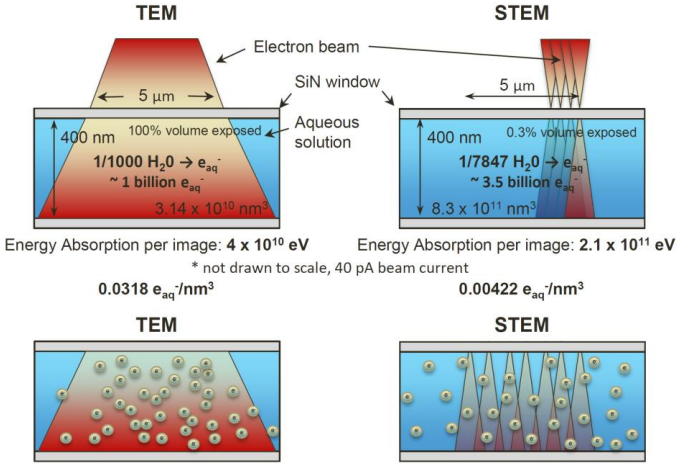
Beam Effects

Lithium Metal

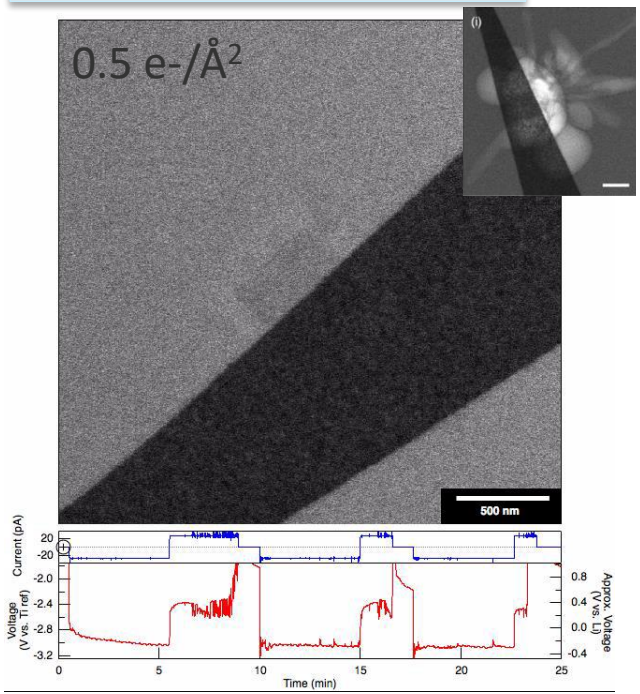


Radiolysis of Liquids

$$H_2O \rightarrow 2.7\ e_{aq}^- + 2.7\ H^+ + 0.61\ H + 0.43 H_2 + 2.87 OH + 0.61\ H_2O_2 + 0.026 HO_2$$

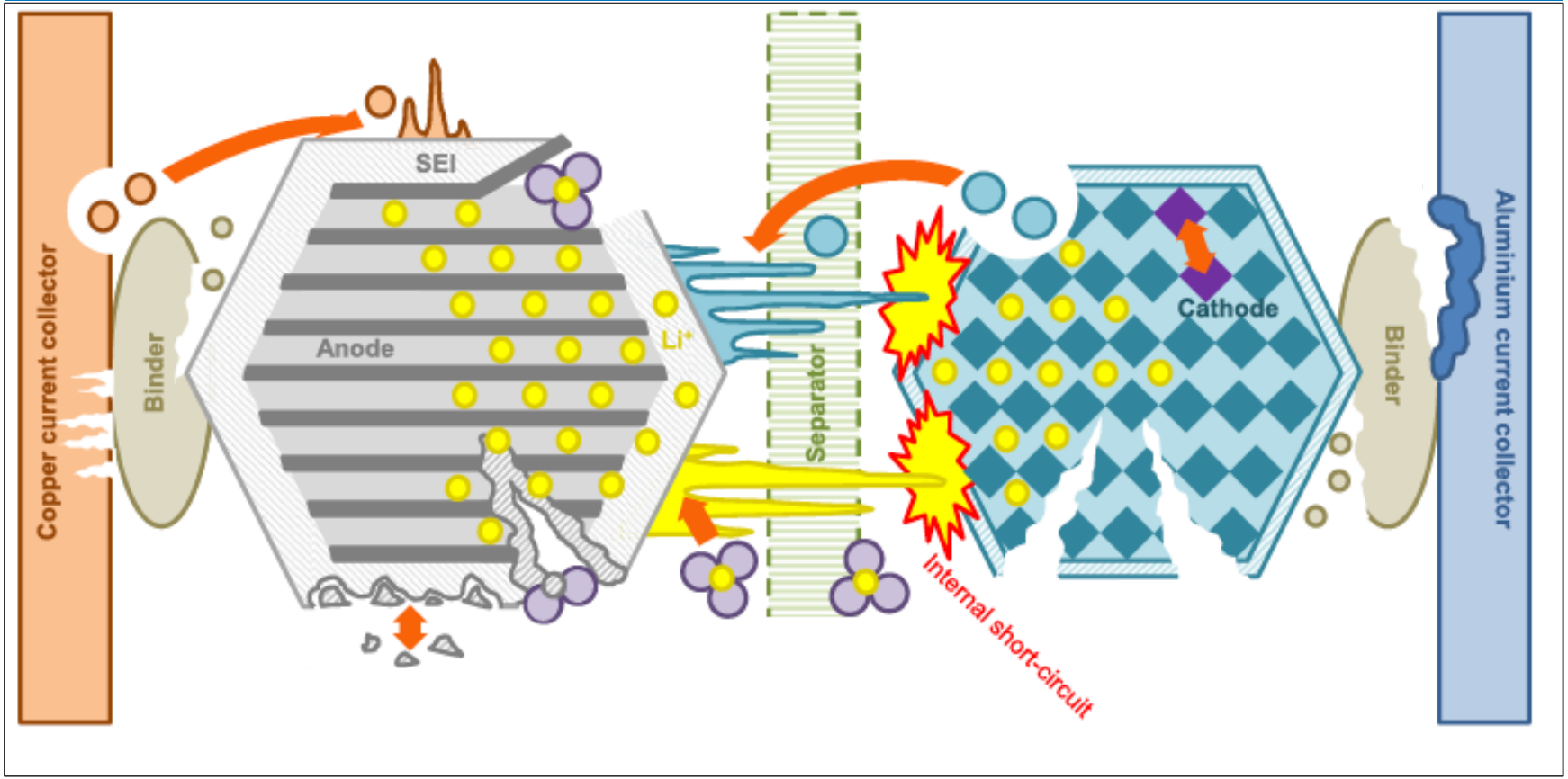


Li Electrodeposition Structure



Leenheer et al., ACS Nano 9, 4379 (2015)

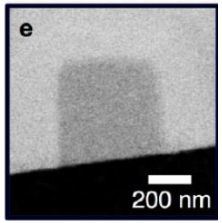
Battery Degradation Pathways

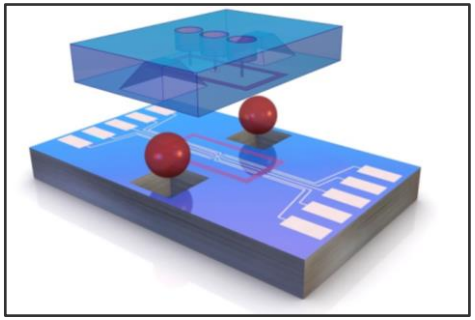


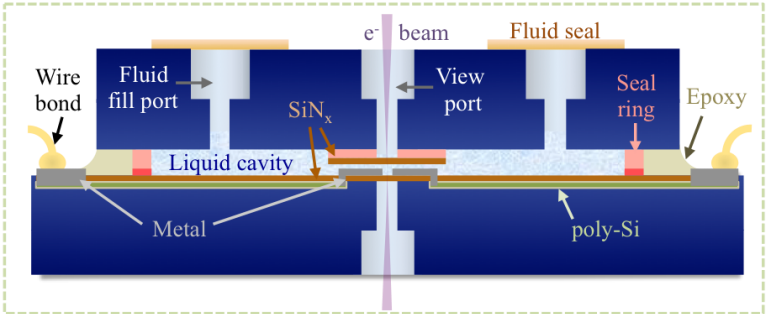
Birkl et al., J. Power Sources 341, 373 (2017)

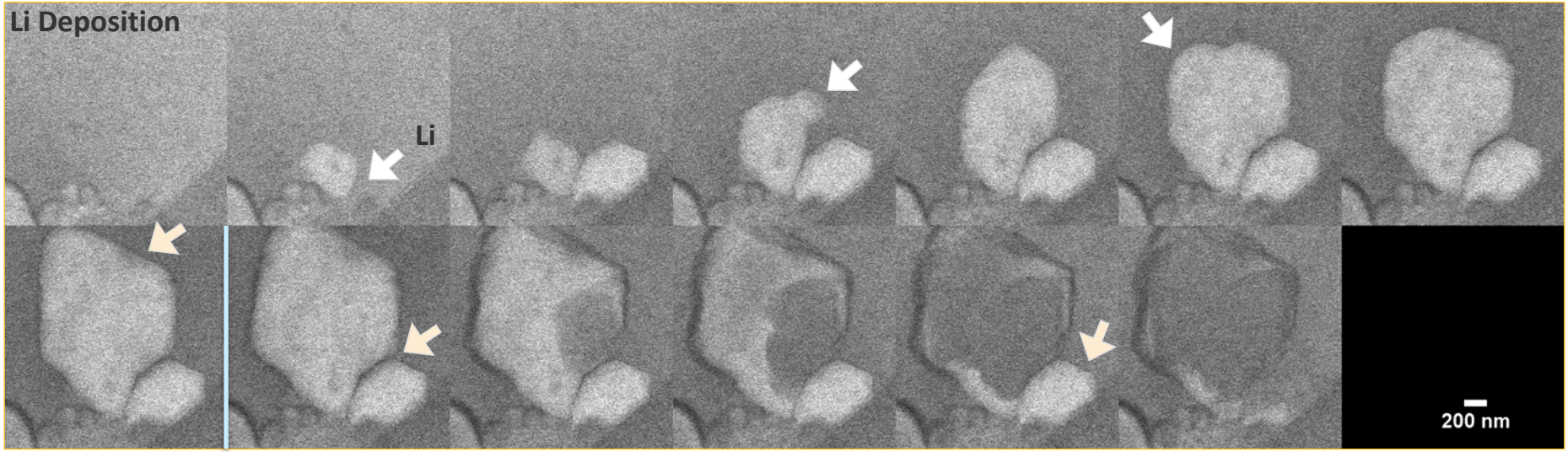
Operando Information Unlocks Pathways

Lithium Metal Batteries





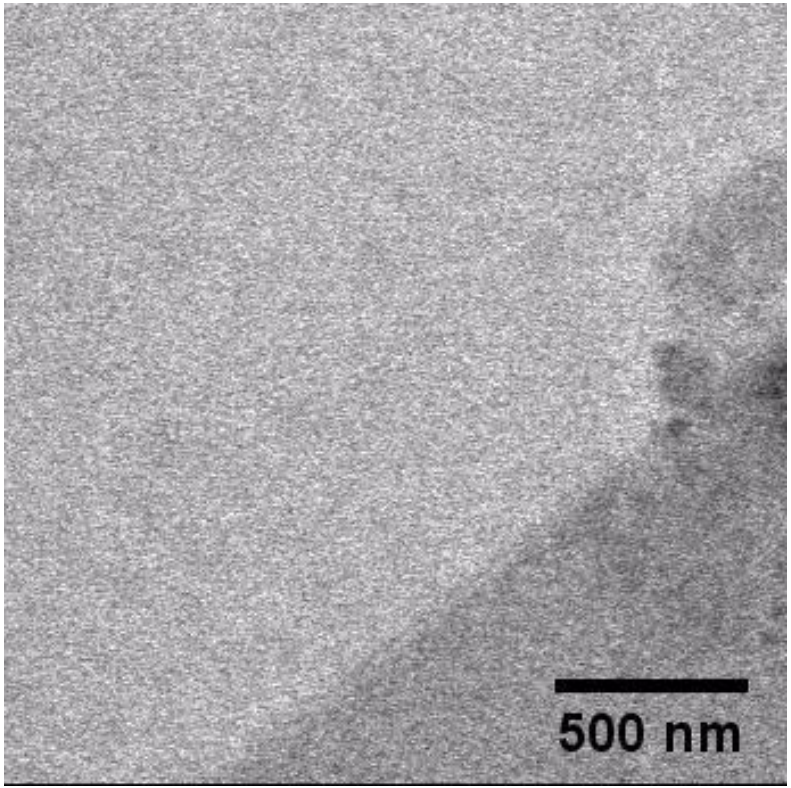


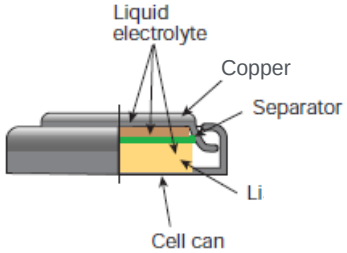


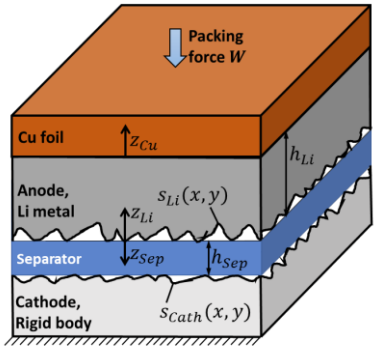
Li Stripping

Operando Information Unlocks Pathways

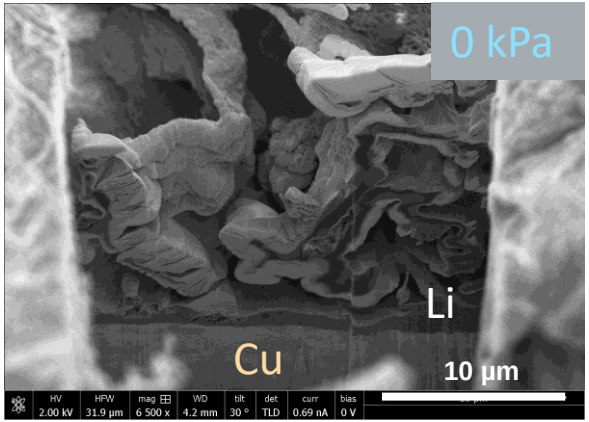
Lithium Metal Batteries

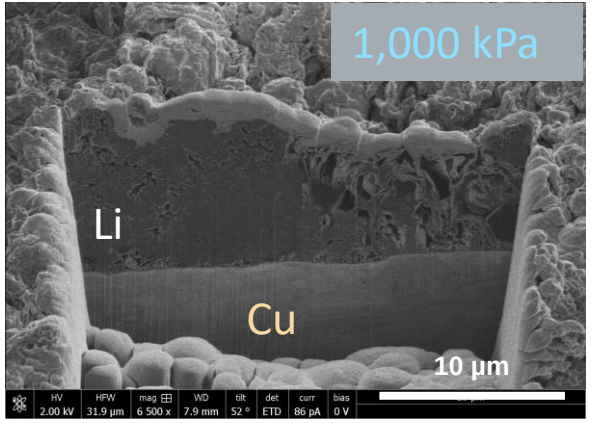






Zhang et al. J. Electrochem. Soc. 166, A3639 (2019)

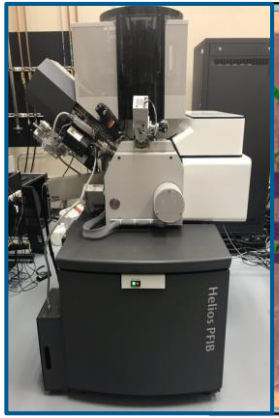


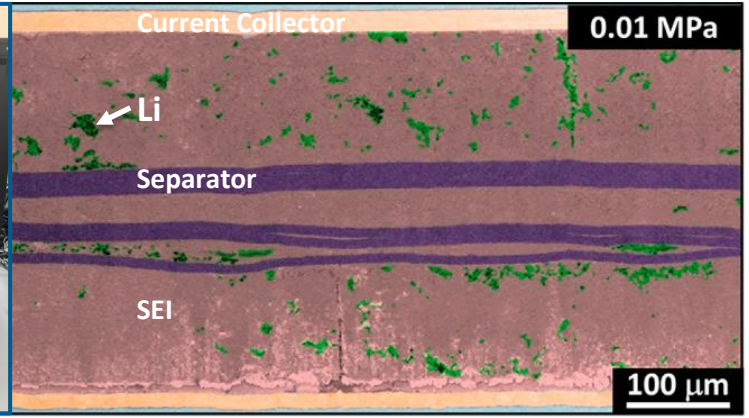


Harrison et al. ACS Appl. Mater. Interfaces 13, 31668 (2021)

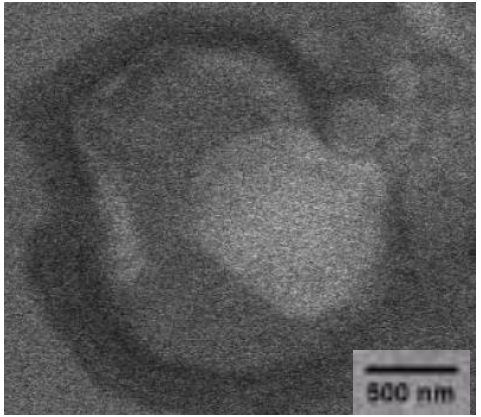
Operando EM Supported by Cryo EM

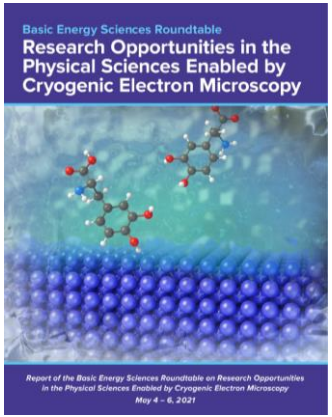
LDRD
Laboratory Directed Research and Development

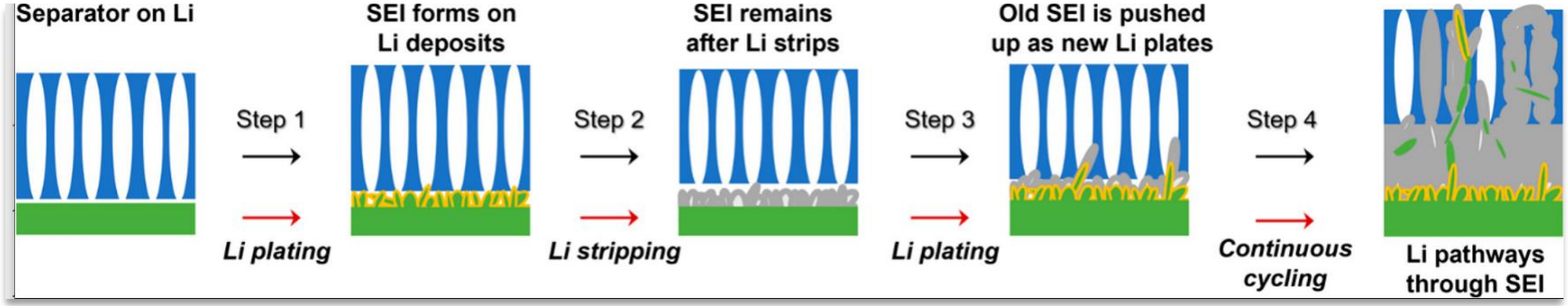




Harrison et al., iScience 24, 103394 (2021)

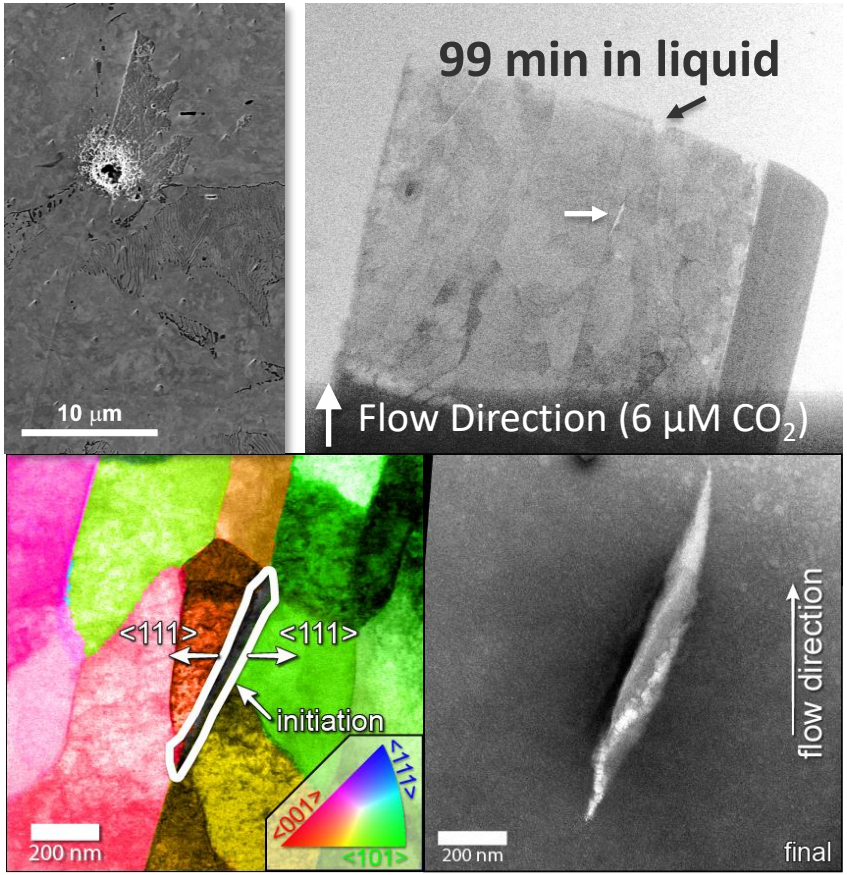


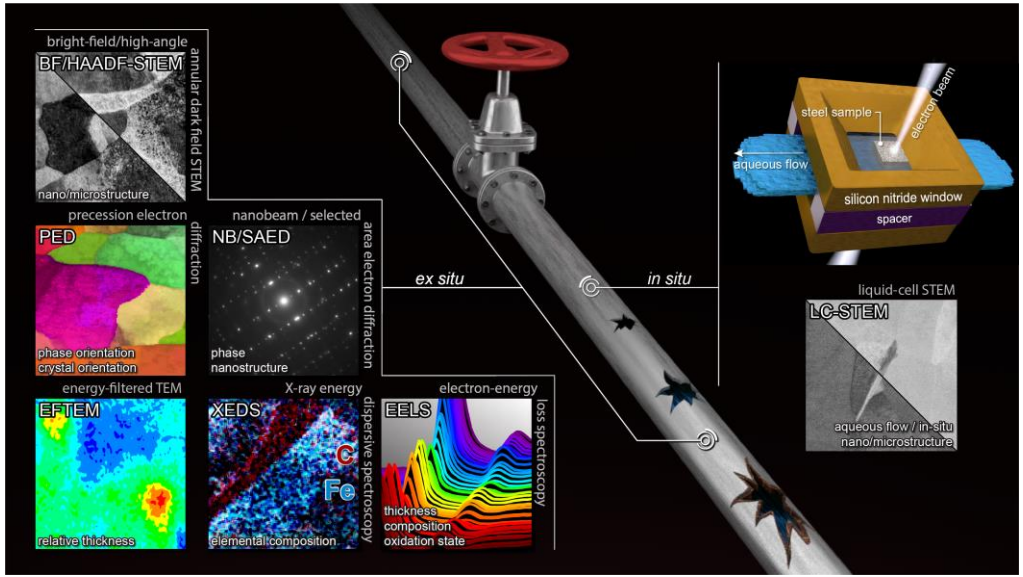




Jungjohann et al., ACS Energy Lett. 6, 2138 (2021)

Often Need Capabilities of Many Optimized EMs





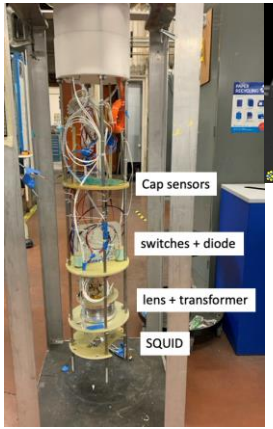
Hayden et al., npj Materials Degradation 3, 17 (2019)

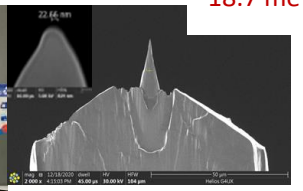
Needed analytical characterization to properly identify *operando* corrosion mechanism

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

Operando Electron Microscopy at NSRCs

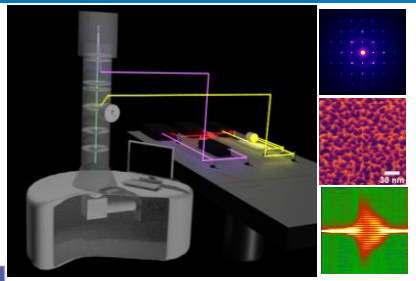
1K TEM





18.7 meV

Operando UEM



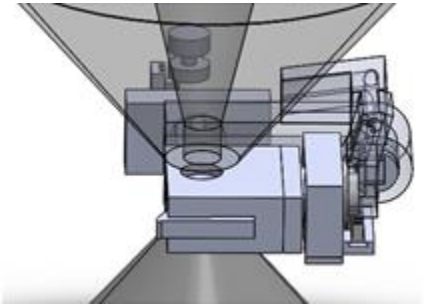
Center for Nanoscale Materials
Argonne National Laboratory

Molecular Foundry
Lawrence Berkeley National Laboratory

Center for Functional Nanomaterials
Brookhaven National Laboratory

Paired EM and X-Ray

Extreme Environment TEM

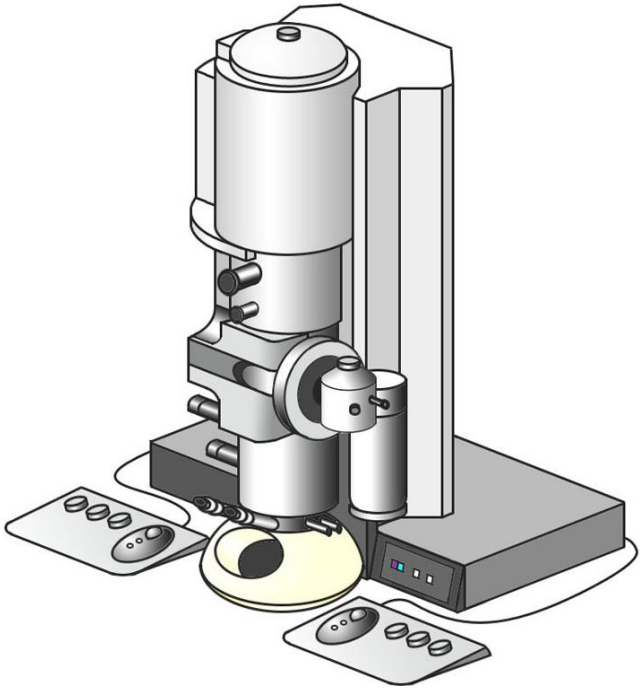


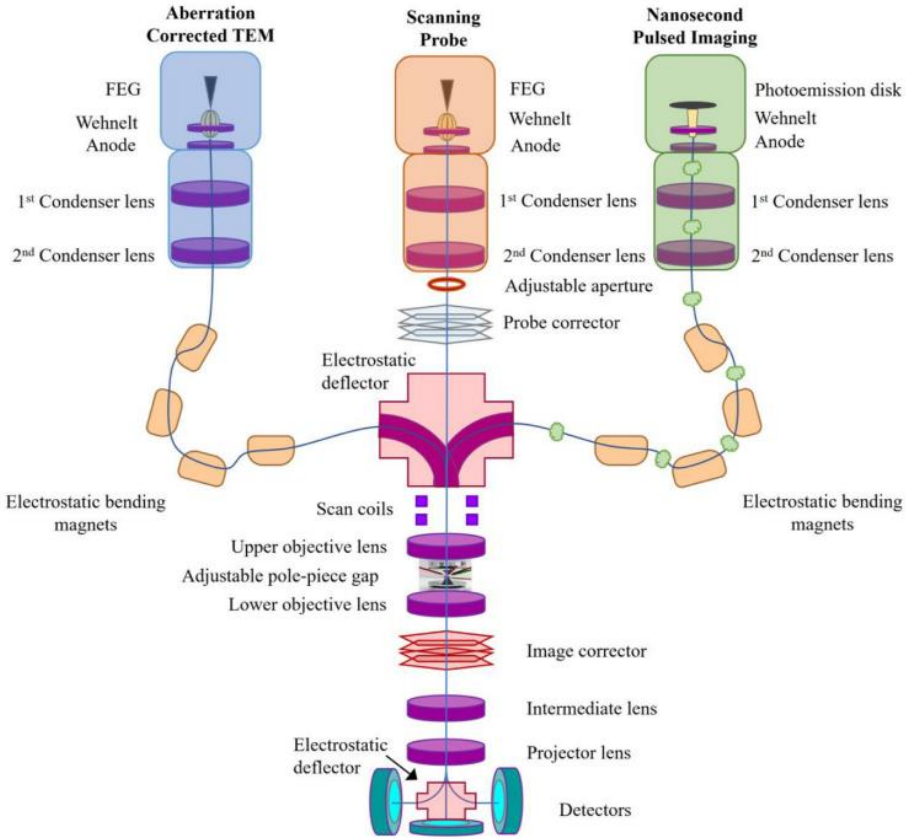
Center for Integrated Nanotechnologies
Sandia National Laboratories
Los Alamos National Laboratory

Center for Nanophase Materials Sciences
Oak Ridge National Laboratory

Liquid-He MAC-STEM

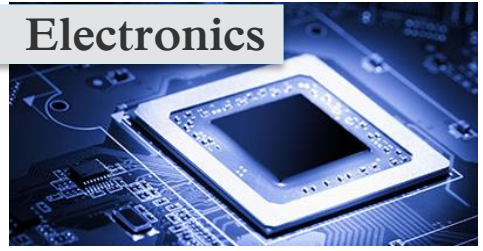
Optimized *Operando* Electron Microscope





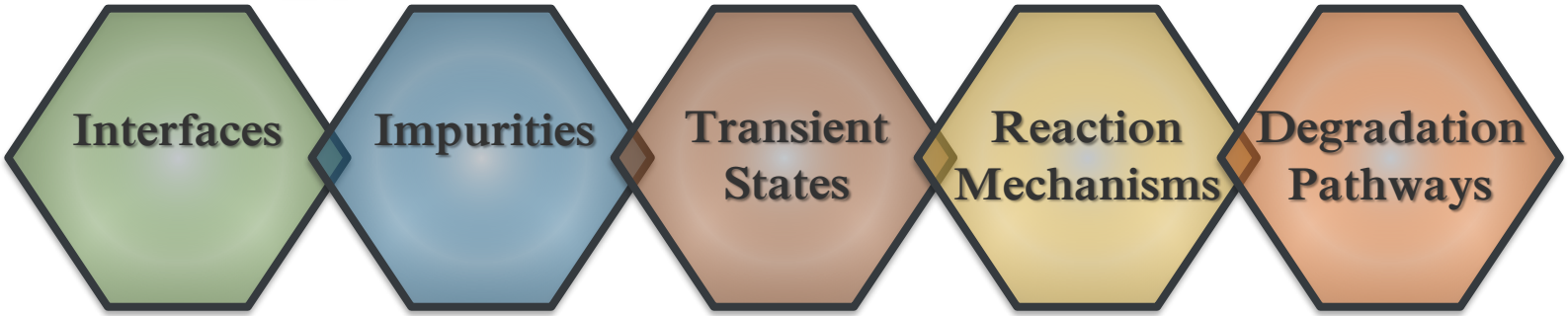
Hattar and Jungjohann, J. Mater. Sci. 56, 5309 (2021)

Concluding Remarks



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



Renae Gannon

Dave Johnson

Steven Randolph

Daniel Long

Katharine Harrison
Laura Merrill
Kevin Zavadil
Khalid Hattar
Andrew Leenheer

Steven Hayden

Thank You BES!

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