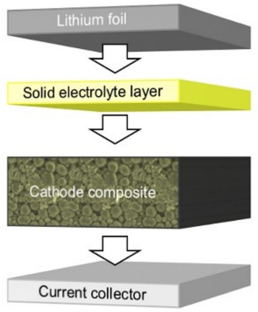
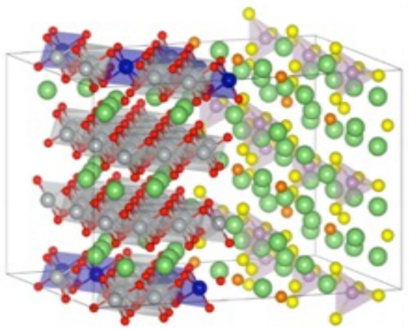
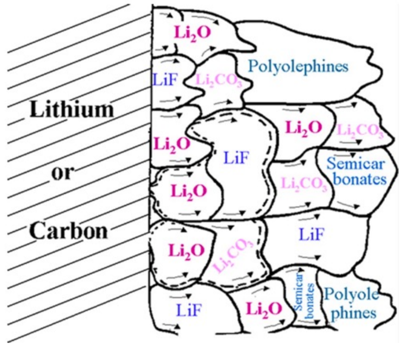
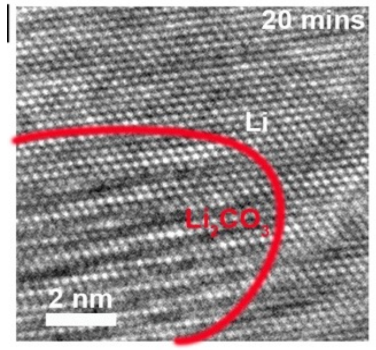
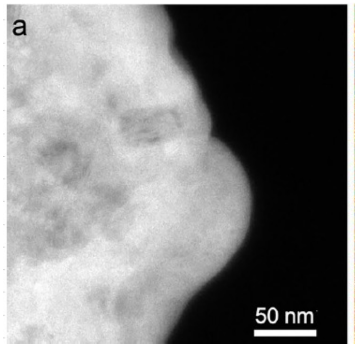
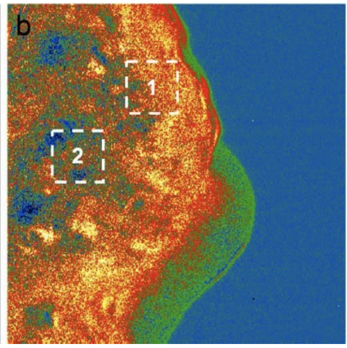








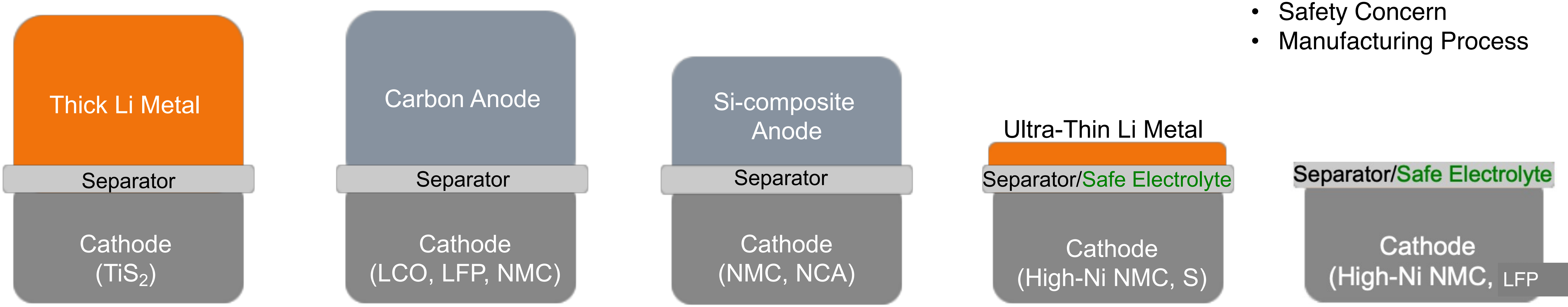
New Perspective on Anode-Free All-Solid-State Batteries

Y. Shirley Meng

University of Chicago
Argonne Collaborative Center for Energy Storage Science
University of California San Diego

Development of Li Metal Battery

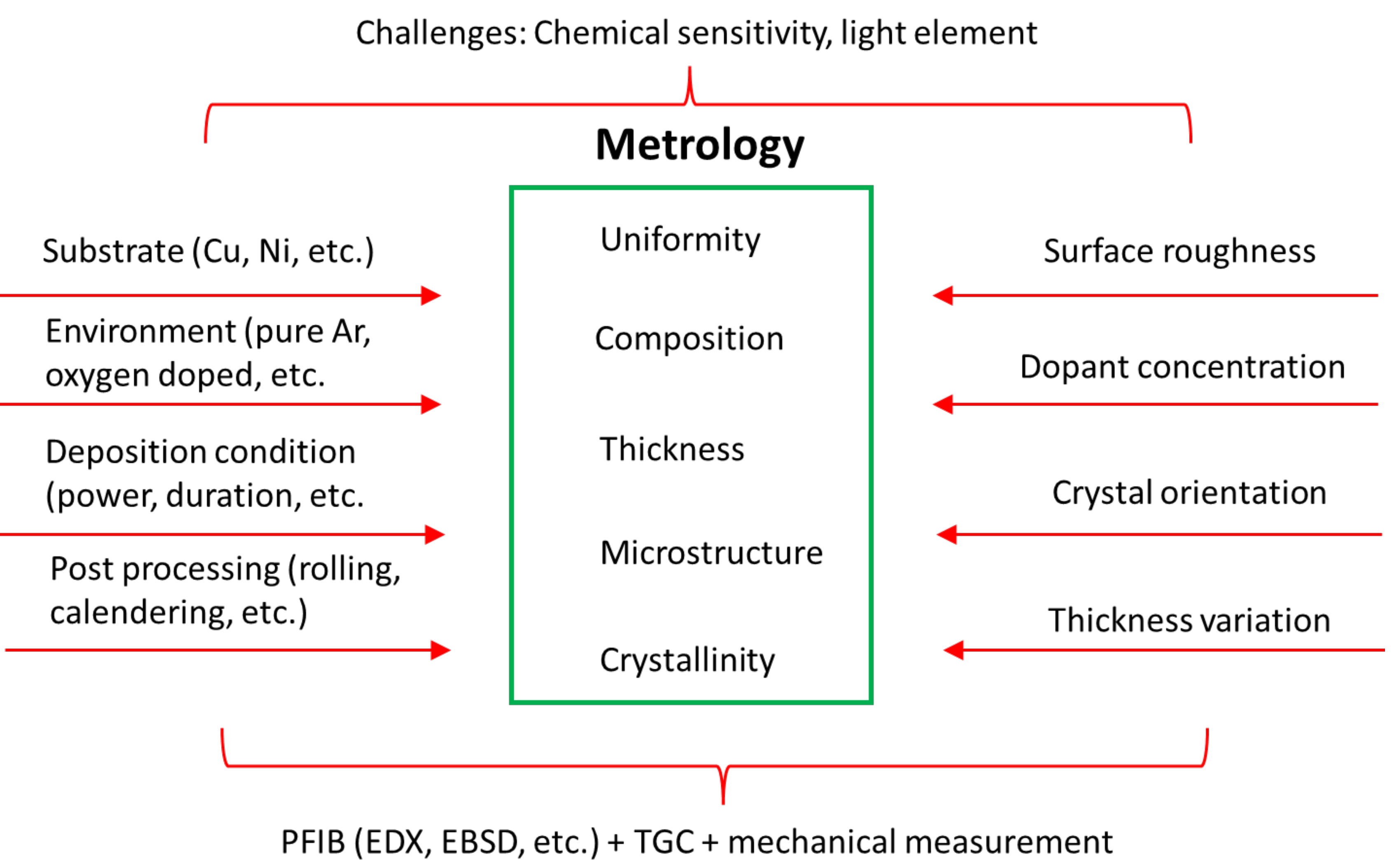
- Li Metal Production Cost
- Safety Concern
- Manufacturing Process



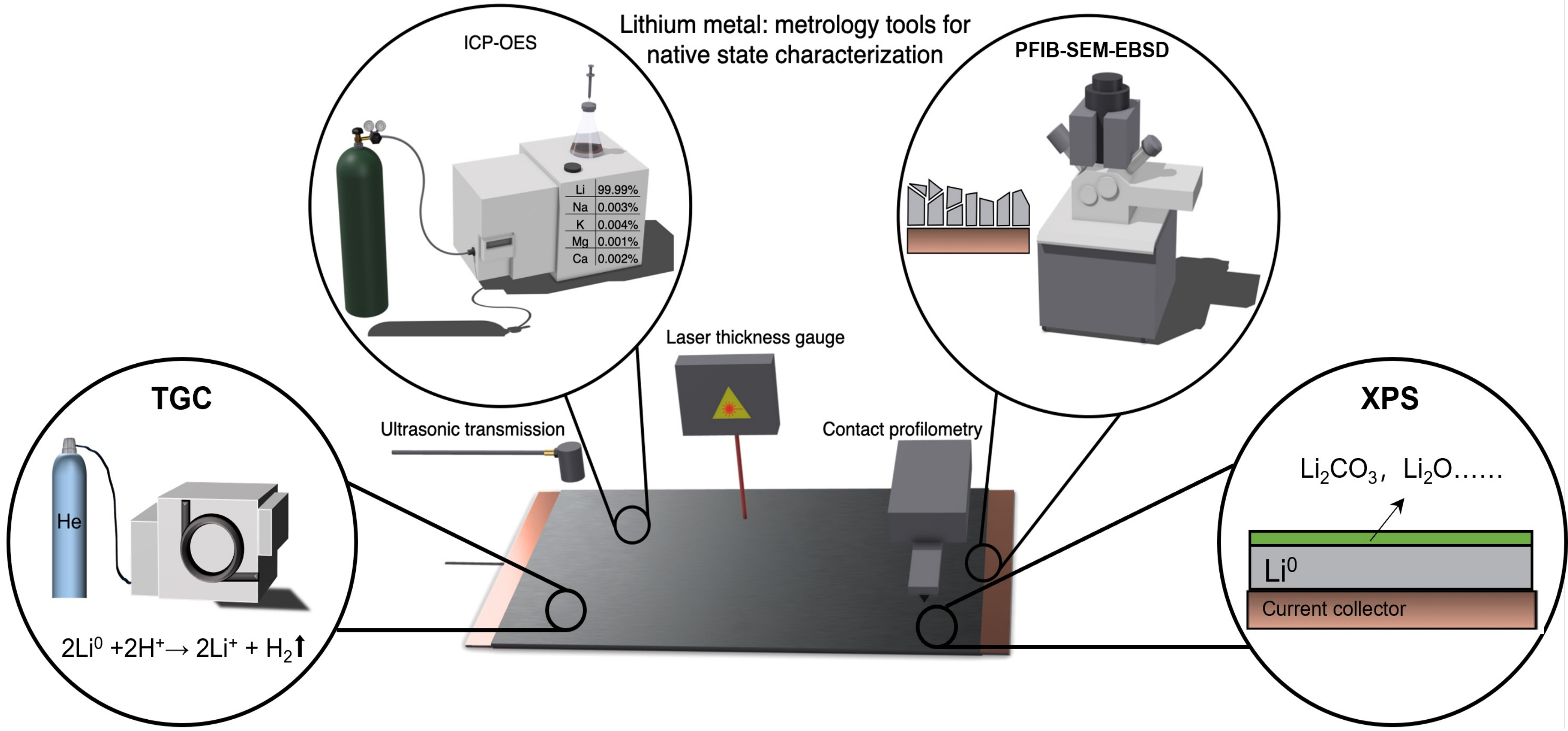
Gen 0	Gen 1	Gen 2	Gen 3	Gen 4
Li-Metal	**Li-ion**	**Li-ion**	**Li-Metal**	**Anode Free**
100-200 Wh/kg	200-250 Wh/kg	250-300 Wh/kg	400-500 Wh/kg	
200-300 Wh/L	600 Wh/L	700 Wh/L	1200 Wh/L	Scientific ONLY?
Dangerous	Safe	Safe	Safe	

Li Metal Anode Quality Control

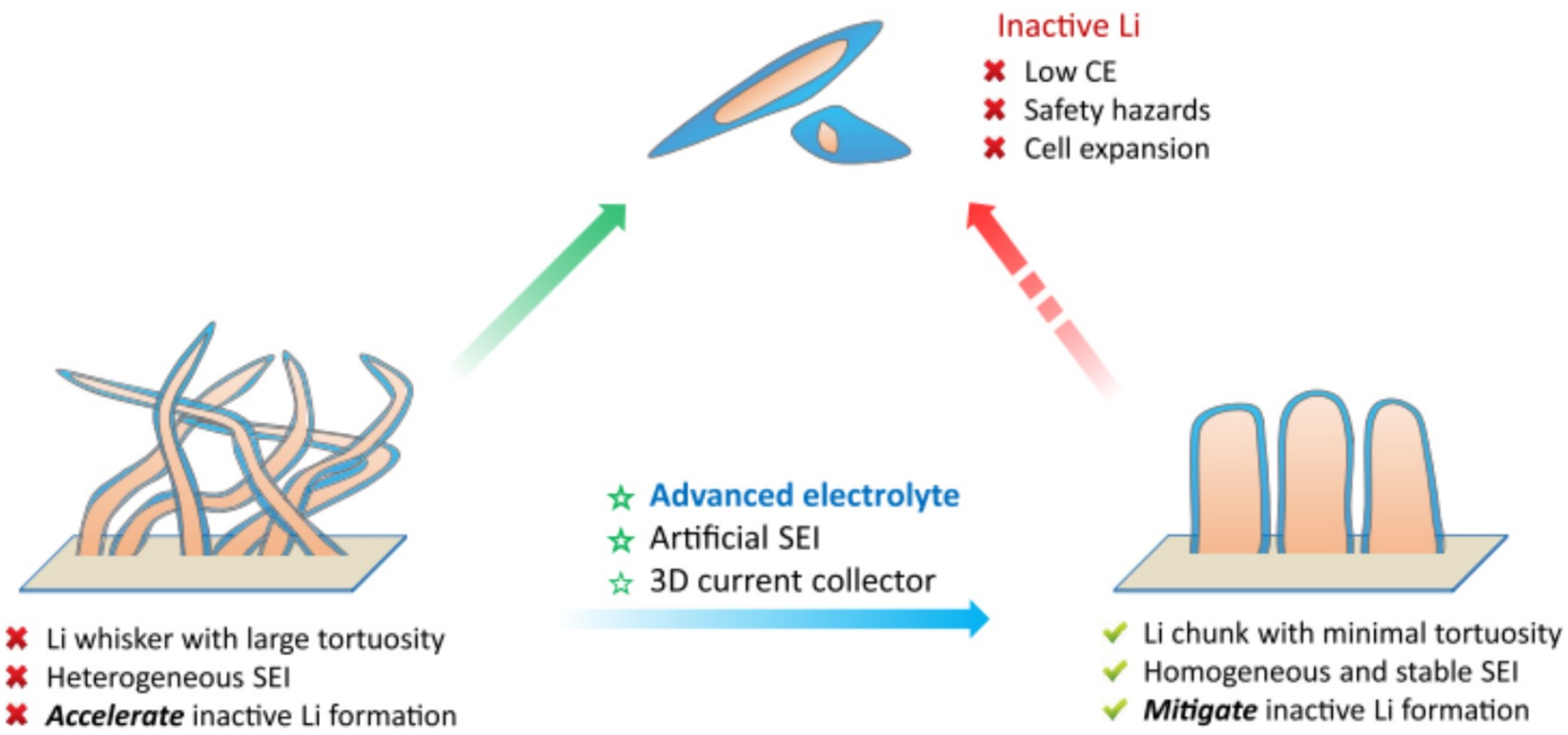
Perspective paper by attendees of Lithium Metal Battery Workshop in La Jolla 2023

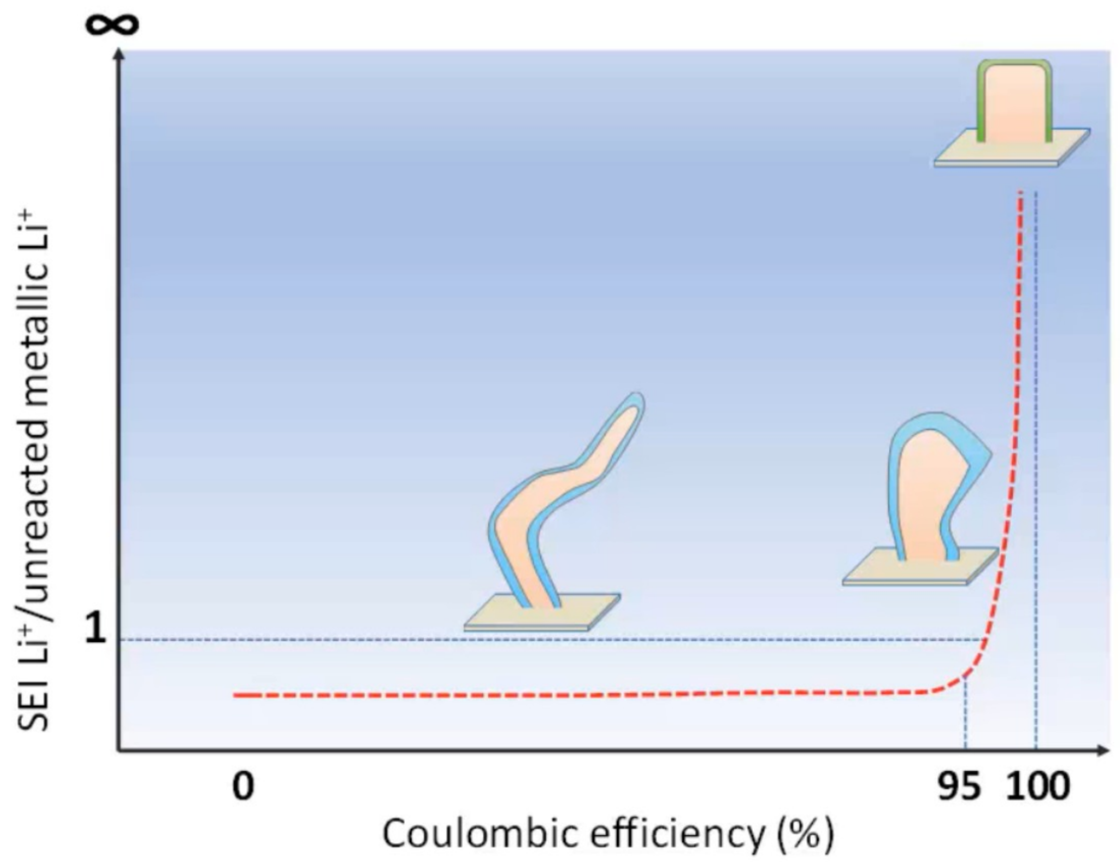


- Purity of Li^0: Determine the energy density
- Can be evaluated by TGC (Accuracy of 99.99%)
- Impurities: Si, Na, Mg, K, Ca, Fe, Cl (ICP-MS)
- Coatings: Li_2CO_3, Li_2O (XPS)
- Crystal Orientation: (110), (100), polycrystal (PFIB+EBSD)
- Uniformity, Porosity and Voids: Voids between current collector (PFIB, adhesion test)



Lithium Metal Anode – Liquid or Solid Electrolytes

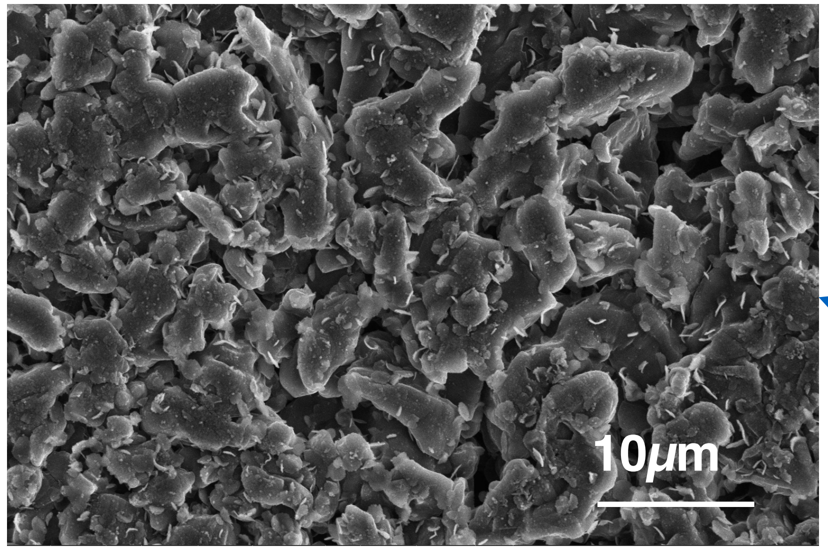


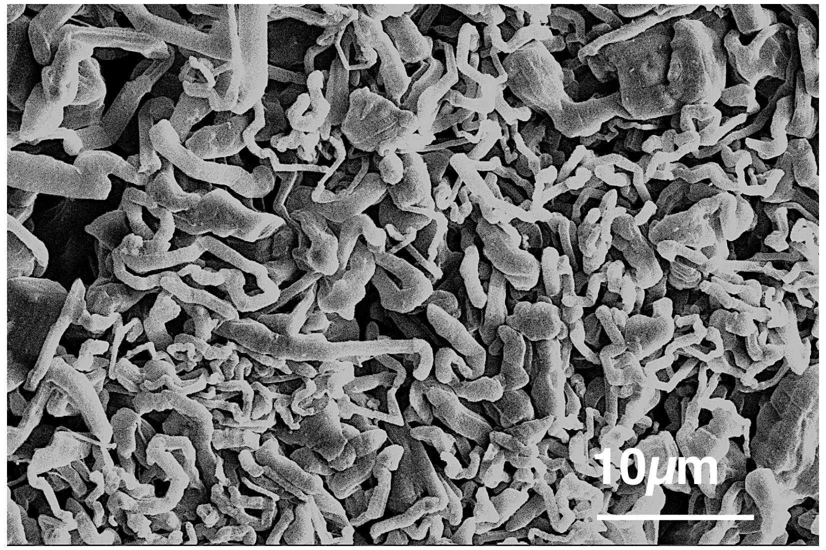


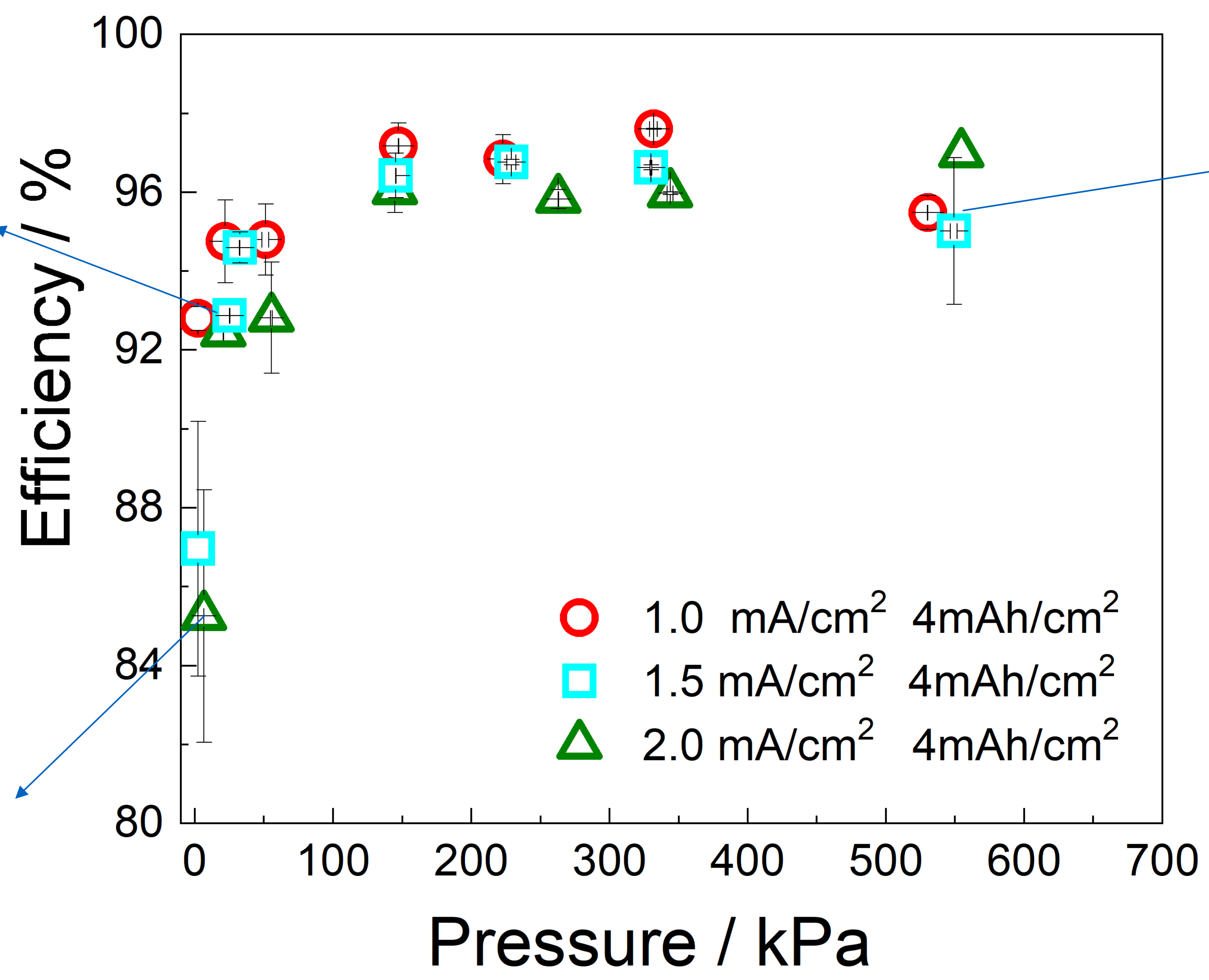
Electrochemistry produces PURE and DENSE Lithium

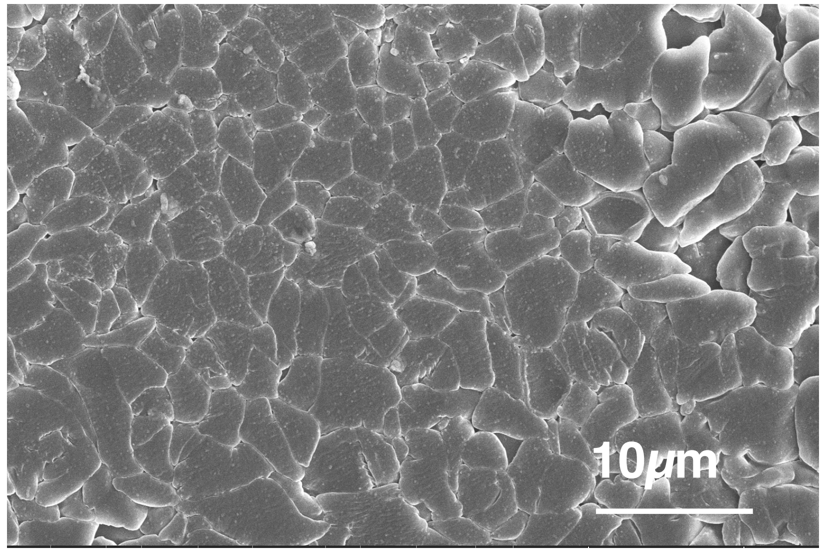
C. Fang, et al., Trends in Chemistry, May 2019, Vol. 1, No. 2
C. Fang, Y. S. Meng, et al. Nature 572, 511–515 (2019)
B. Lu , C. Fang and Y. S. Meng,   AEM 2202012, 2022

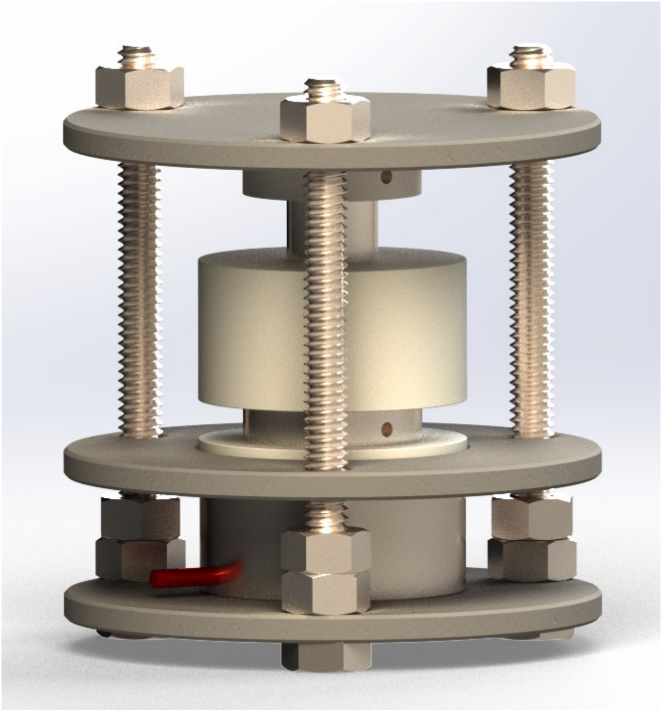
Trend of Pressure Effect on 1st Cycle CE











Pressure Control Setup

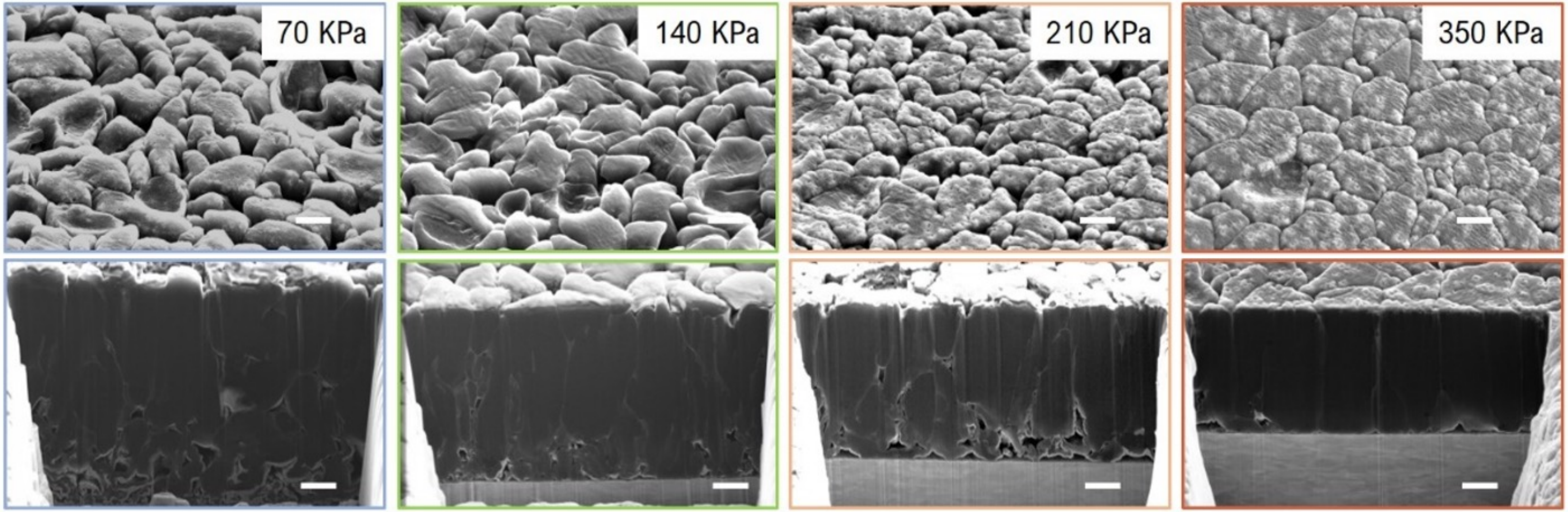
High concentration ether electrolyte

B. Lu, W. Bao, W. Yao, J. Doux, C. Fang and Y. S. Meng*, "*Editors' Choice—Methods—Pressure Control Apparatus for Lithium Metal Batteries*", **J. Electrochem., Soc.**, 169, 070537, 2022.

Top view SEM:
2mA/cm^2; 4mAh/cm^2

- **0.1 kPa** resolution
- **50 μm thick Li foil** is used to minimize the Li deformation issue
- Minimum amount of electrolyte is used (~5μL)

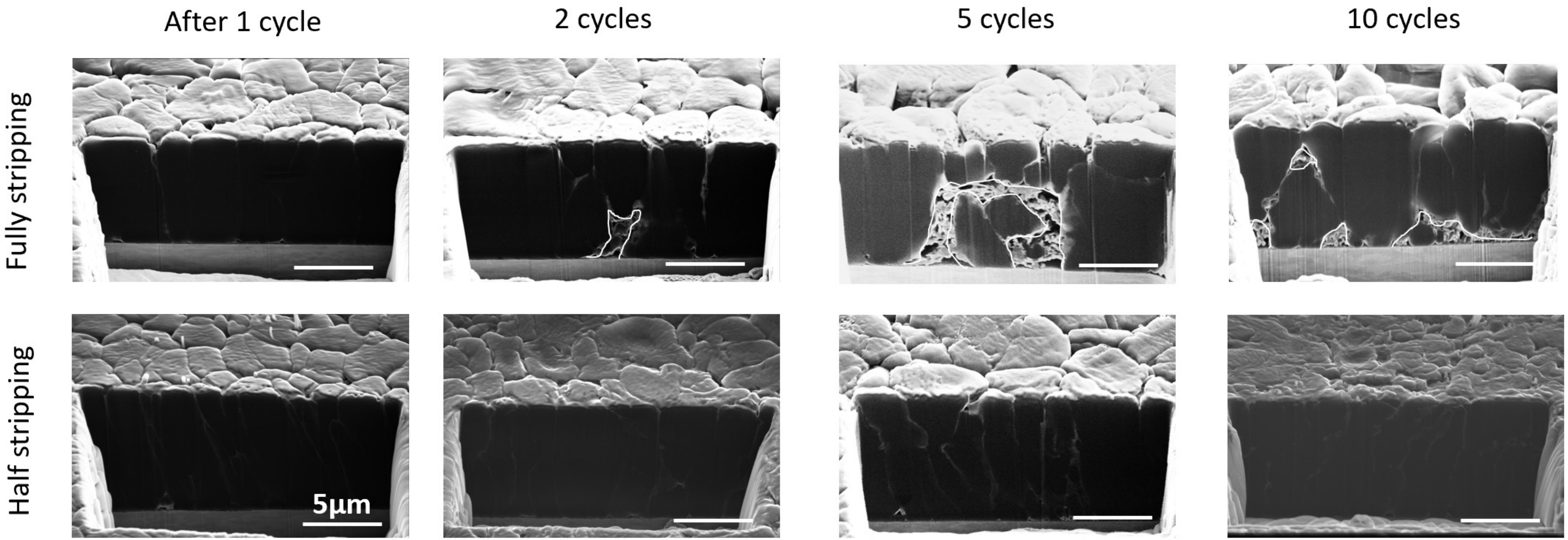
Pressure Effect on Plating Morphology



Top view and cross-sectional SEM images of Li plated under a range of pressure. Scale bar: 2μm

High concentration ether electrolyte
2mA/cm^2; 2mAh/cm^2

Li Reservoir



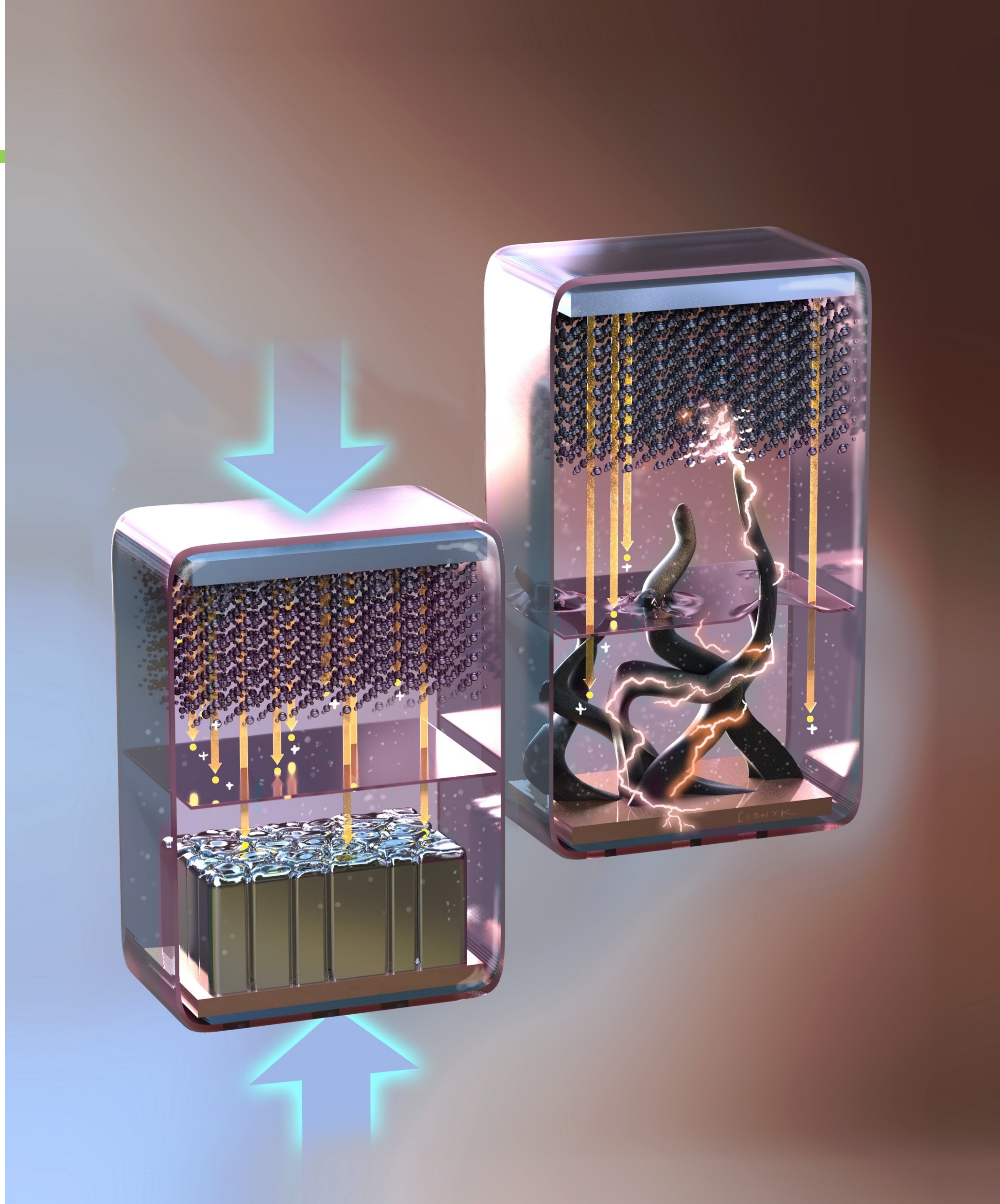
High concentration ether electrolyte

$2 mA/cm^2$; $2 mAh/cm^2$

C. Fang and Y. S. Meng et.al. – Nature Energy, 2021

Li Morphology Determines

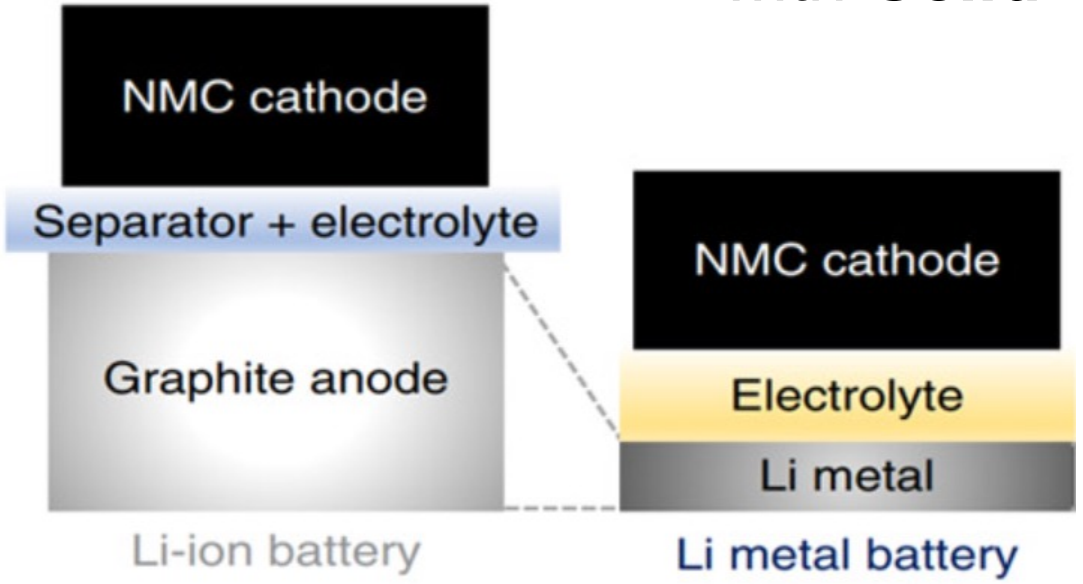
- Fast Charging vs. Fast Discharging
- Self-Discharge Rate
- Safety / Reactivity

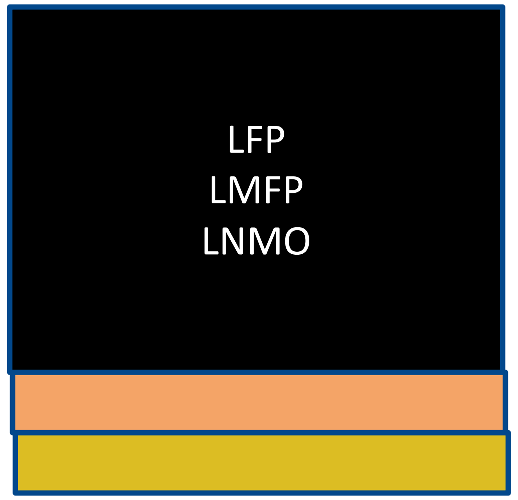


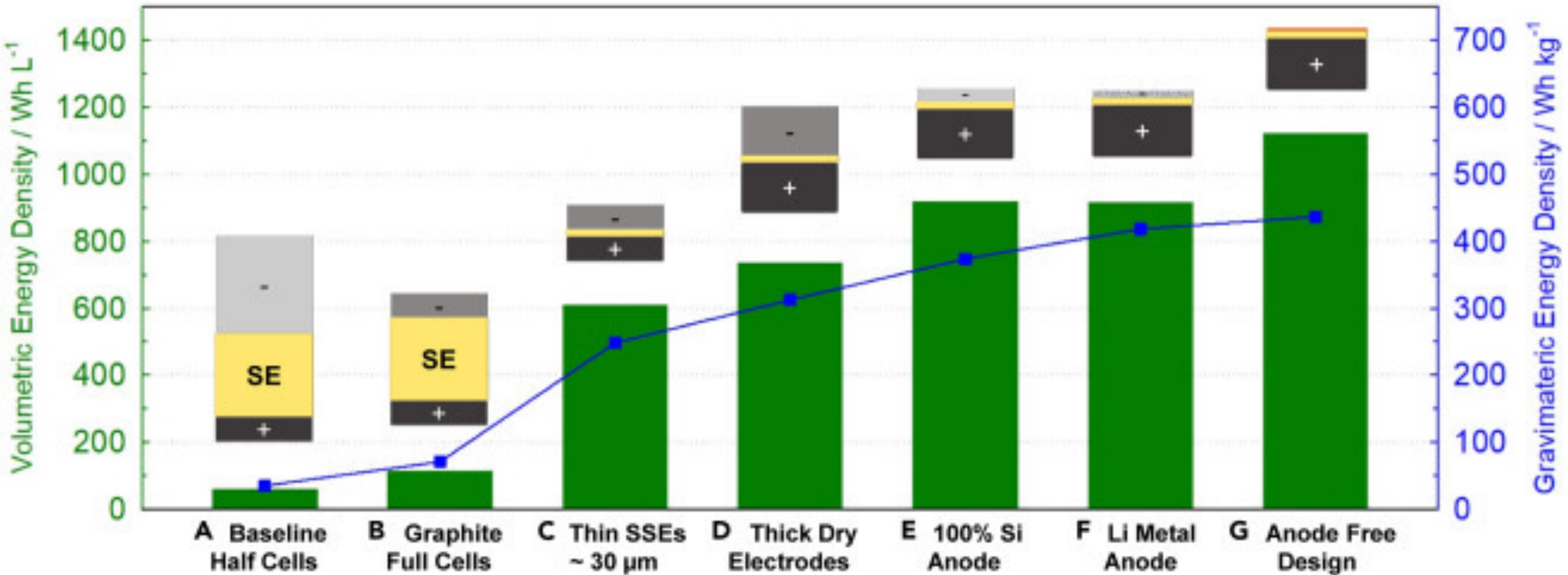
All Solid-State Batteries – Platform Technology

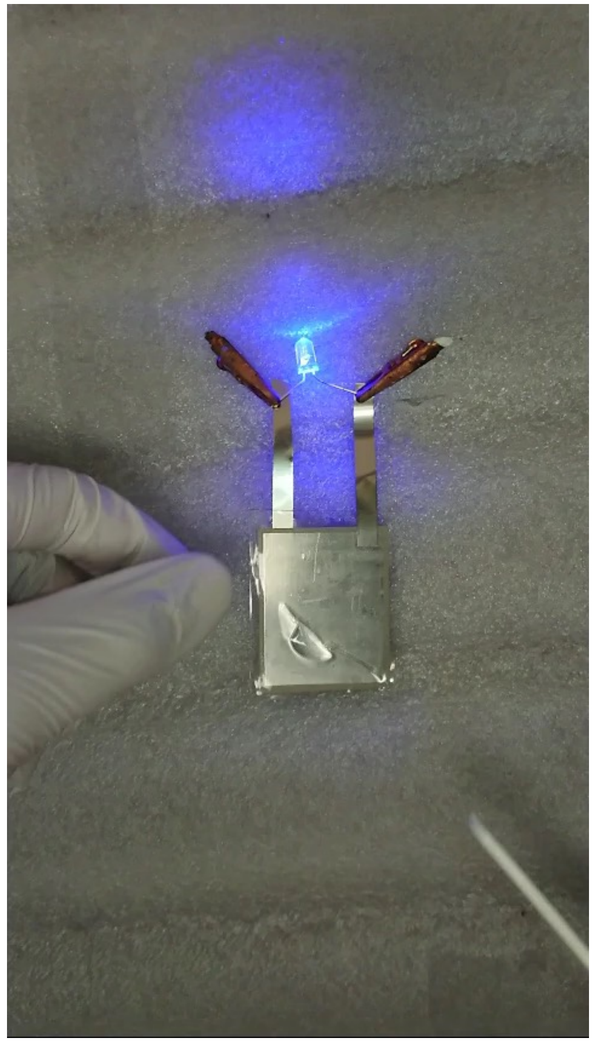
High-Energy-Density *and* ***Safe Batteries***

with ***Solid-State Electrolyte***

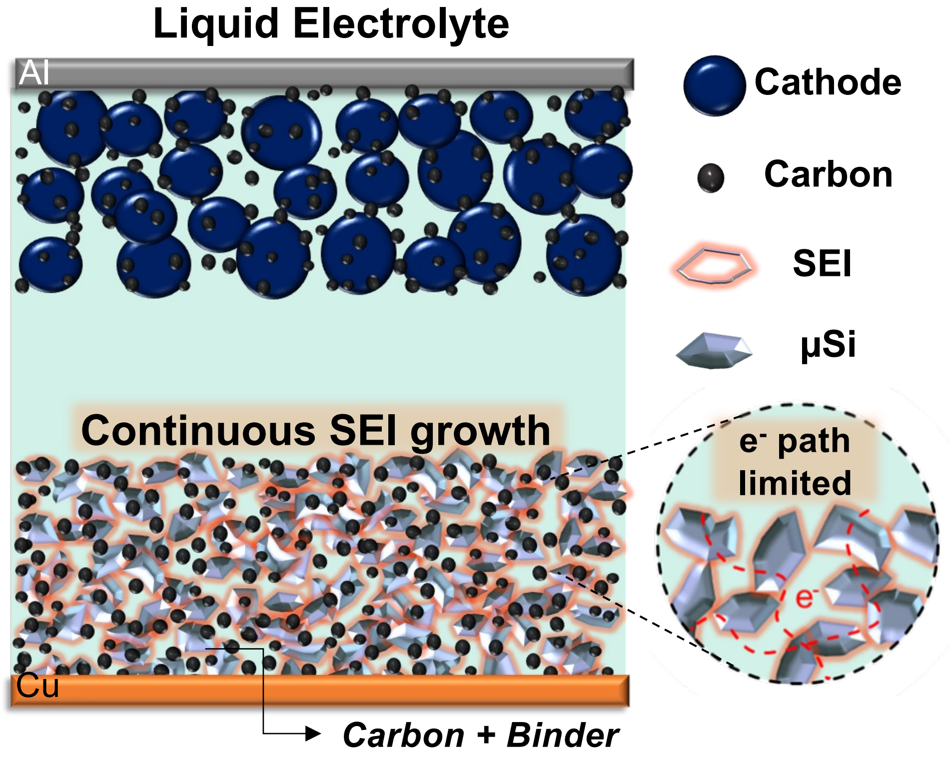




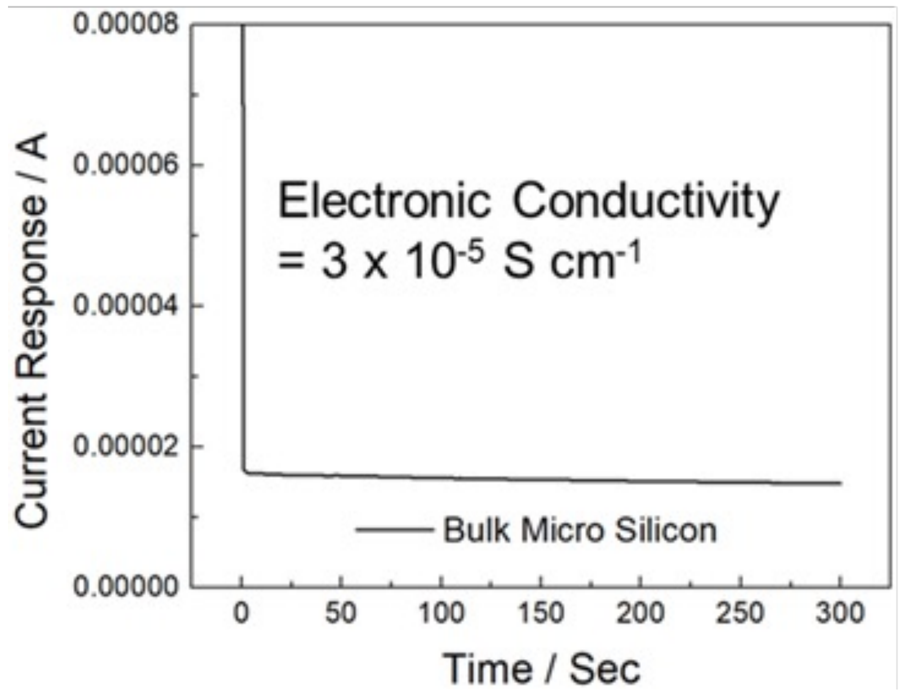


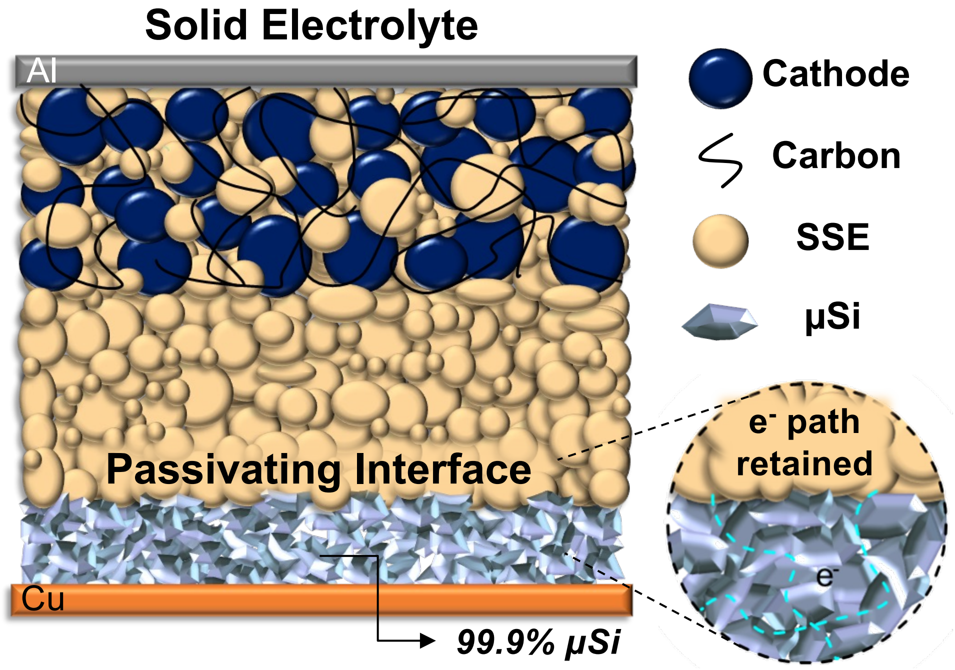


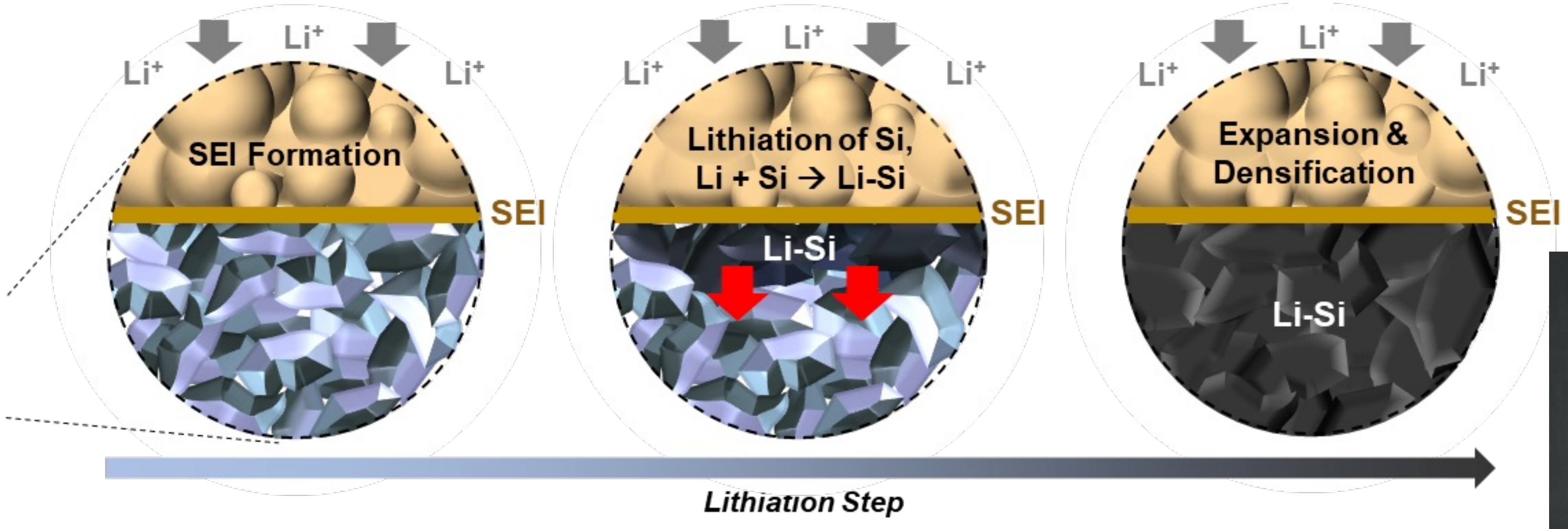
All Solid State Battery with Pure Si Anode



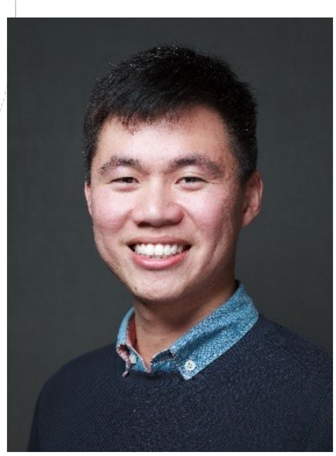
Silicon in Liquid
1. Continuous SEI Growth
   - Trapped Li-Si accumulation
   - Poor calendar life / self discharge
2. Excess carbon + binder (20-40%)
   - Poor specific / volumetric energy





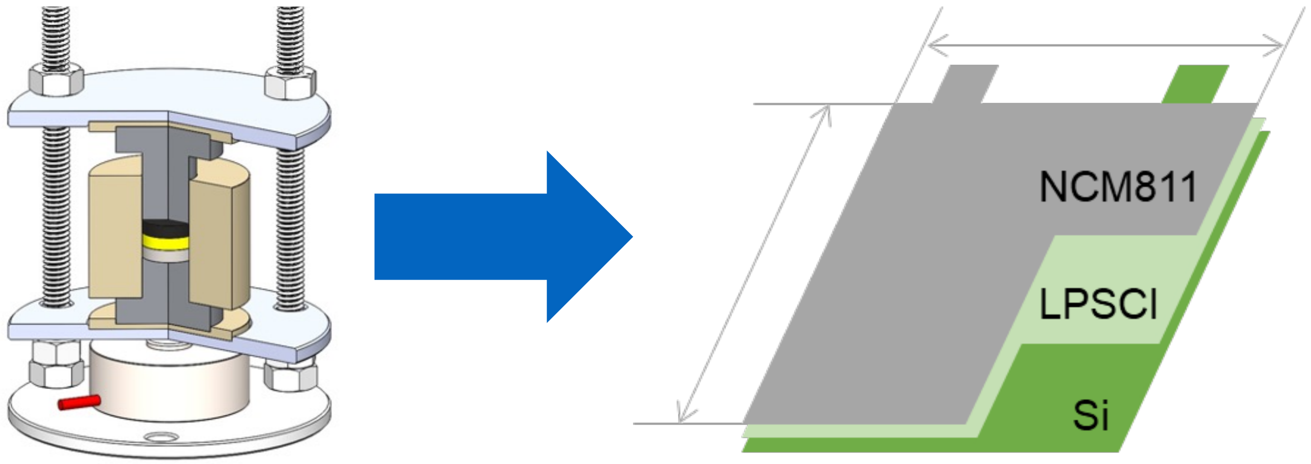


Tan, D.; Meng, Y. S. *et al.*, Carbon Free High Loading Silicon Anodes Enabled by Sulfide Solid Electrolytes for Robust All Solid-State Batteries. (*Science 2021*)



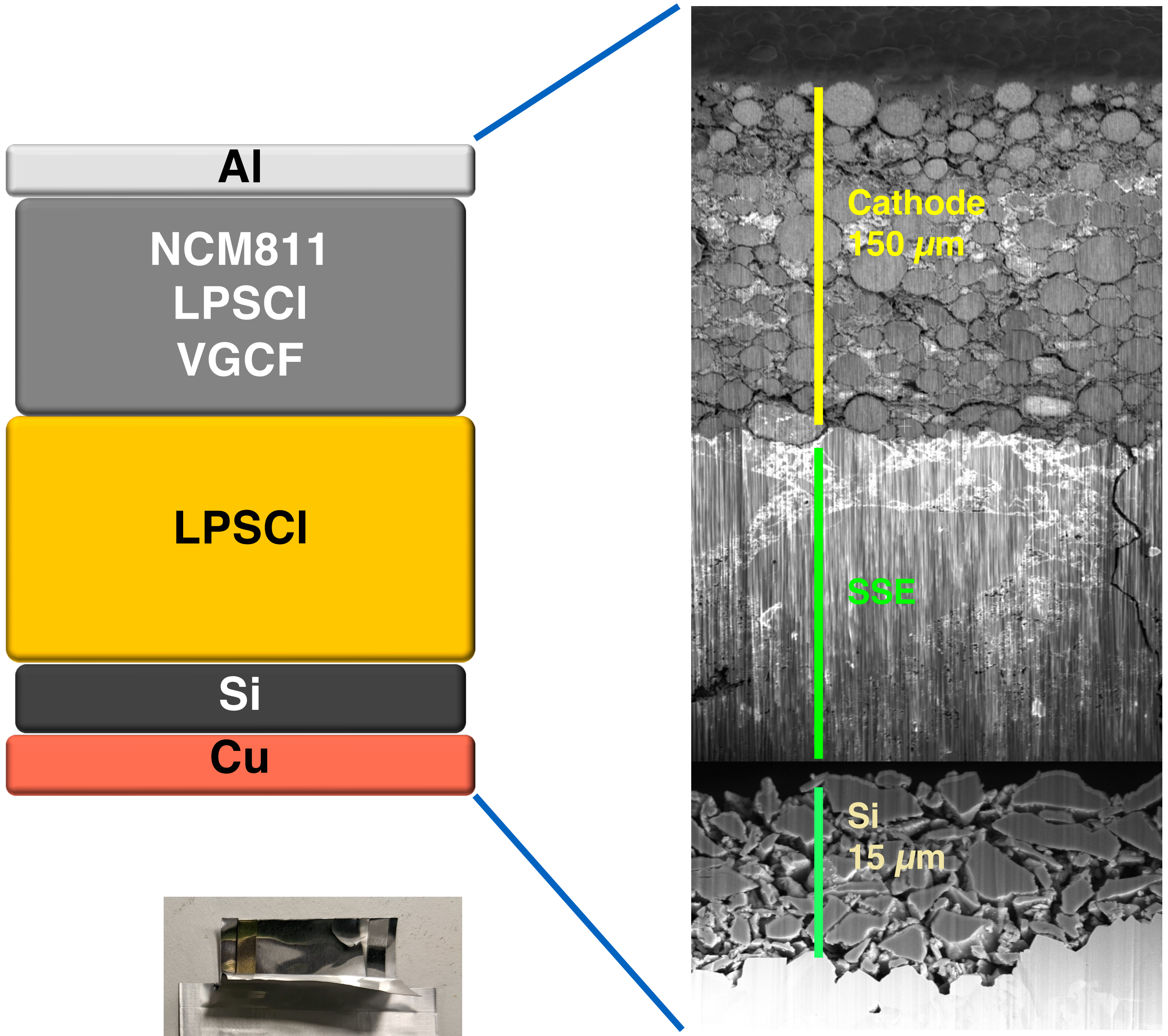
Dr. Darren Tan
CEO of UNIGRID

LGES-UCSD Frontier Research Laboratory



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



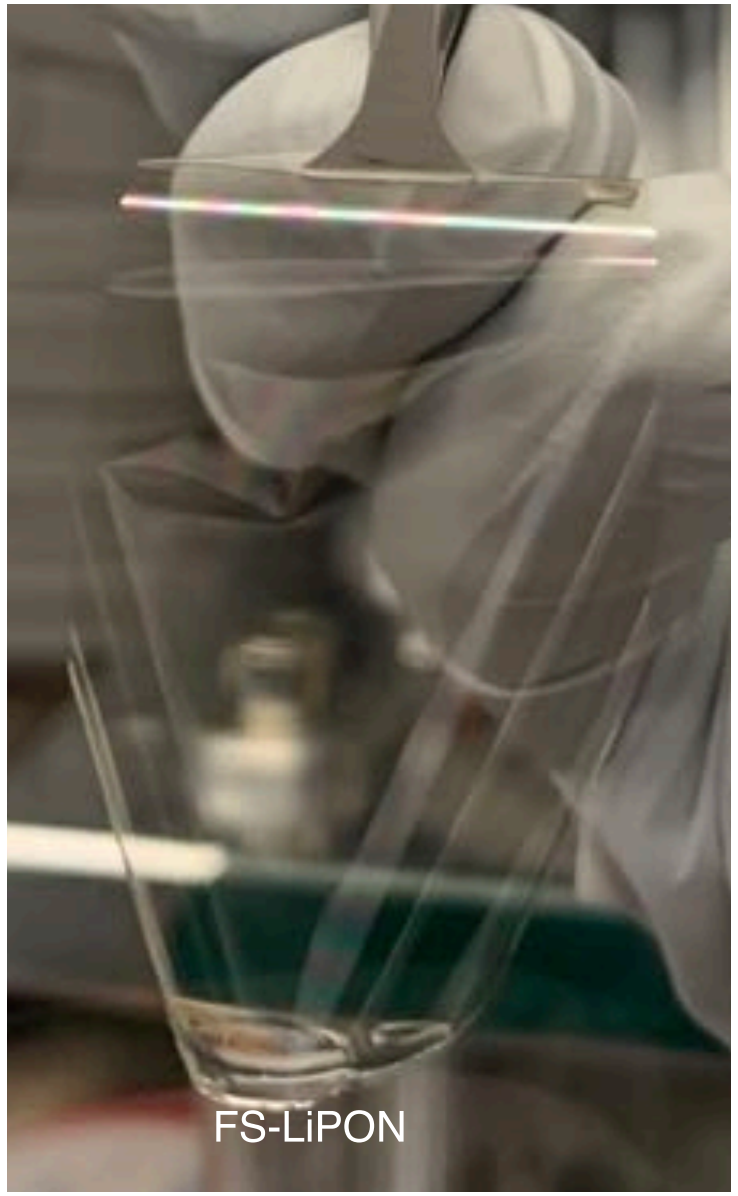
Dr. Yu Ting Chen
(Now at Ampcera)

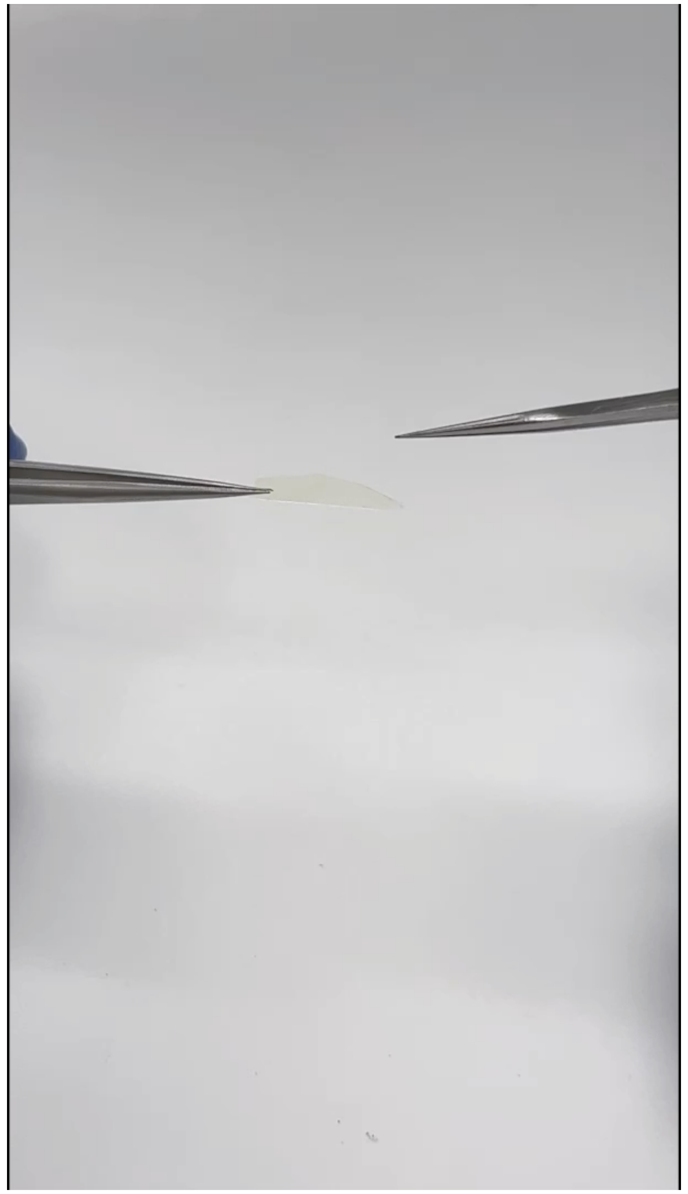
Single layer all-solid-state pouch cell

Unpublished data from Meng group

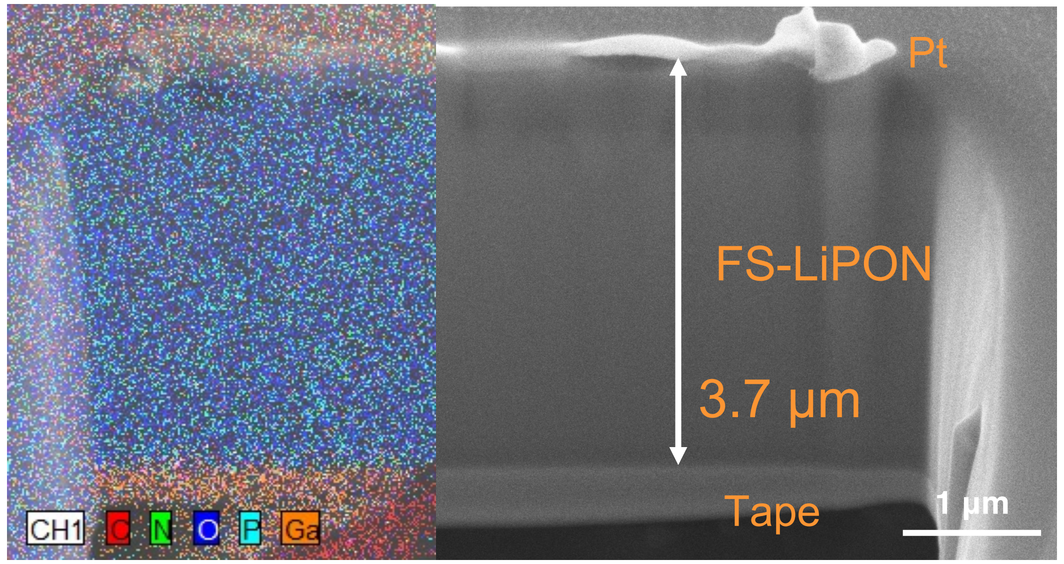
A unique form of LiPON thin film

Free-standing LiPON film

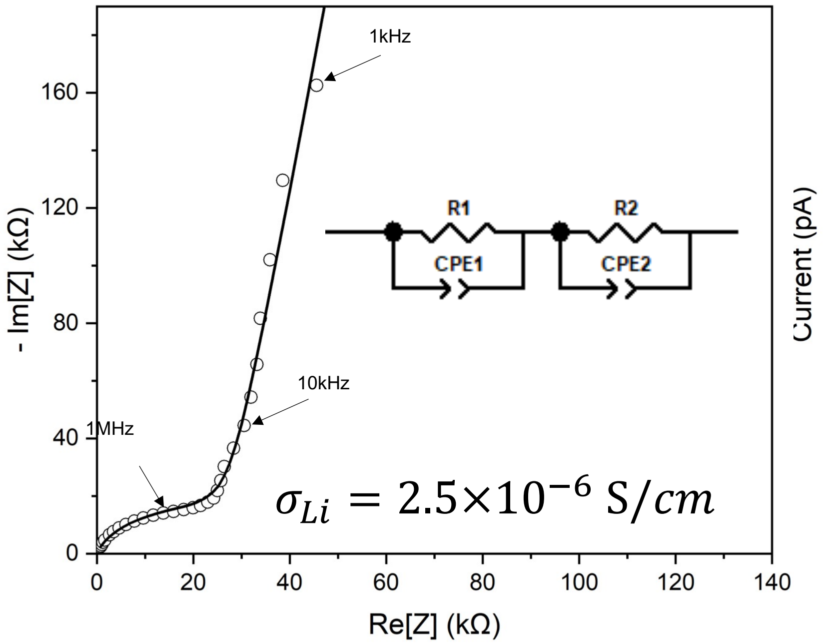


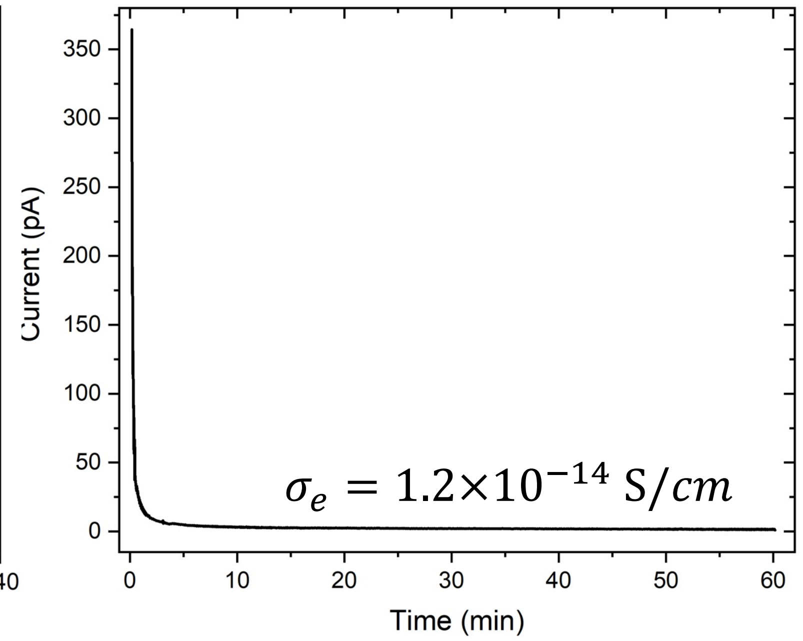


Fully dense solid-state electrolyte



Consistent Li/electron transport characteristic as LiPON



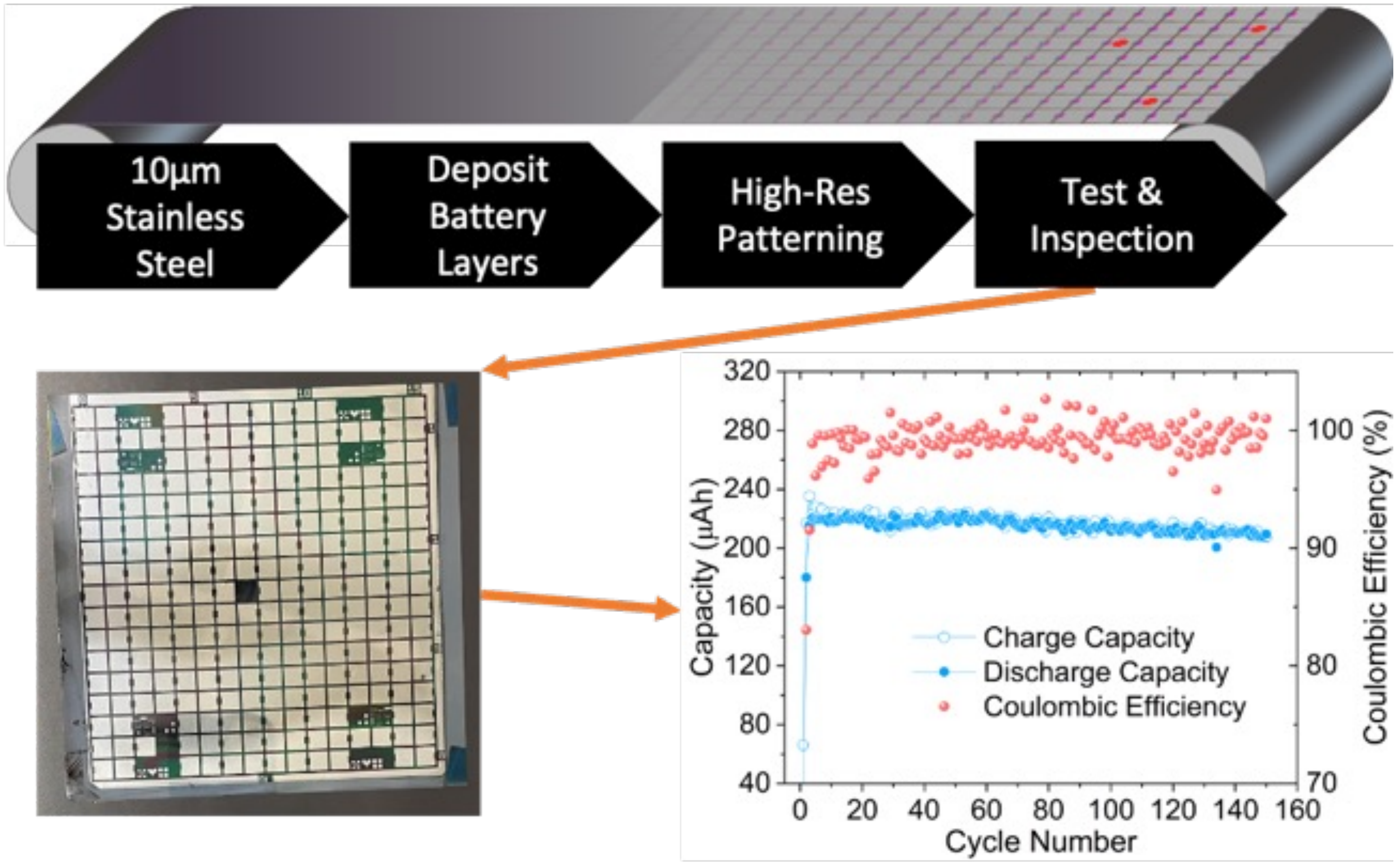


D. Cheng, Y. S. Meng et al. 2023, **Nature Nanotechnology**

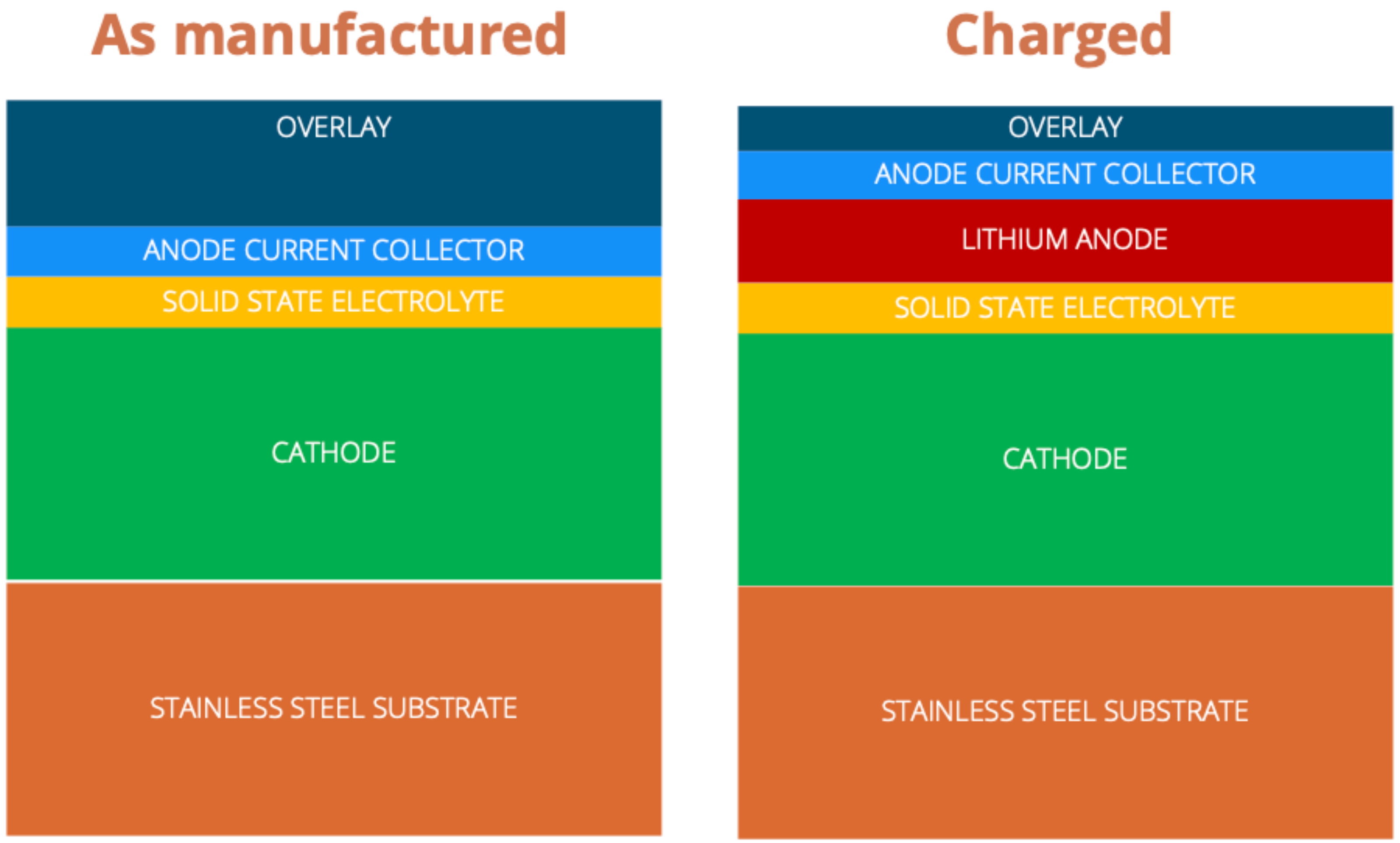
From Basic Science to Breakthrough Innovation

Enabled Free Standing LiPON Film
Pressure free dense Li plating

Thin Film Battery (Ensurge) – Anode Free Micro-Battery



ENSURGE™



D. Cheng, K. Tran, S. Rao, Z. Wang, R. van der Linde, S. Pirzada, H. Yang, A. Yan, A. Kamath, and Y. S. Meng, " Manufacturing Scale-Up of Anodeless Solid-State Lithium Thin-Film Batteries for High Volumetric Energy Density Applications", *ACS Energy Letters*, 2023, 8, 11, 4768–4774

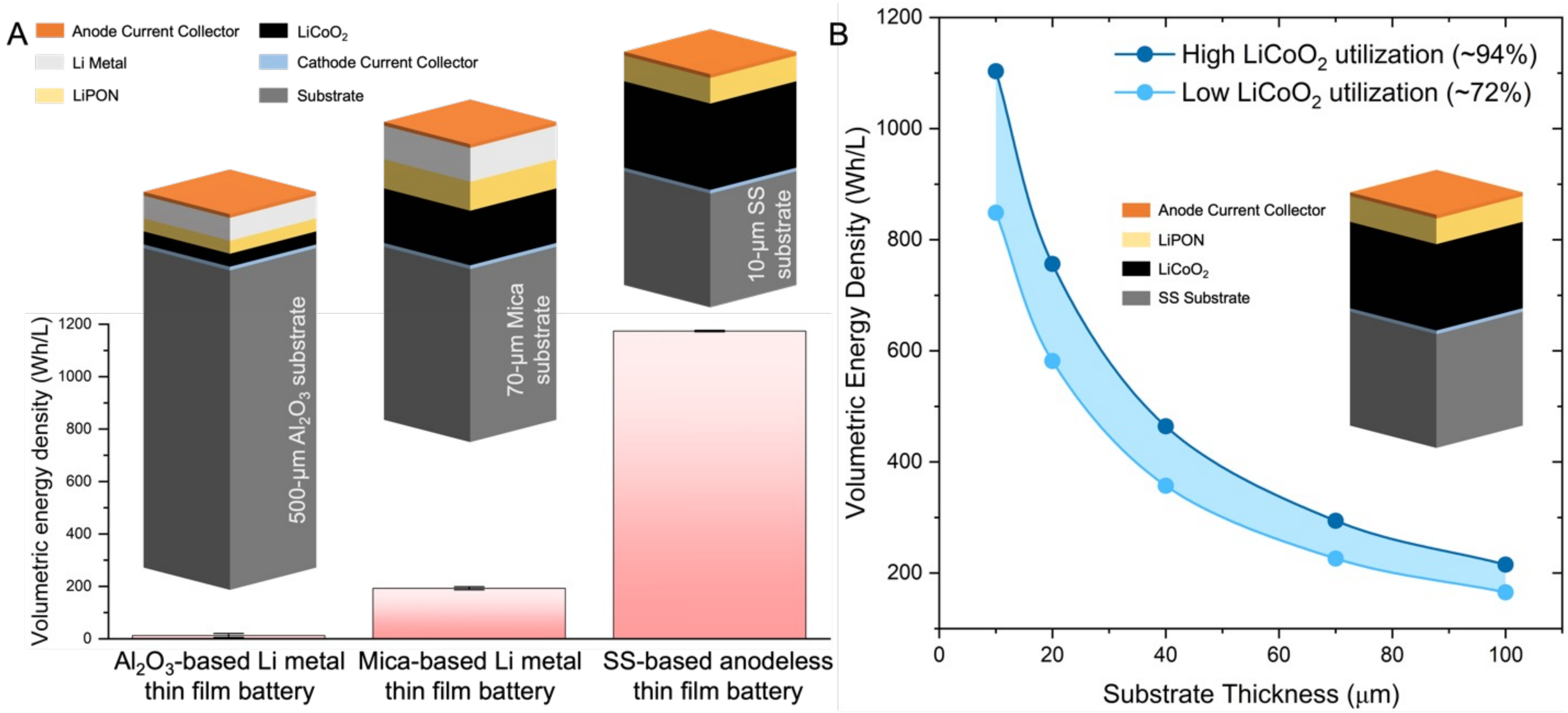
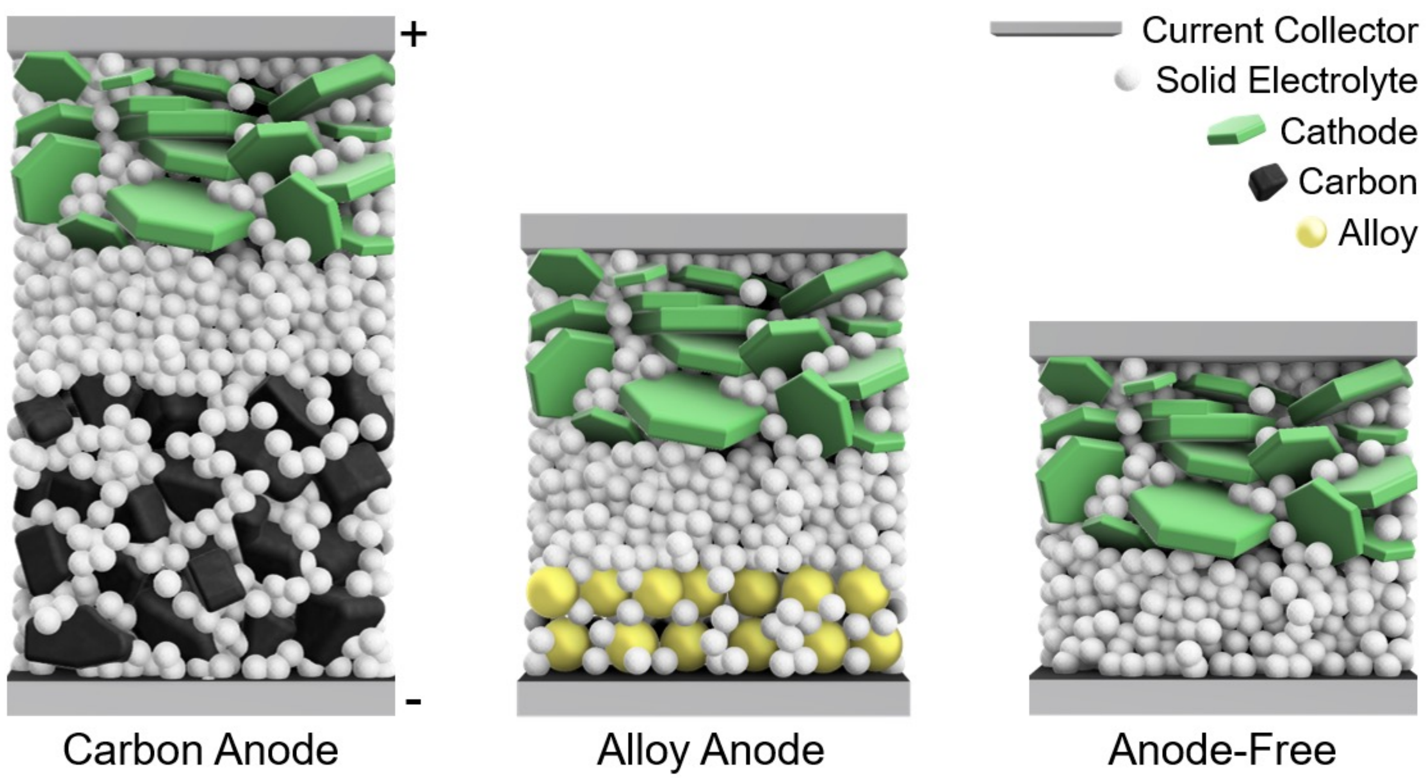


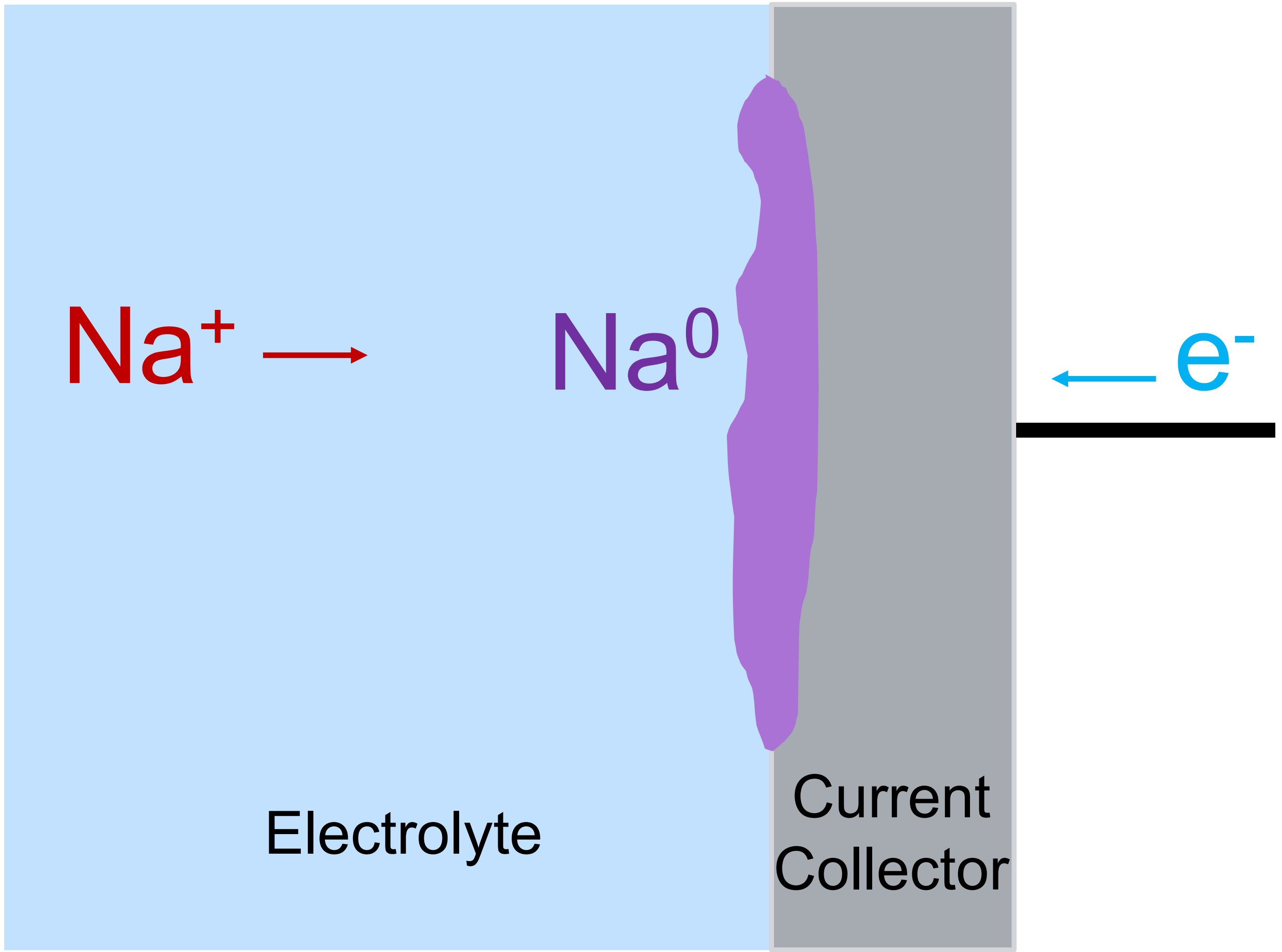
Figure 1. (A) Schematics of Li metal thin film batteries with different cell architectures and corresponding VEDs. (B) VEDs of SS-based anodeless thin film battery with varying SS thicknesses

D. Cheng, K. Tran, S. Rao, Z. Wang, R. van der Linde, S. Pirzada, H. Yang, A. Yan, A. Kamath, and Y. S. Meng, "Manufacturing Scale-Up of Anodeless Solid-State Lithium Thin-Film Batteries for High Volumetric Energy Density Applications", *ACS Energy Letters*, 2023, 8, 11, 4768–4774

Anode Selection → Anode-Free

"**Anode-Free**": Na/Li metal is directly deposited onto the current collector surface





G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", *ChemRxiv. Cambridge: Cambridge Open Engage;* 2023

Sodium Anode-Free Solid-State Batteries

G. Deysher, J.A.S. Oh, ... Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", *ChemRxiv. Cambridge: Cambridge Open Engage;* 2023

Can achieve 3 goals simultaneously…

1. Maximize energy density

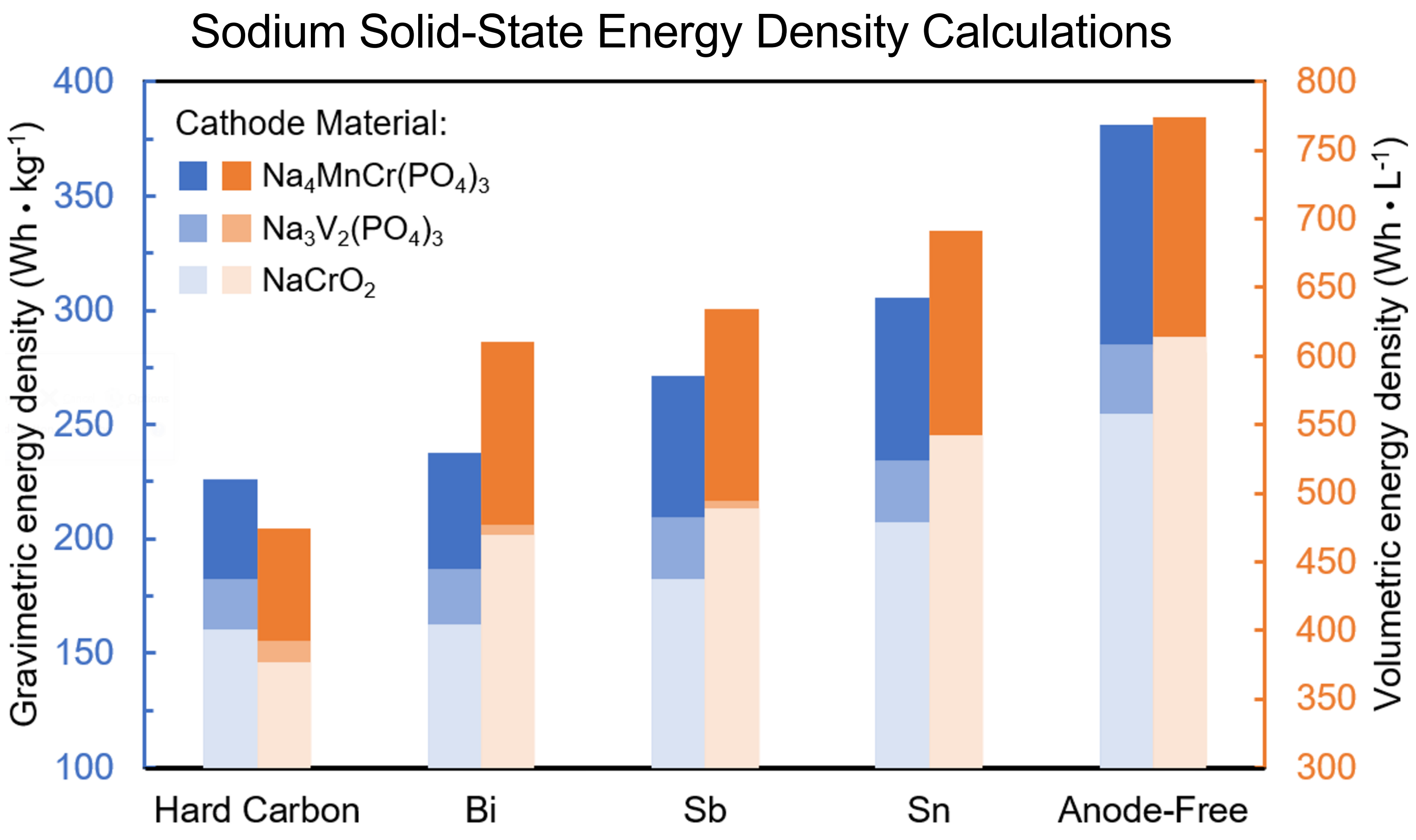
- Lowest reduction potential → highest cell voltage
- Smaller and lighter cells

2. Minimize cost

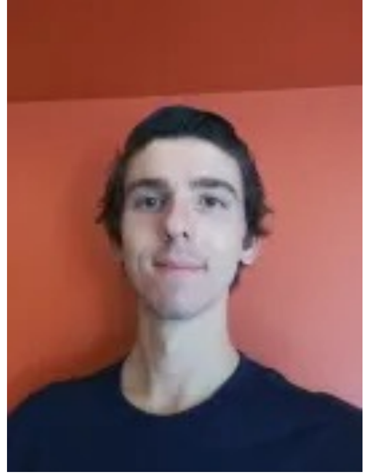
- No anode material cost, lower processing cost
- Sodium cheaper than Lithium

3. Improved safety

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

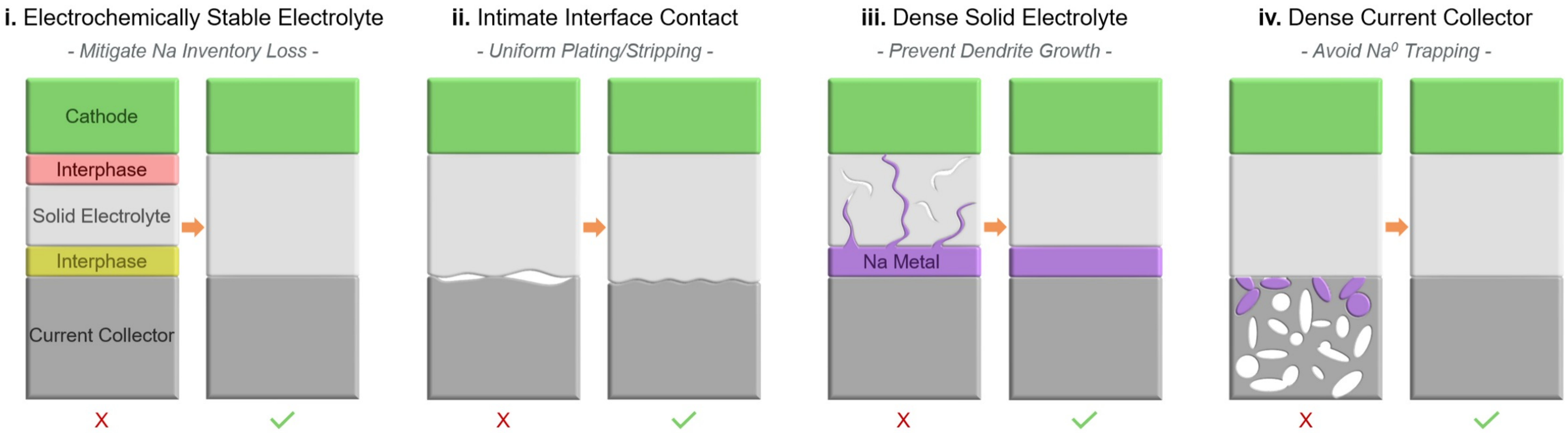


Critical Design Factors


Grayson Deysher

G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", *ChemRxiv. Cambridge: Cambridge Open Engage;* 2023

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



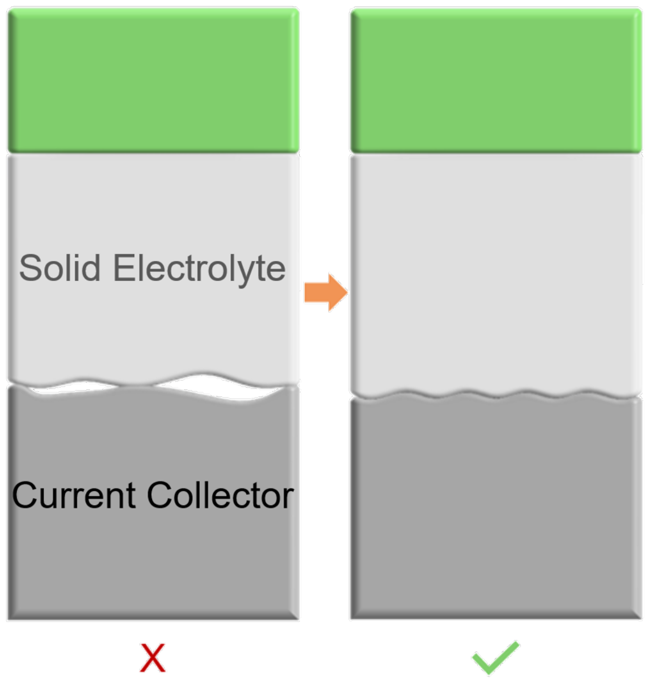
- Must design a cell from the ground up
  - Material selection and cell architecture

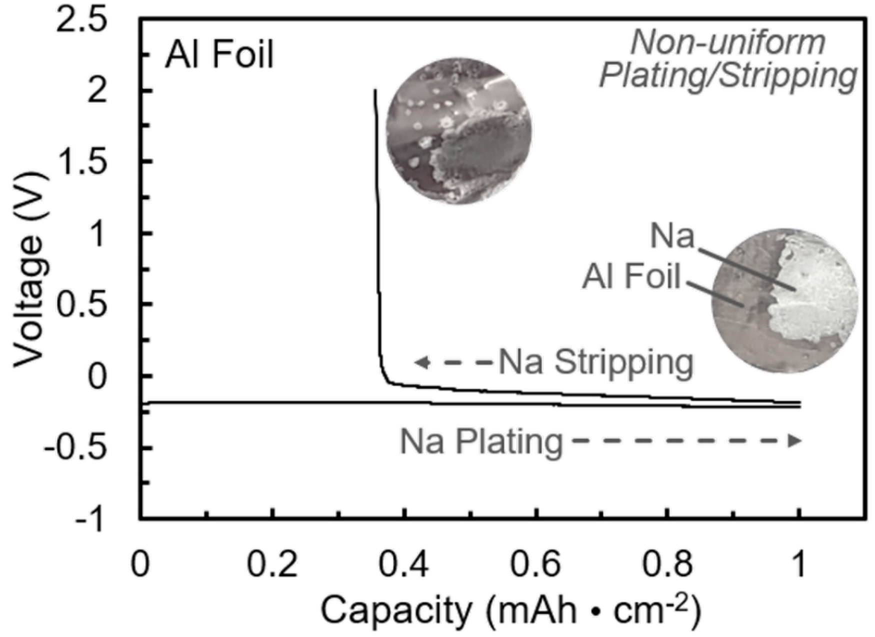
Intimate Interface Contact

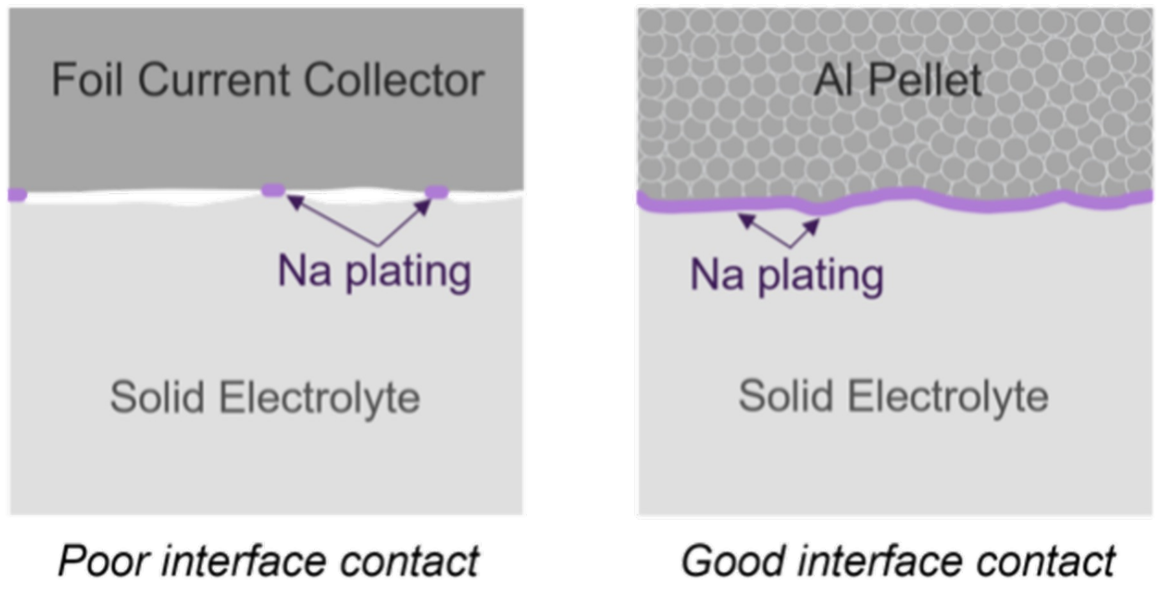
G. Deysher, J.A.S. Oh, … Y.S. Meng, “ An Anode-Free Sodium All-Solid-State Battery “, *ChemRxiv. Cambridge: Cambridge Open Engage;* 2023

ii. Intimate Interface Contact

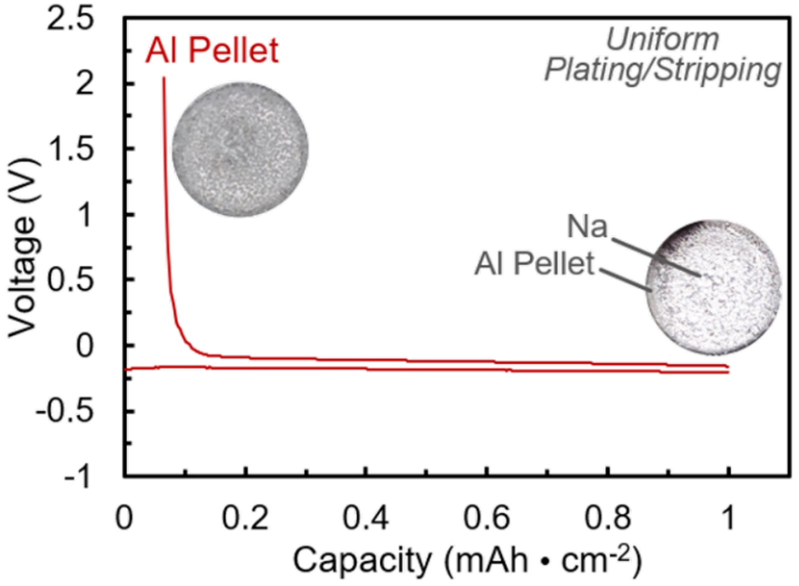
- Uniform Plating/Stripping -



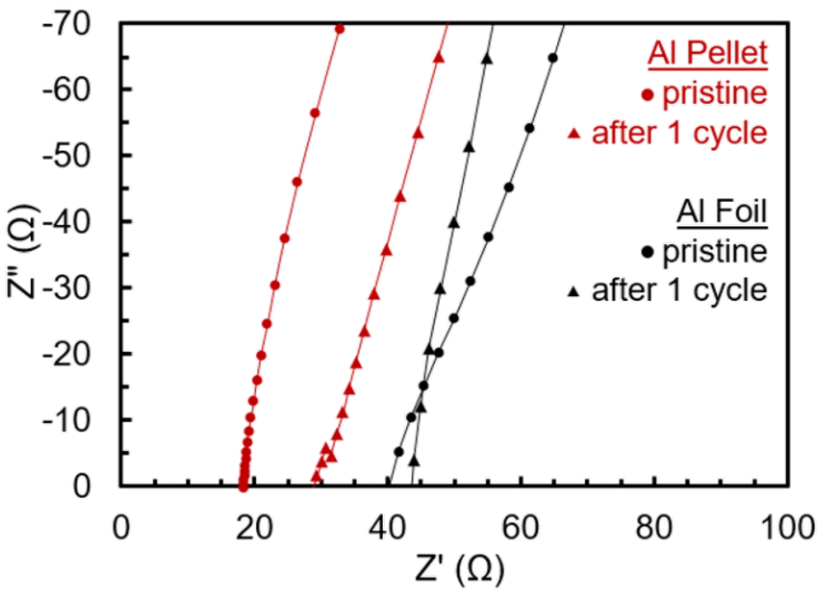


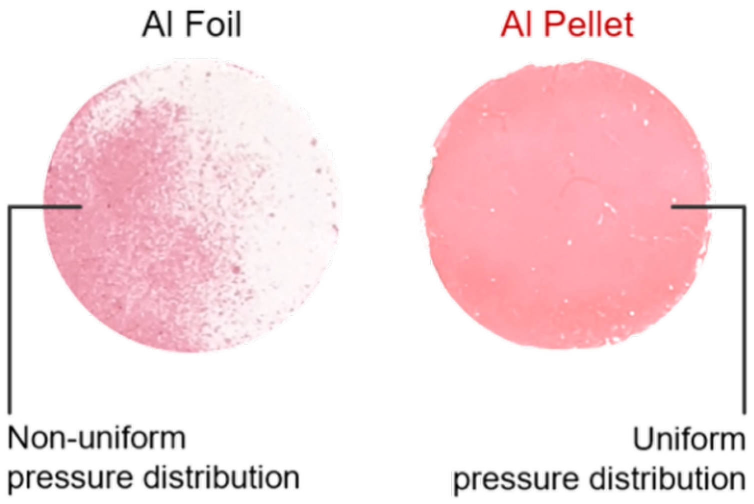


- Pelletized Al can achieve intimate contact with the NBH electrolyte



Al Pellet = Lower interface resistance



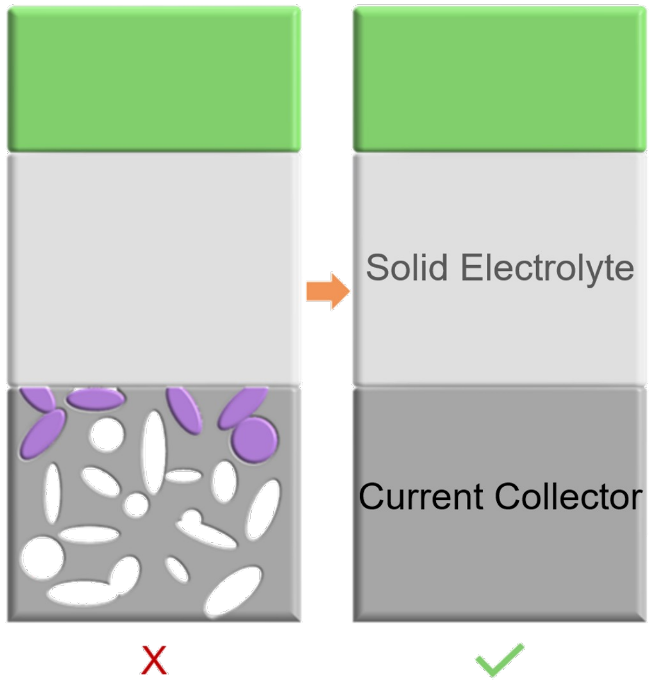


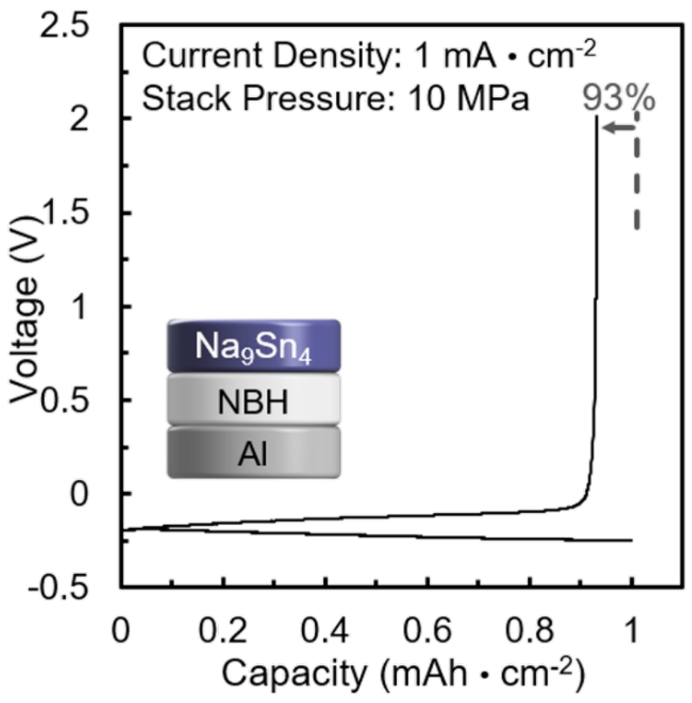
Designed Dense Current Collector

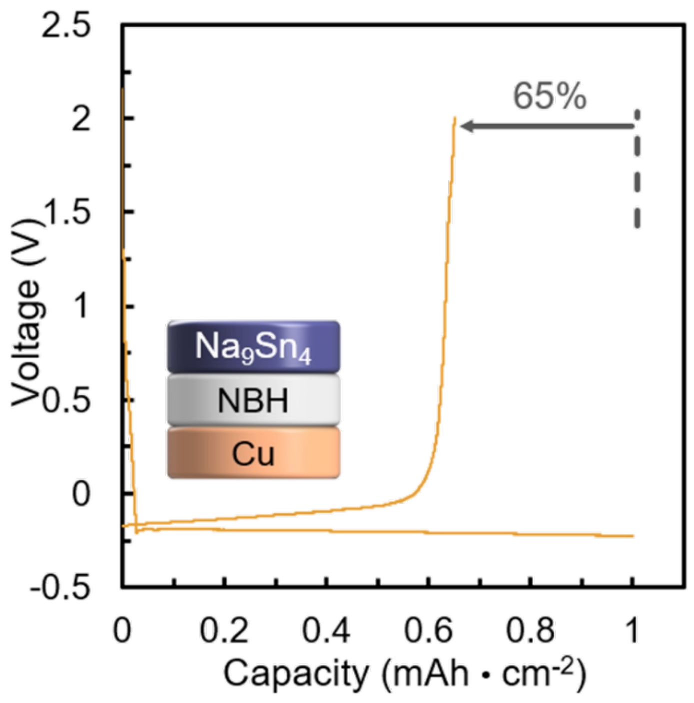
G. Deysher, J.A.S. Oh, … Y.S. Meng, "An Anode-Free Sodium All-Solid-State Battery", *ChemRxiv.;* 2023, Patent Pending

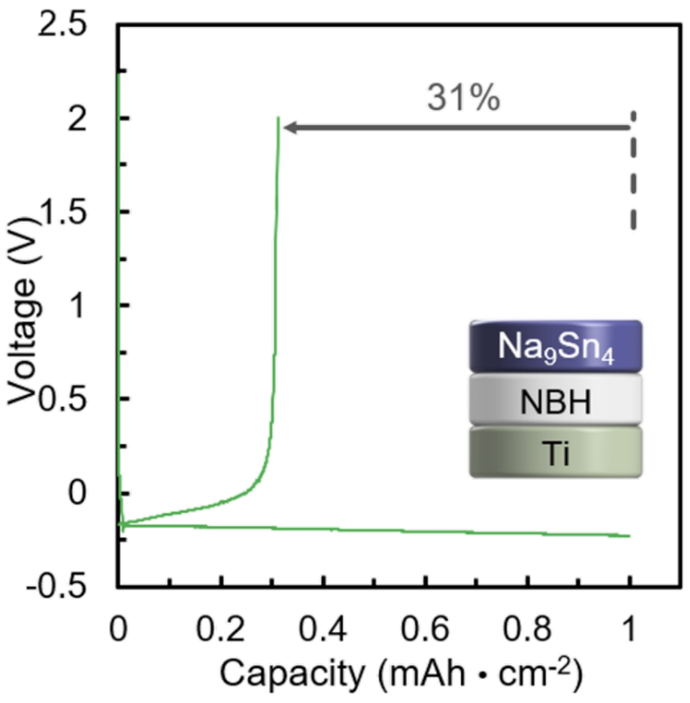
iv. Dense Current Collector

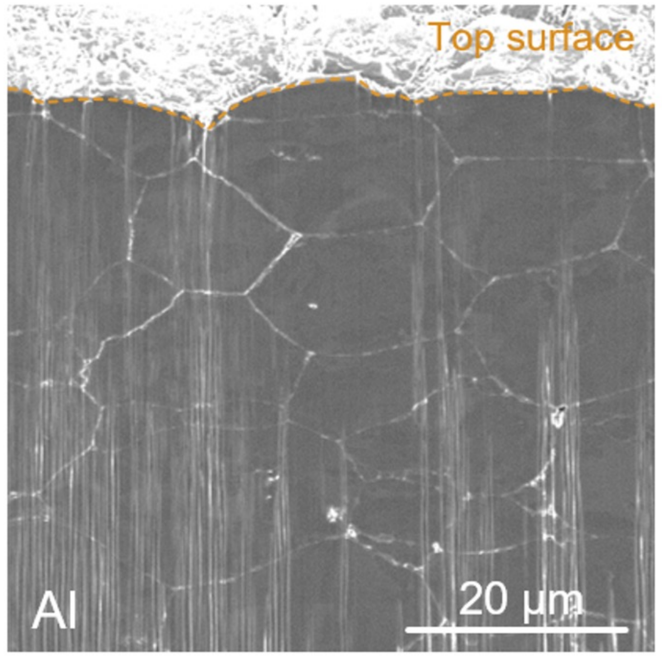
- Avoid Na^0 Trapping -

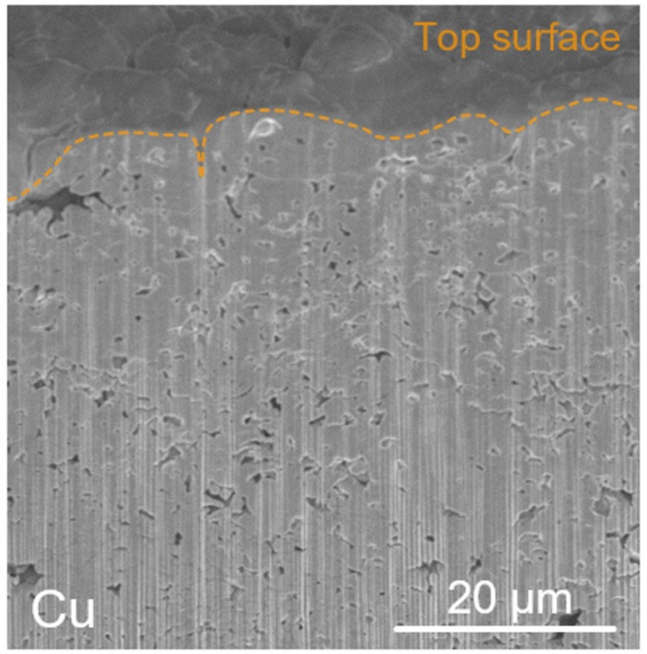


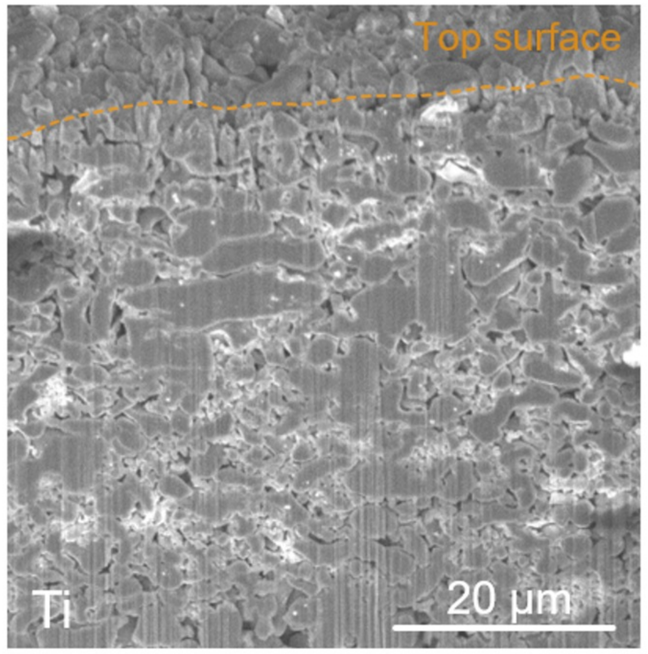








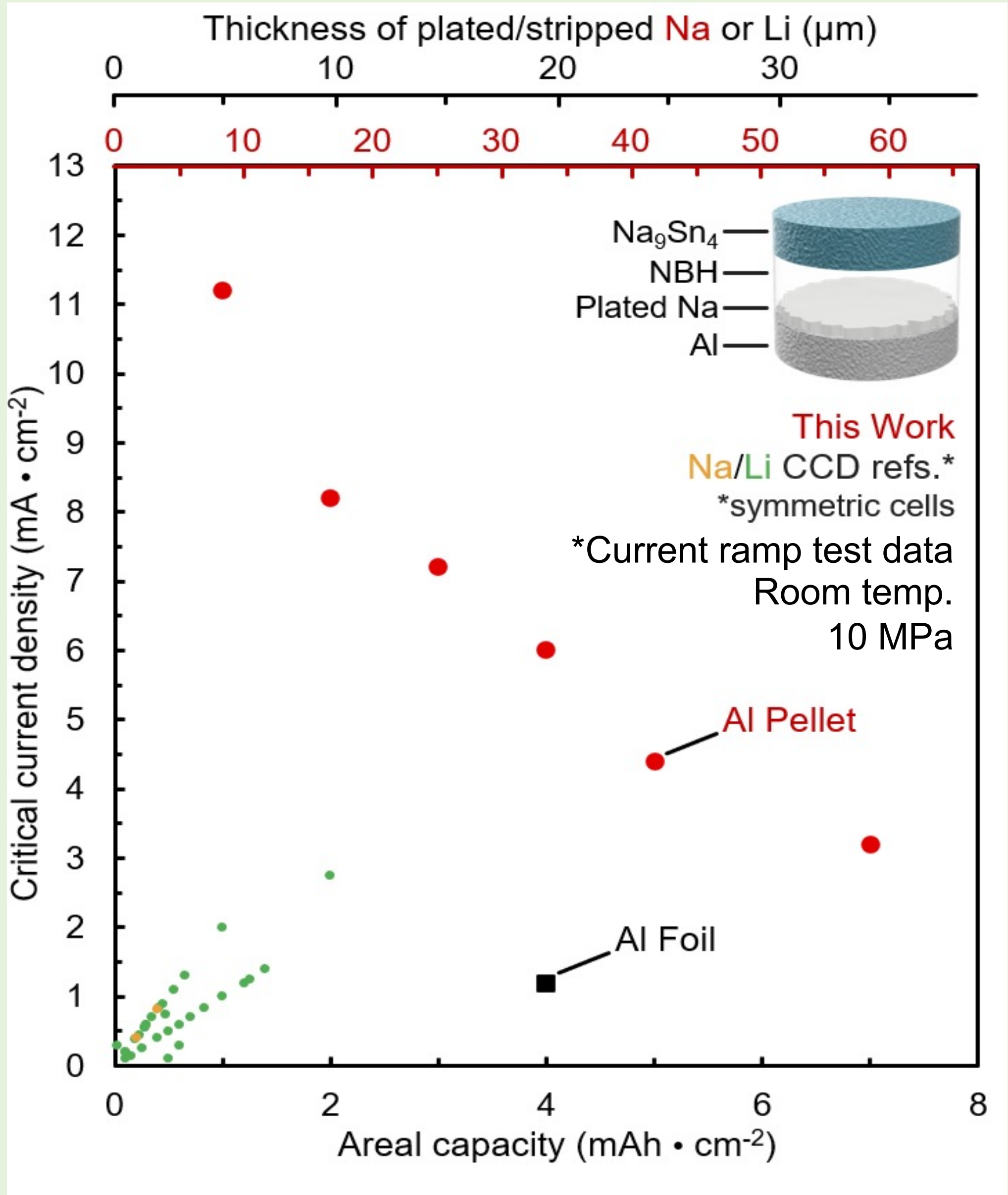




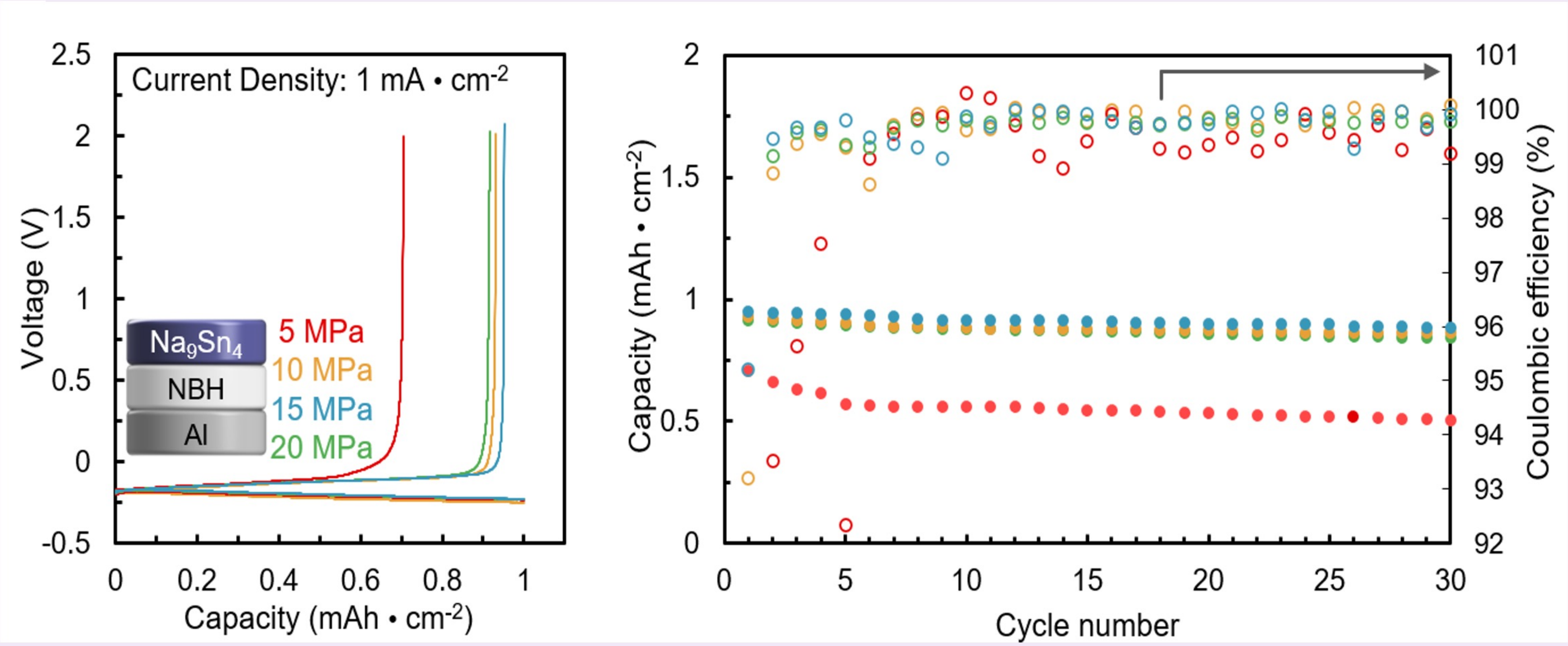
- Soft Al can be easily densified during cell fabrication ✓
  - Unlike Cu and Ti

G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", *ChemRxiv.;* 2023, Patent Pending

Current Density



Cell Stack Pressure

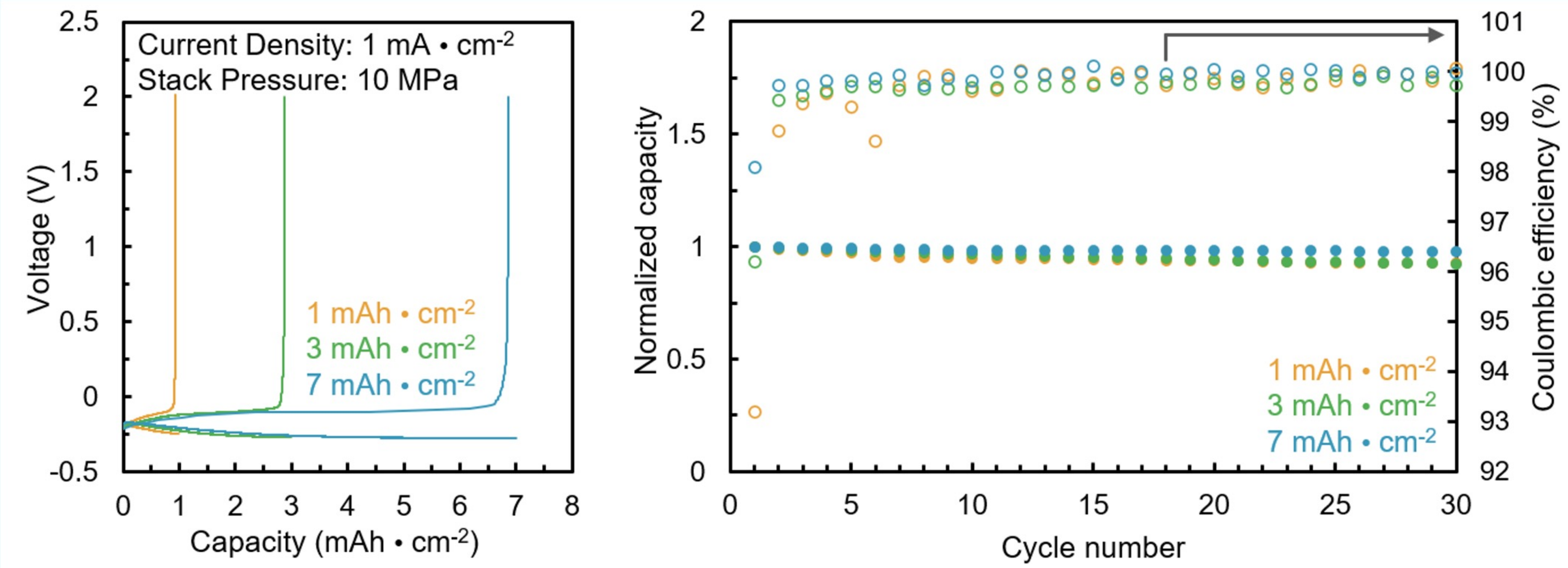


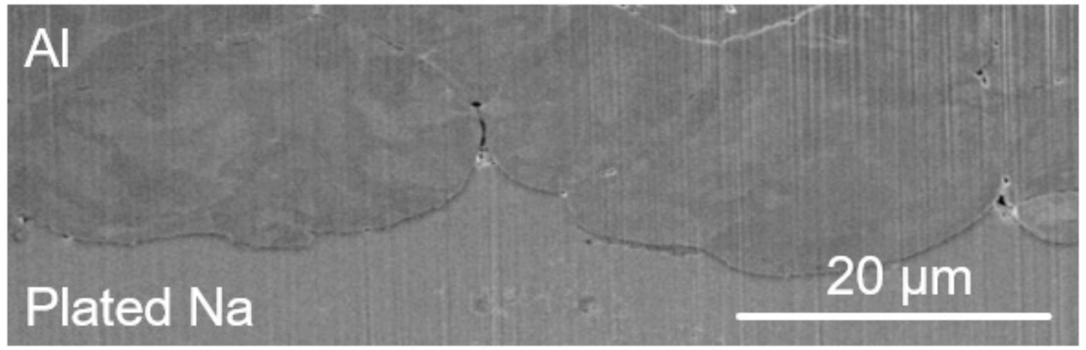
- High critical current density
  - Pathway to fast charging
- Low pressure cyclability
  - Pathway to practical commercial cells

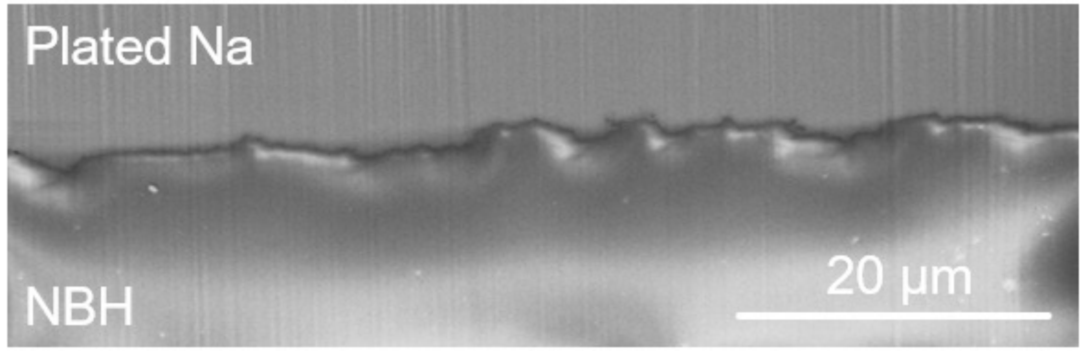
Pushing the Limits of Cell Performance

G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", *ChemRxiv.*; 2023, Patent Pending

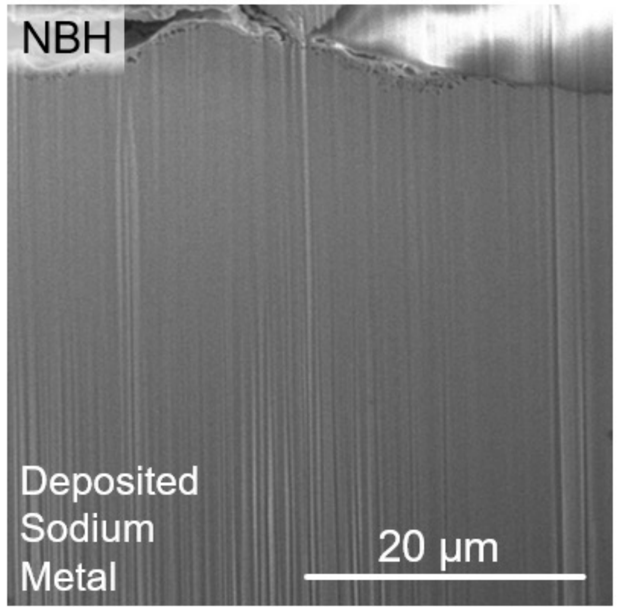
Areal Capacity

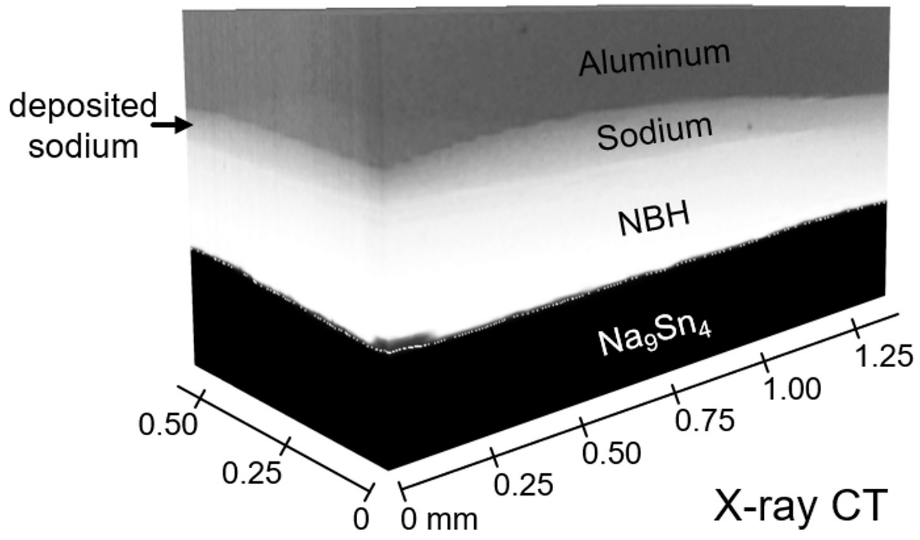






- Can cycle up to 7 mAh/cm^2 (60 microns)!
  - Intimate interfaces and dense sodium observed with cryo-FIB
  - Uniform plating observed with X-ray CT
- Cyclability is not a function of capacity

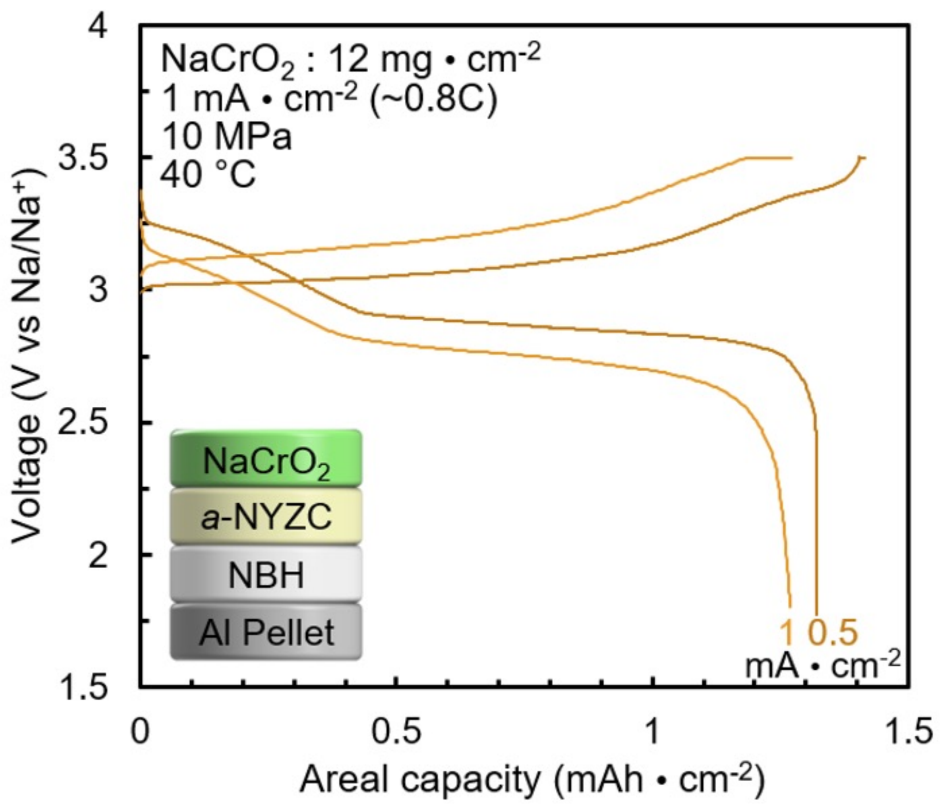


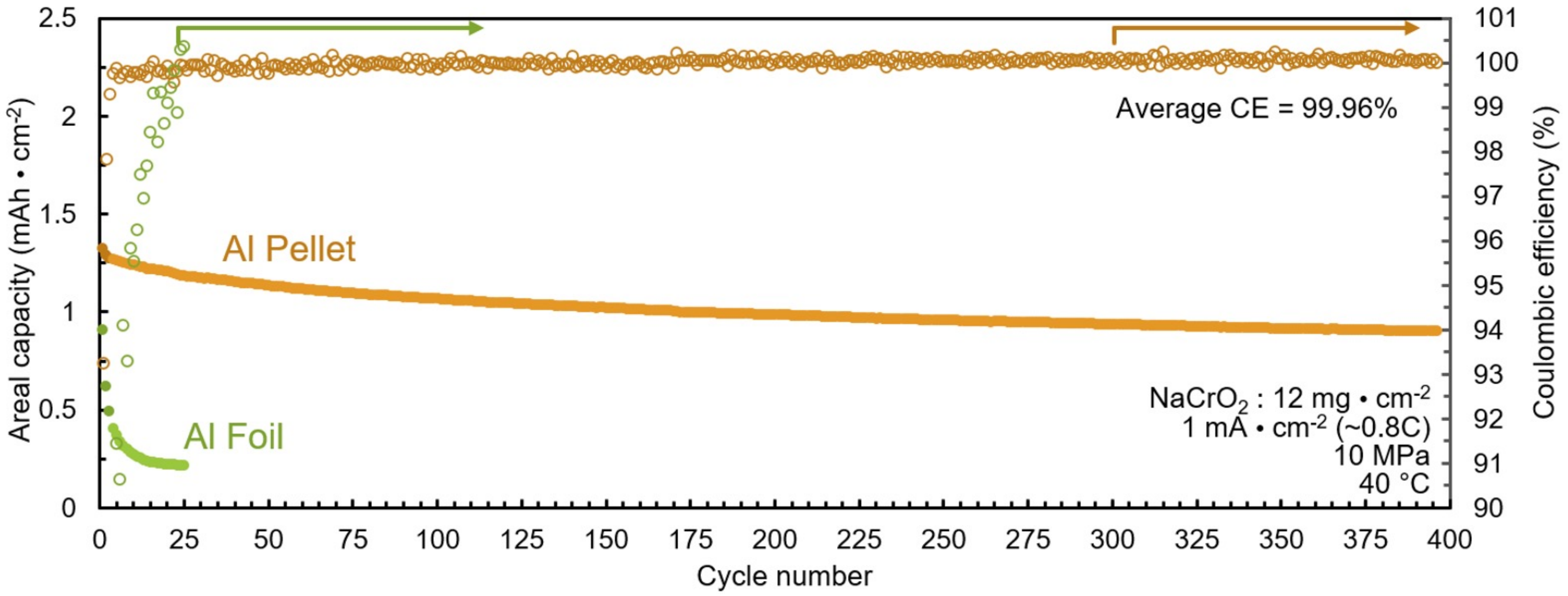


Sodium Anode-Free Solid-State Full Cell

G. Deysher, J.A.S. Oh, … Y.S. Meng, " An Anode-Free Sodium All-Solid-State Battery ", *ChemRxiv.;* 2023, Patent Pending

- Need to enable full-cell cycling ($NaCrO_2$ cathode)





- High Coulombic efficiency and stable cycling
- Significantly improved compared to traditional foil current collector

Acknowledgements

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NSF
Solid State Sodium Battery

LG Energy Solution
LGES-UCSD Frontier Research Laboratory

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ThermoFisher SCIENTIFIC
Workflow design for battery
Next-gen Cryo EM for Energy and Quantum materials
Falcon Camera etc.

Sustainable Power and Energy Center

KJ GROUP
Battery Prototyping

sdni San Diego Nanotechnology Infrastructure

nano3 SCIENCE ENGINEERING MEDICINE

UC IRVINE MATERIALS RESEARCH INSTITUTE

Solid State Battery Team at LESC group