FARADAY INSTITUTION WARWICK, SEP 10, 2025

ESRA

Energy Storage Research Alliance

Innovation Beyond Lithium Ion

Shirley Meng

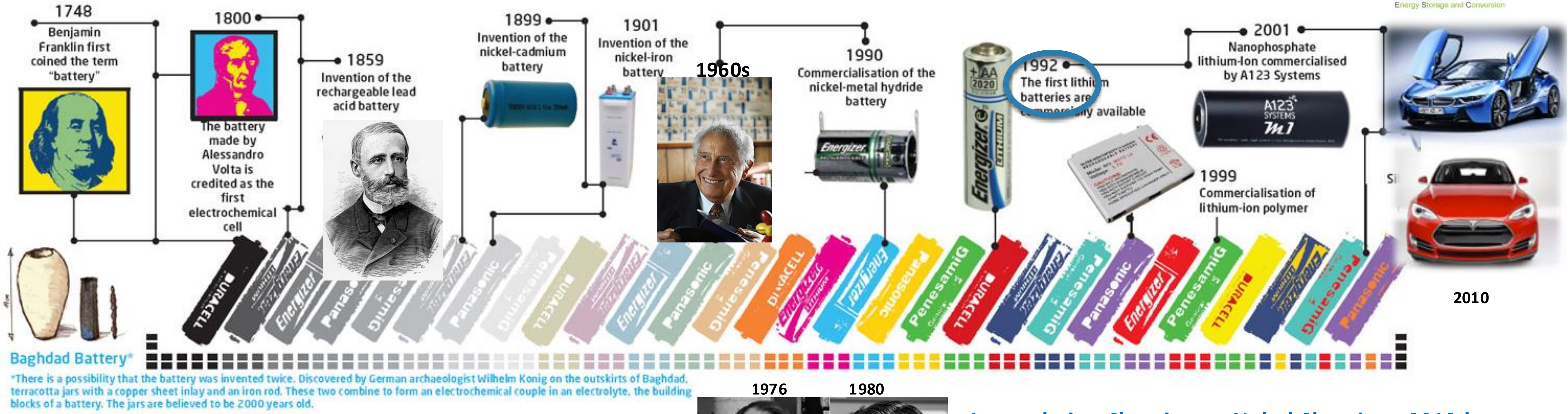
ESRA Director

Argonne National Laboratory/ University of Chicago

Argonne National Laboratory | Berkeley Lab | Pacific Northwest National Laboratory | Columbia University | Duke University | Massachusetts Institute of Technology | Princeton University | UC San Diego | The University of Chicago | University of Houston | University of Illinois Chicago | University of Illinois Urbana-Champaign | University of Michigan | Xavier University of Louisiana

A Brief History of Battery

Laboratory for Energy Storage and Conversion



1976 1980

Intercalation Chemistry – Nobel Chemistry 2019 !

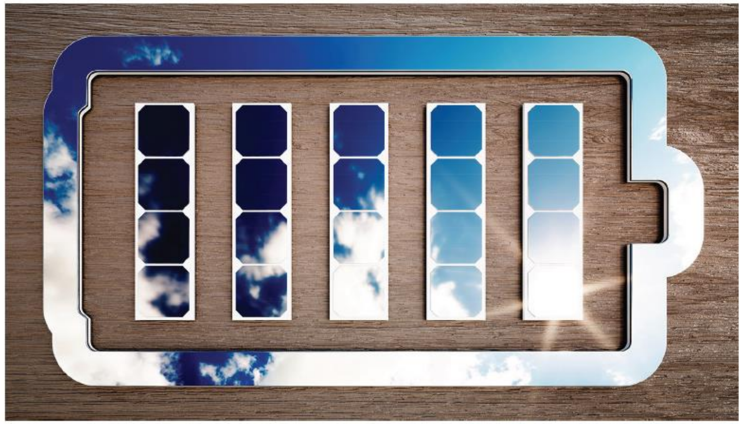
IoT
mWh

Humanoids
Wh

Drones
kWh

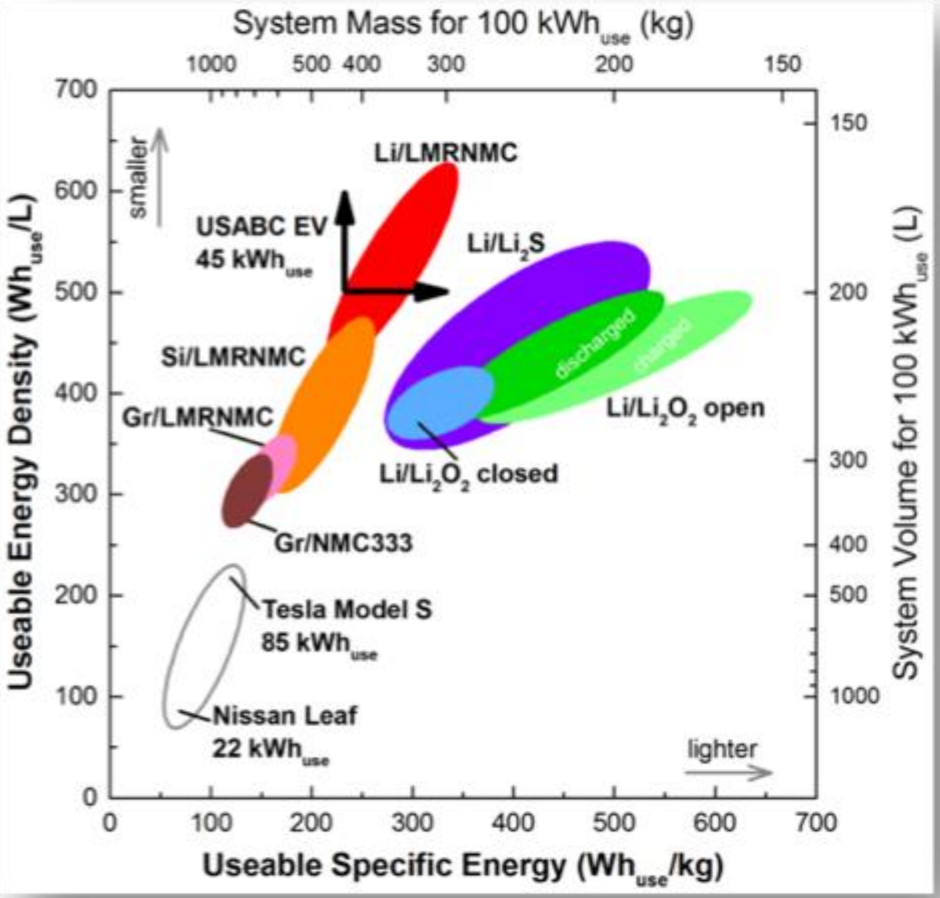
Heavy Duty Truck
MWh

Energy Storage for Renewables
GWh



1Wh is a large energy unit 3600J

Materials Science and Interfacial Engineering



Courtesy of Argonne National Lab

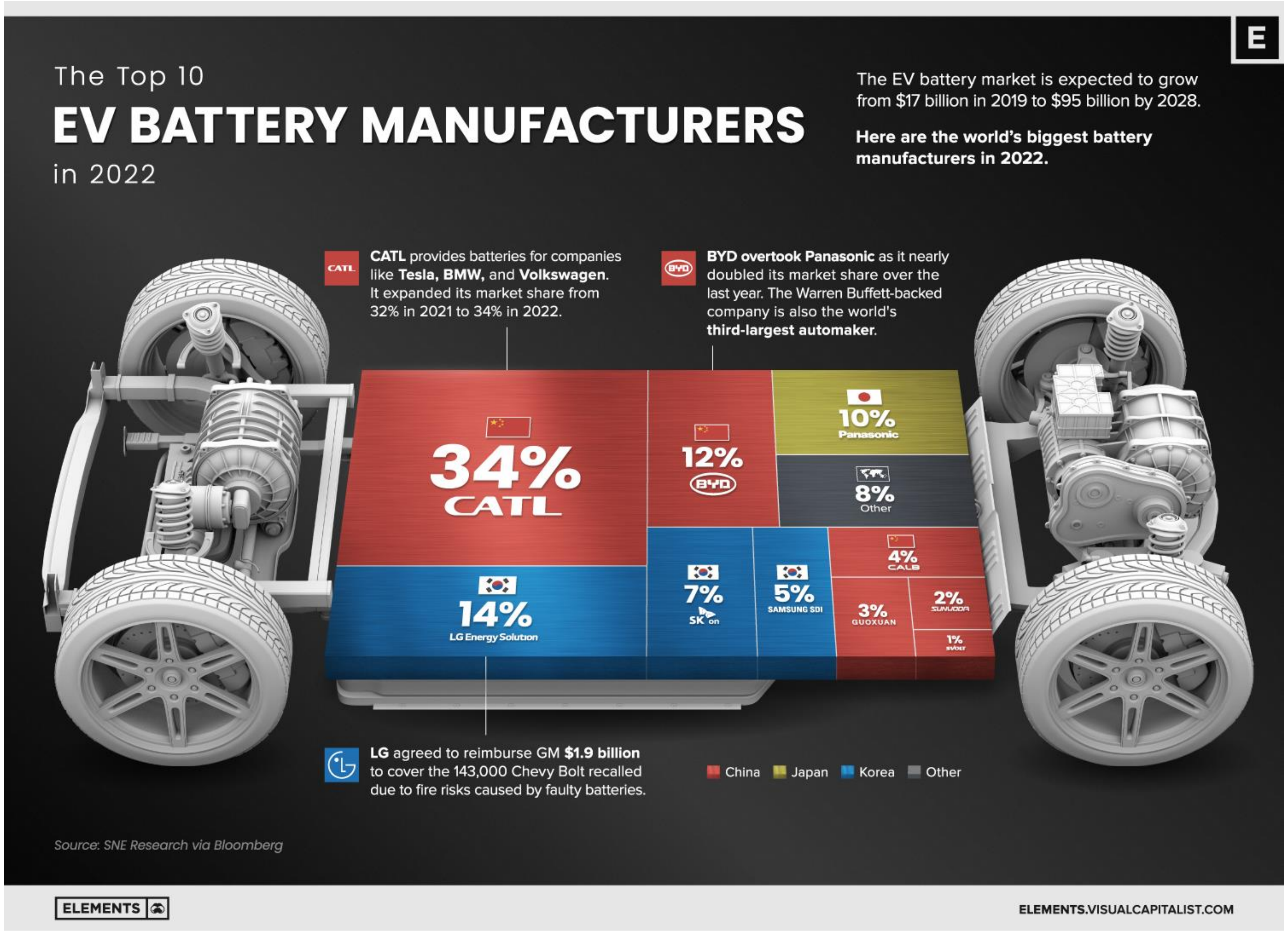
Cathode Materials: $LiCoO_2$ → Li(Ni,Mn,Co)O_2 → LFP → Li Rich (Mn-Rich) Oxides

Anode Materials: Graphite → Silicon/Carbon Composite → Li Metal → Anode-Free

Electrolytes Materials: Carbonates (EC,DEC,EMC) → Highly Concentrated / Weakly Solvated → Solid State

- **Tripled the Energy Density - 18650 Cylindrical Cell 1Ah → 3.3Ah**
- **Lowered the Cost 10 Times - 2005 (2000$/kWh) Today (<100$/kWh)**
- **Extended Cycle Life - 300 cycles to 10,000 cycles deep DOD**
- **Recycling of LiB - Happening Now!!!**

World Production of LIB >1TWh/Year 2024 (Today)



In 2000, BYD won an order from Motorola

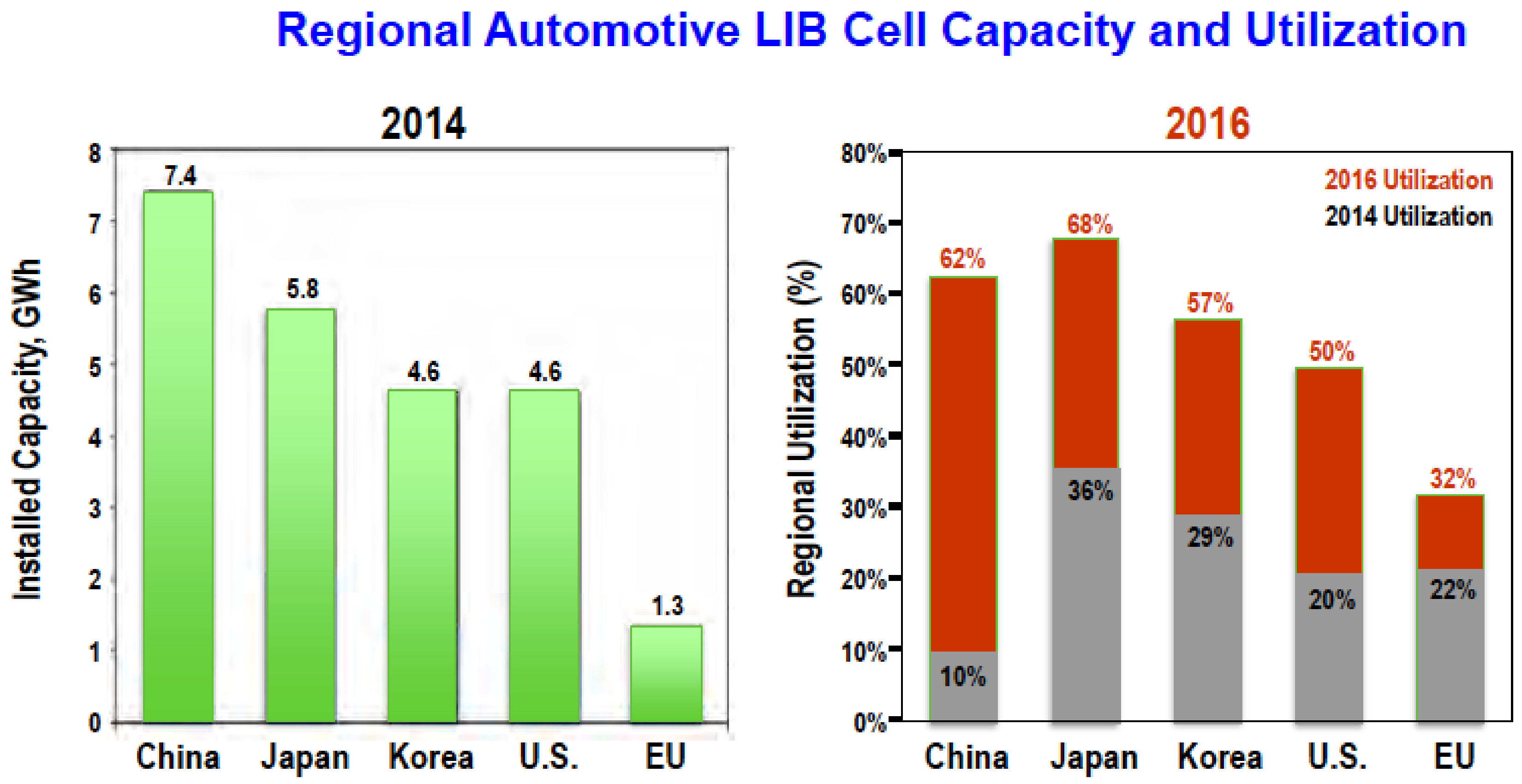
In 2001, China entered WTO

In 2004, CATL became an iPod supplier. China's lithium battery industry emerged. China's annual output of lithium-ion batteries is 800 million units, accounting for 38% of the global share, second only to Japan.

Start in 2002 "Electric Vehicle Key Project"
- 863 National High-Tech Development Plan
- Spent **880 million yuan** for EV research in five years

Start in 2013 China Central government subsidies
- 60,000 yuan for passenger electric cars (>250 km
- 300,000 yuan for electric buses
- Exemption from vehicle purchase tax
- Local subsidies: up to 60% of EV retail price
- Non-subsidy measures: license-plate restrictions

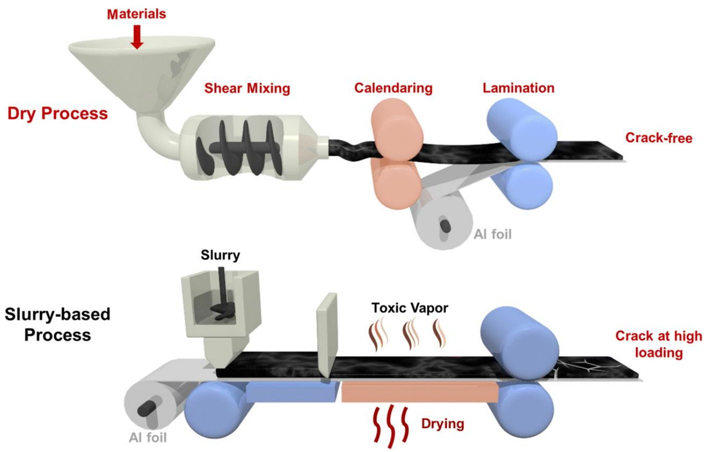
2014 We All Started from The Same Spot! (Past)

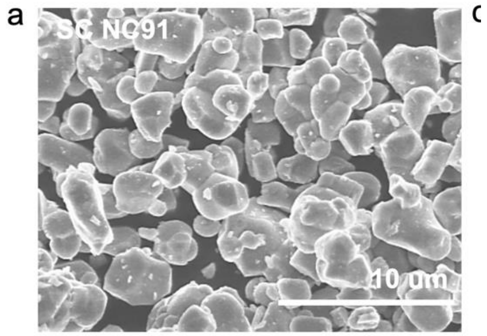


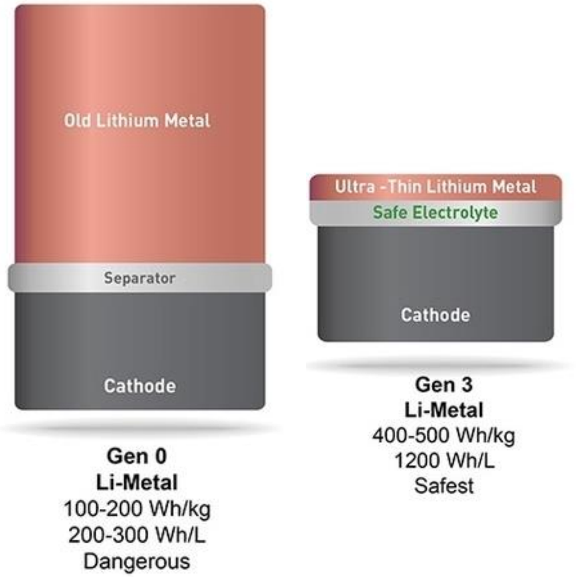
- Automotive lithium-ion battery demand growing but short of global manufacturing capacity.
- Utilization of U.S. plants increased from 20% in 2014 to ~50% in 2016.
- Forecasted compound annual growth rates in lithium-ion demand: 22%–41% (through 2020).

The Race for Better Lithium Batteries is NOT OVER yet

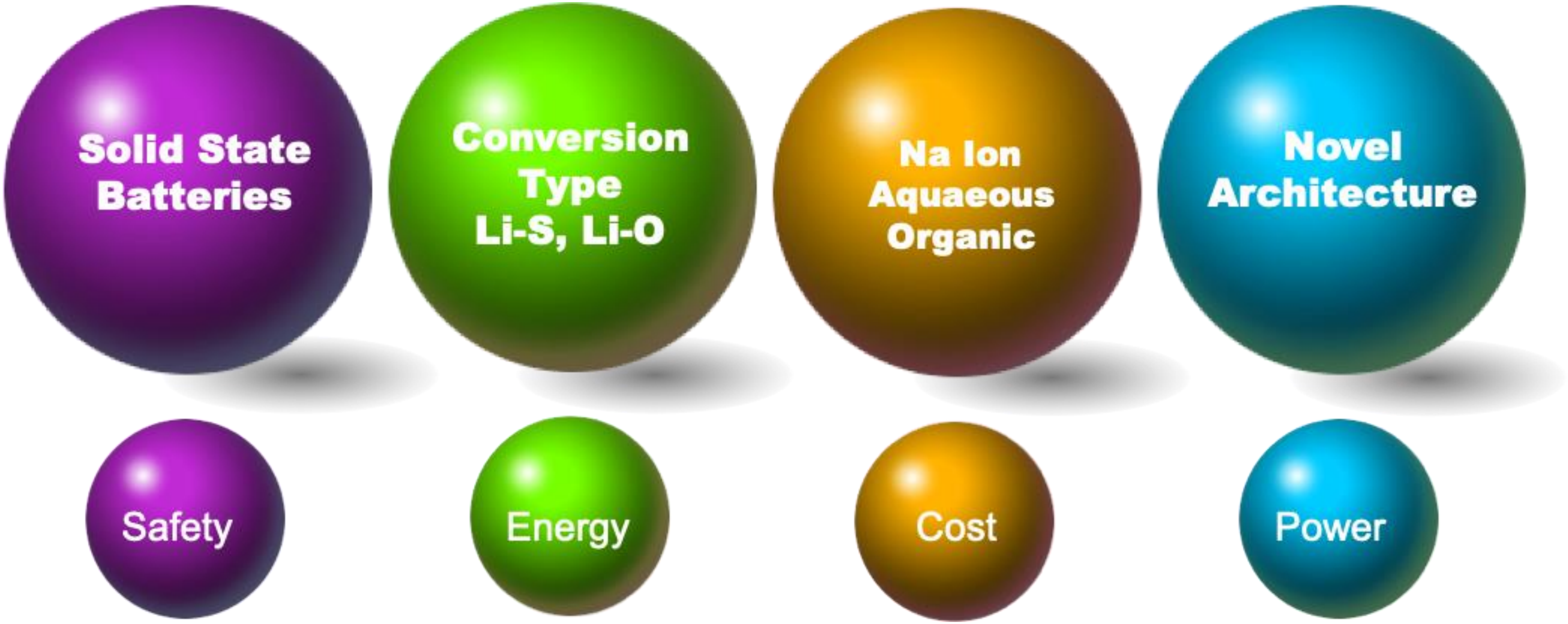
Dry Battery Electrode (DBE) Processing	Single Crystal NMC/NCA	Electrolyte Genome	Anode-Free
All Dry 4680 in Cybertruck 2024 Many New Players in the Field	Better Cost Performance Ratio Allowing Ultra-long life	-60 to +60 C Wider operation temperatures Enabling Thick Electrode/ New Chemistry	Projected Energy Density Over 500 Wh/Kg







Next Decade of Energy Storage and Battery Technology



High energy batteries that never catch fire	Batteries last more than 30 years	Batteries can be 100% recycled (supply chain)	Batteries that can be charged full in 5 minutes

Major hub program – Office of Science, BES

Science Enabling the Next Tera-Watthour Energy Storage Solution

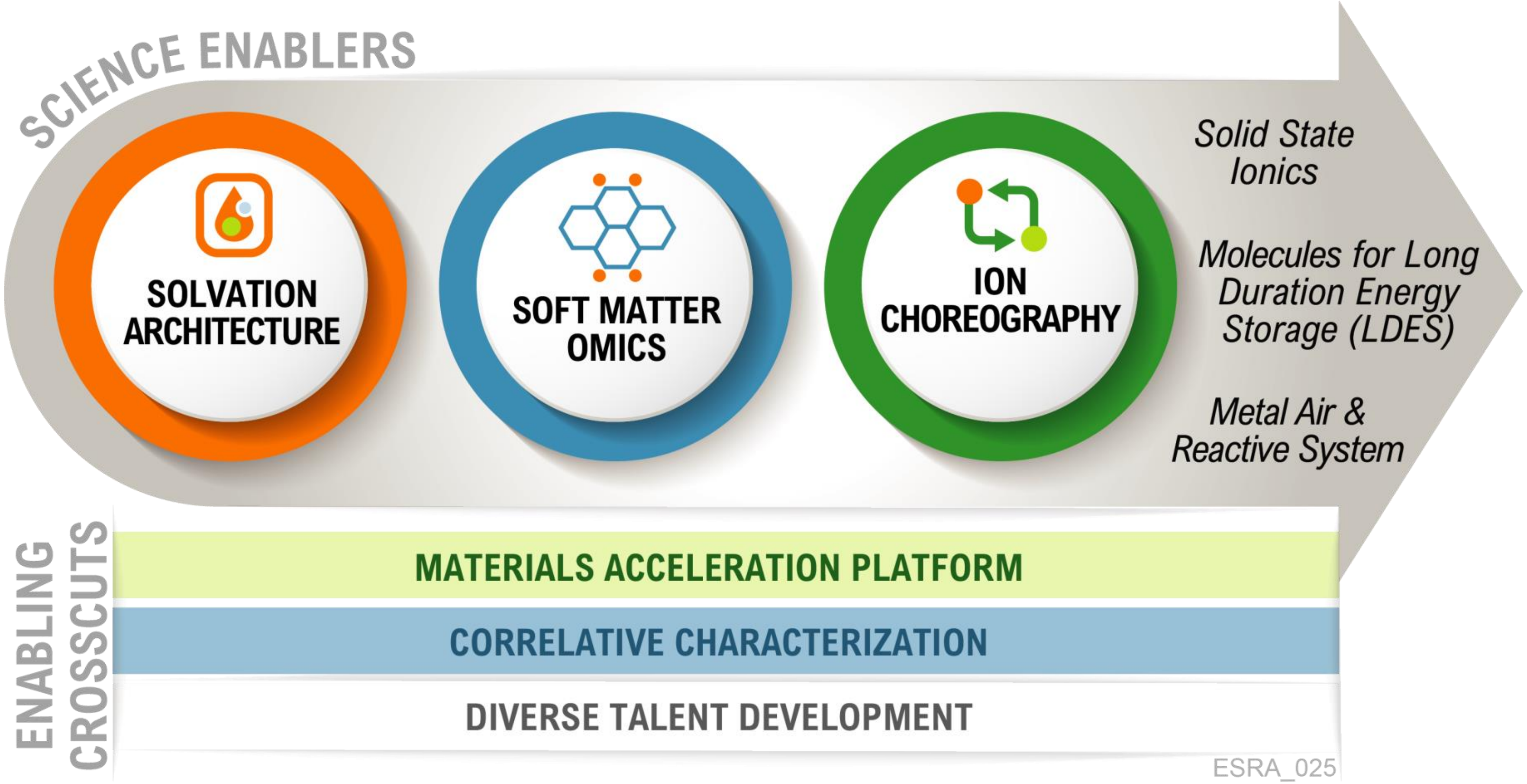
ESRA Vision

To create an innovation ecosystem that enables discoveries in materials chemistry through fundamental understanding of ion-matter interactions in electrochemical phenomena — laying the scientific foundation for breakthroughs in energy storage technologies

ESRA

Energy Storage Research Alliance

ESRA



ESRA GOALS

- ✓ Integrative and autonomous materials discovery with advanced AI
- ✓ Most cutting-edge facilities covering all relevant temporal and length scales
- ✓ Close to unity transference number in liquids
- ✓ Order-of-magnitude higher transport in soft matter
- ✓ Suppression of parasitic reactions in all solids

Argonne National Laboratory · Berkeley Lab · Pacific Northwest National Laboratory · Columbia University · Duke University · Massachusetts Institute of Technology · Princeton University · UC San Diego · The University of Chicago · University of Houston · University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · Xavier University of Louisiana

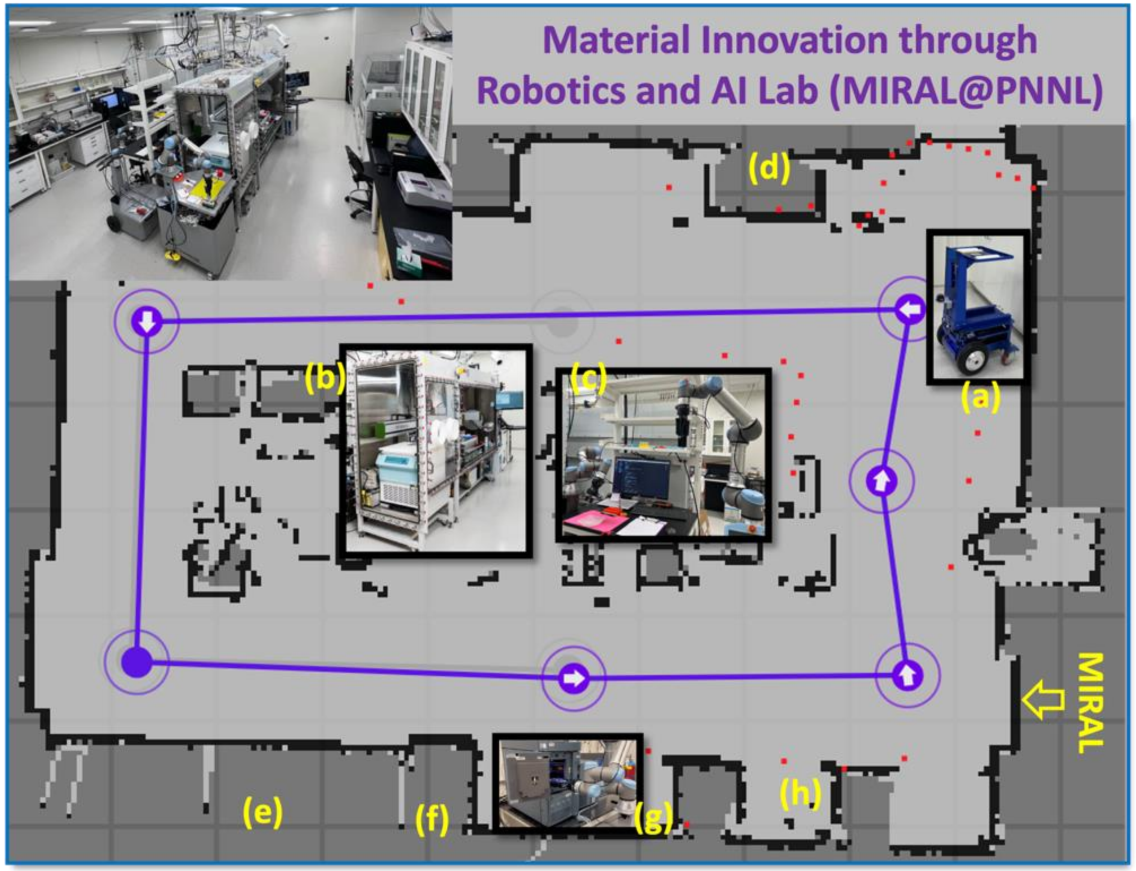
An Energy Innovation Hub funded by DOE Office of Science

Shirley Meng ESRA Director

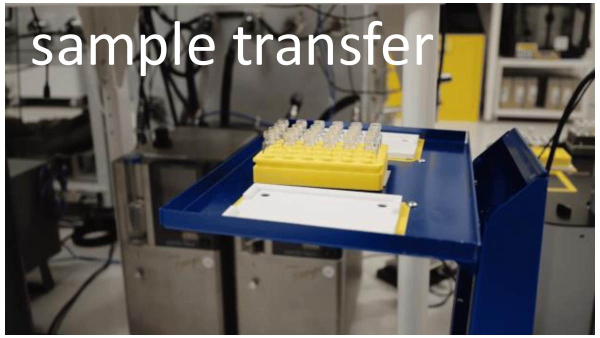
MIRAL @ PNNL

Materials Innovation through Robotics and AI Lab

Dr. R. Feng



MIRAL layout (top left) and navigation map of its autonomous mobile robot (a) between modular workstations, including robotic synthesis, sampling, and transform (SST) (b, c), UV-Vis (d), HPLC-MS (g), Raman (e), and HTP electrochemical testing (h).



- Accelerate data collection
- Standardize database
- Fast-track discovery

Argonne National Laboratory · Berkeley Lab · Pacific Northwest National Laboratory · Columbia University · Duke University · Massachusetts Institute of Technology · Princeton University · UC San Diego · The University of Chicago · University of Houston · University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · Xavier University of Louisiana

ESRA Core Team

ESRA

https://energystoragera.org/

3 National Laboratories	12 Universities

Female 30%

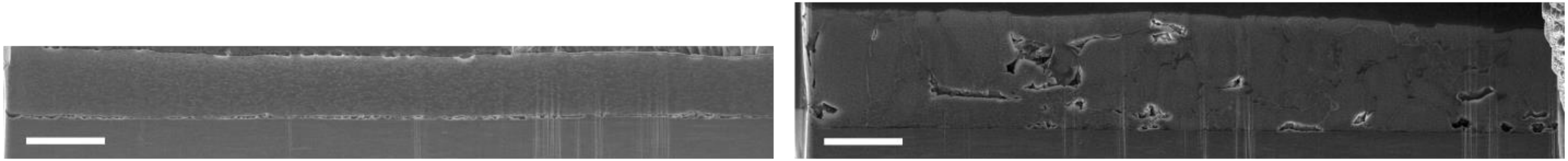
3 MSI
1 HBCU

Argonne National Laboratory · Berkeley Lab (Bringing Science Solutions to the World) · Pacific Northwest National Laboratory · Columbia University · Duke University · MIT Massachusetts Institute of Technology · Princeton University · UC San Diego · The University of Chicago · University of Houston · UIC University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · Xavier University of Louisiana

Analysis of Na Metal Deposition and Stripping

(a) 1 M $NaPF_6$ in DME

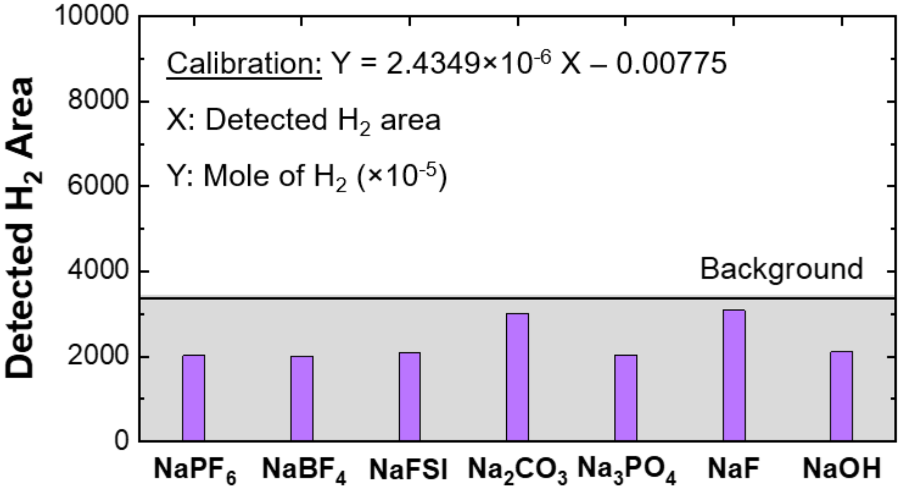
(b) 1 M $NaPF_6$ in EC:DMC (1:1)



180 kPa

250 kPa

The sodium was plated at 0.5 mA/cm2 for 1 mAh/cm^2 on Al foil. The images are acquired under 5kV voltage and 0.2 nA current using a TLD detector. The scale bars are 10 μm.



Standard	Detected H_2 Area
$NaPF_6$	2025
$NaBF_4$	2004
NaFSI	2100
Na_2CO_3	3013
Na_3PO_4	2037
NaF	3127
NaOH	2115

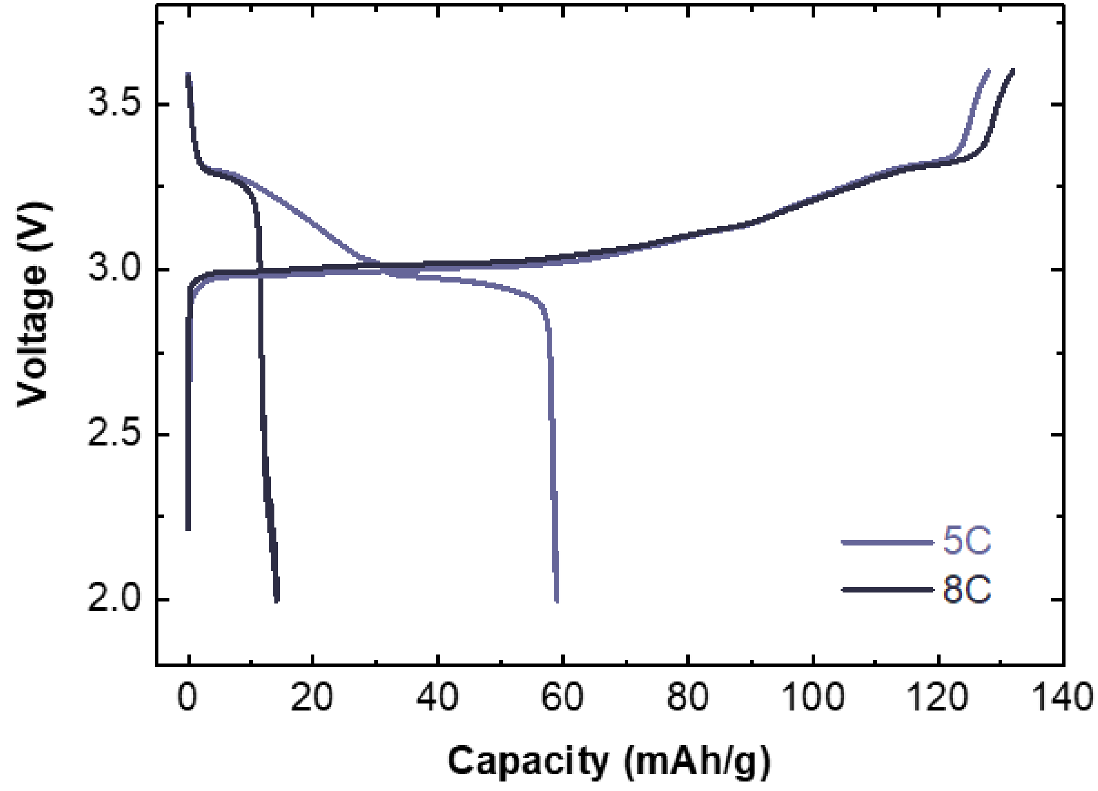
The controlled TGC experiment on standard commercial powders showed no hydrogen generation. This test was performed using ethanol as the solvent.

Power of Sodium Battery

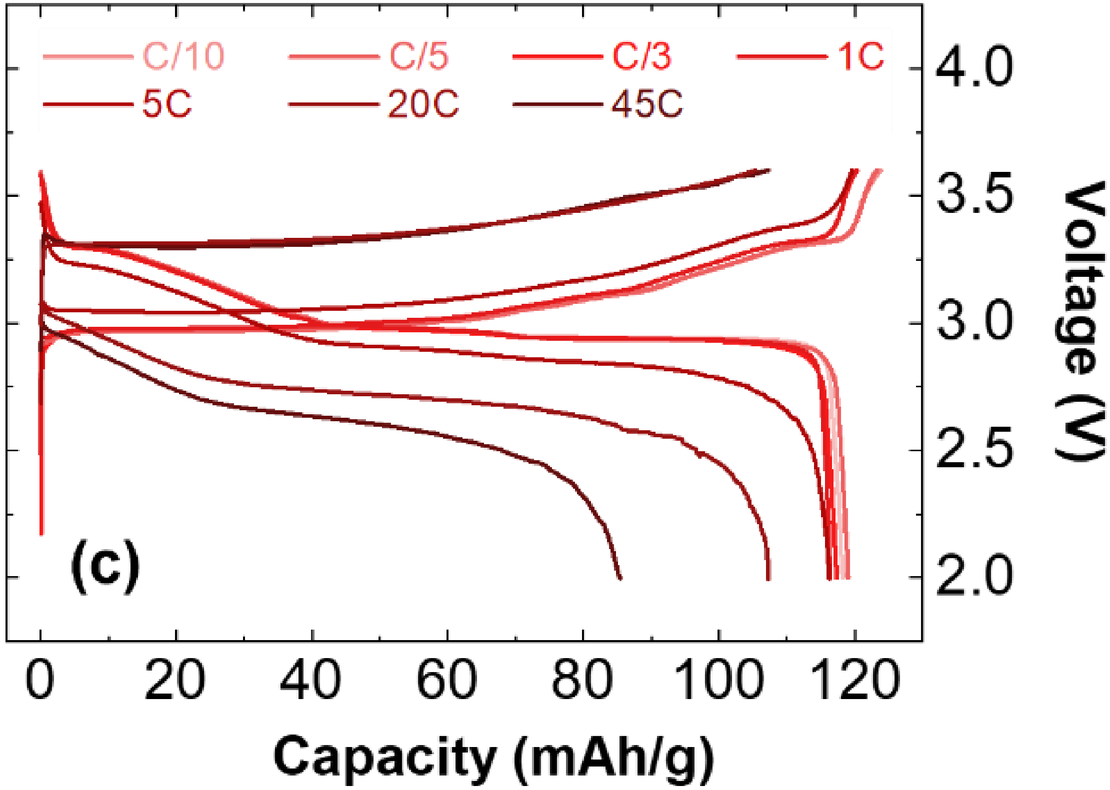
1C = 1 hour charging/ 20C = 3 min charging!

Laboratory for Energy Storage and Conversion

Na Metal as anode, $NaCrO_2$ as the cathode. The cells have controlled 100% excess of sodium inventory.



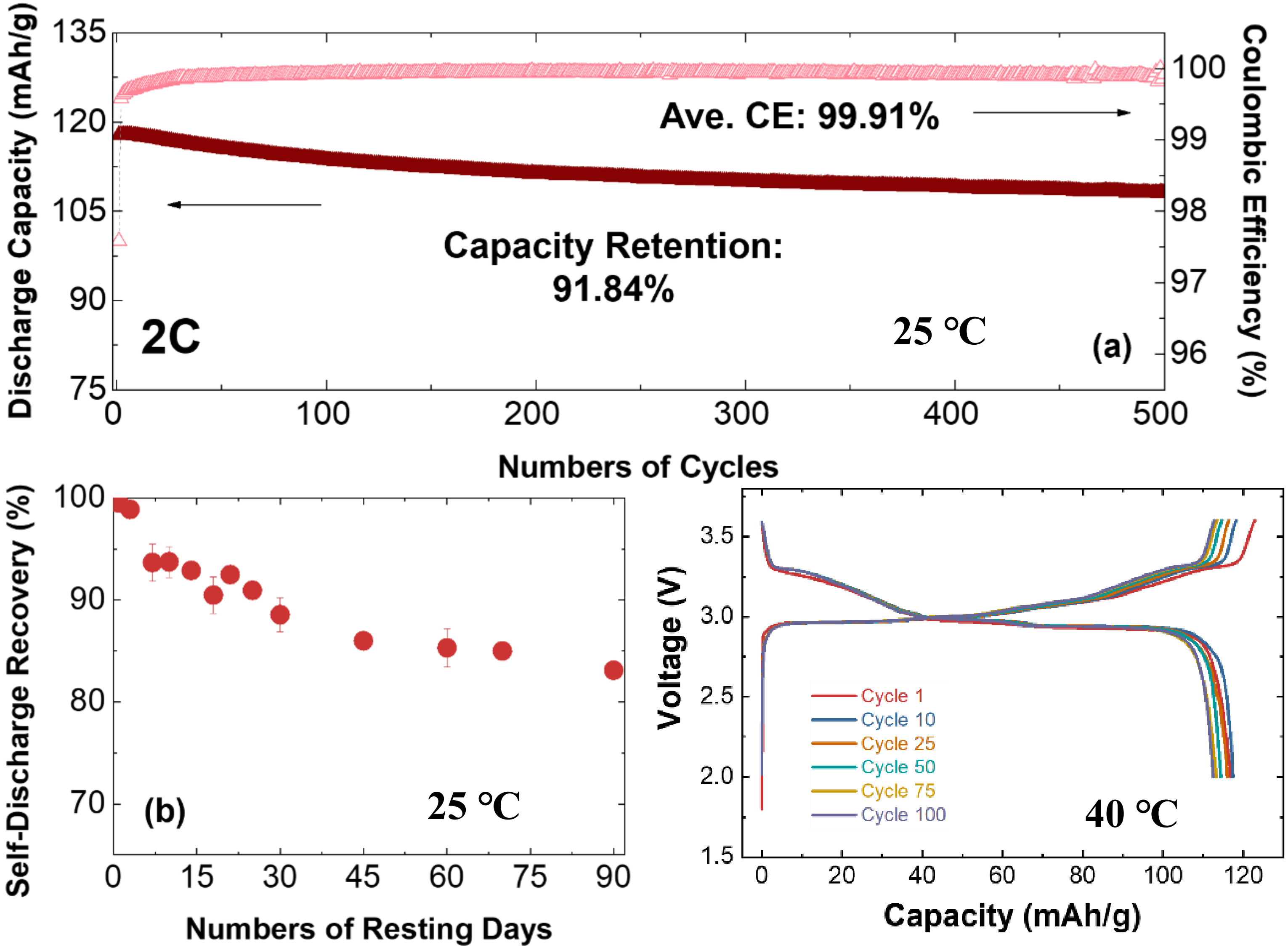
1M $NaPF_6$ in EC:DMC (1:1)



1M $NaPF_6$ in DME

THE UNIVERSITY OF CHICAGO
PRITZKER SCHOOL OF MOLECULAR ENGINEERING

B. Sayahpour, … M. Zhang and Y.S. Meng, " Quantitative analysis of sodium metal deposition and interphase in Na metal batteries ", *Energy & Environmental Science,* January 2024



Dr. Baharak Sayahpour (ASML)

We made the anode, electrolyte, cathode

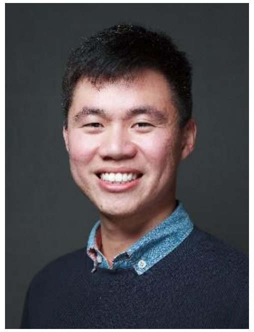
Active work since my CAREER award in 2010

National Science Foundation

THE UNIVERSITY OF CHICAGO
PRITZKER SCHOOL OF MOLECULAR ENGINEERING

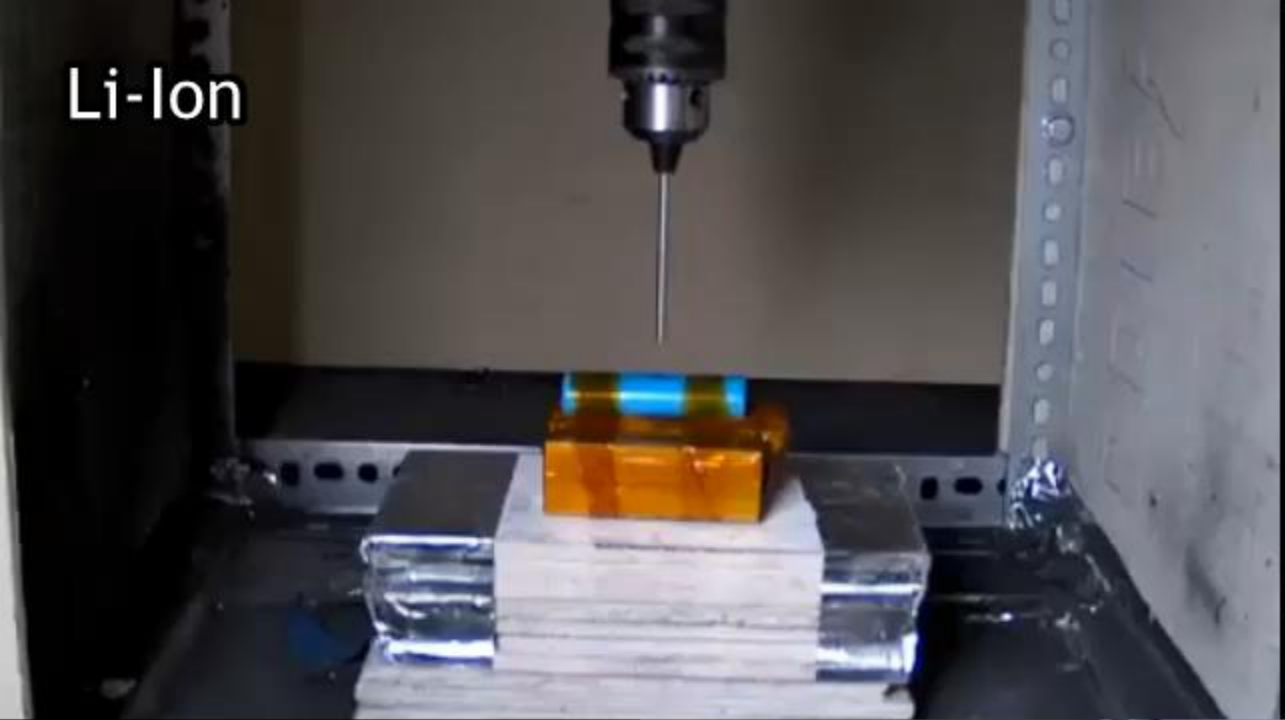
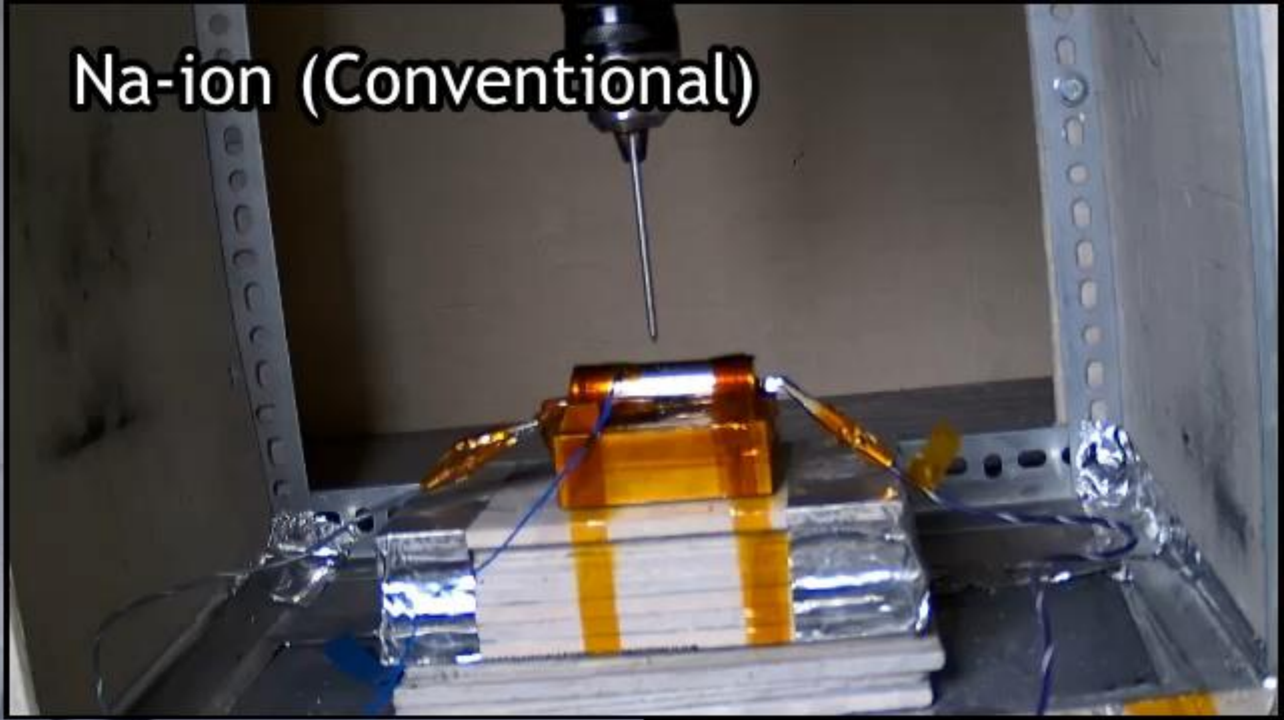
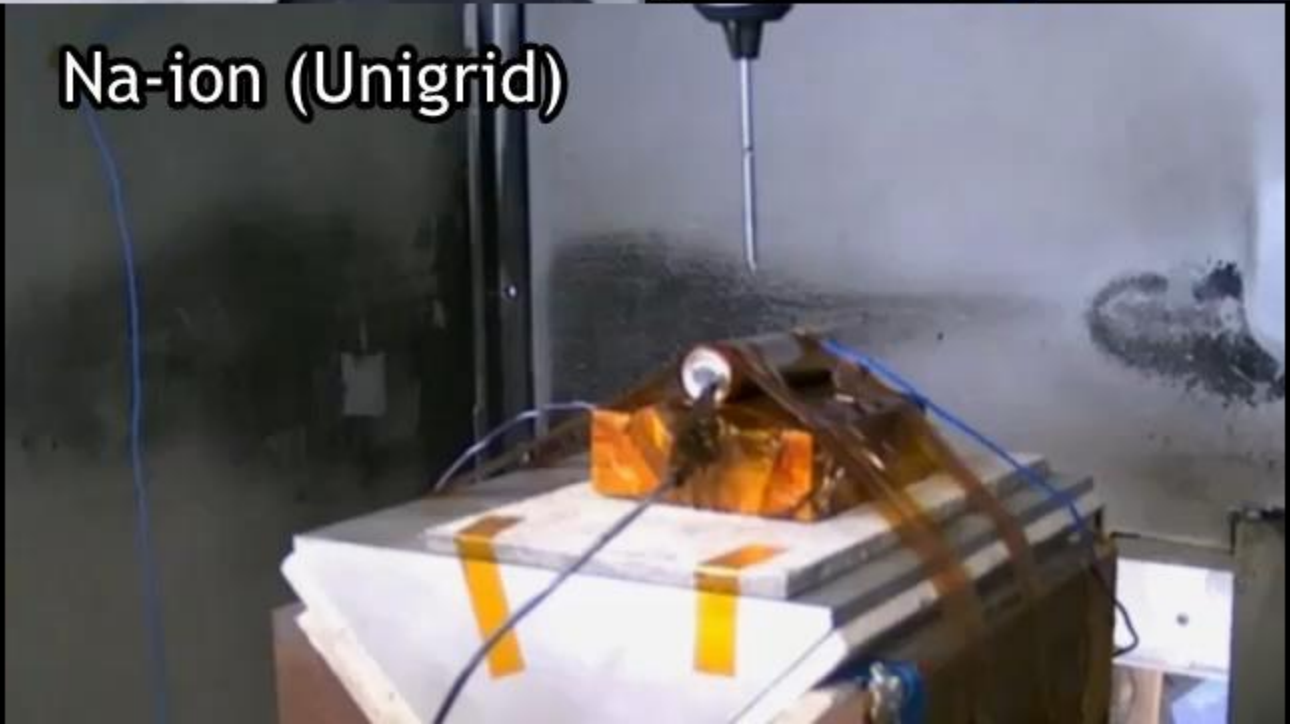
UNIGRID

UNIGRID's Value: Energy & Safety



Dr. Darren Tan

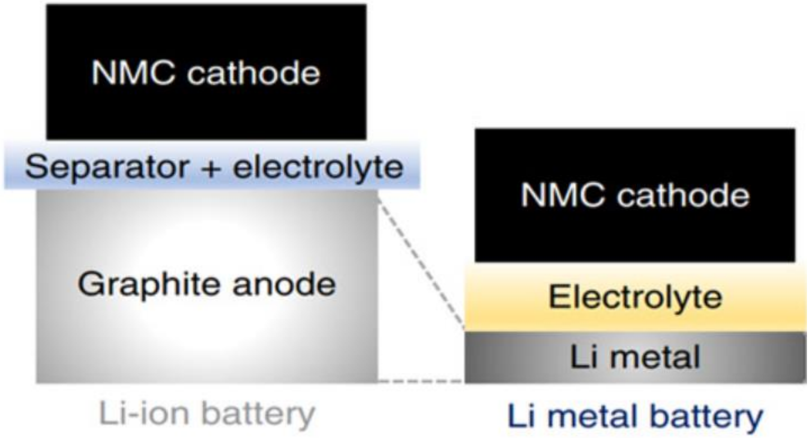
Sodium Ion Battery Landscape	Key IP	Cathode	Anode	Wh/kg	Wh/L	Cycles	Market
UNIGRID	**Anode**	**Any**	**Alloy**	**180 Wh/kg**	**450 Wh/L**	**>3000**	**EV / ESS**
FARADION	Cathode	Layered Oxide	Carbon	160 Wh/kg	200 to 300 Wh/L	>3000	EV / ESS
CATL	Cathode	Layered Oxide / PBAs	Carbon	160 Wh/kg		–	EV / ESS
Natron Energy	Cathode	Symmetric Prussian Blue Analogues	–	20 Wh/kg	18 Wh/L	>50000	Backup Power
中科海钠 HiNa Battery	Cathode	Layered Oxide	Carbon	145 Wh/kg	180 to 300 Wh/L	>4500	EV
容百科技 Ronbay Technology	Cathode	Prussian Blue Analogues	Carbon	–		–	EV / ESS
ZOOLNASM 众钠能源	Cathode	Poly-anionic	Carbon	–		–	EV / ESS
钠创 Natrium	Cathode	Layered Oxide & Poly-anionic	Carbon	145 Wh/kg		>5000	EV / ESS
EVE	Cathode	Layered Oxide	Carbon	145 Wh/kg		>5000	EV / ESS
Tiamat Energy	Cathode	Poly-anionic	Carbon	110 Wh/kg		>5000	EV / ESS
LiFUN	Cathode	Layered Oxide / PBAs	Carbon	140 Wh/kg		>4000	EV / ESS
Nippon Electric Glass	Separator	Layered Oxide	Carbon	–	–	–	ESS
amte power	Cathode	–	Carbon	140 Wh/kg	180 to 300 Wh/L	>1000	ESS
SVOLT	Cathode	–	Carbon	160 Wh/kg		>2000	EV / ESS

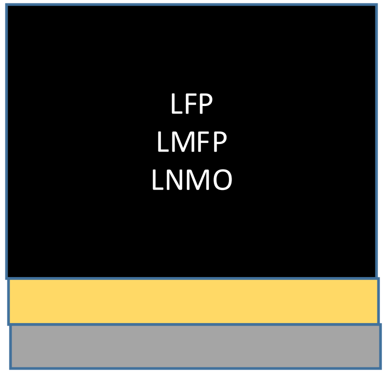

Li-Ion

Na-ion (Conventional)

Na-ion (Unigrid)

All Solid-State Batteries – Platform Technology

High-Energy-Density** and **Safe Batteries

*with **Solid-State Electrolyte***





Energy Density > 500Wh/kg
Conversion type Cathodes
Metal Anodes
Ultra Thin Separator

Safety
Particularly for Oxides Sulfides ?
Polymers X

Fluorine - Free Chemistry

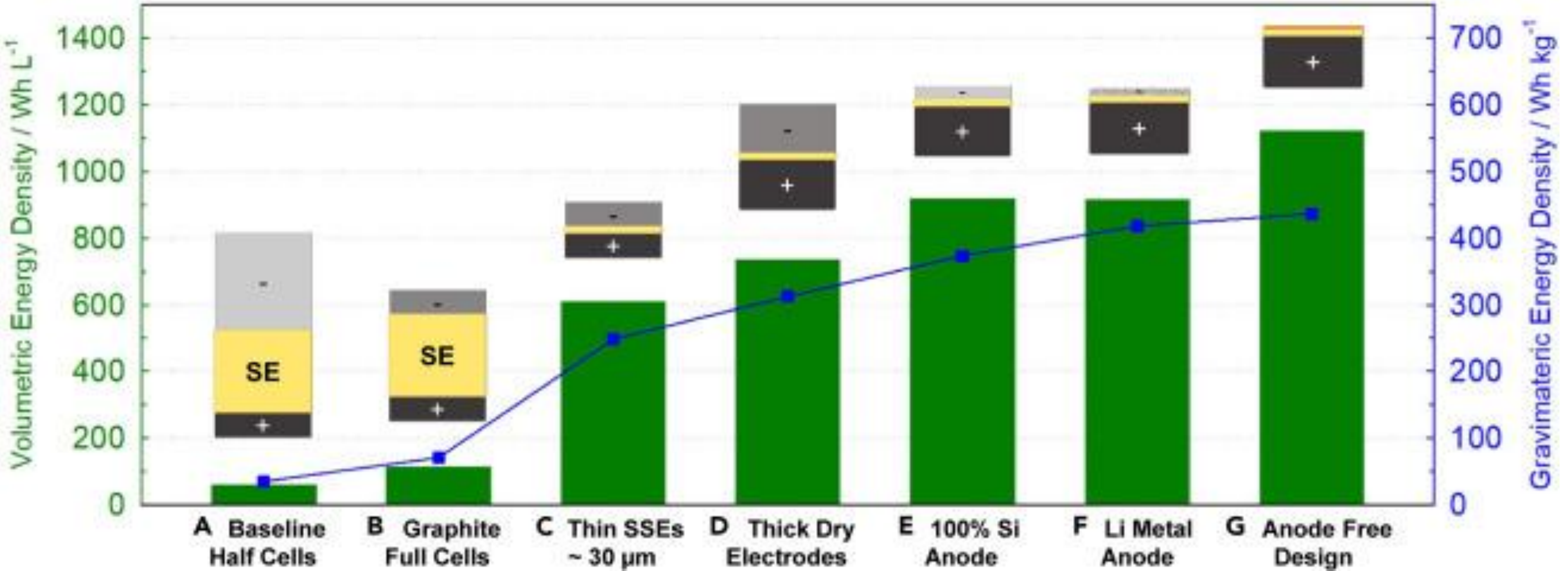
Stackable Design

Dry Processing

Ultralong Cycle Life

Wider Operation Temperature

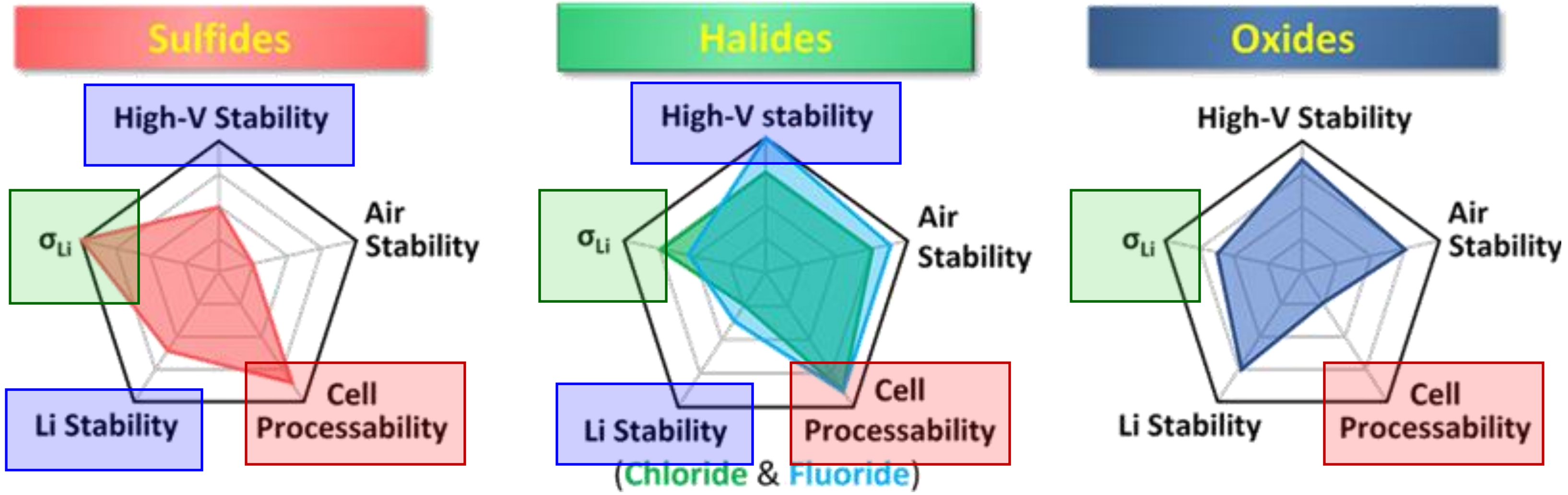
Enable Conversion Chemistry

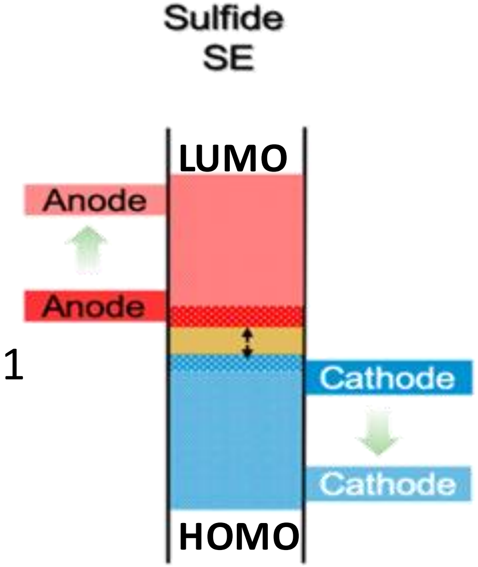


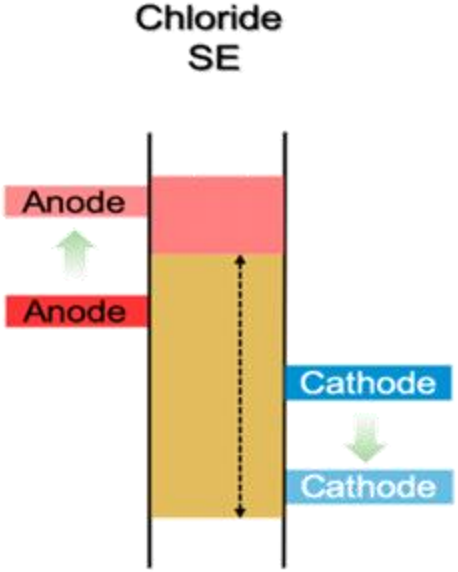
Materials Selection: Inorganic Solid-State Electrolytes

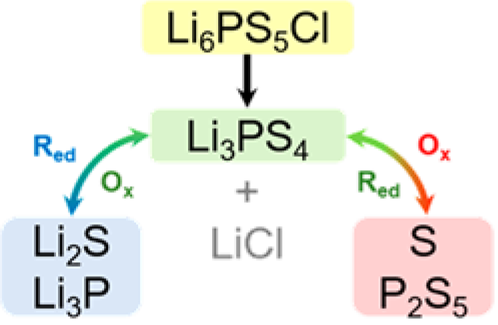
1. **Ionic conductivity**
   - All > 10^{-3} S cm^{-1}
2. **Processibility**
   - Young's modulus ↓
   - Synthesis temperature ↓
3. **Solid electrolyte interphase (SEI)**
   - Ionic conductive ↑
   - Electronic conductive ↓

- ☐ **Li_6PS_5Cl (LPSCl)[2]**
  - Stable SEI against Li
  - Compatible with LBO-coated NCM811
- ☐ **Chlorides**
  - Good oxidation stability
- **Air Stability? – Dry Room Compatibility**





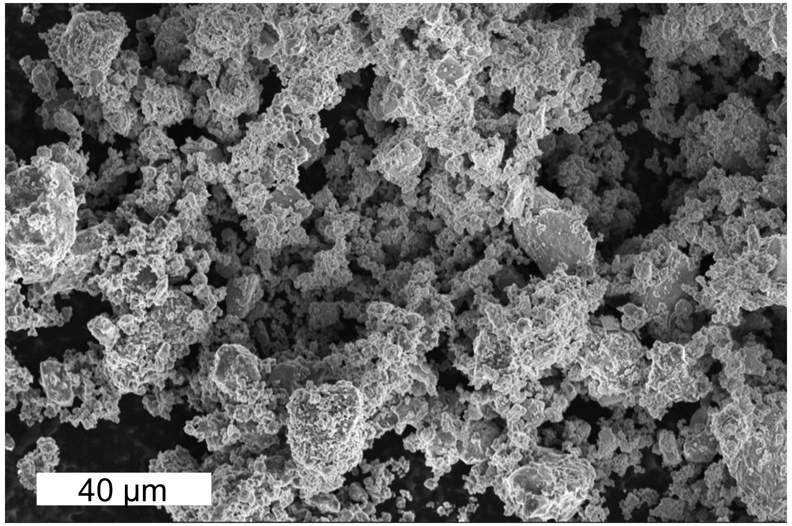


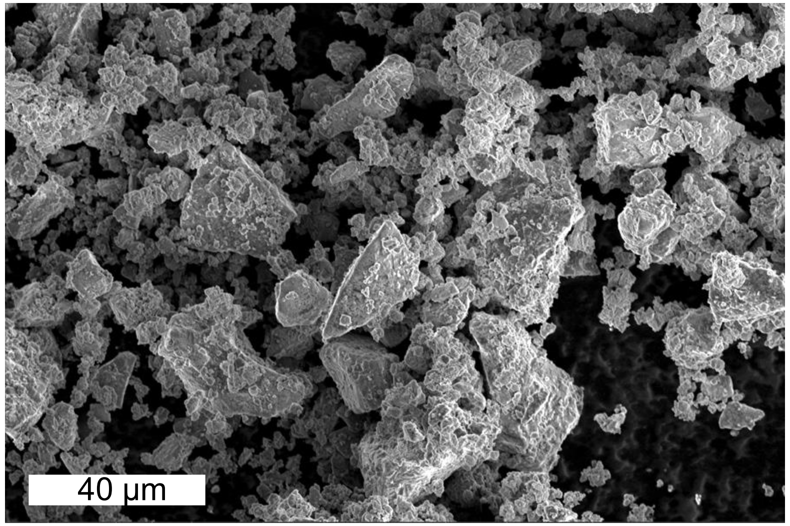


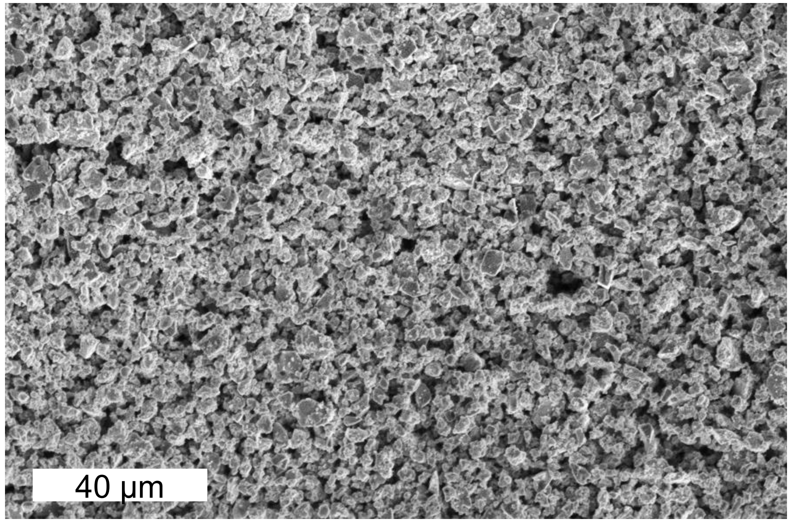
Kwak, Hiram, *et al.*, *ACS Energy Letters*, **2022**, 7, 5, 1776-1805.
Banerjee, Abhik, et al. *Chemical reviews* 120.14 (2020): 6878-6933.
Tan, Darren HS, et al. *ACS Energy Letters* 4.10 (2019): 2418-2427.

Why do We Choose Li_6PS_5Cl – Metric Ton Quantity

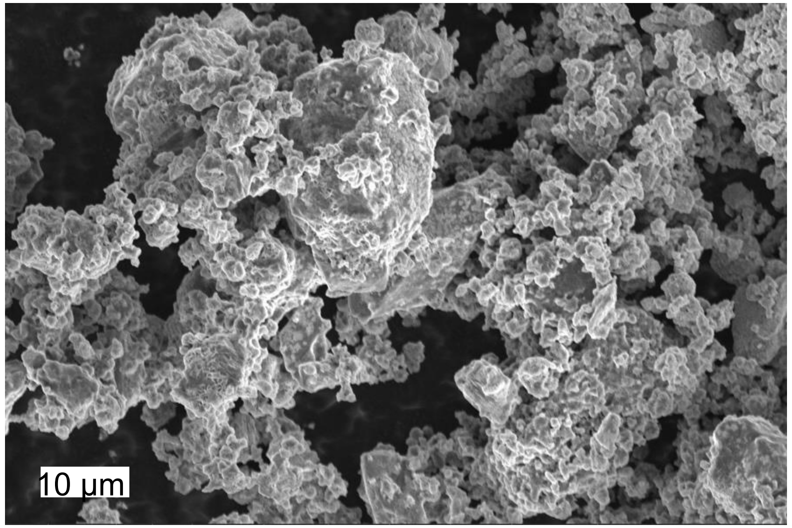
USA Supplier 1:	USA Supplier 2:	Japan Supplier 1	

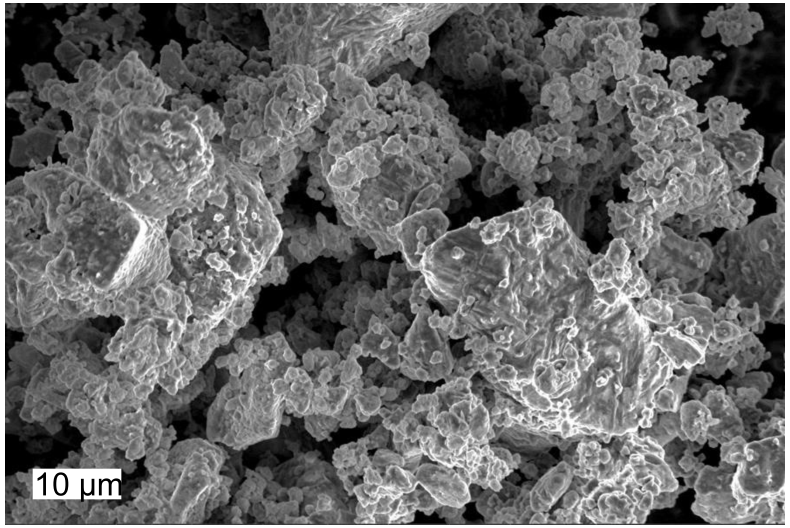


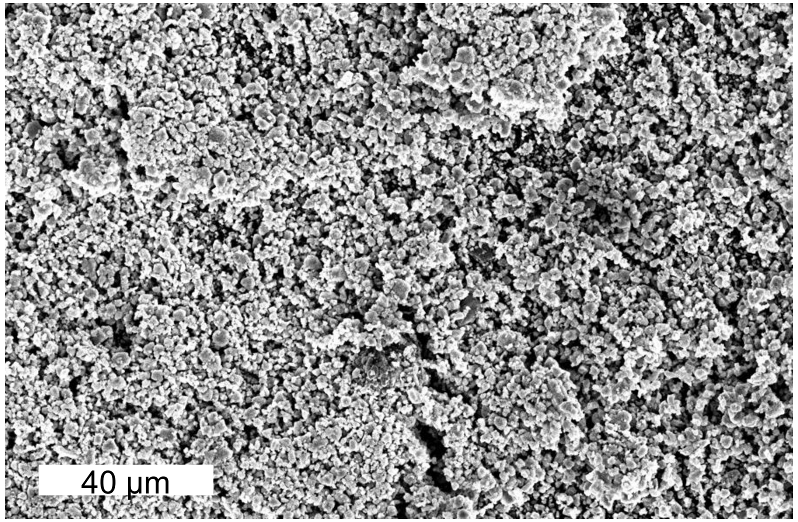




(A)

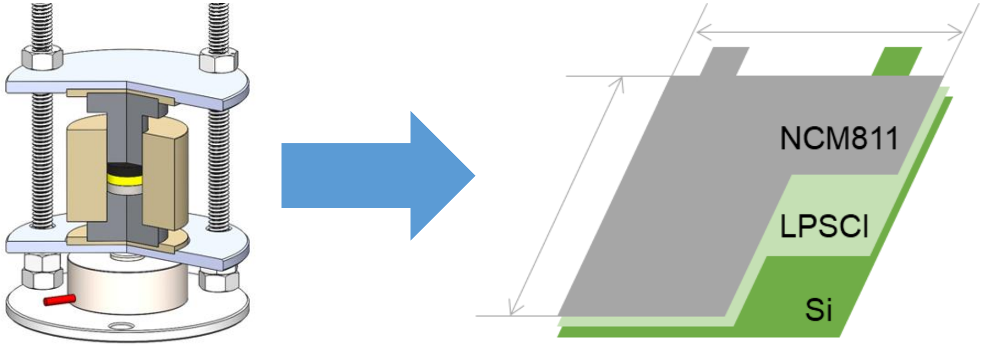




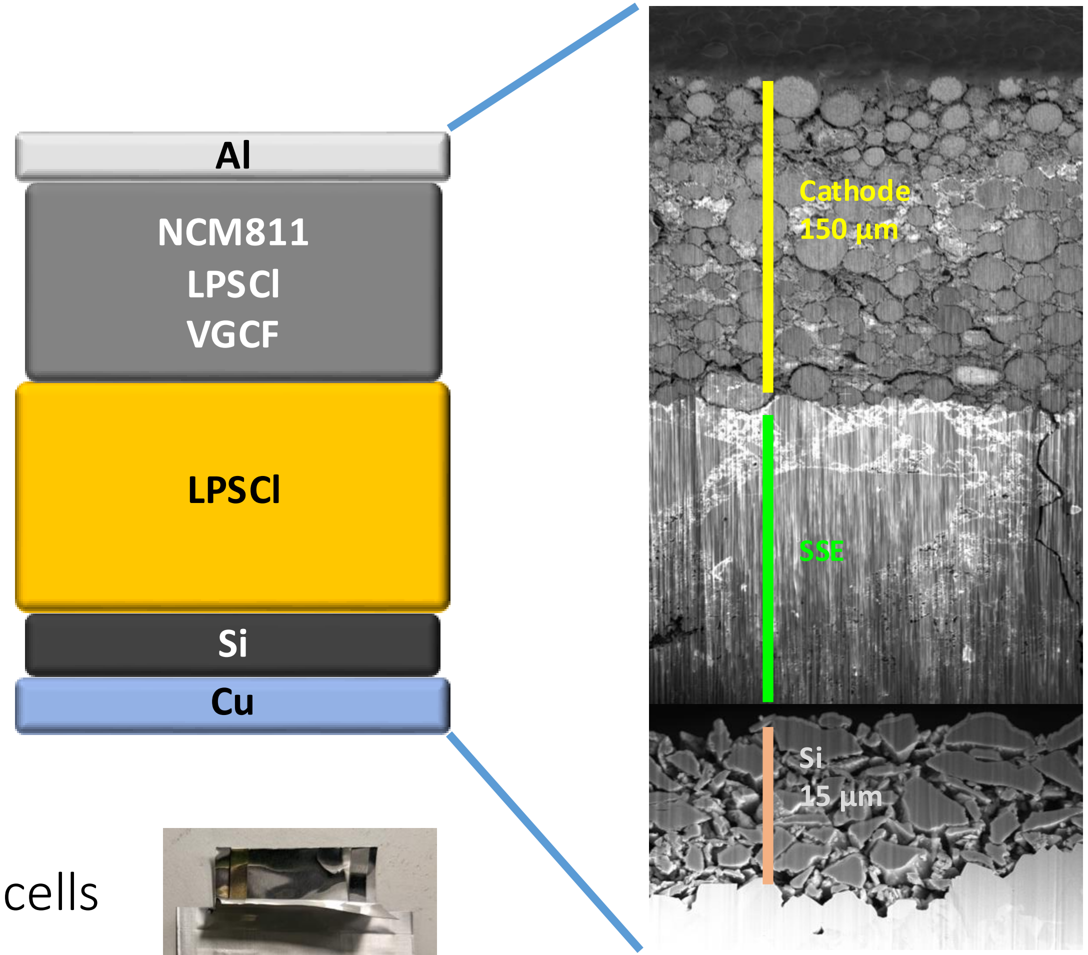


(B)

Defining Cell Configuration



Requirements:	Pellet Type	Pouch Type
SSE Thickness	~ 700 µm	< 100 µm
Areal Loading	< 2 mAh cm^{-2}	4-6 mAh cm^{-2}
Cell Size	< 1 cm^2	> 10 cm^2
Stack Pressure	~ 50 MPa	< 5 MPa
Layers	1	≥1



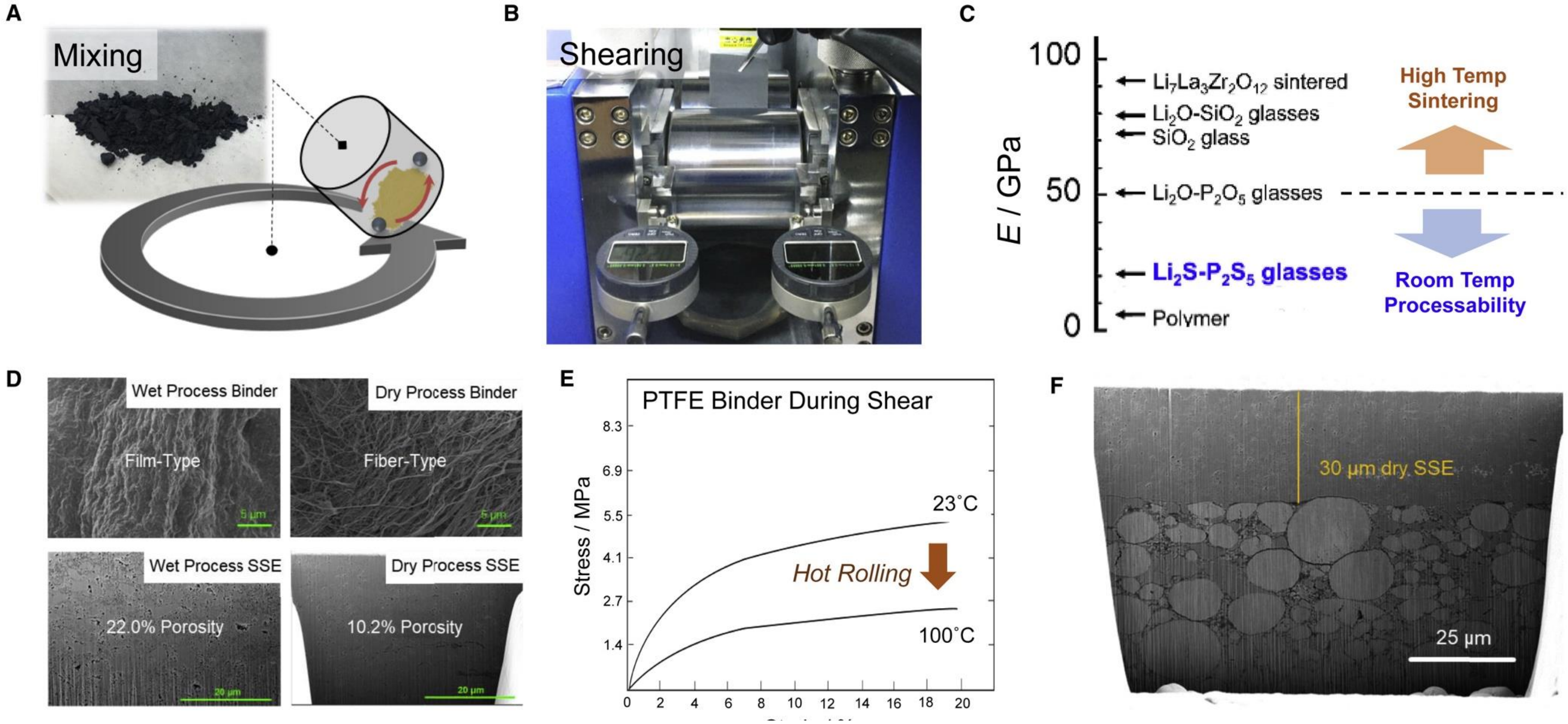
- LPSCl is dry room compatible → Ready for pouch cells
- Setting key parameters for pouch demonstration based on µSi | LPSCl | NCM811

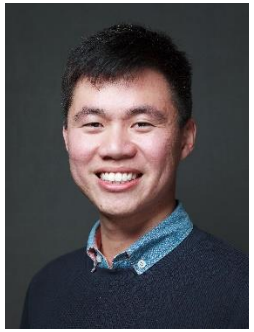
Single layer all-solid-state pouch cell

D. Tan, J. Jang and Y.S. Meng Joule 2022

https://doi.org/10.1016/j.joule.2022.07.002

Joule





Dr. Darren Tan

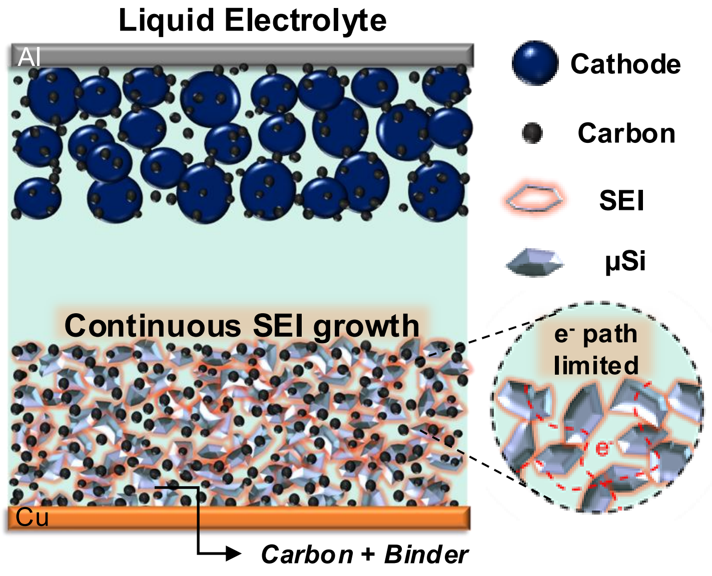
Dr. Jihyun Jang

Funded by

LG Energy Solution

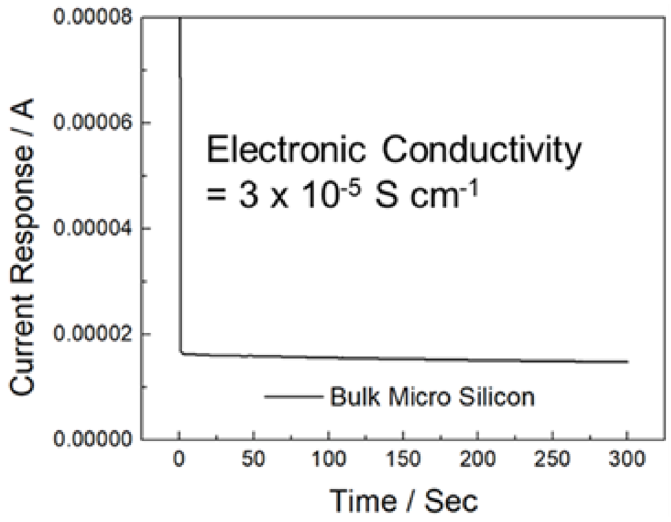
LGES-UCSD Frontier Research Laboratory

All Solid-State Battery with Pure Si Anode

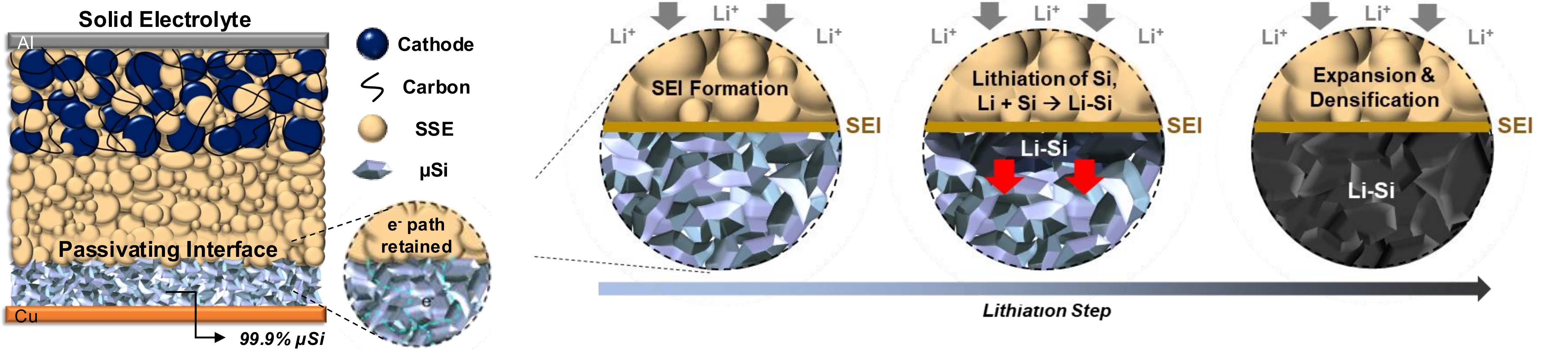


Silicon in Liquid

1. Continuous SEI Growth
   - Trapped Li-Si accumulation
   - Poor calendar life / self discharge
2. Excess carbon + binder (20-40%)
   - Poor specific / volumetric energy

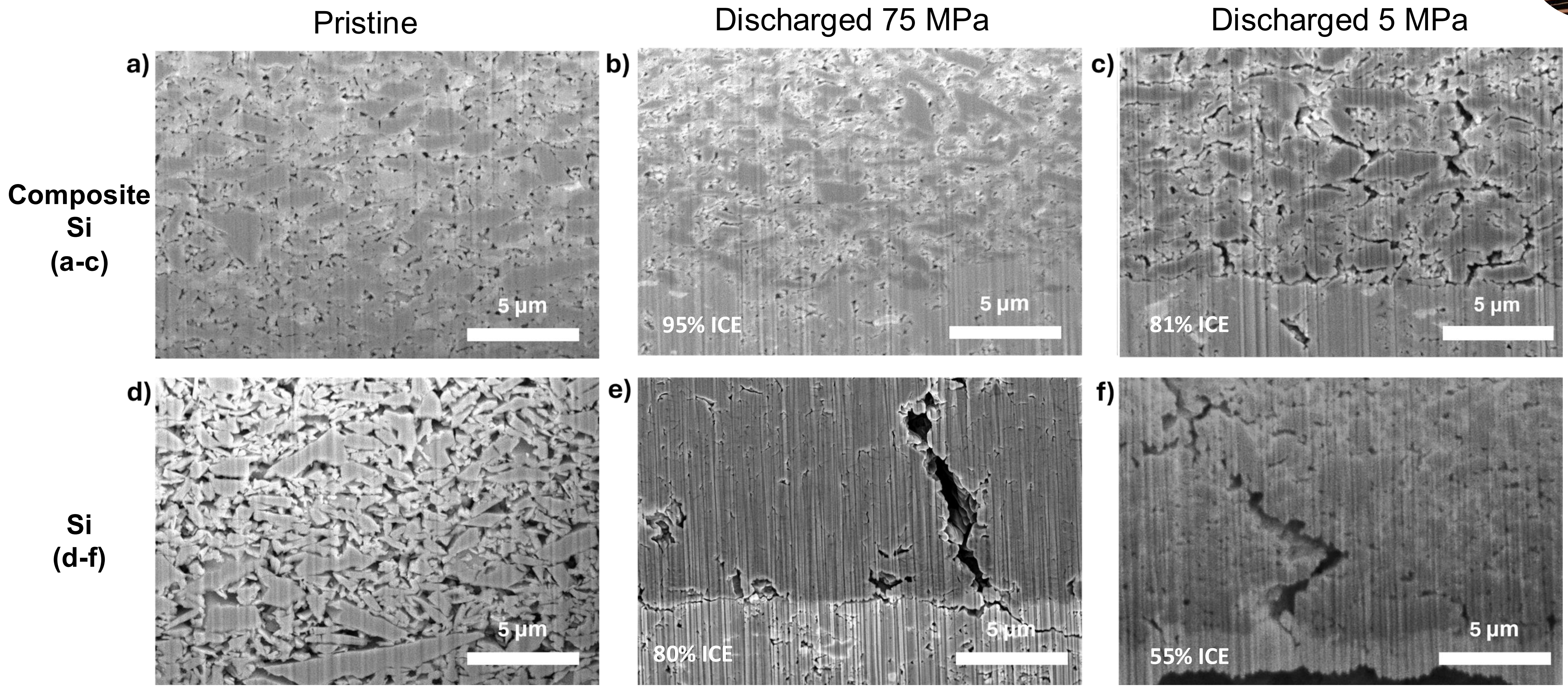


Dr. Darren Tan
CEO of UNIGRID



Tan, D.; Meng, Y. S. *et al.*, Carbon Free High Loading Silicon Anodes Enabled by Sulfide Solid Electrolytes for Robust All Solid-State Batteries. (*Science 2021*)

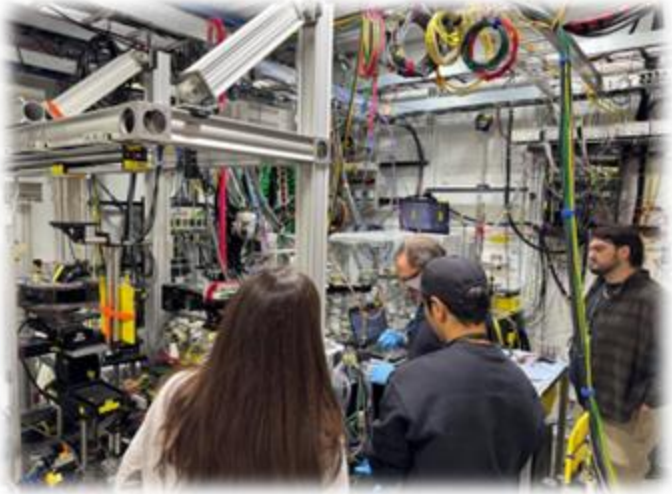
Morphology Impact on Stack Pressure



- Si particle morphology in composite anode sustained after cycled regardless of stack pressure (Fig a-c)
- Pure Si morphology highly dependent on stack pressure (Fig. d-f)

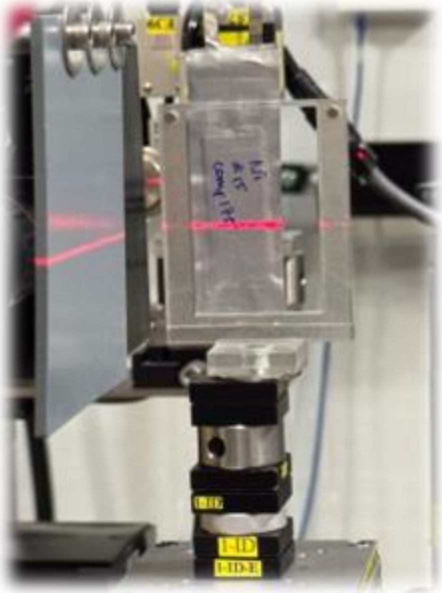
APS-U XCT experiment @ 1-ID (Nov 8-11, 2024)

Thanks! John Okasinski and Andrew Chihpin Chuang



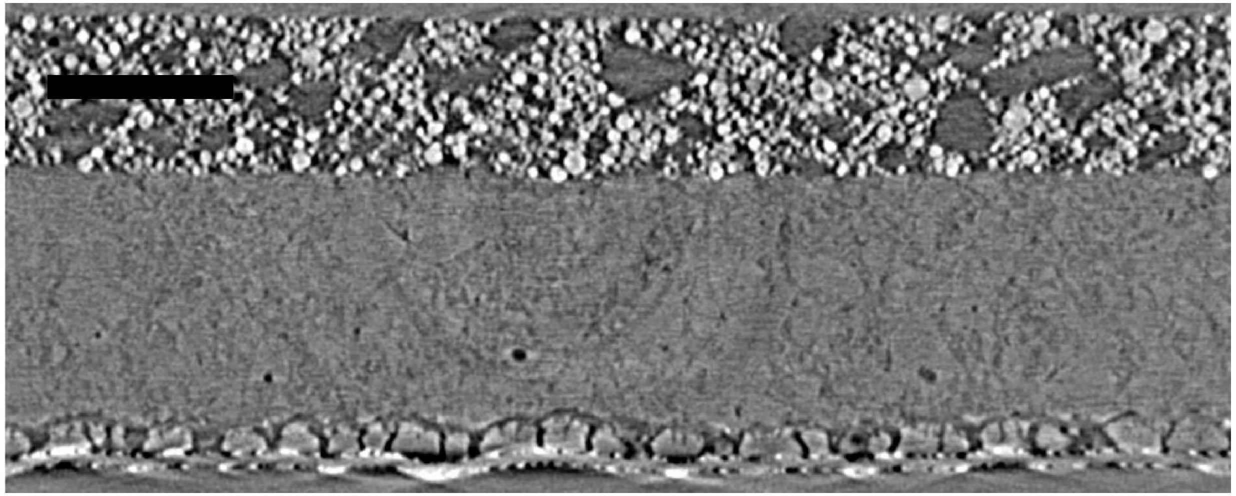
Experimental conditions

- 52 keV, fly scan (~10 min/scan), FOV 1 x 1 mm^2
- **60 tomography scans** taken – **1.5 TB**
- **Samples**
  - *Ex-situ* Pellet cell
  - ASSB pouch cells
  - *Operando* pellet-type cell holder

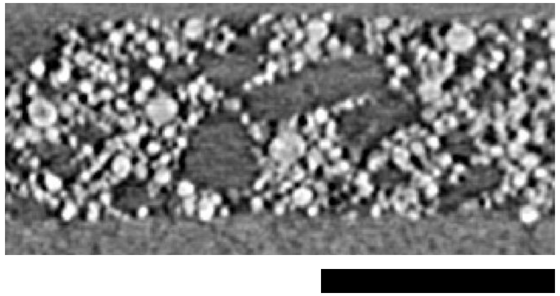


ASSB Pouch cells "preliminary" results from APS-U

X Synchrotron Source

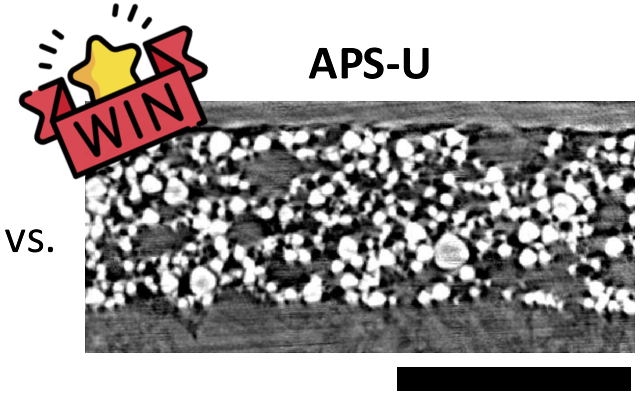


X Source



vs.

APS-U

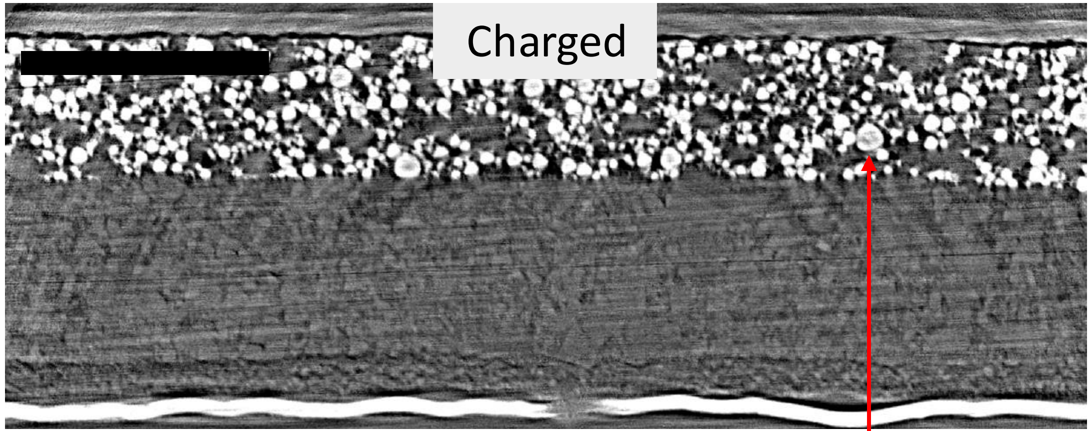


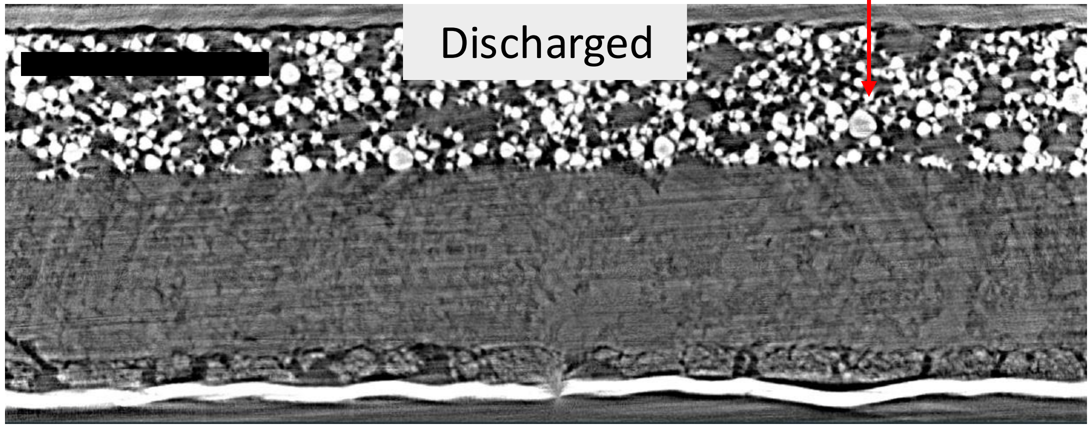
Unpublished data

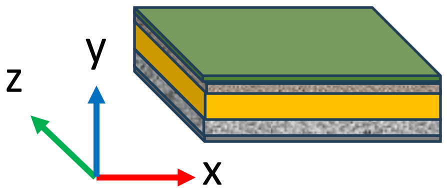
Scale bar: 200 µm

"Advanced" Photon Source – U

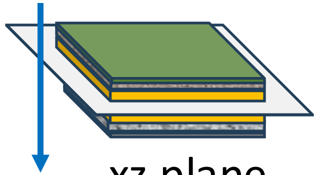
Same cell, same spot – *in-situ*

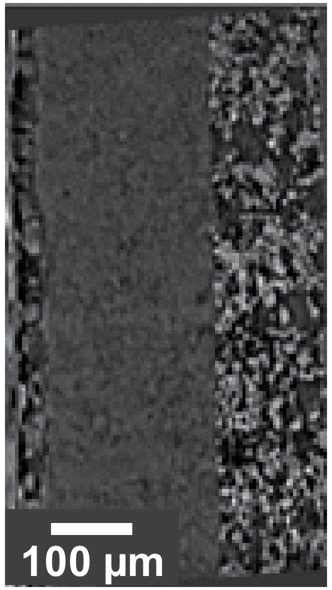


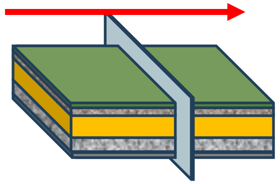


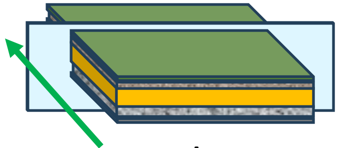


X-Ray Tomography of Cycled ASSB Pouch Cell









- Flat and intimate contact between cathode and solid electrolytes
- Wavy Current Collector
- Si mud- cracking captured in operando

<u>Tomography condition</u>

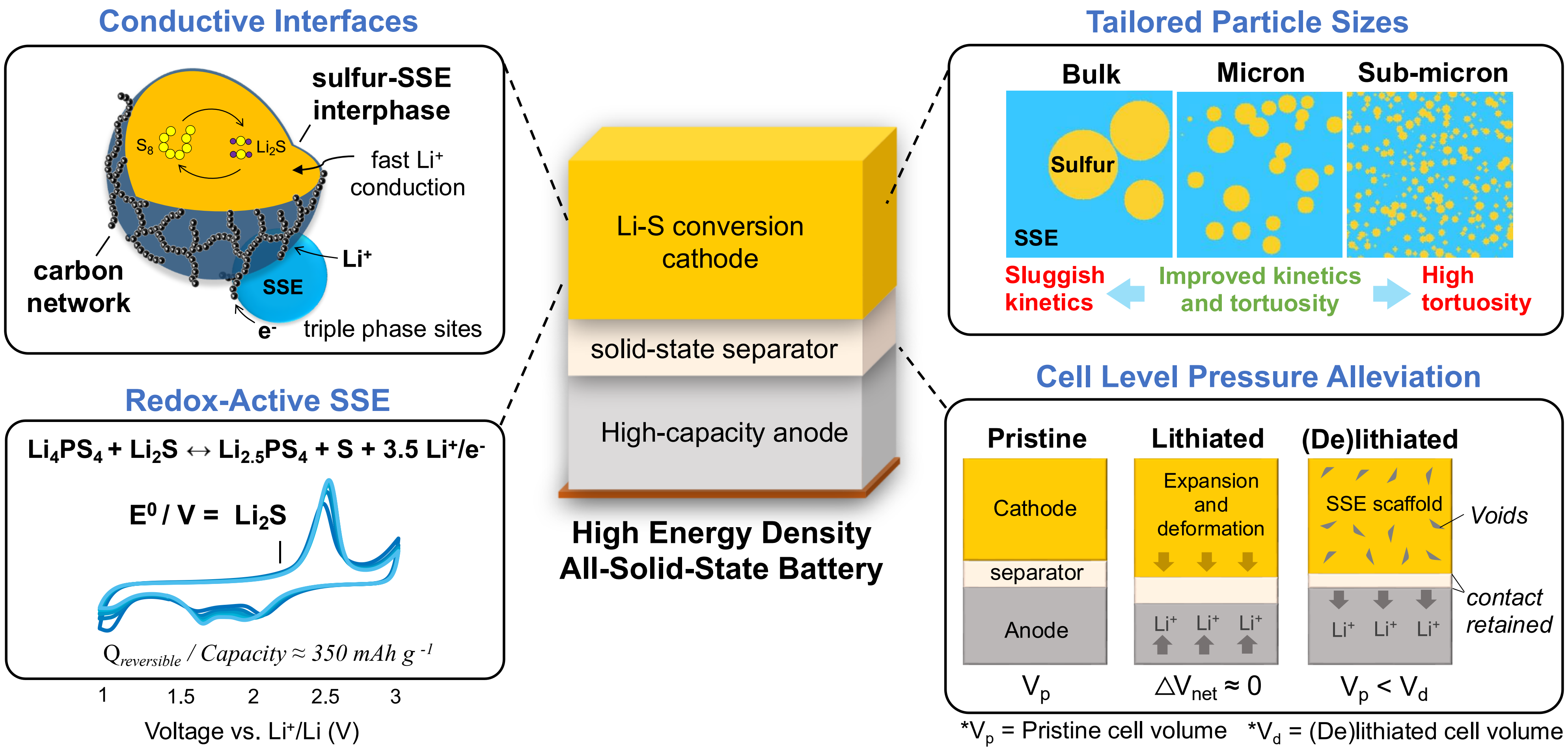
- 10X lens / 35keV / Absorption contrast / 720 slices

C.-J. Huang, Y. S. Meng, *et al.*, *ACS Energy Letters*, **2025**, **10**, 3459-3470.

Li-S Cathode Development

Dr. Ashley Cronk
NSF Fellow

- Critical cathode design parameters to enable high utilization and practical operation at RT



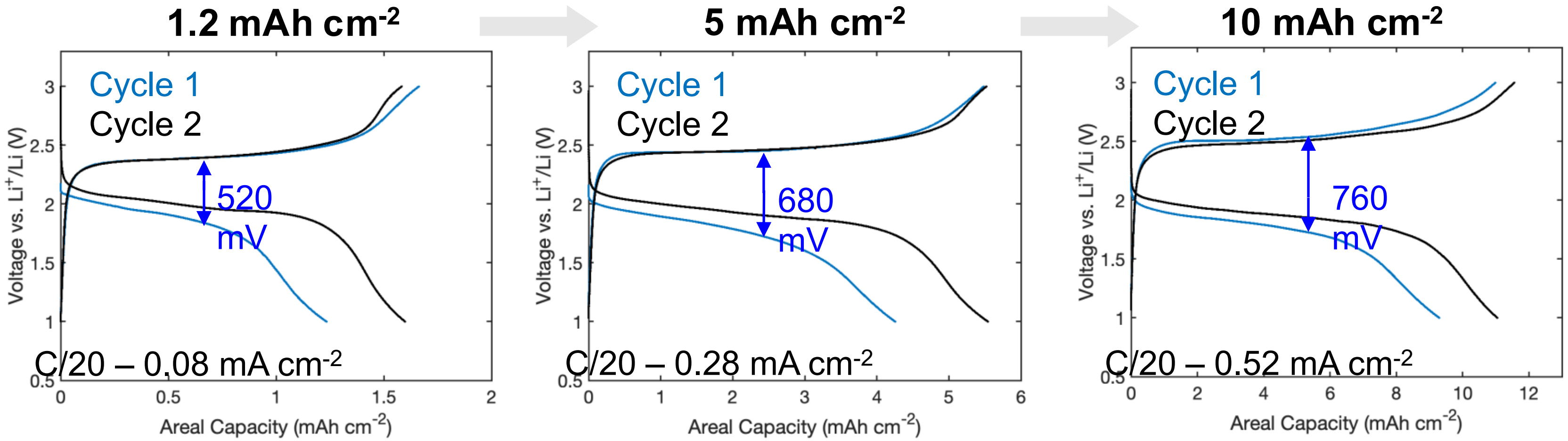
A. Cronk, Y.S. Meng, et al., " A highly utilized and practical lithium-sulfur cathode enabled in all-solid-state batteries", *Nat Energy, Under Rebuttal,* 2024

Patent Pending

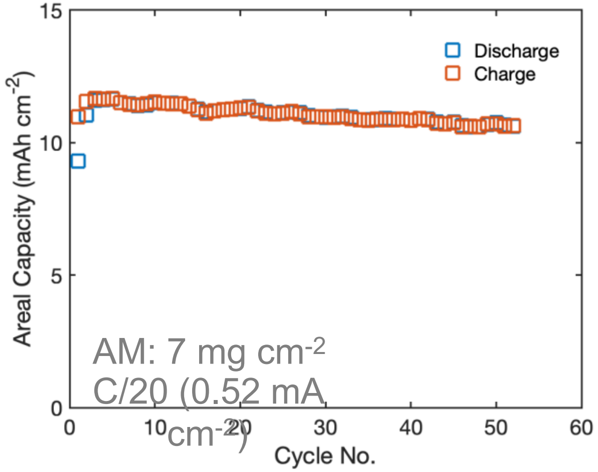
Realizing High Areal Capacity Lithium Sulfur SSB

LGES-UCSD Frontier Research Laboratory

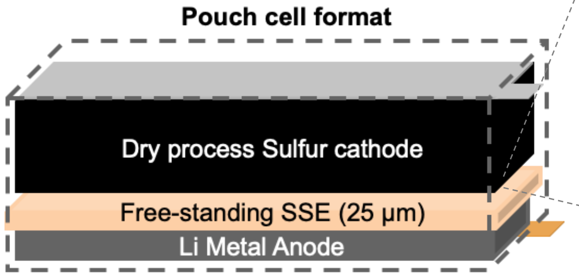
Our composite design enables > 10 mAh cm^{-2}

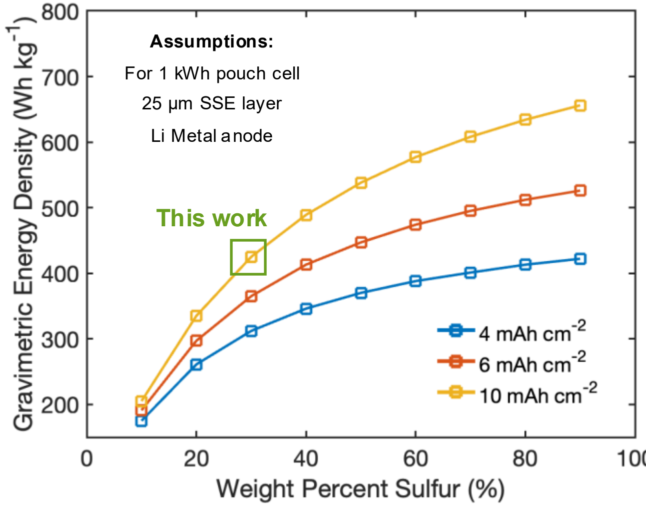


Stable cycling at 10 mAh cm^{-2}



Estimated gravimetric energy density



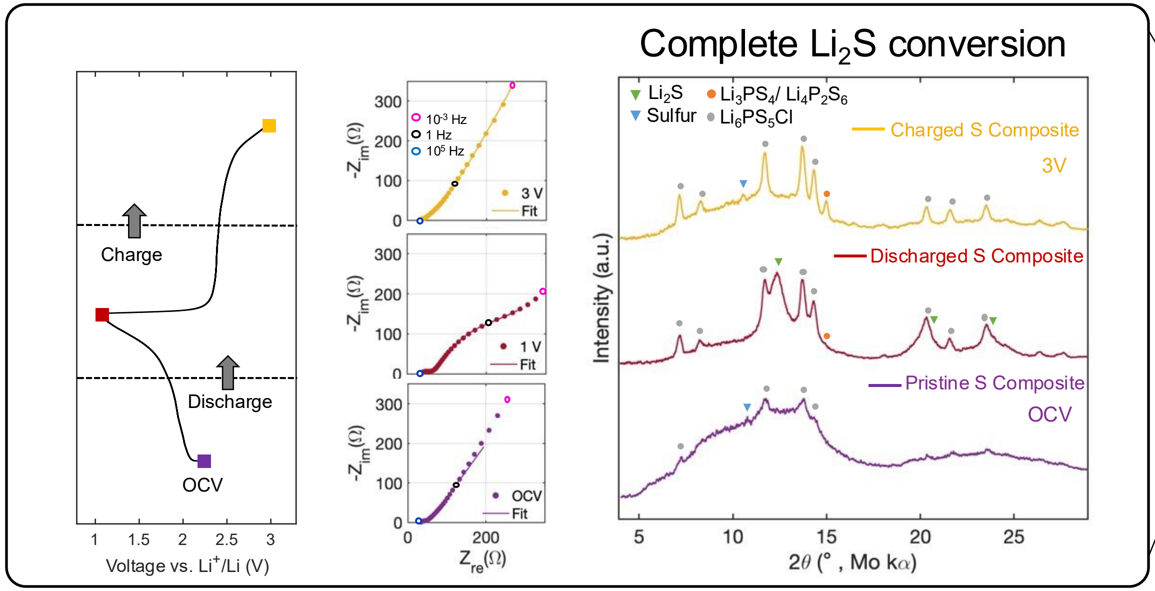


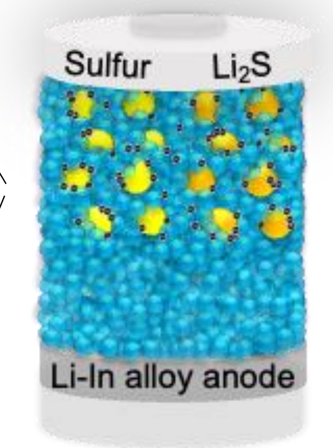
- ✓ This work ~ 415 Wh kg^{-1}
- ➢ Room for improvement by increasing S wt.%
- ➢ At 10 mAh cm^{-2}, limited by Li Metal CCD

But we can solve this by Lithiated Si !!!

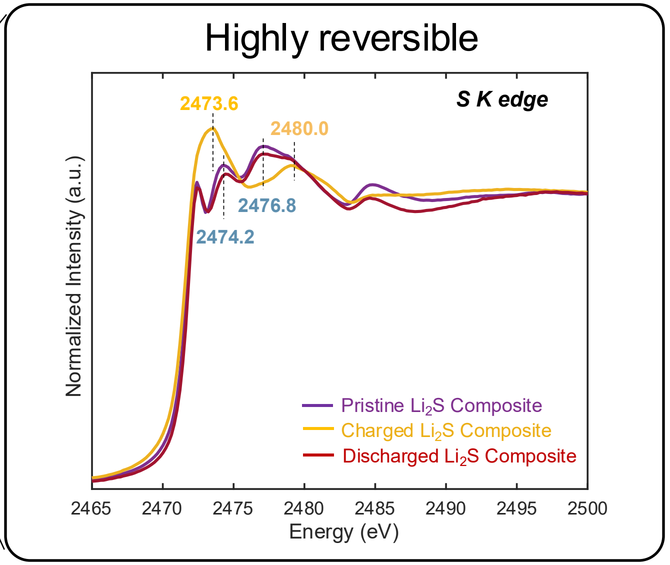
A reversible solid-state Li-S cathode

- Sulfur system



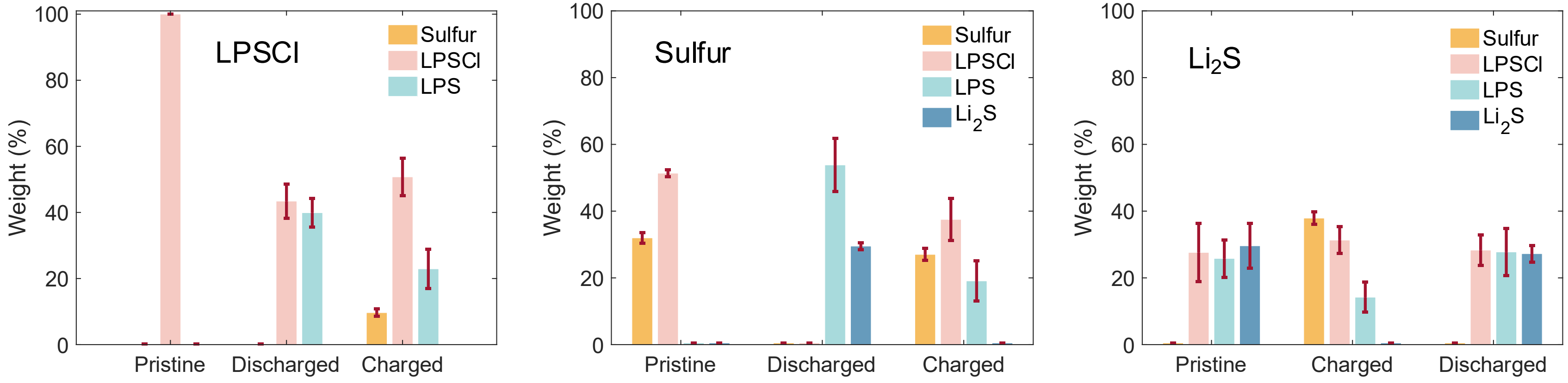


- Li_2S system



Linear combination fitting of XAS results confirms reversible behavior

- LPSCl contributes capacity through LPS and sulfur formation



Patent pending; "A highly utilized and practical lithium sulfur cathode realized with sulfide solid electrolytes"

Remaining Challenges

Precursors

Li2S price needs to come down by 5X -10X

SSE particle size control must be done

Processibility

Dry room compatibility - yes!

Dry processing – at scale!!!

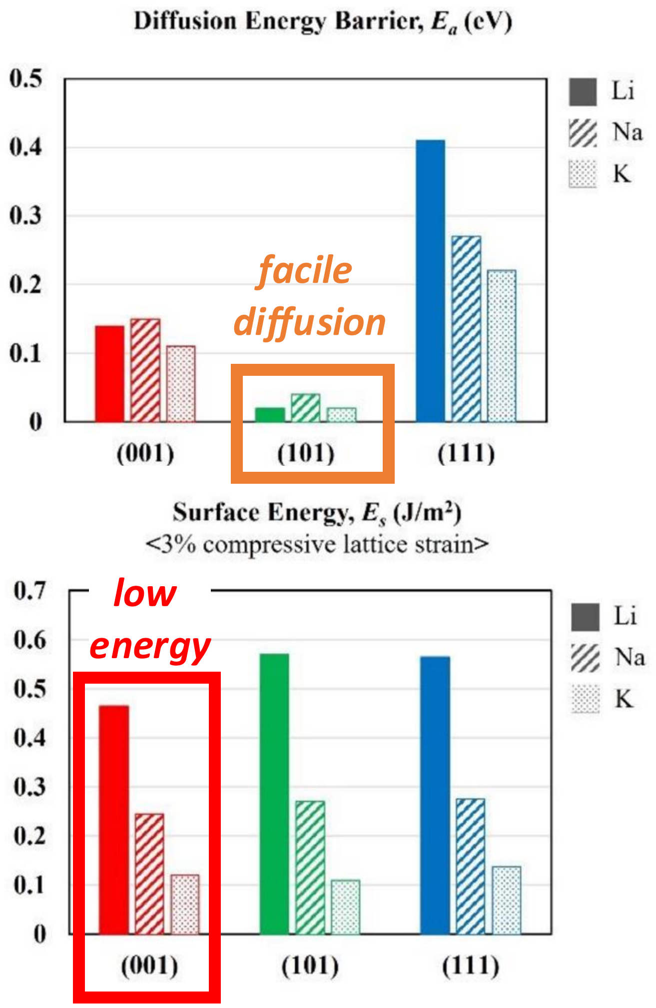
Pressure

Pressure reduction from 100MPa – 50MPa – 5MPa

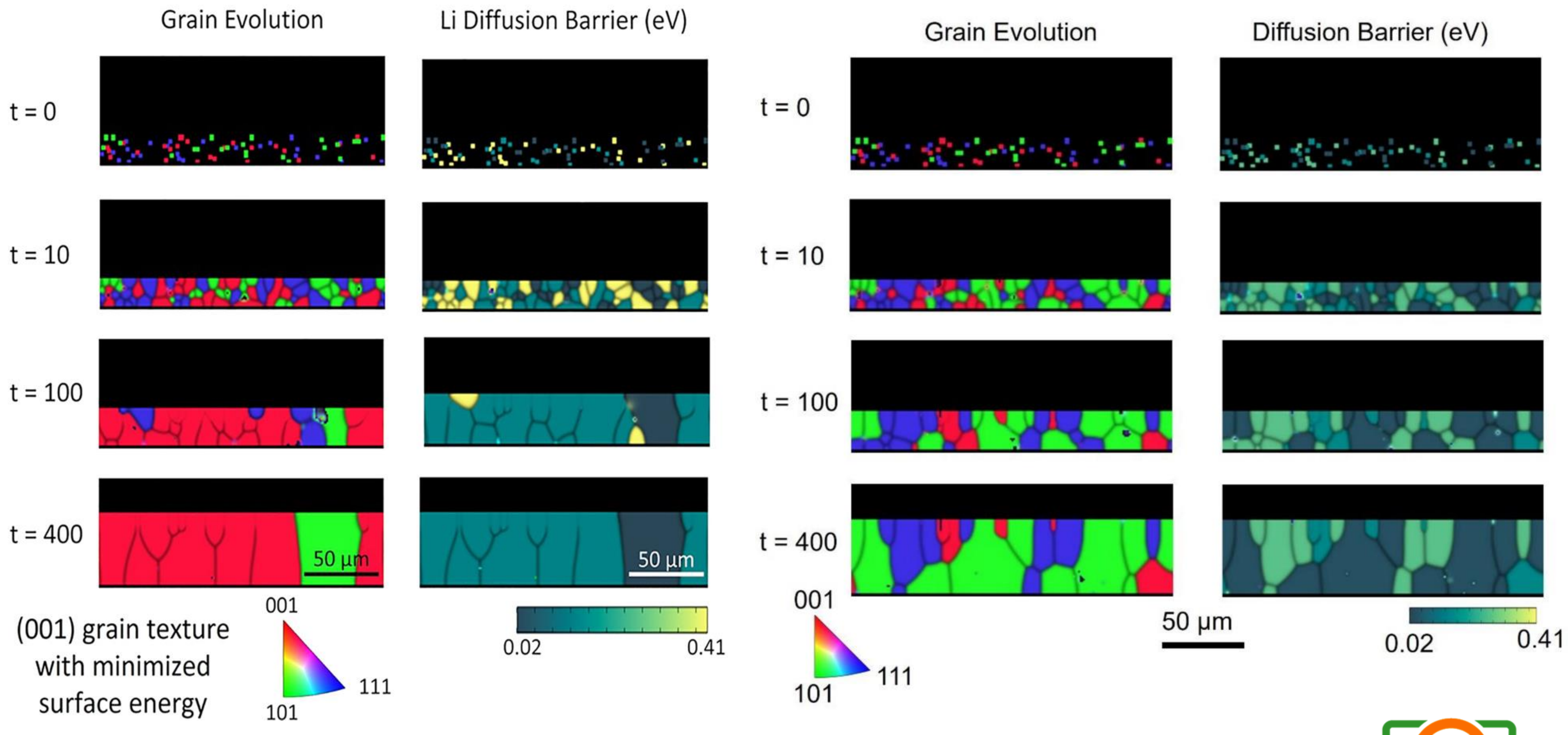
Design SSB component and architecture for 1-2MPa

Thermodynamic-based Phase Field Modelling

Competition between surface energy and diffusion dictates grain growth



Li metal vs. **Na metal**

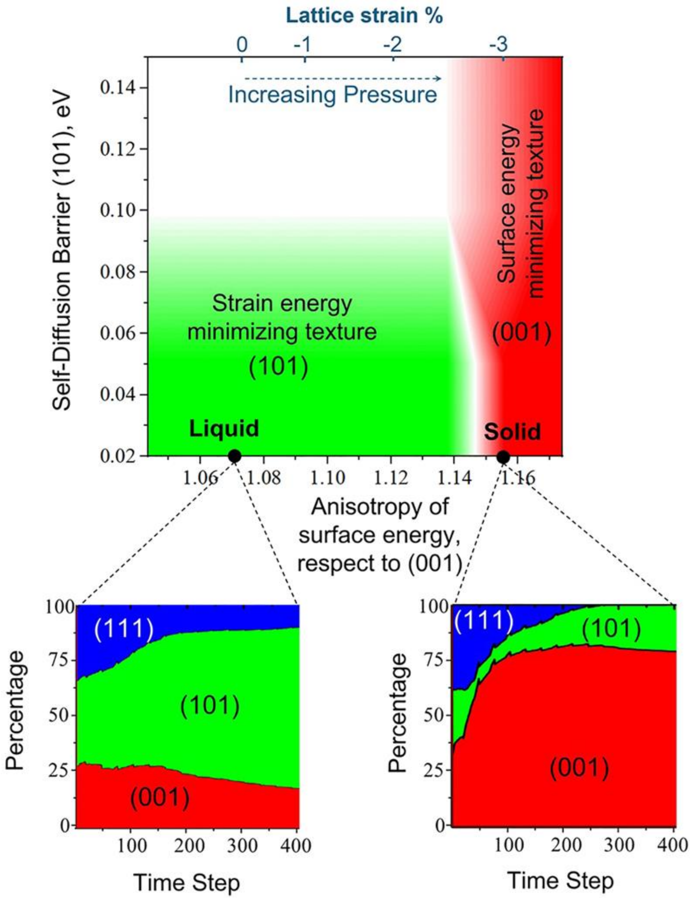


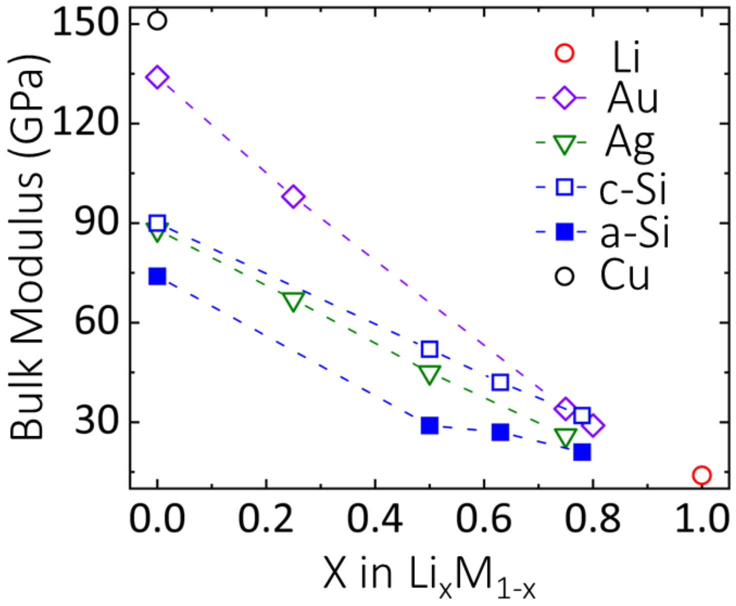
M. Zhang, * et al., Joule 9, 101847 2025

Argonne National Laboratory · Berkeley Lab · Pacific Northwest National Laboratory · Columbia University · Duke University · MIT · Princeton University · UC San Diego · The University of Chicago · University of Houston · University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · Xavier University of Louisiana

Minimizing External Pressure Effect for SSBs

Lattice strain at current collector interface modulates surface energy and grain growth



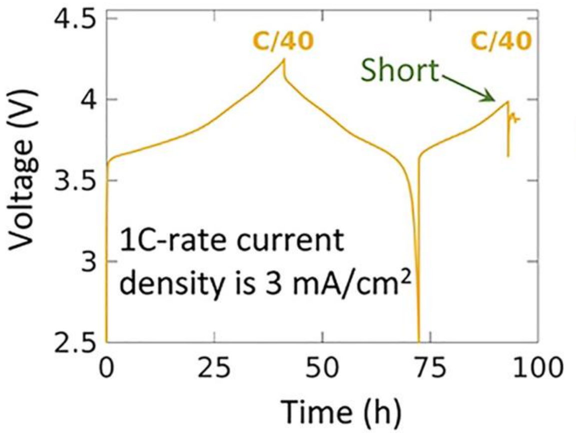


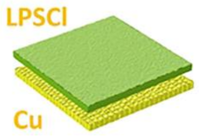
- Optimal interfacial contact in solid-state batteries requires the application of adequate load stress. Mechanical properties of *all* involved solids must be appropriately designed.
- At any given SSE, a ***reduced bulk modulus difference*** between the substrate and Li corresponds to a ***smaller lattice strain*** within the Li phase – favorable grain growth condition.

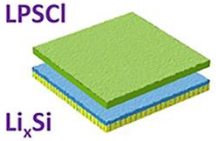
M. Zhang, * et al., Joule 9, 101847 2025

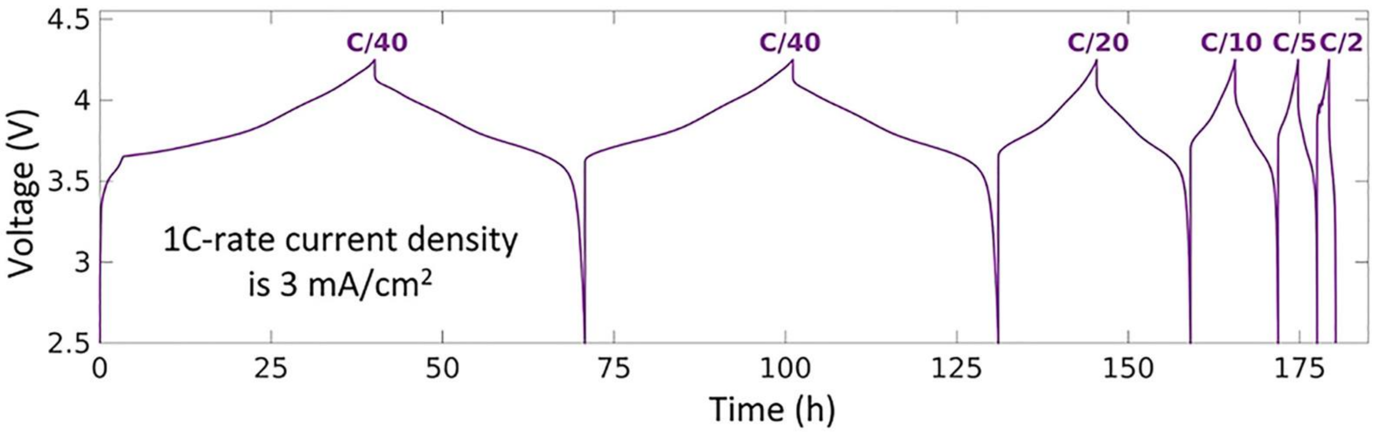
Directed Texture Improves Critical Current Density

Li_xSi substrate with tailored mechanical property triggered **101 grain growth**

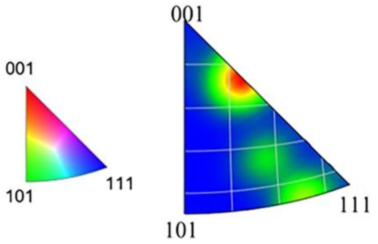


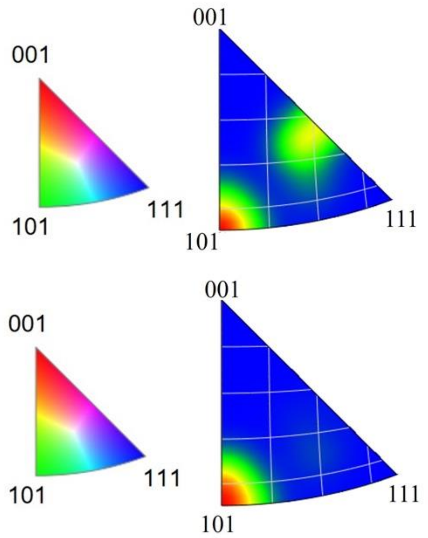




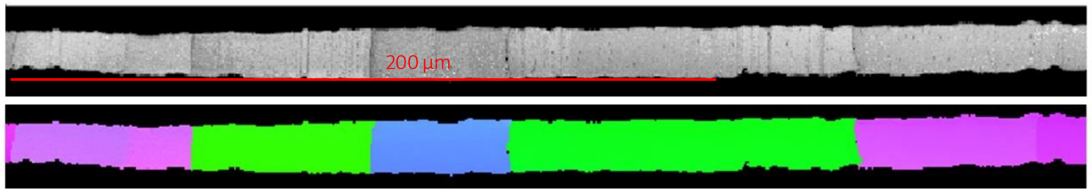


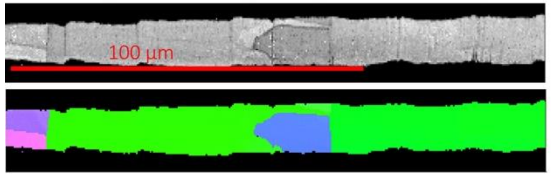
Li deposition on Cu at 25 °C, 5 MPa





Li deposition on Li_xSi at 25 °C, 5 MPa





Argonne National Laboratory · Berkeley Lab · Pacific Northwest National Laboratory · Columbia University · Duke University · Massachusetts Institute of Technology · Princeton University · UC San Diego · The University of Chicago · University of Houston · University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · Xavier University of Louisiana

Sodium Anode-Free Solid-State Batteries

Can achieve 3 goals simultaneously…

1. Maximize energy density

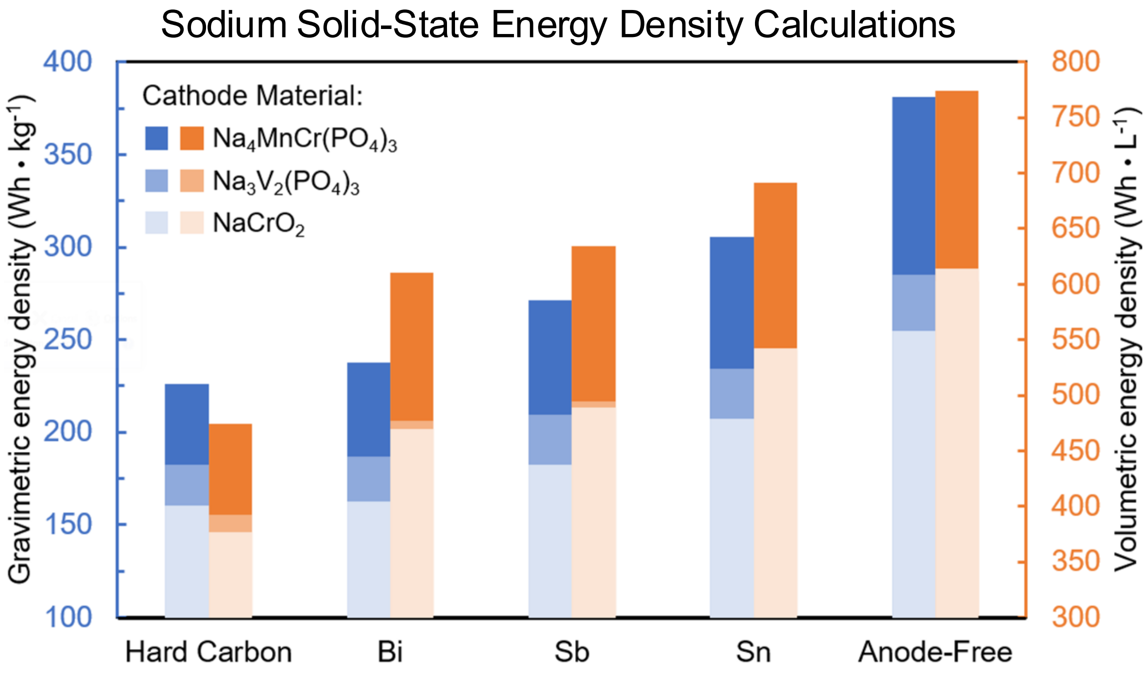
- Lowest reduction potential → highest cell voltage
- Smaller and lighter cells

2. Minimize cost

- No anode material cost, lower processing cost
- Sodium cheaper than Lithium

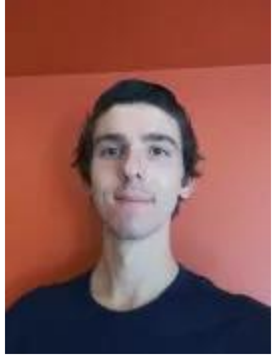
3. Improved safety

- No flammable organic liquid electrolytes
- No large amounts of sodium metal foils



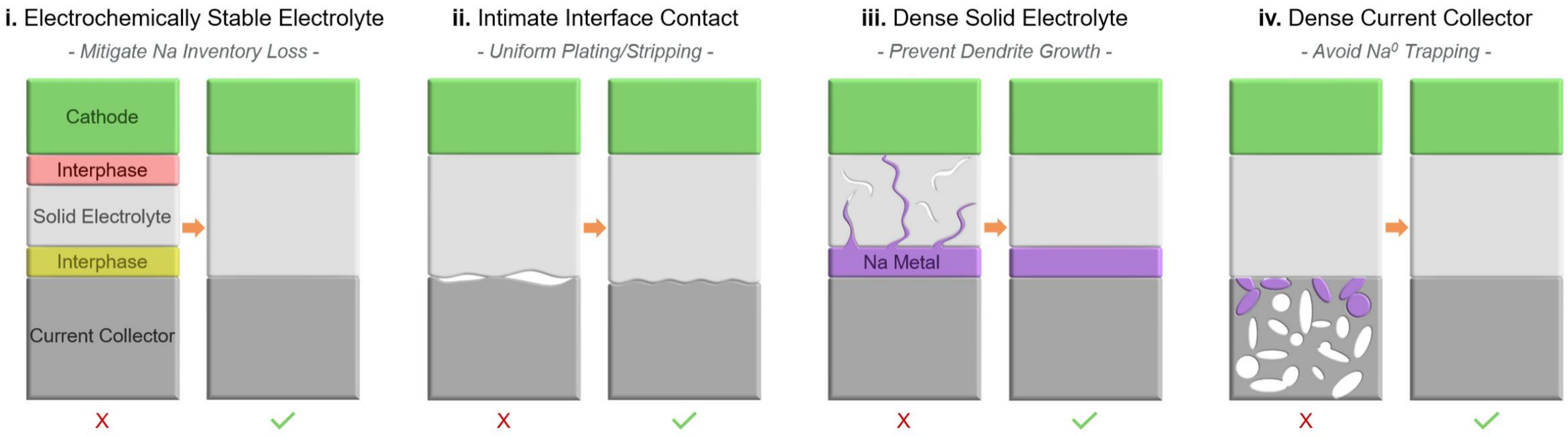
Critical Design Factors

G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", 2024, Nature Energy



Dr. Grayson Deysher

- 4 fundamental criteria for enabling anode-free solid-state batteries

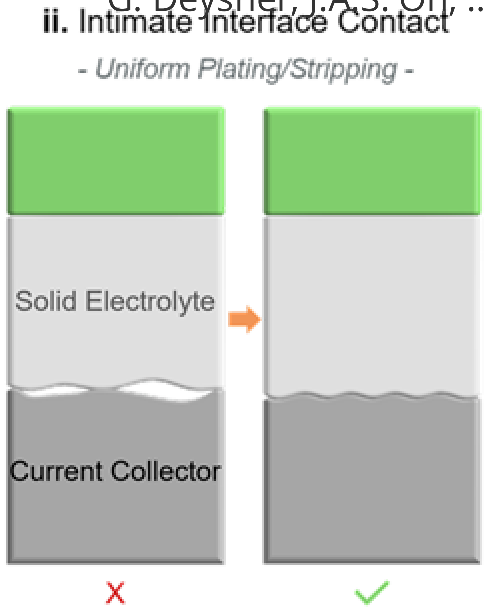


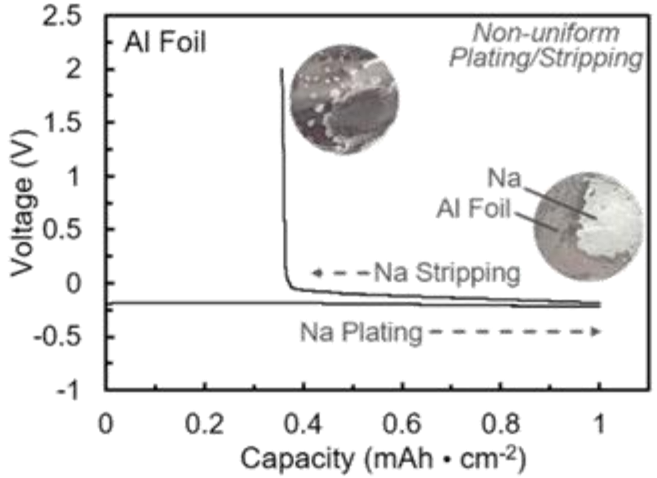
- Must design a cell from the ground up
  - Material selection and cell architecture

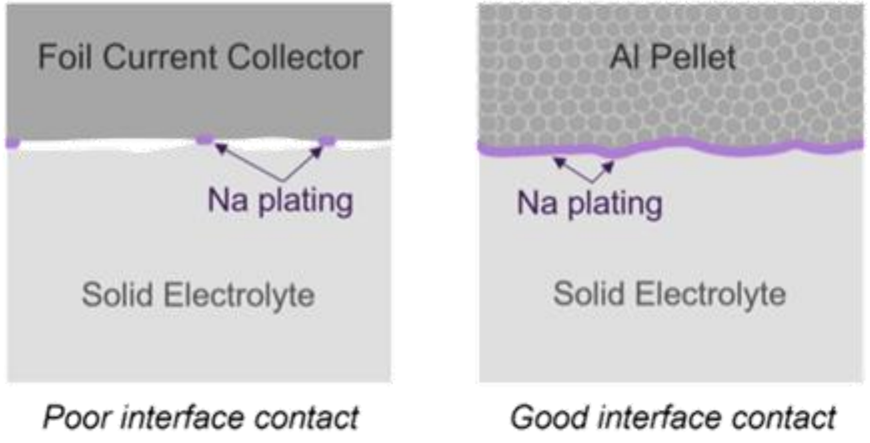
Intimate Interface Contact

G. Deysher, J.A.S. Oh, … Y.S. Meng, "[An Anode-Free Sodium All-Solid-State Battery](#)", 2024, Nature Energy

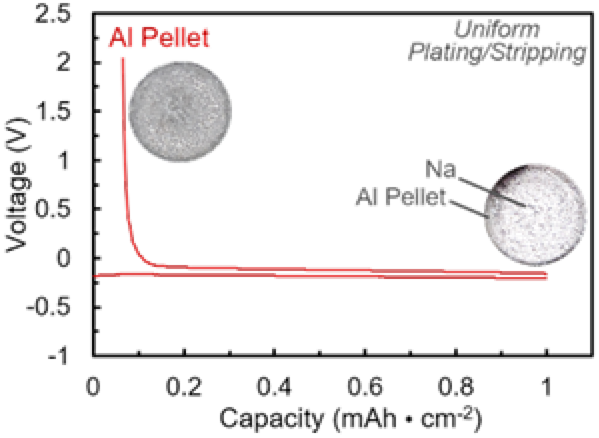
Patent Pending



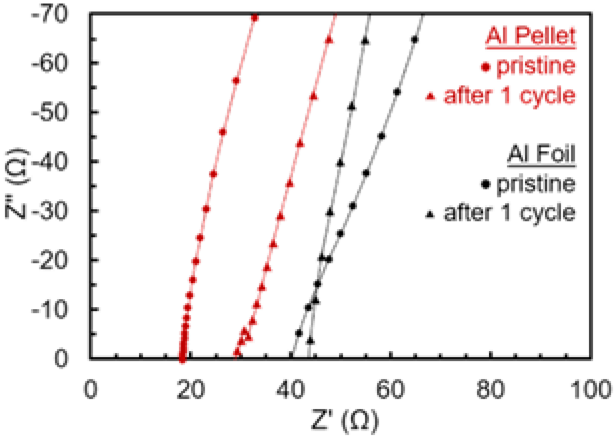


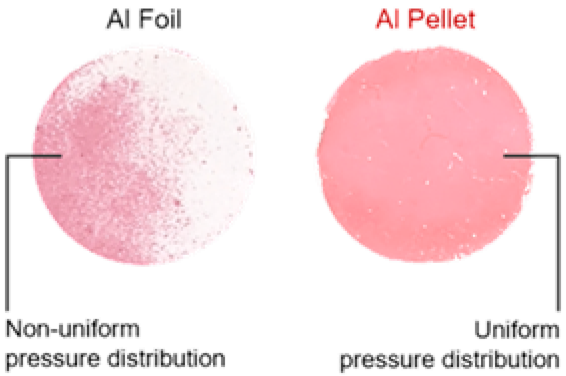


- Pelletized Al can achieve intimate contact with the NBH electrolyte



Al Pellet = Lower interface resistance

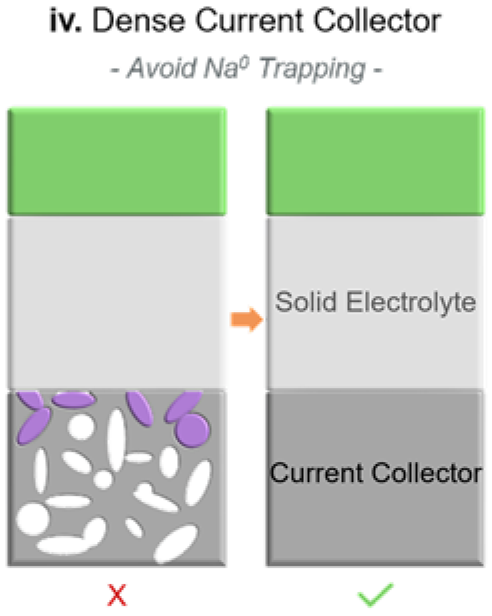


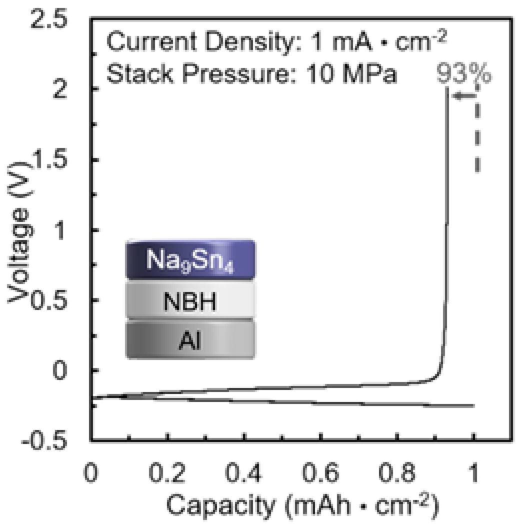


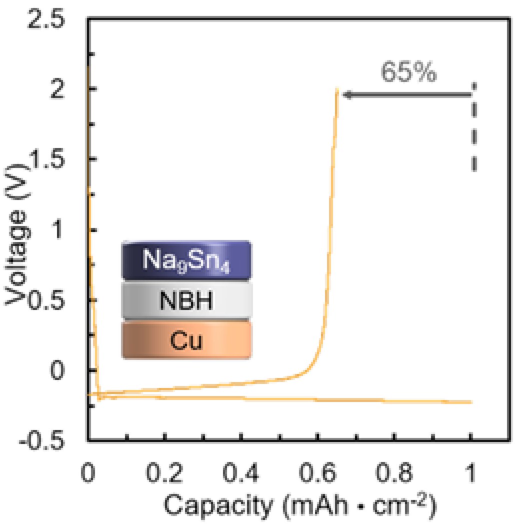
Designed Dense Current Collector

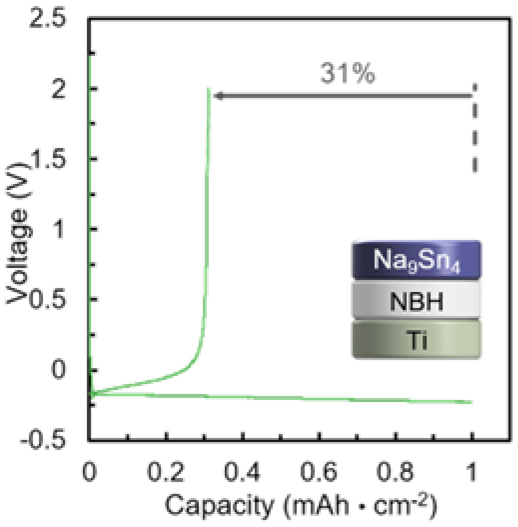
G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", 2024, Nature Energy

Patent Pending

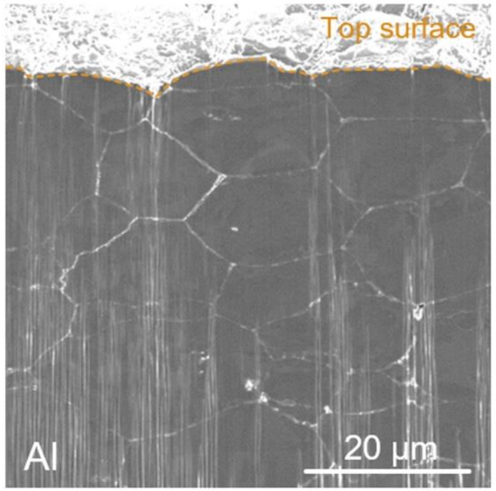


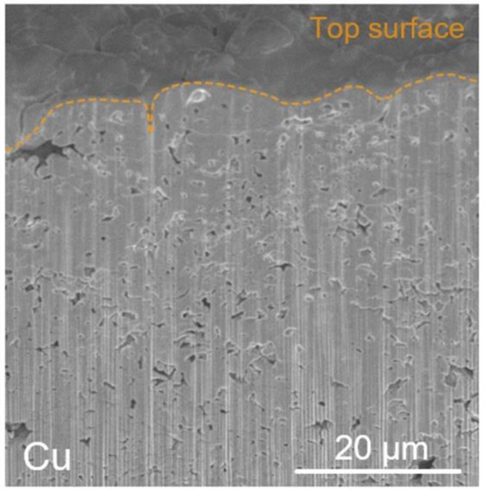


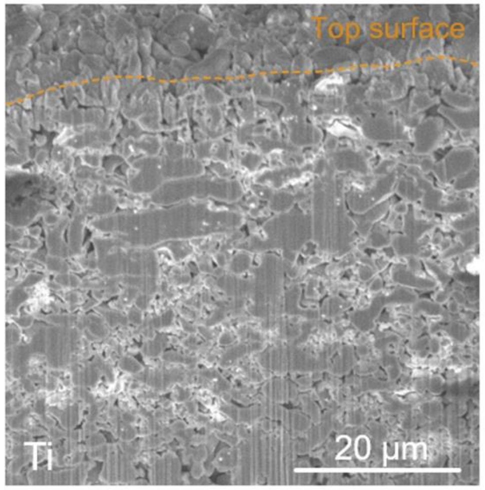




- Soft Al can be easily densified during cell fabrication
  - Unlike Cu and Ti



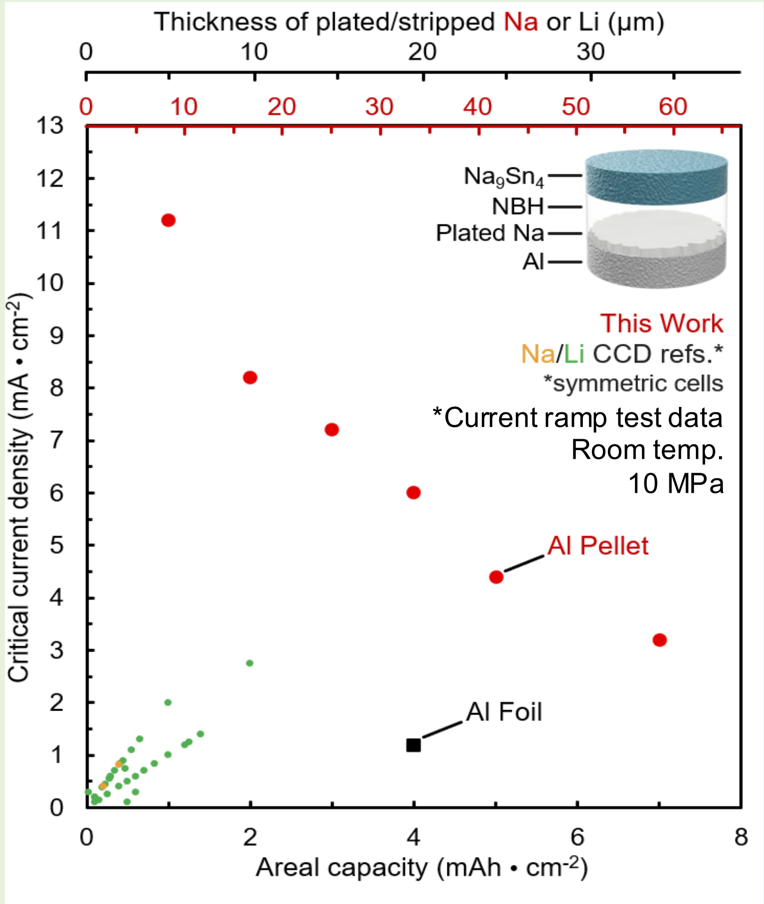




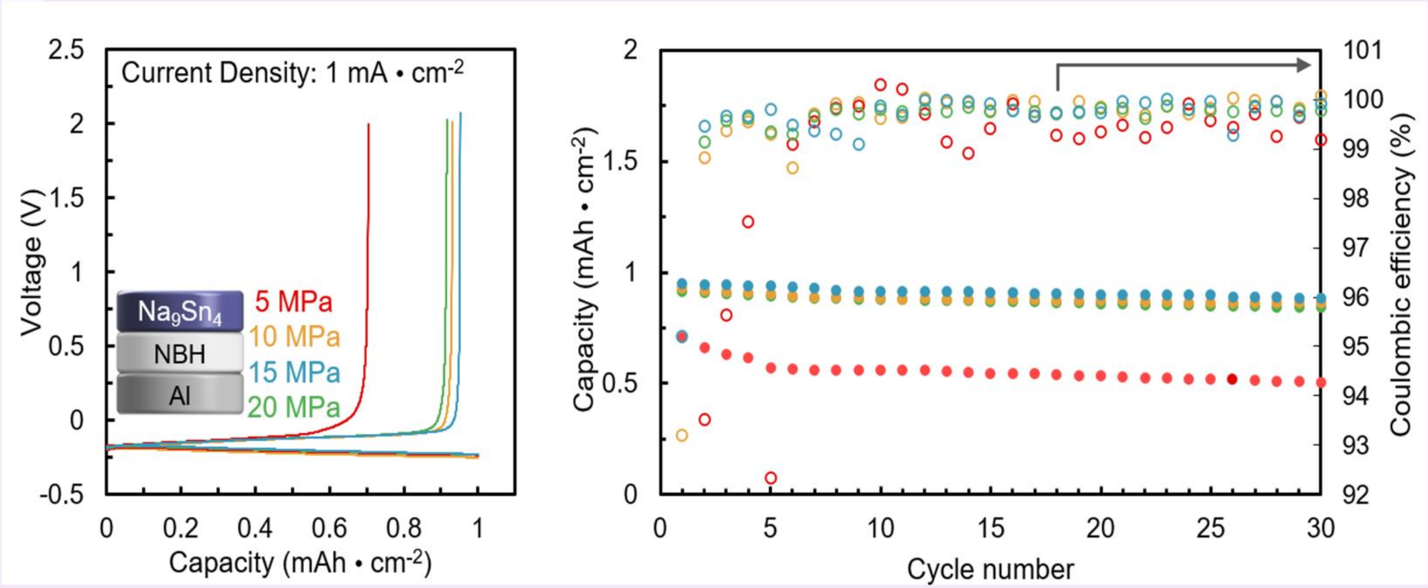
G. Deysher, J.A.S. Oh, … Y.S. Meng, "An Anode-Free Sodium All-Solid-State Battery", 2024, Nature Energy

Current Density

Patent Pending



Cell Stack Pressure

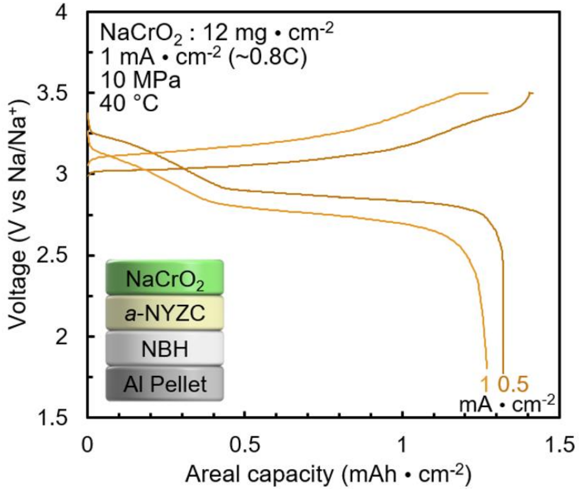


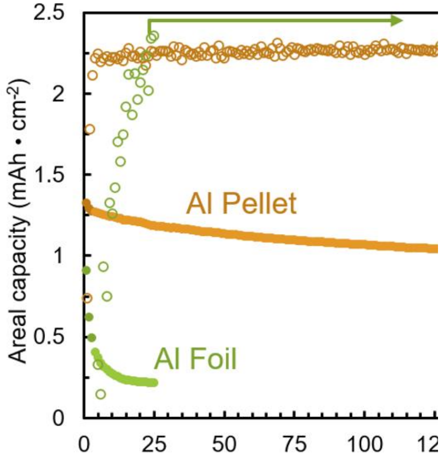
- High critical current density
  - Pathway to fast charging
- Low pressure cyclability
  - Pathway to practical commercial cells

Sodium All Solid-State Full Cell

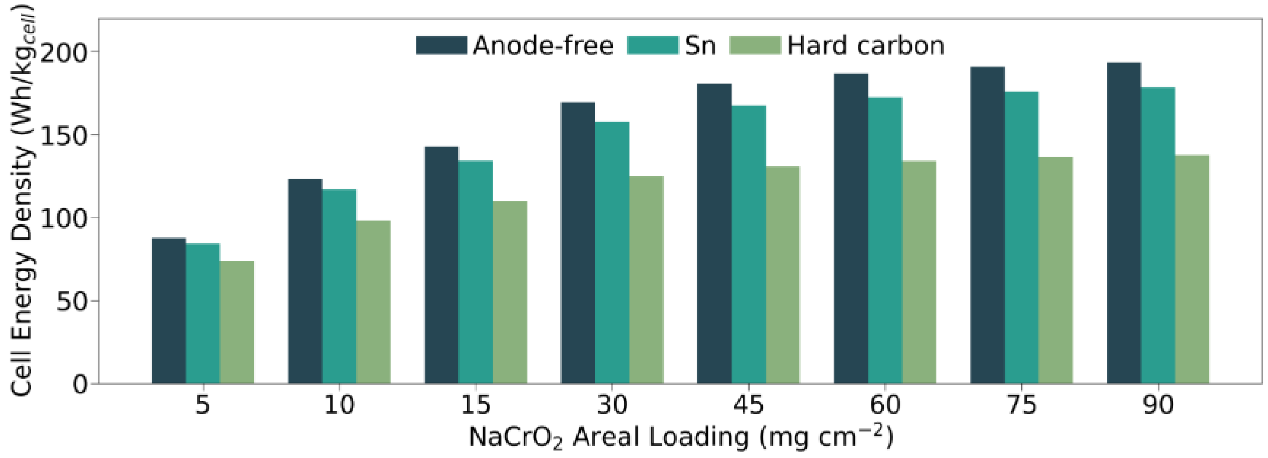
G. Deysher, J.A.S. Oh, … Y.S. Meng, "An Anode-Free Sodium All-Solid-State Battery", 2024, Nature Energy   Patent Pending

- Enable full-cell cycling ($NaCrO_2$ cathode)





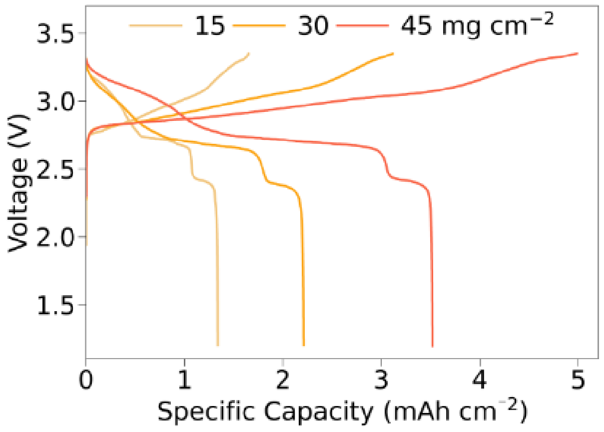
a



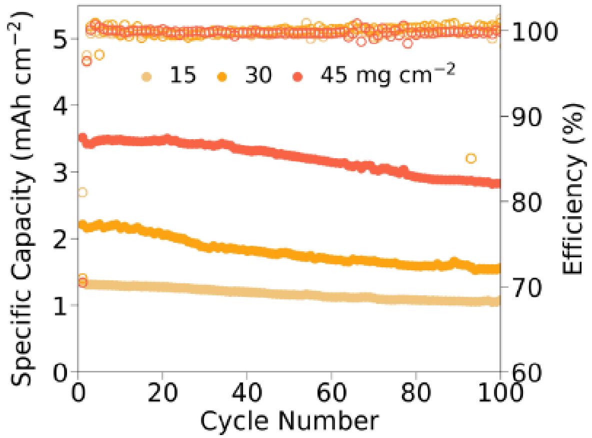
Thick Battery Cathode enabled by novel superionic Na conductor

Dr. J.A.S. Oh Patent Pending and To be Submitted

c



d



e

Global Race for Solid State Battery – West vs. East

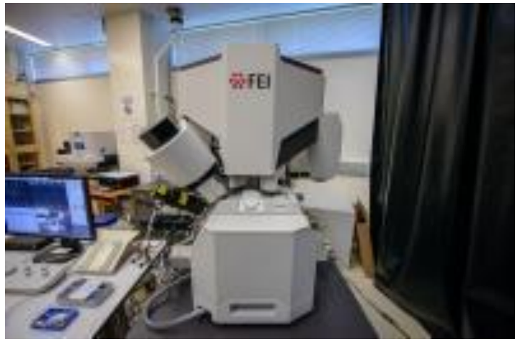
Tariff (Protectionism) Can Only Get Us That Far

Innovations are the Best Option Forward

Collaborators and Funding

Sustainable Power and Energy Center

sdni
San Diego Nanotechnology Infrastructure



UC IRVINE MATERIALS RESEARCH INSTITUTE

U.S. DEPARTMENT OF ENERGY | Office of Science

NECCES

(John Vetrano, Jane Zhu and Craig Henderson)

BATTERY 500 CONSORTIUM

Vehicle Technology Office
(Tien Duong and David Howell)

LGES Frontier Research Laboratory (2021 – present)
Various Industrial Partners including
(LG Energy Solution / ThermoFisher Scientific / Shell / UL /Nissan /Cummins/ SES/ Supernal /GM / Applied Materials/Tesla/BMW)

Na Batteries 2010 - 2024

NSF

National Science Foundation
DMR program (Na Batteries)