From Zincate Restoration to HER-Resistant MnTe: Stabilizing Anodes for Aqueous Energy Storage

Nian Liu

Associate Professor

School of Chemical and Biomolecular Engineering

Georgia Institute of Technology

nian.liu@chbe.gatech.edu

Presentation # 1004

DOE OE Energy Storage Peer Review & Annual Meeting, 2026

Georgia Tech

Project Overview

- Goal: Develop safe, low-cost, high-energy aqueous Zn and Mn batteries by stabilizing reactive metal anodes in nonflammable water-based electrolytes.
- Current Practice: Conventional aqueous metal batteries rely largely on Zn/Mn chemistries or direct metal plating/stripping, but suffer from active-material loss, passivation, hydrogen evolution, short cycle life, and limited practical energy.
- Why Georgia Tech / Liu Lab: We combine nanoscale electrode design, aqueous battery testing, and advanced characterization, strengthened by collaborations with Sandia and DOE user facilities.
- Innovation: We regulate where metal redox occurs: Ag-seeded carbon nanoshells restore escaped zincate in Zn anodes, while MnTe alloying suppresses HER and enables phase-mediated Mn redox.
- Duration: FY25-FY26; value delivered this year includes two completed anode platforms, mechanistic validation, low-temperature Zn discharge, and full-cell/AA-format demonstrations.
- Impact: This work advances safer and lower-cost rechargeable aqueous batteries for grid backup, resilient infrastructure, and scalable energy storage using earth-abundant materials.
- Vertical/Investment Area: Materials and Systems Innovation; Safety & Reliability.
- Alignment/Supports strategic pathway: Supports DOE OE goals to stabilize grid services and grow grid capacity through durable, nonflammable, and domestically scalable storage technologies.

Project Team (started Jan 2025)



Prof. Nian Liu
Georgia Tech



Dr. Zhitao Chen
Georgia Tech



Dr. Jieun Kang
Georgia Tech



Dr. Timothy N. Lambert
Sandia



Dr. Jason Huang
Sandia



Dr. Calvin D. Quilty
Sandia

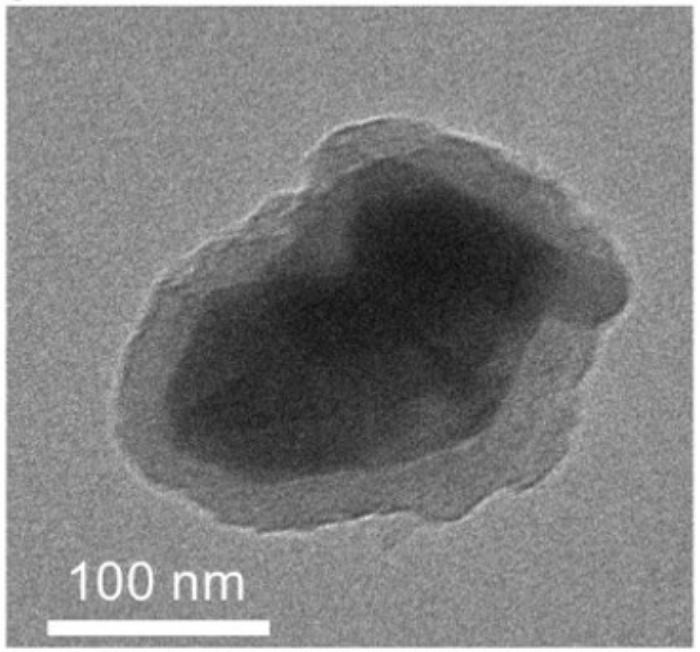


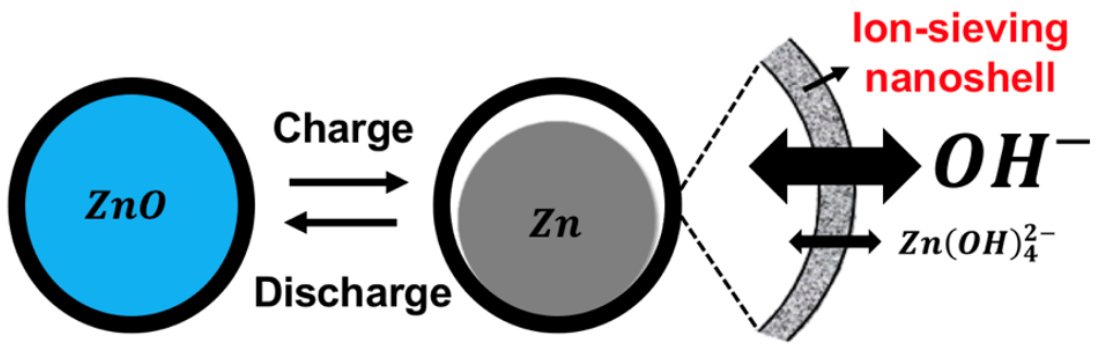
Dr. Quinn Campbell
Sandia

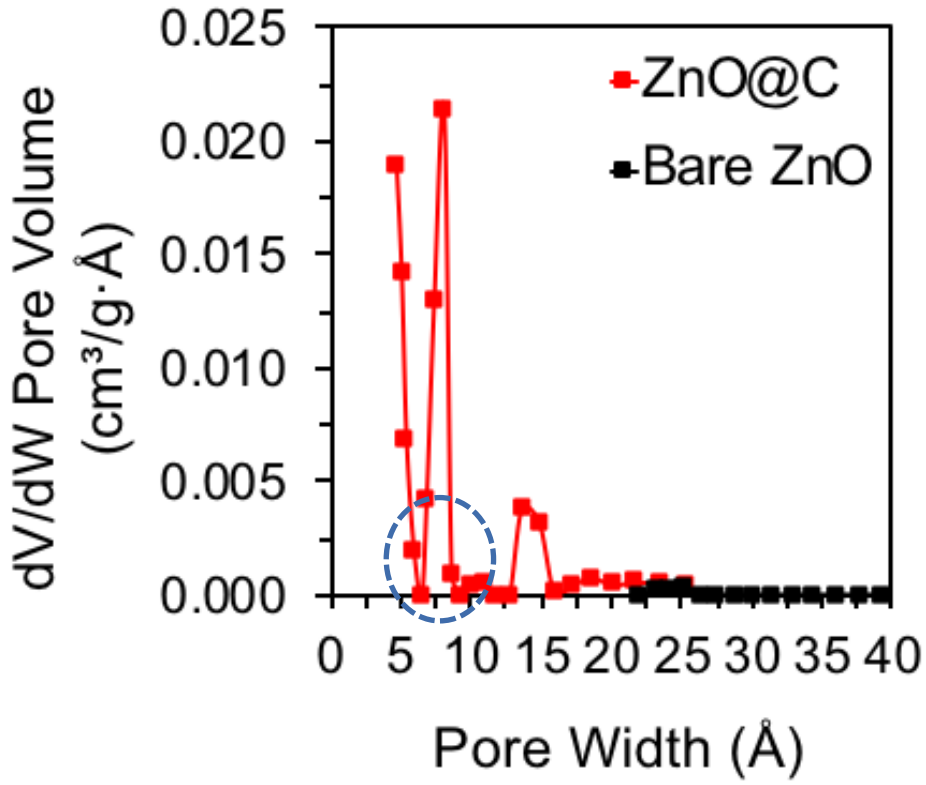


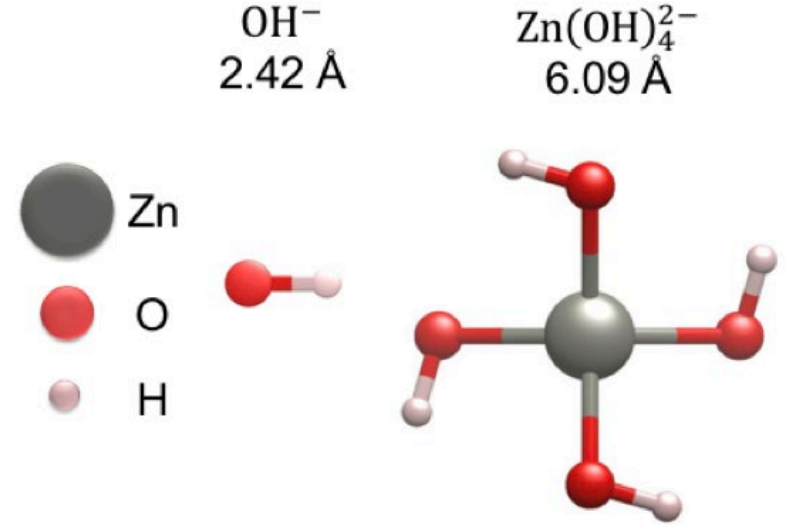
Dr. John Watt
CINT

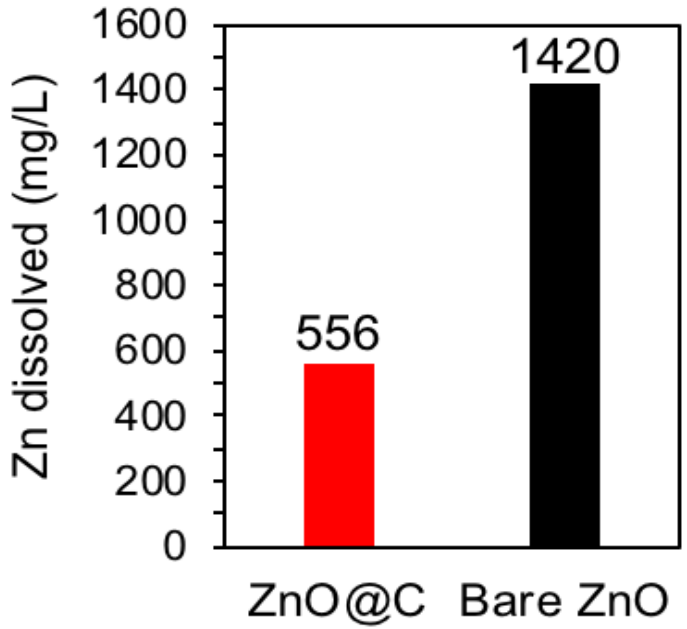
ZnO @ ion-sieving carbon anode avoids passivation and shape change





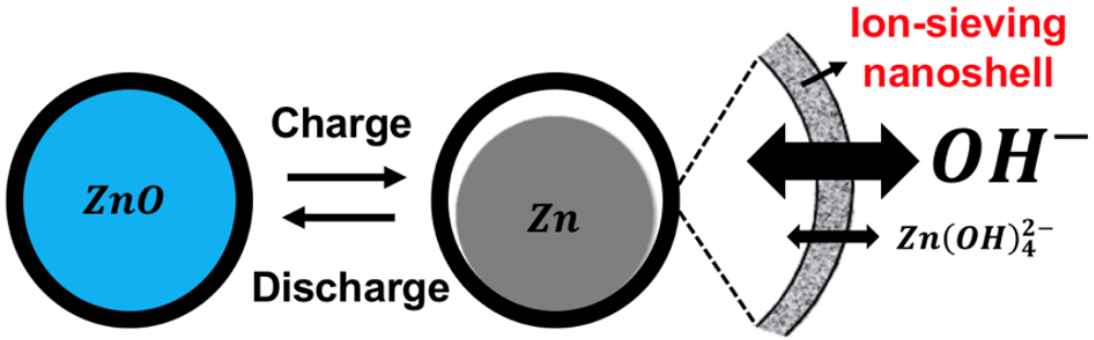


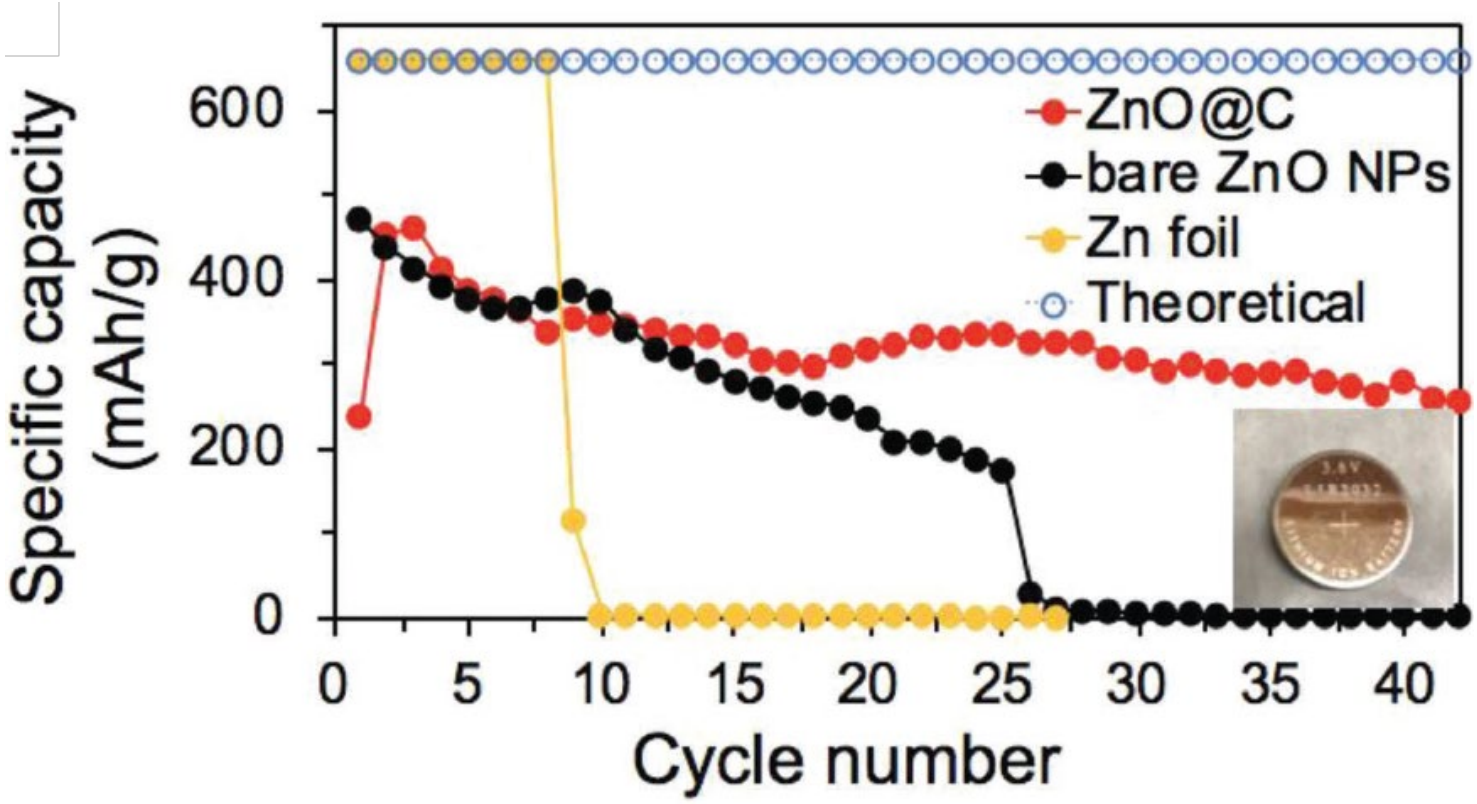




Y. Wu, N. Liu*, et al. ***Adv. Energy Mater.*** 8 (36), 1802470 (2018)

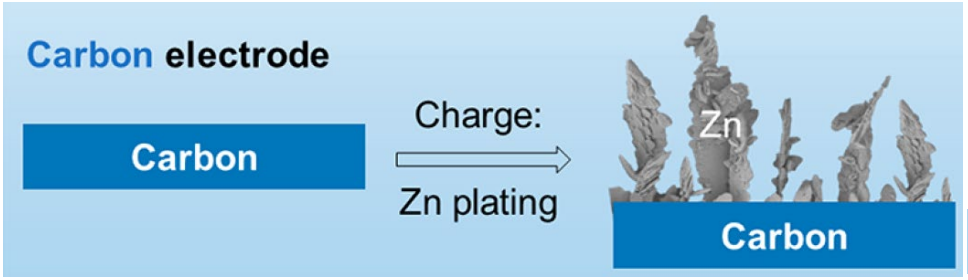
ZnO @ ion-sieving carbon anode avoids passivation and shape change



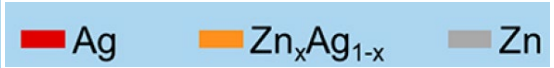


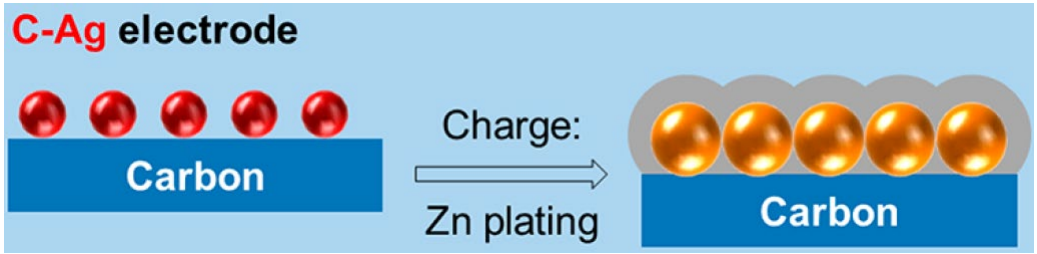
Y. Wu, N. Liu*, et al. ***Adv. Energy Mater.*** 8 (36), 1802470 (2018)

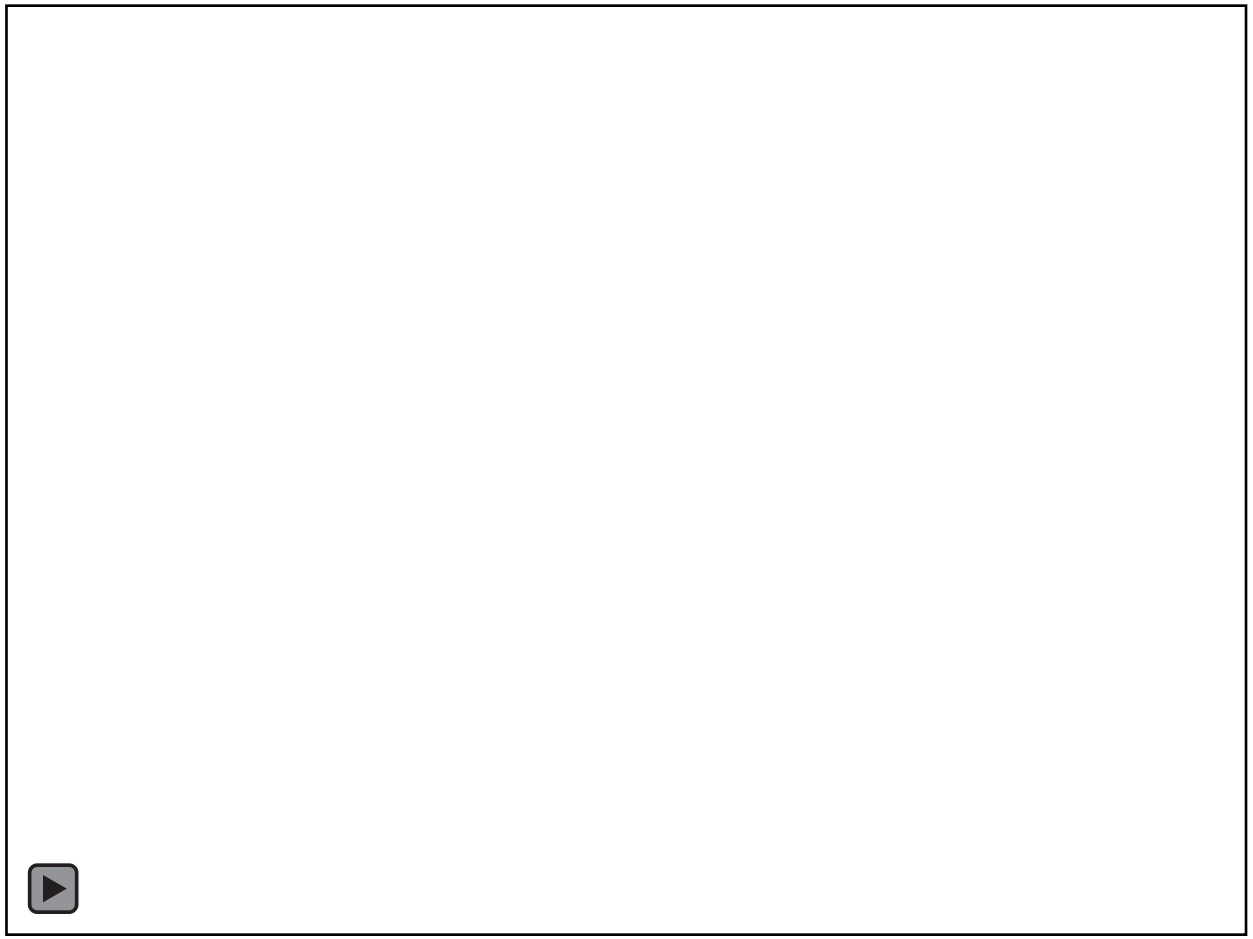
Soluble zincate: Passive encapsulation → Active management

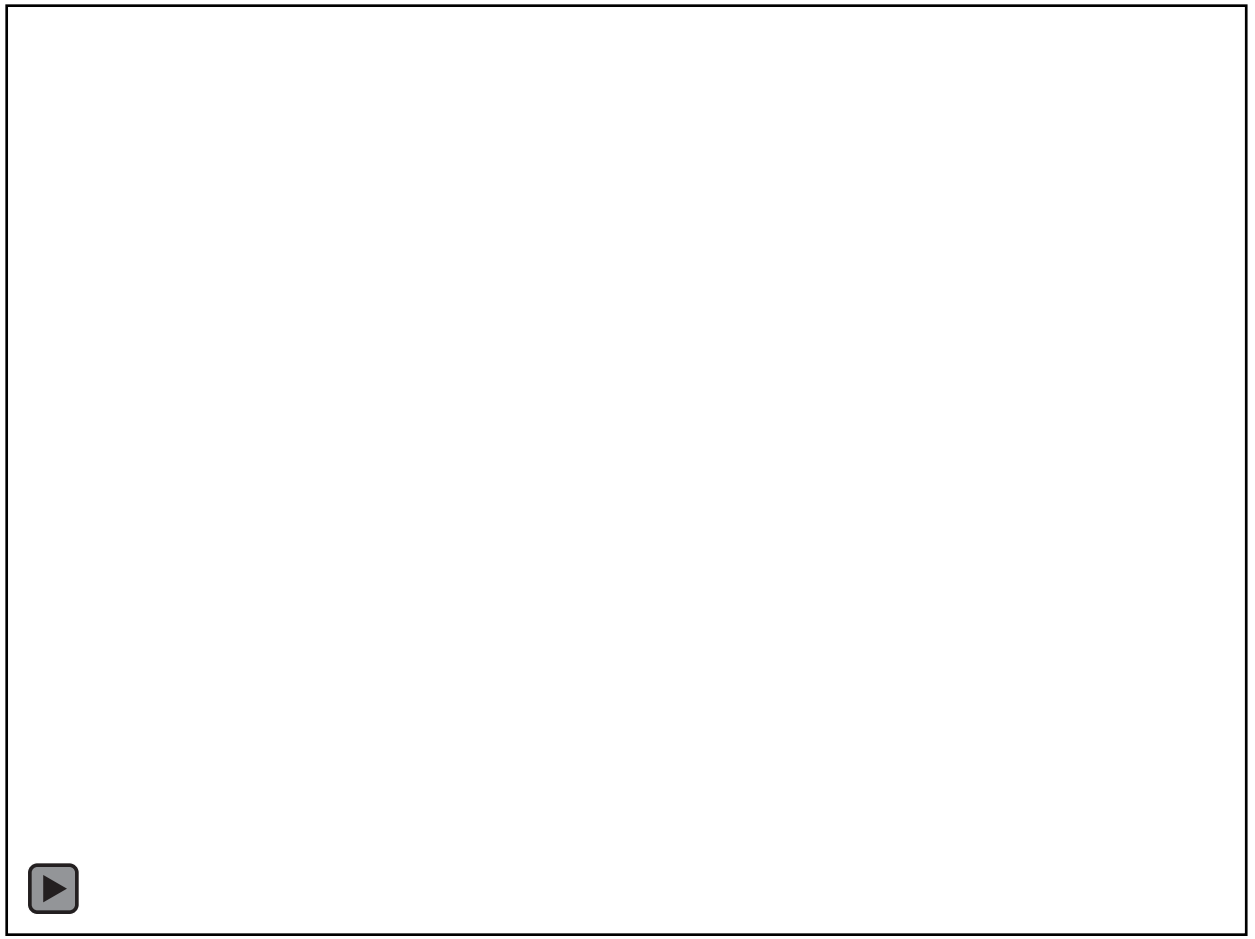


Y. Zhang, N. Liu* et al.
ACS Energy Lett.
2021, 6 (2), 404–412

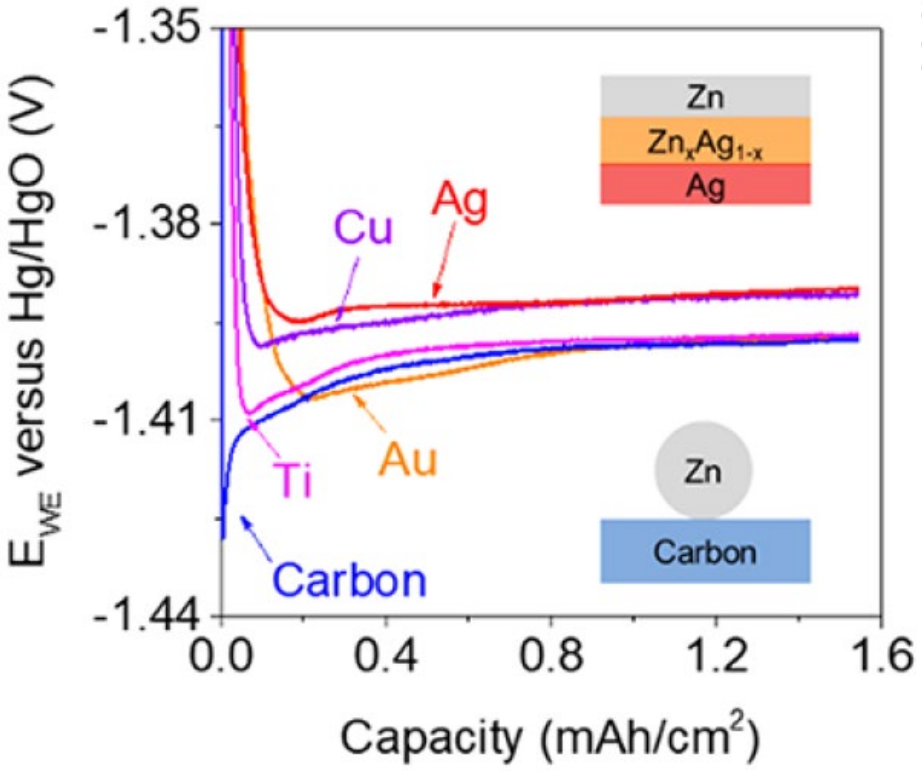


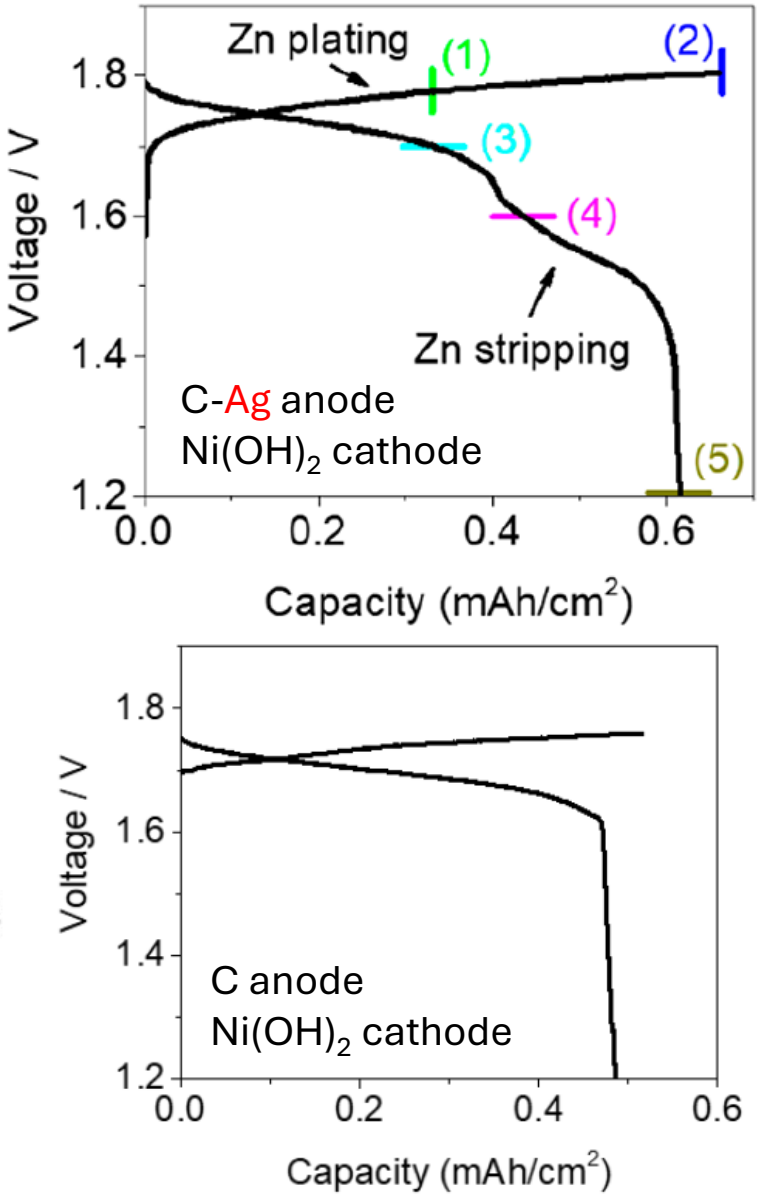


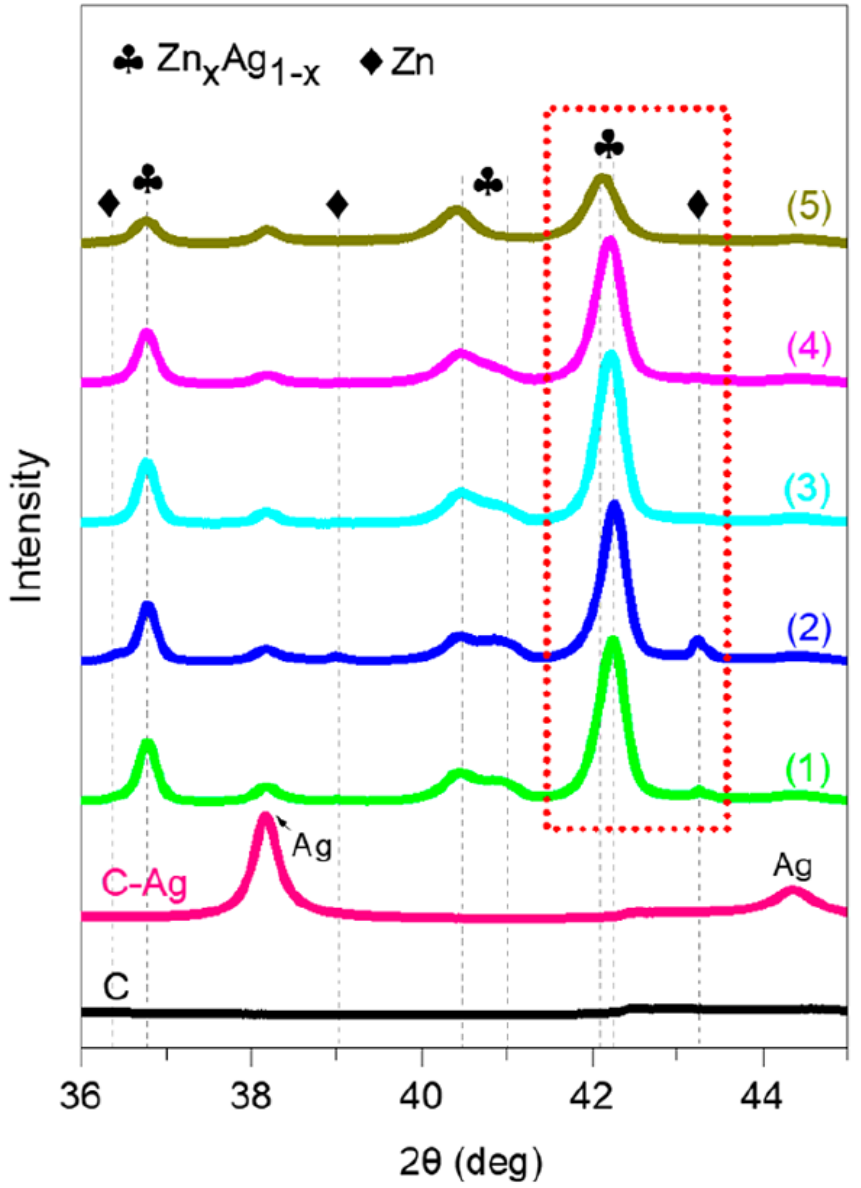




Alloy-seeded Zn anode: mechanism







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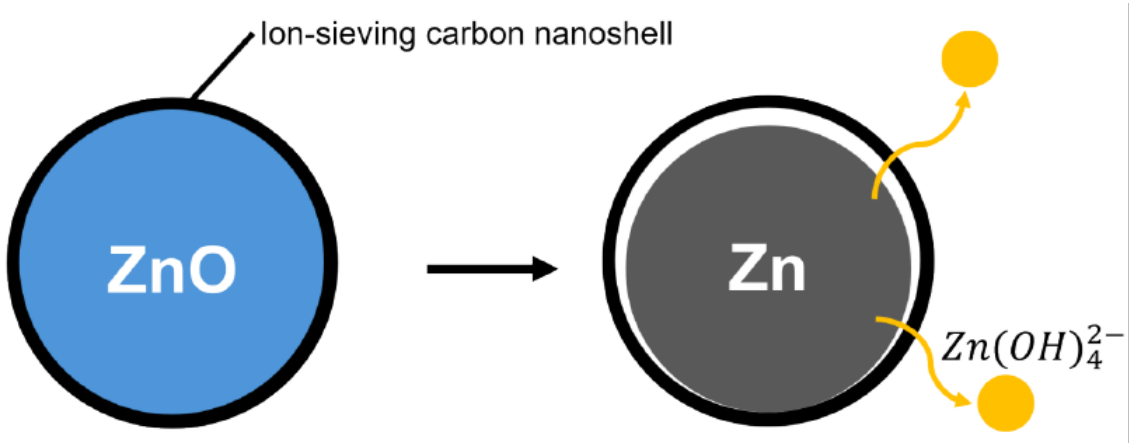
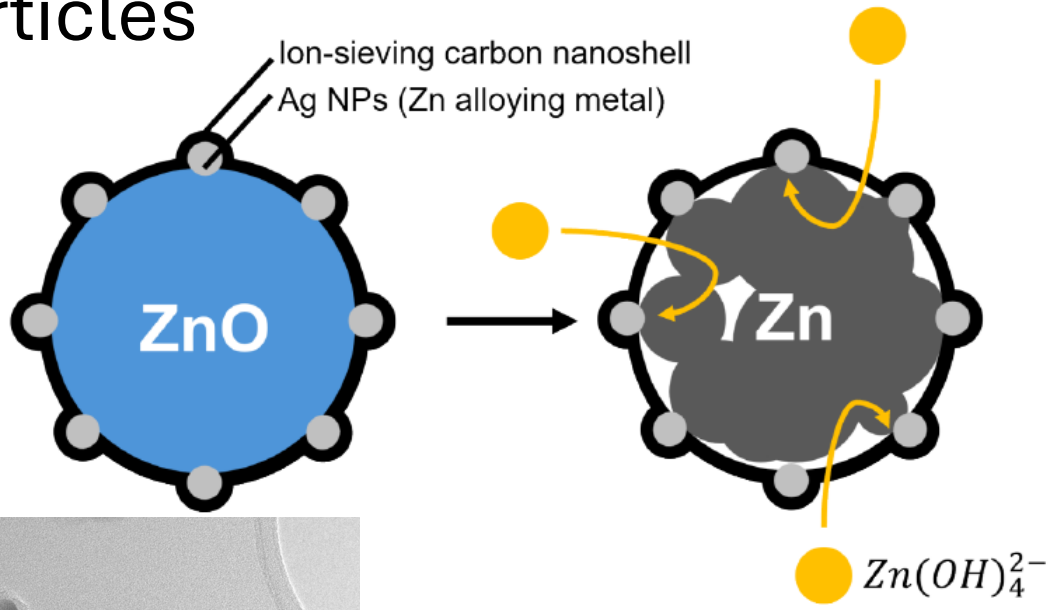
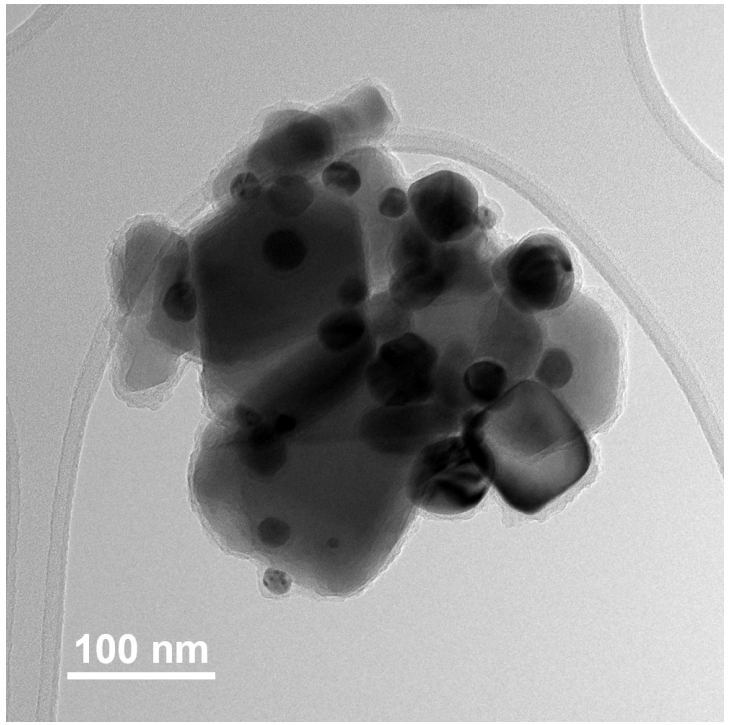
Apply alloy-seeding mechanism to particles

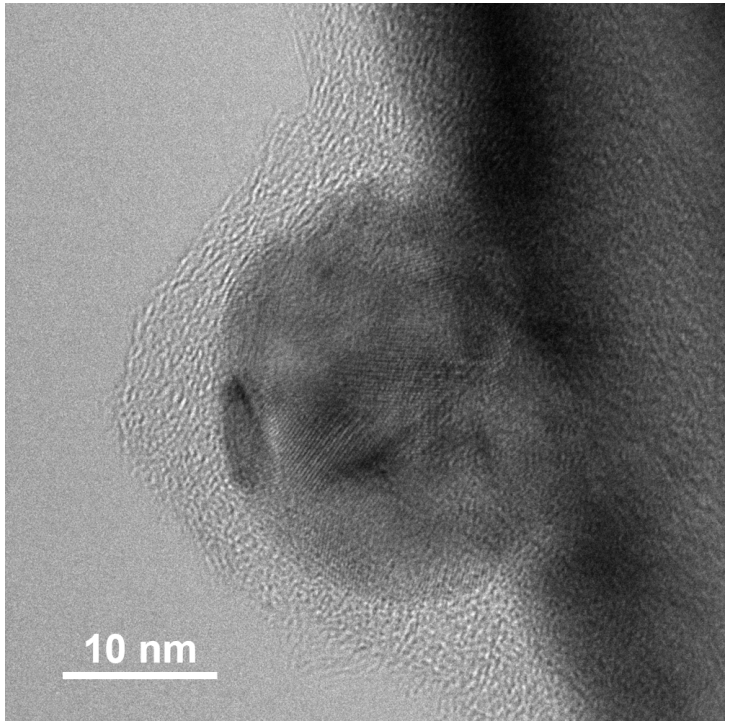




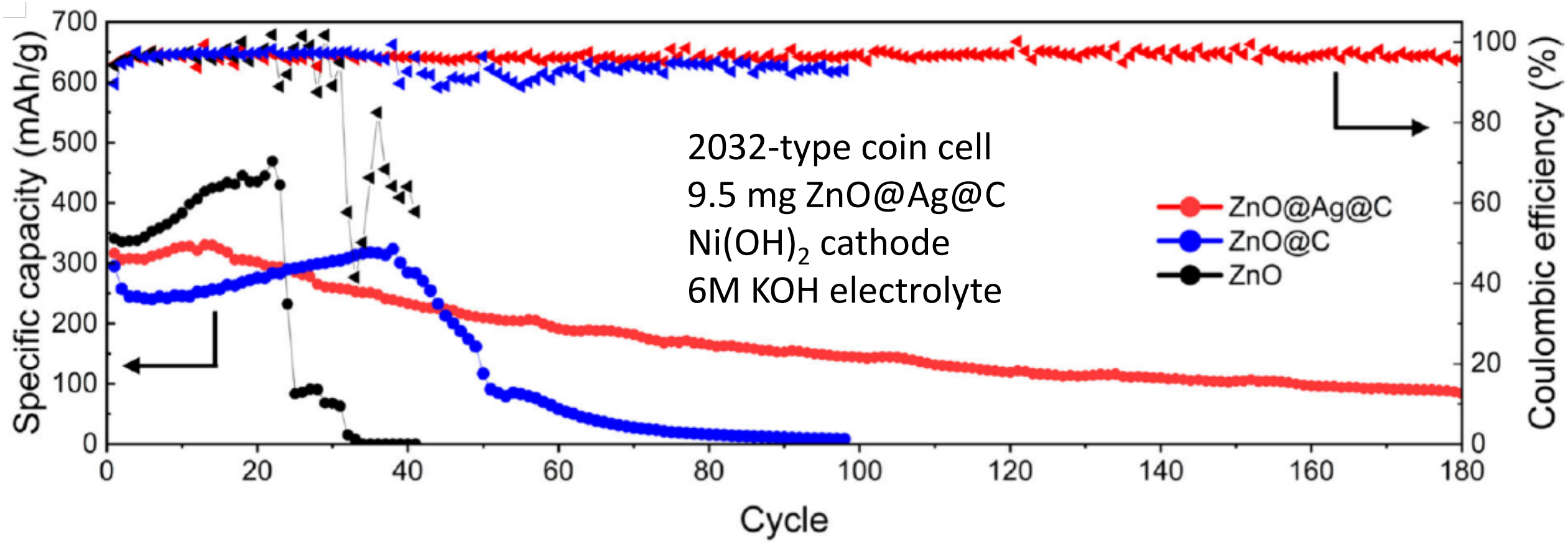
30 grams of ZnO@Ag@C powder (75:15:10)







Z. Chen, J. Watt, T. N. Lambert, M. Wang, N. Liu, et al.
ACS Energy Lett. 2026, 11, 3907−3915



- Bare ZnO nanoparticles can still cycle, but start to show the consequence of unconstrained shape change after 22 cycles
- ZnO@C decays to 50% capacity in 45 cycles
- ZnO@Ag@C extends cycle life to 90 cycles

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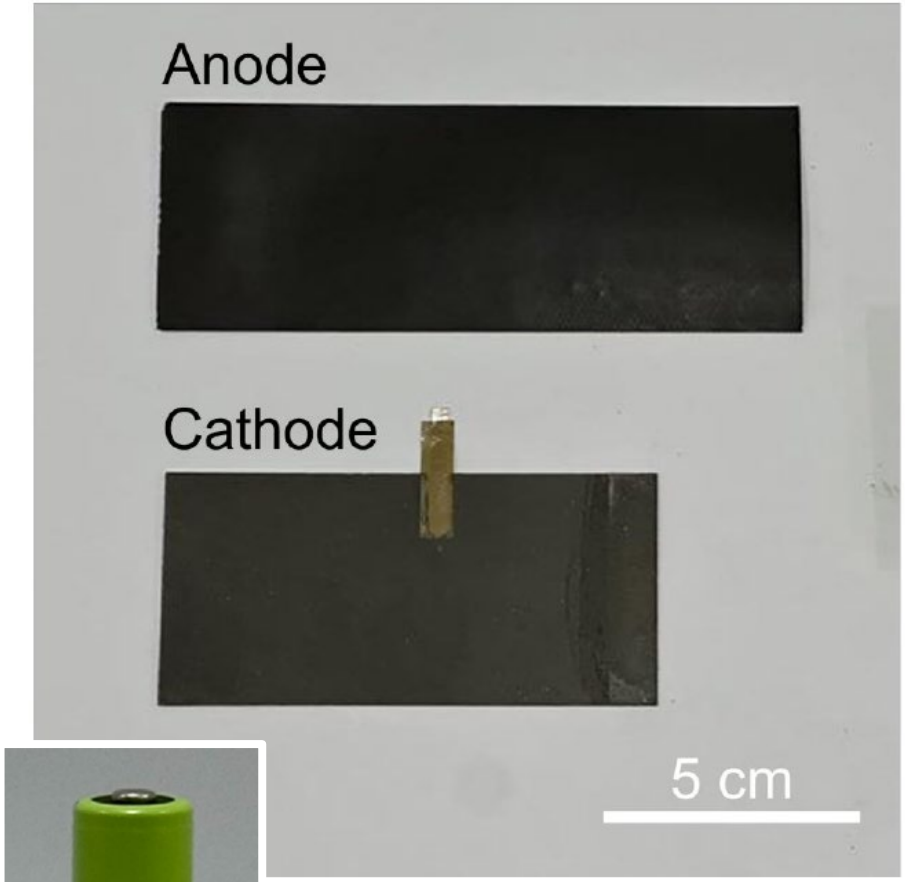
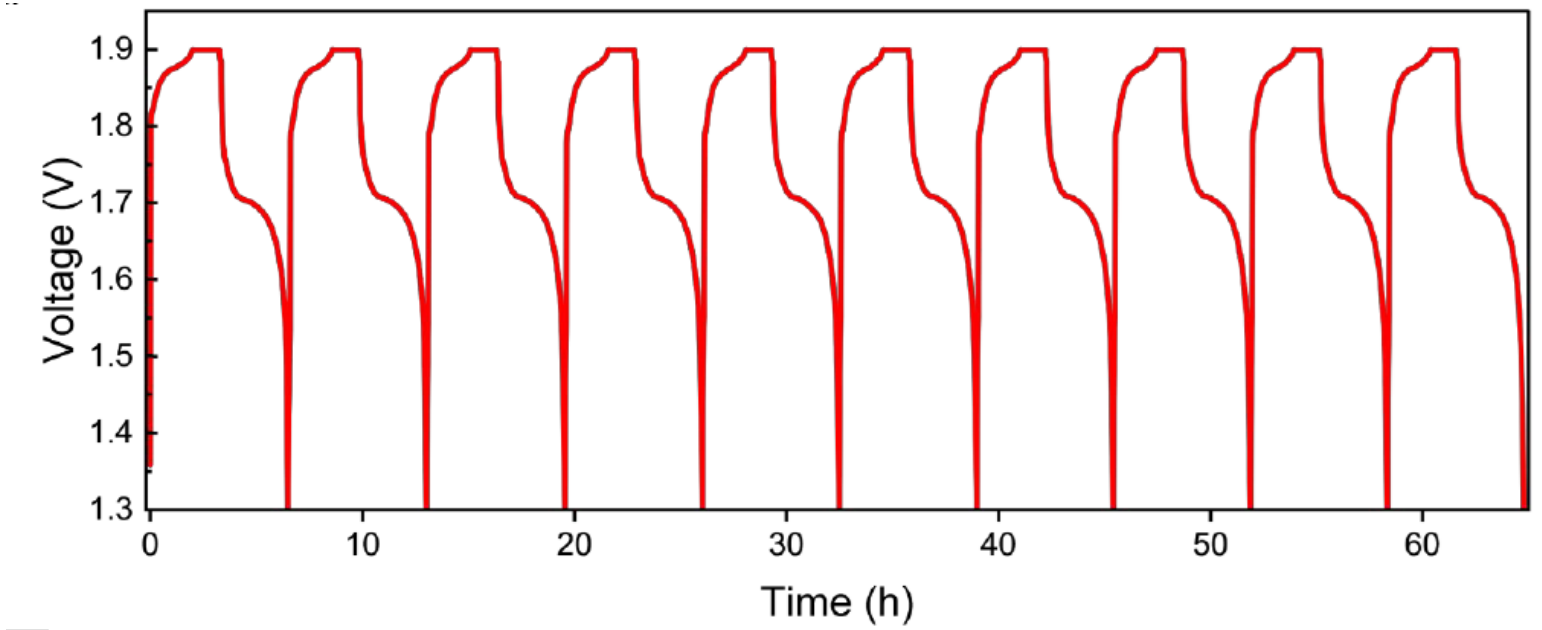
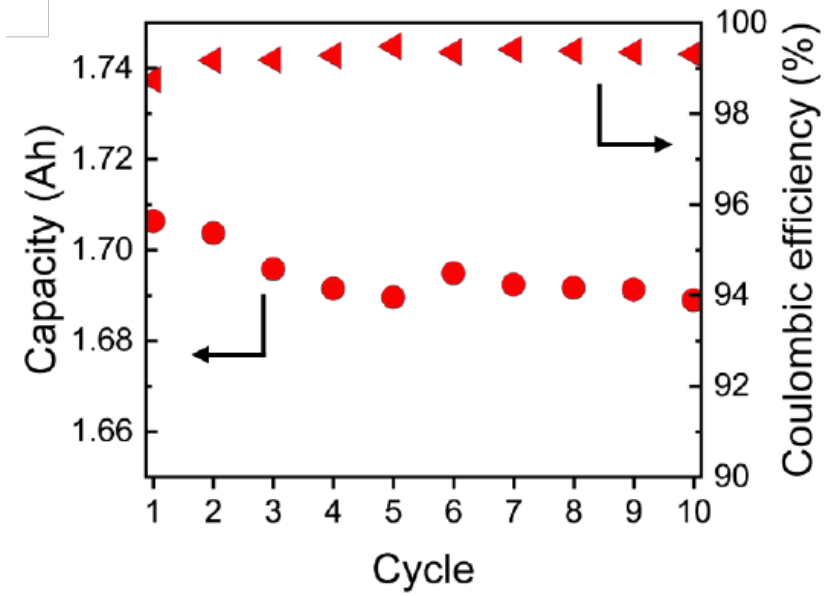


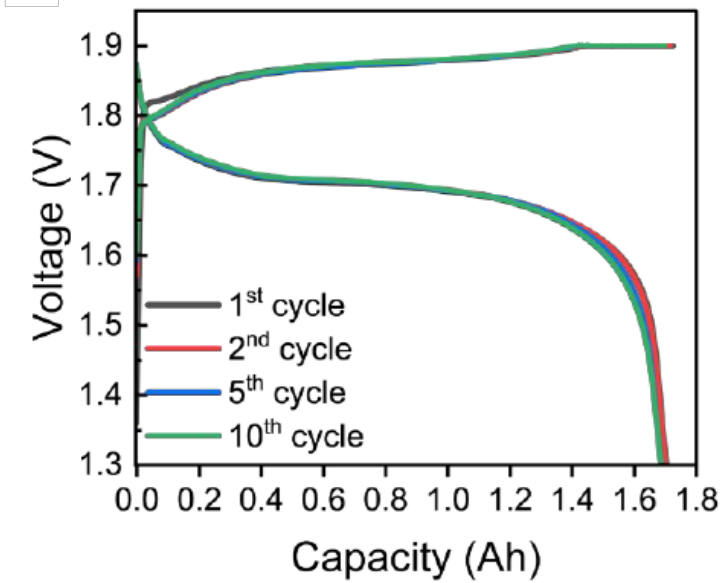


AA cylindrical cell

GP Batteries







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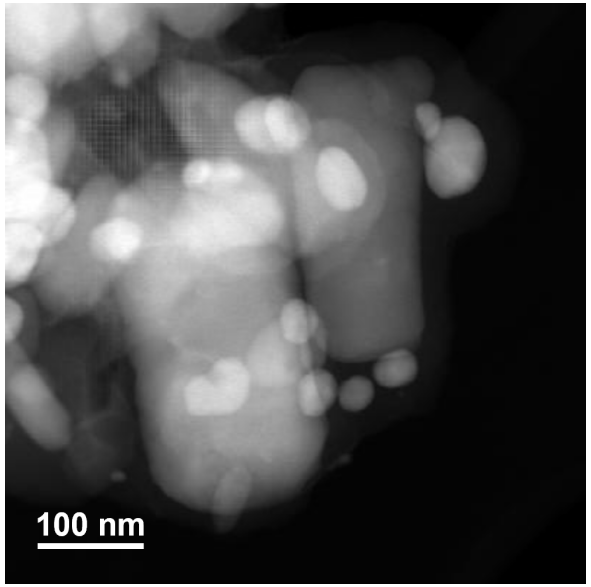
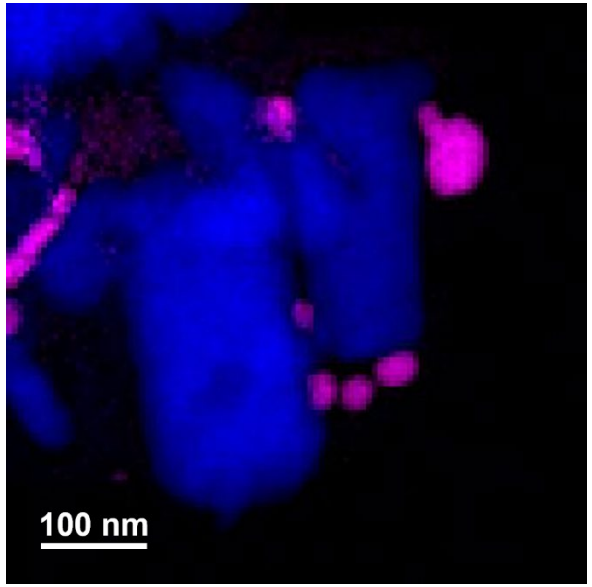
EELS mapping for pristine ZnO@Ag@C

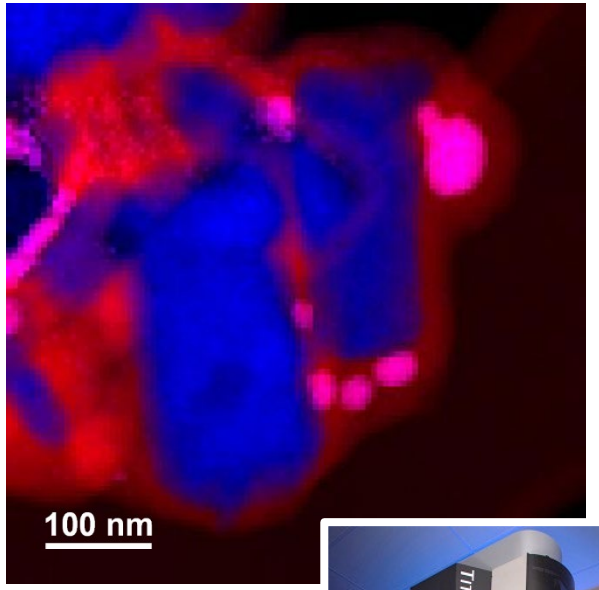
STEM



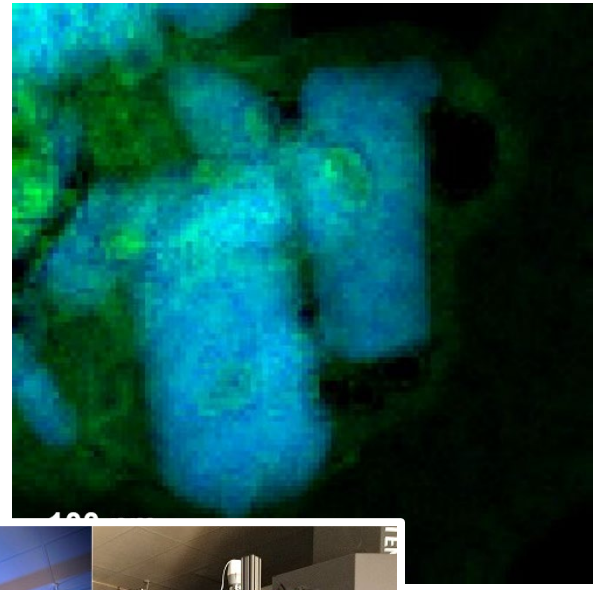
Zn + Ag



Zn + Ag + C



Zn + O



EELS: Electron Energy Loss Spectroscopy

- ZnO are decorated by Ag nanoparticles in the carbon nanoshell
- Carbon nanoshell demonstrates complete coverage on the surface of ZnO@Ag



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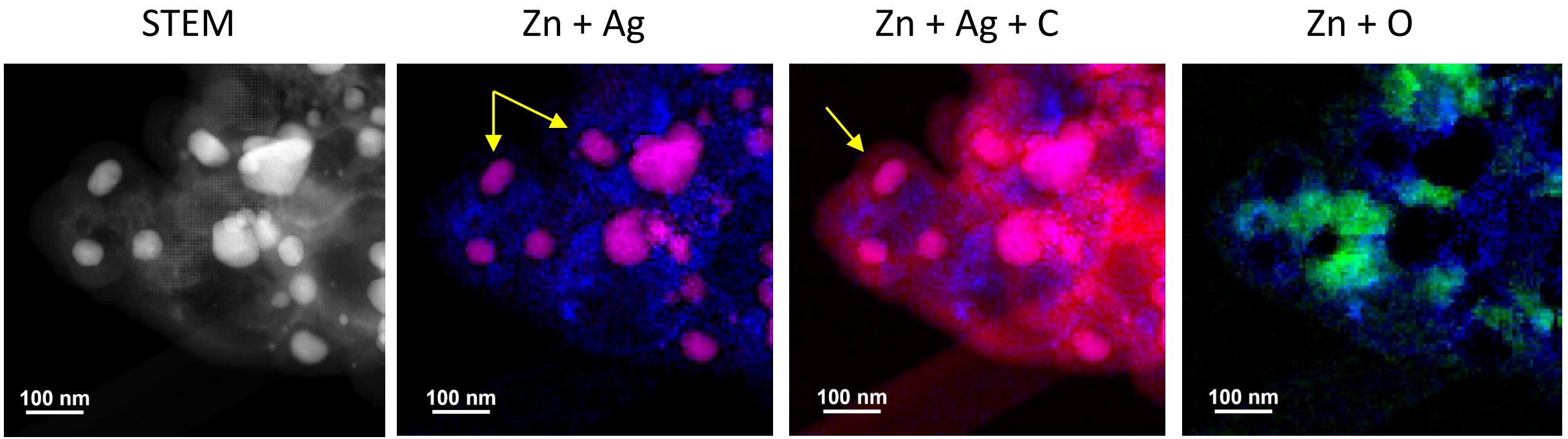
EELS mapping for ZnO@Ag@C after charging



- After charging, only small amount of O signal can be detected
- Ag nanoparticles are surrounded by Zn in the carbon nanoshell without any material leaking out
- Carbon nanoshell demonstrates high mechanical strength without any break

Z. Chen, J. Watt, T. N. Lambert, M. Wang, N. Liu, et al.
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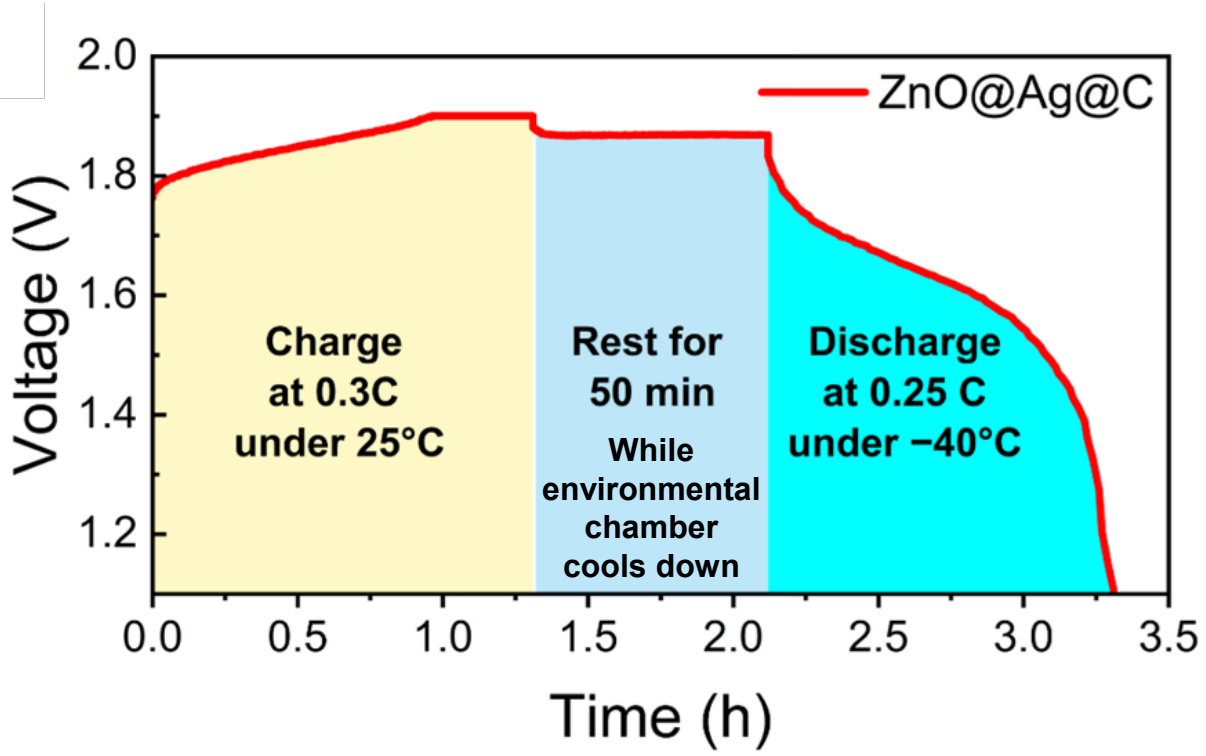
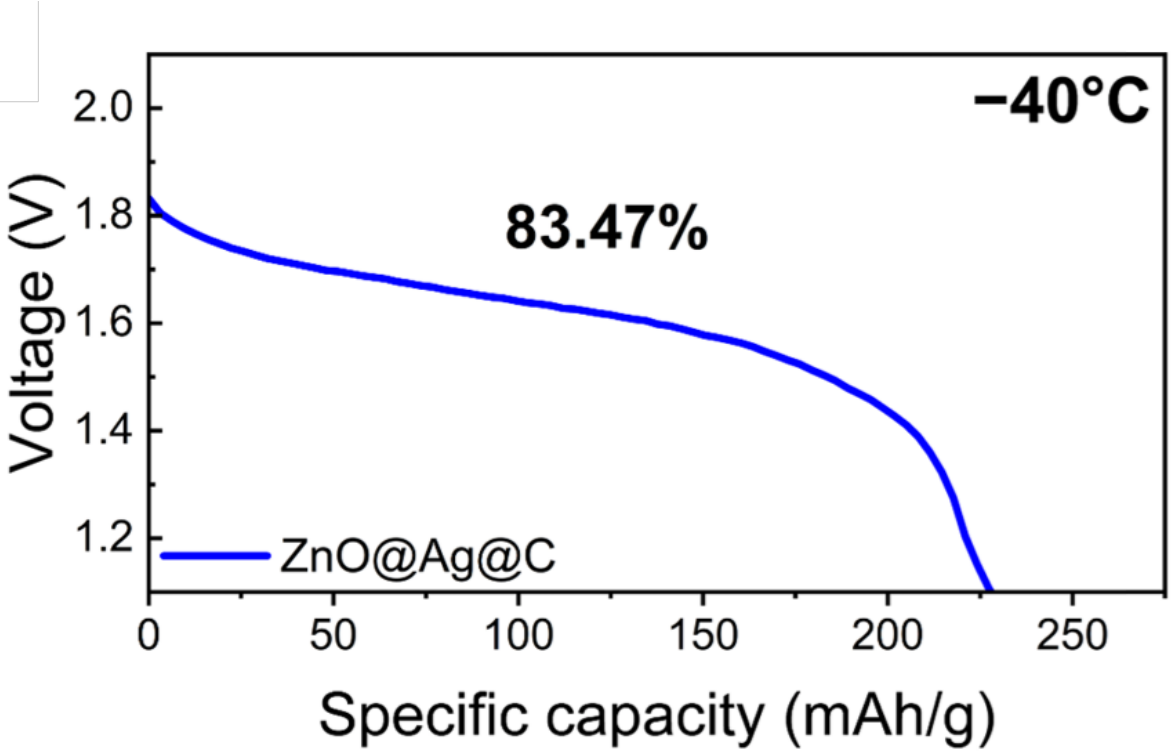
ZnO@Ag@C is capable to discharge at −40°C





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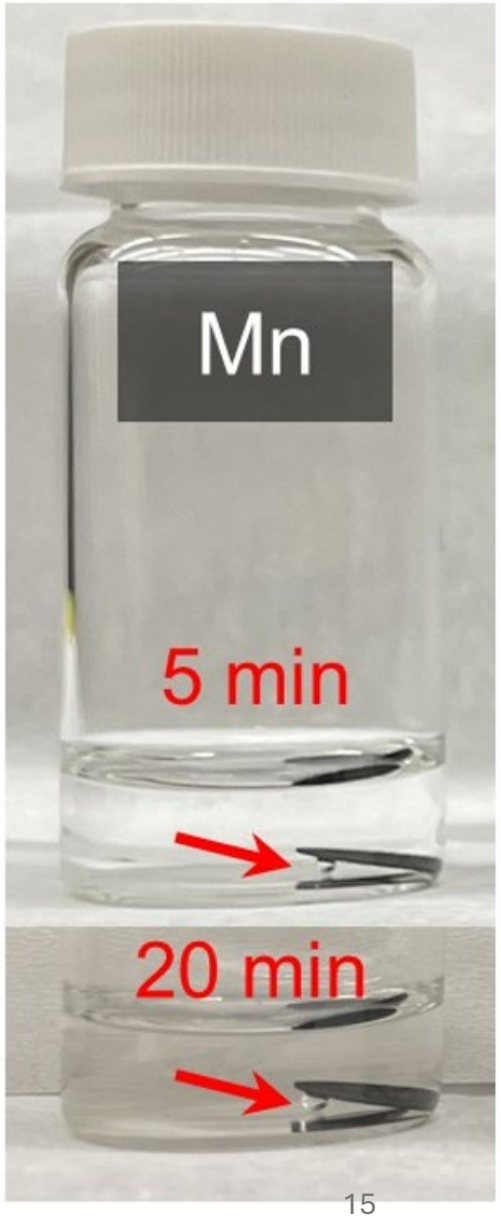
Mn metal anode: higher energy yet more severe HER than Zn

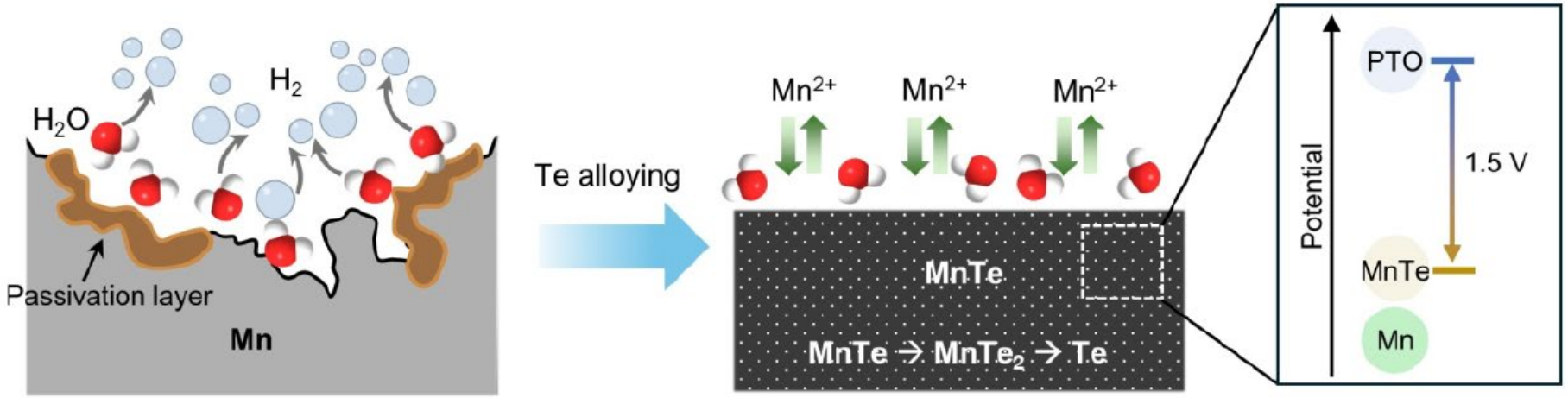
- Zn anode: 5851 mAh cm^{-3}, ~$2.4 kg^{-1}, E° = −0.76 V vs SHE
  Mn anode: 7258 mAh cm^{-3}, ~$2 kg^{-1}, E° = −1.19 V vs SHE
  The standard electrode potential is 0.42V lower than Zn, leading to higher cell voltage

- Promise of an all-Mn aqueous battery
  (2 Mn (II) ↔ Mn (IV) + Mn (0), assemble at symmetric/discharged state, 1.5V → 1.9V, 33% higher theoretical specific energy than Zn-MnO_2 chemistry)

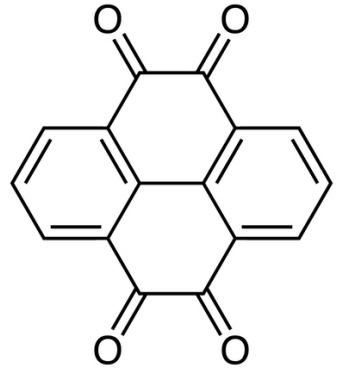
- Design challenge:
  The same negative potential that increases cell voltage also drives severe water reduction, corrosion, passivation, and poor Mn plating/stripping reversibility



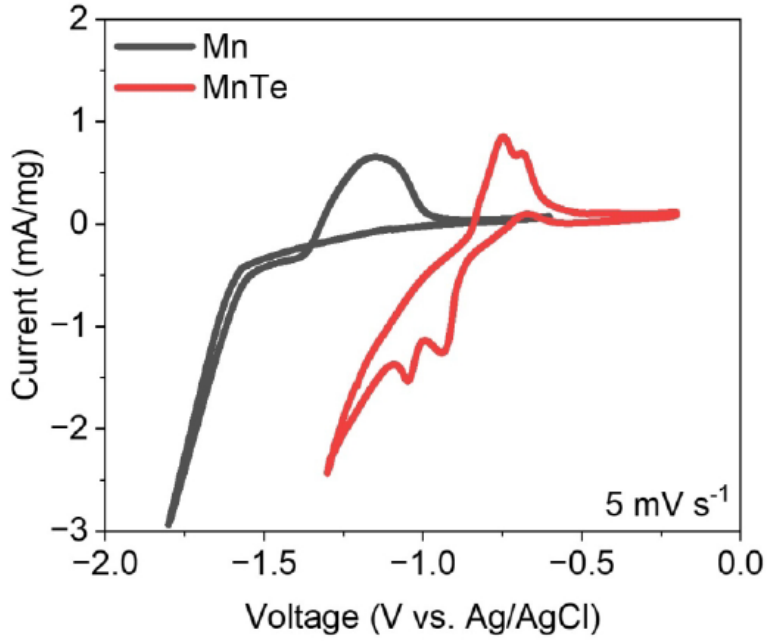
Te alloying shifts Mn redox into a safer potential window

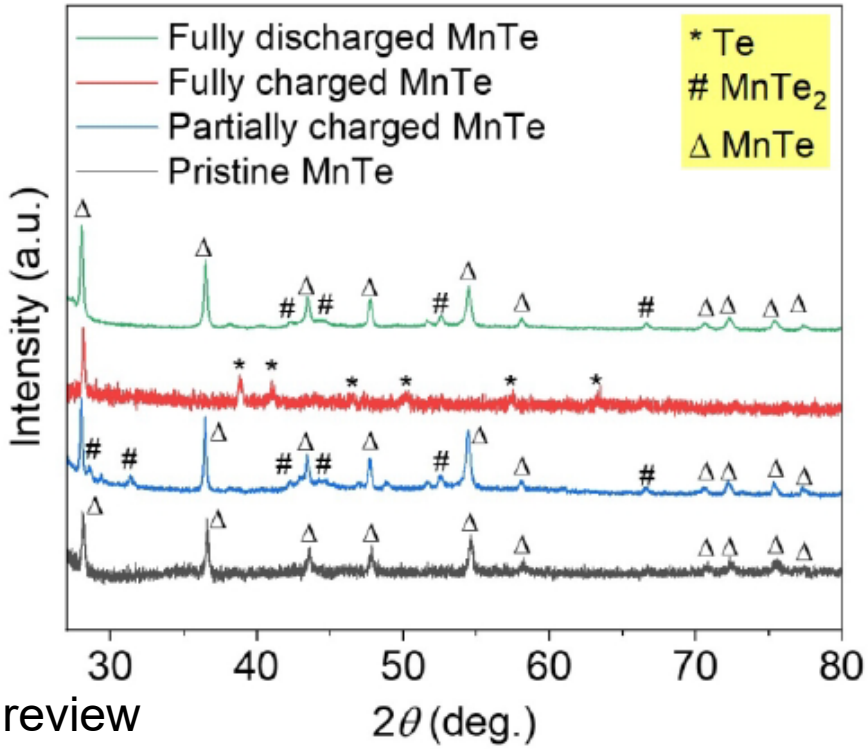


- Severe HER and corrosion
- Suppressed HER and corrosion
- Increased redox potential



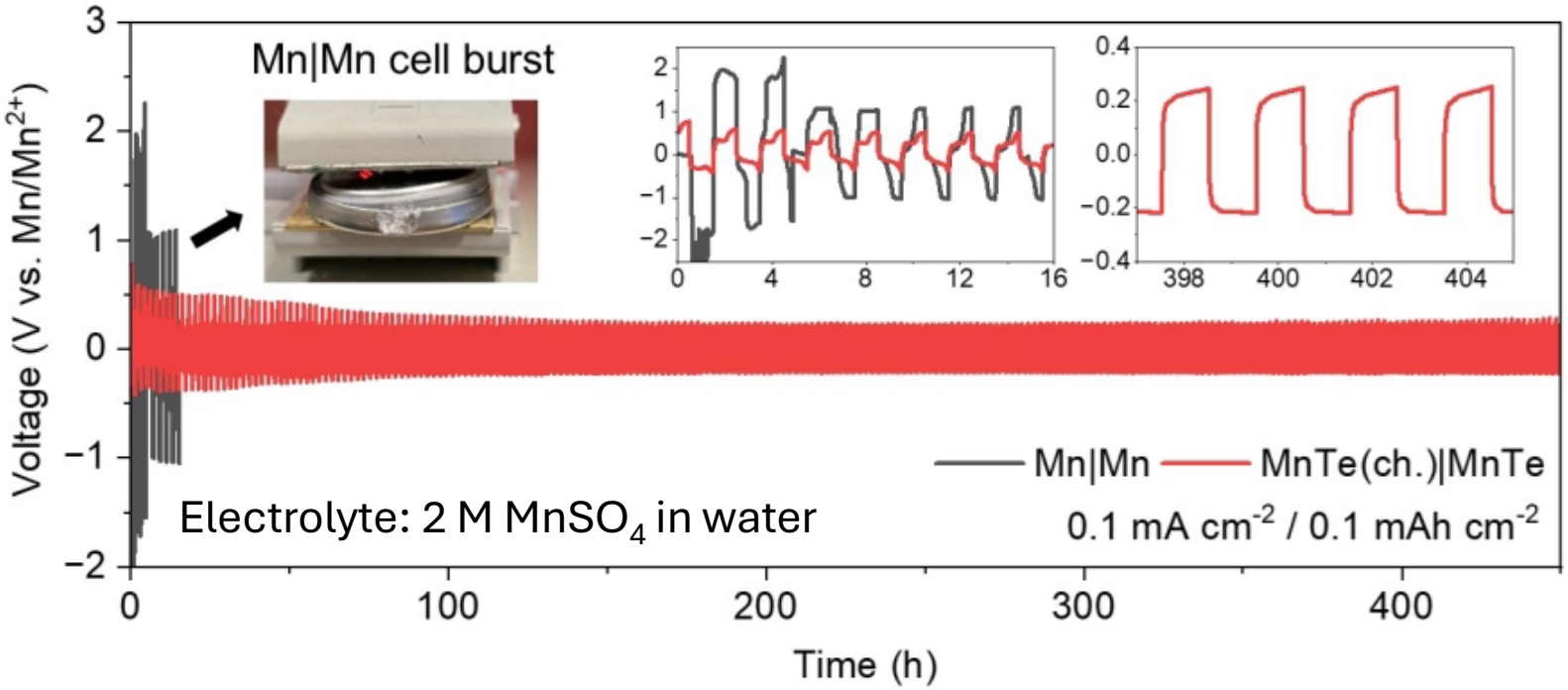
PTO: pyrene-4,5,9,10-tetraone

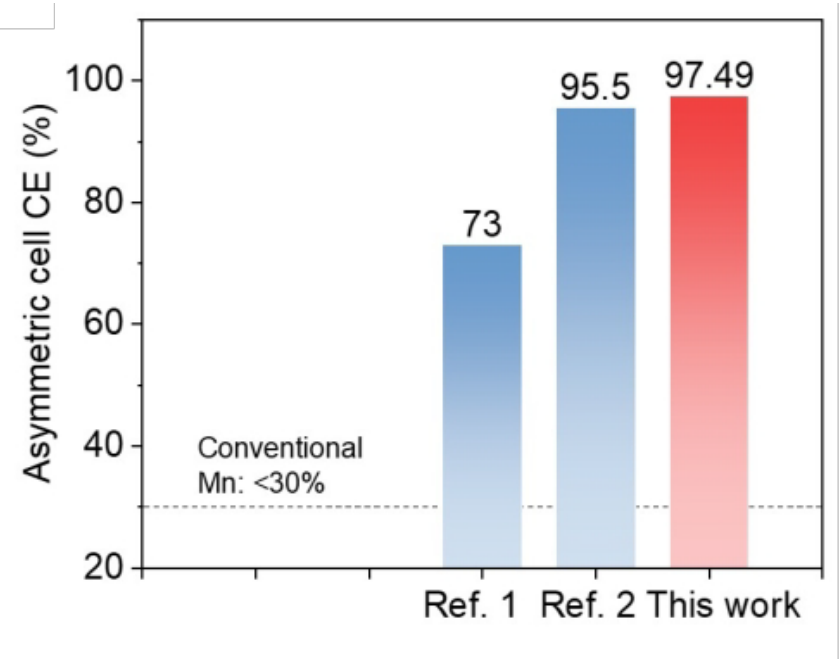




J. Kang, T. N. Lambert, N. Liu, et al. ***Materials Horizons***, under review

Half cell: stable MnTe anode with suppressed HER



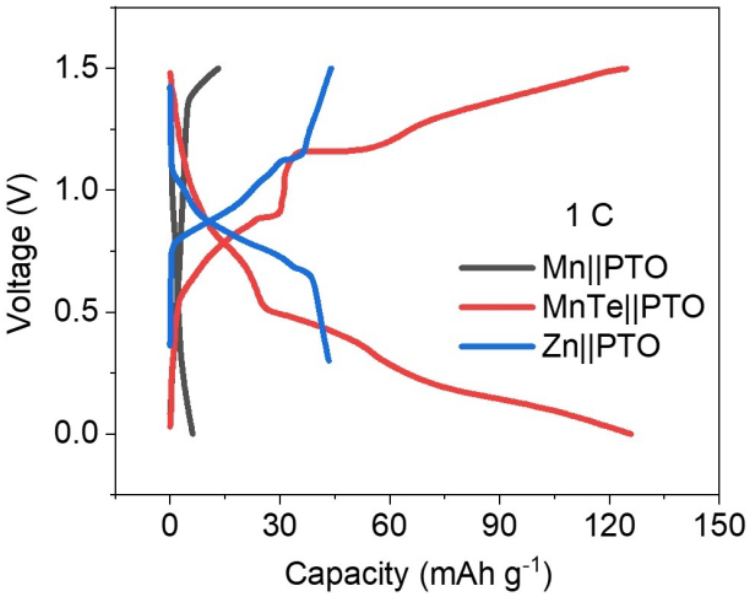


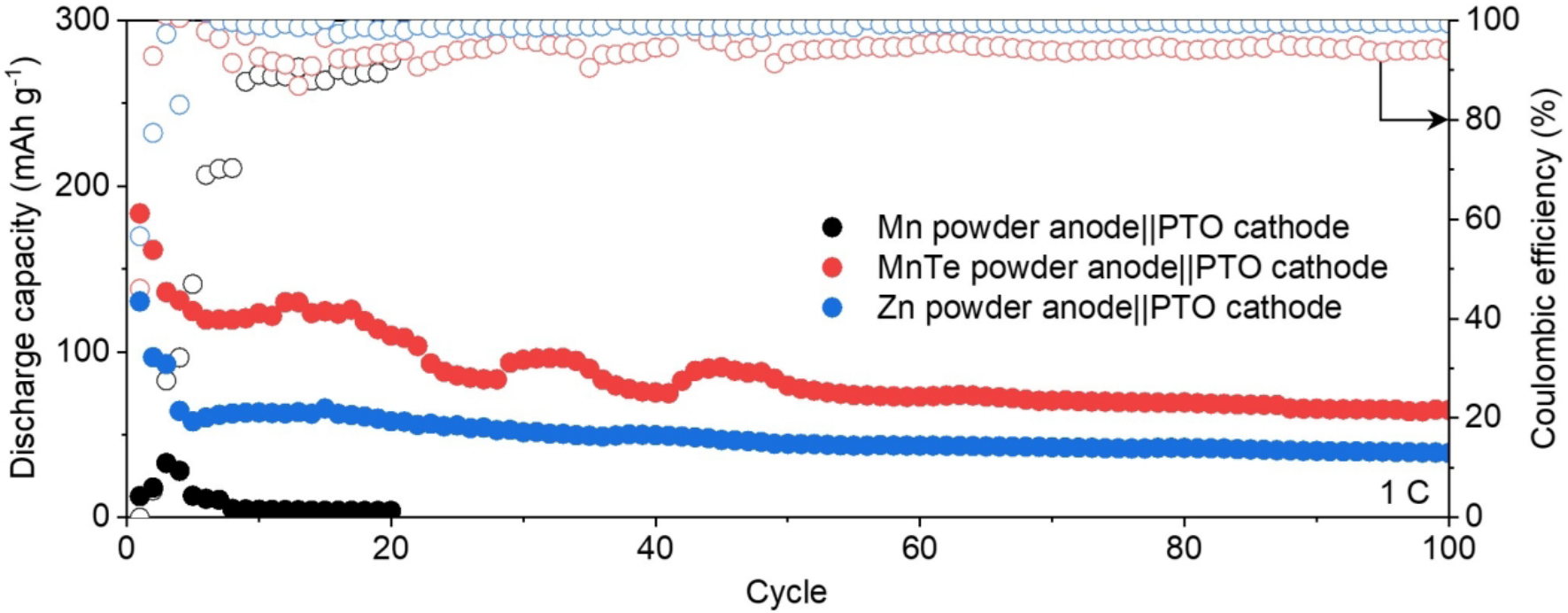
- Te alloying converts unstable Mn plating/stripping into reversible Mn extraction/ reinsertion within MnTe, avoiding the gas-driven failure observed for Mn metal cells.
- Under identical conditions, MnTe sustains >450 h symmetric cycling and reaches 97.5% Coulombic efficiency, demonstrating strongly suppressed HER and improved Mn redox reversibility.

J. Kang, T. N. Lambert, N. Liu, et al. ***Materials Horizons***, under review

Full cell: MnTe anode || PTO cathode

Electrolyte: 2 M $MnSO_4$ or $ZnSO_4$ in water





- In full cells, MnTe enables stable aqueous operation with a PTO cathode up to 1.5 V, while pristine Mn shows rapid failure from parasitic reactions.
- Under the same powder-anode configuration, MnTe||PTO retains ~70 mAh g^{-1} after 100 cycles at 1 C and outperforms Zn||PTO, supporting alloy-mediated Mn redox as a practical path beyond conventional Zn-based aqueous cells.

J. Kang, T. N. Lambert, N. Liu, et al. ***Materials Horizons***, under review

Summary and next steps

- Zn: Ag-seeded carbon nanoshells convert zincate dissolution from an irreversible loss pathway into a recoverable process.
- Mn: MnTe alloying suppresses HER/corrosion and enables reversible phase-mediated Mn redox.
- Program impact: These results advance low-cost, nonflammable aqueous batteries toward durable backup-power and grid-storage applications.
- Next steps:
  - Thick Zn anode for higher areal capacity (30 mAh/cm^2)
  - Higher capacity cathode (250 mAh/g) to pair with MnTe anode for Mn-ion battery
  - A spectrum of Mn alloy compositions that tune potential and side reaction

Acknowledgment

- This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.
- Sandia National Laboratories
- GP Batteries (Dr. Mingde Wang, Dr. Bin Wang)

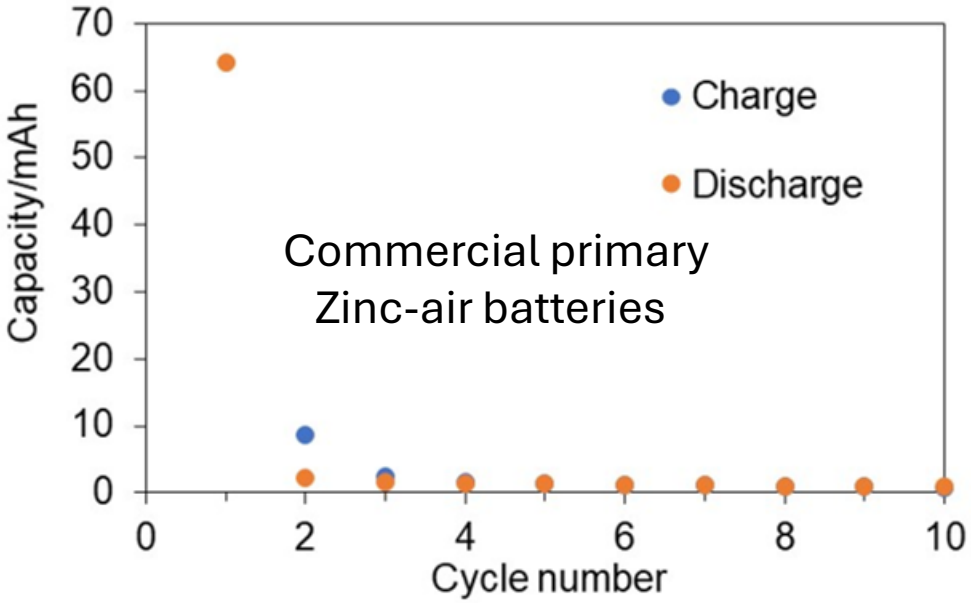
- Contact me: nian.liu@chbe.gatech.edu

Backup Slides

Irreversibility of Zn anode in alkaline electrolyte

Root causes of ZnO passivation

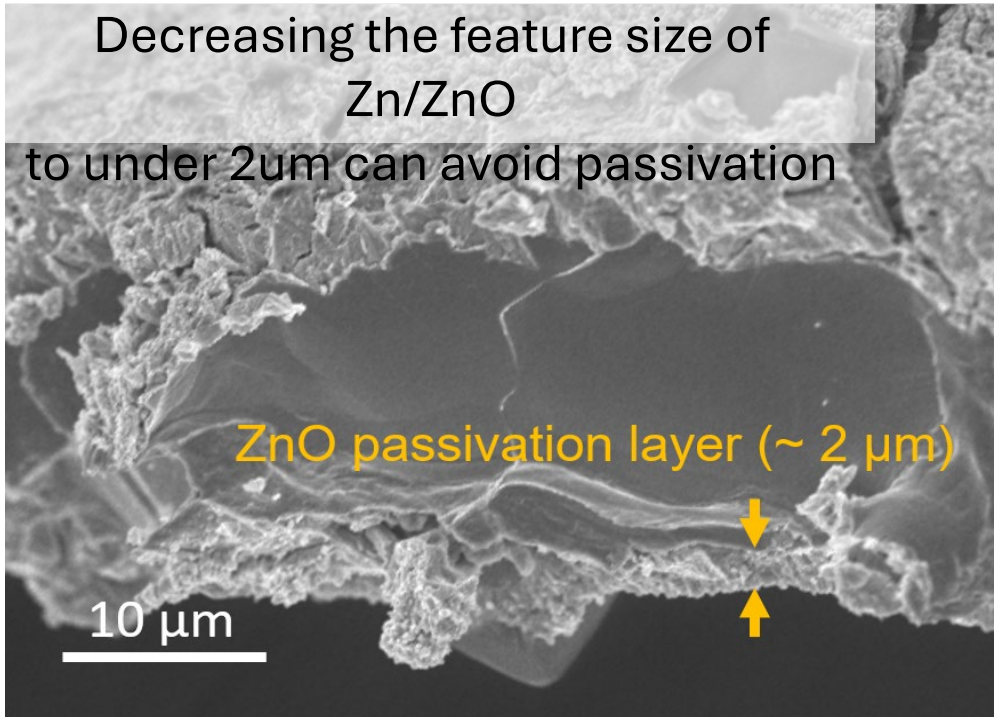




- Cannot deeply discharge (low utilization)
- Cannot recharge (poor reversibility)

Y. Zhang, N. Liu*, et al. Nano Energy 53, 666-674 (2018)

Our hypothesis 1:

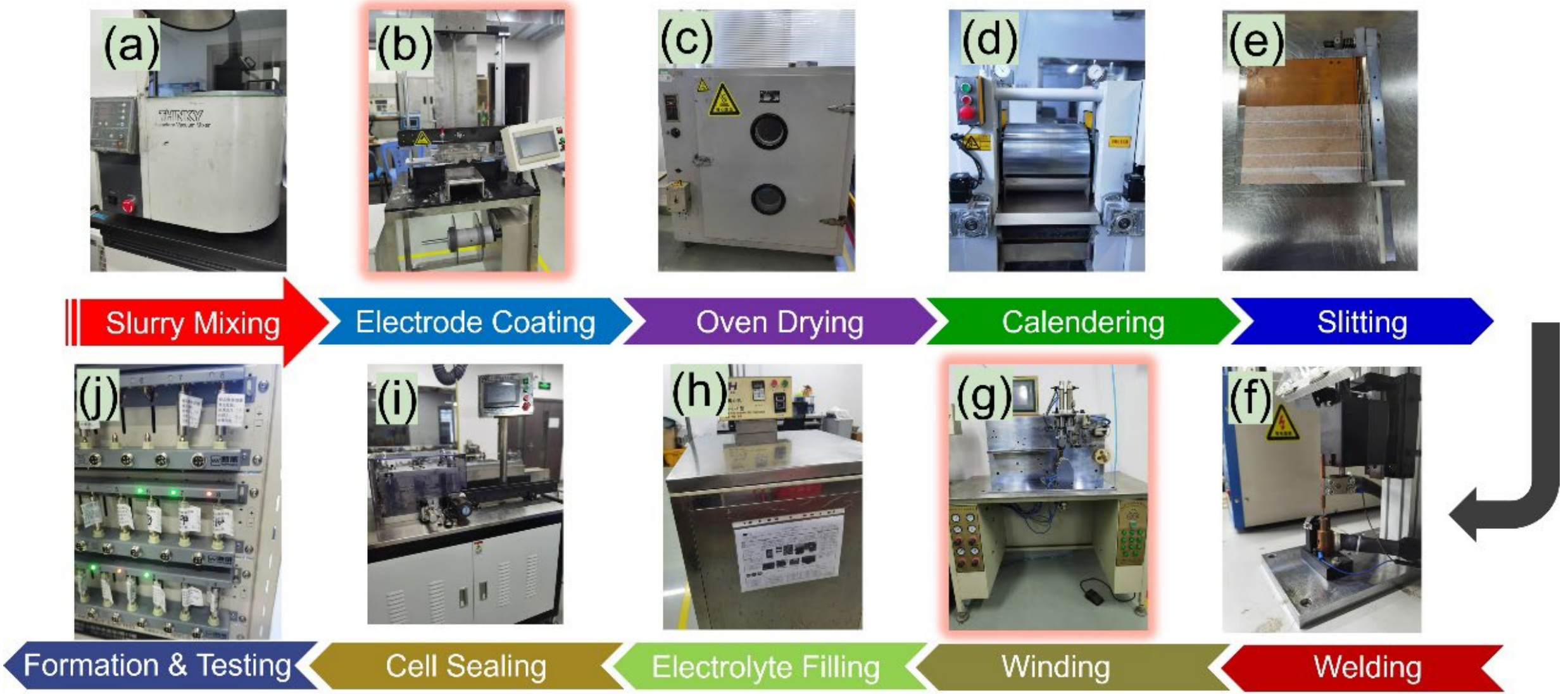


$$ZnO + H_2O + 2OH^- \leftrightarrow Zn(OH)_4^{2-}$$

$$Zn(OH)_4^{2-} + 2e^- \leftrightarrow Zn + 4OH^-$$

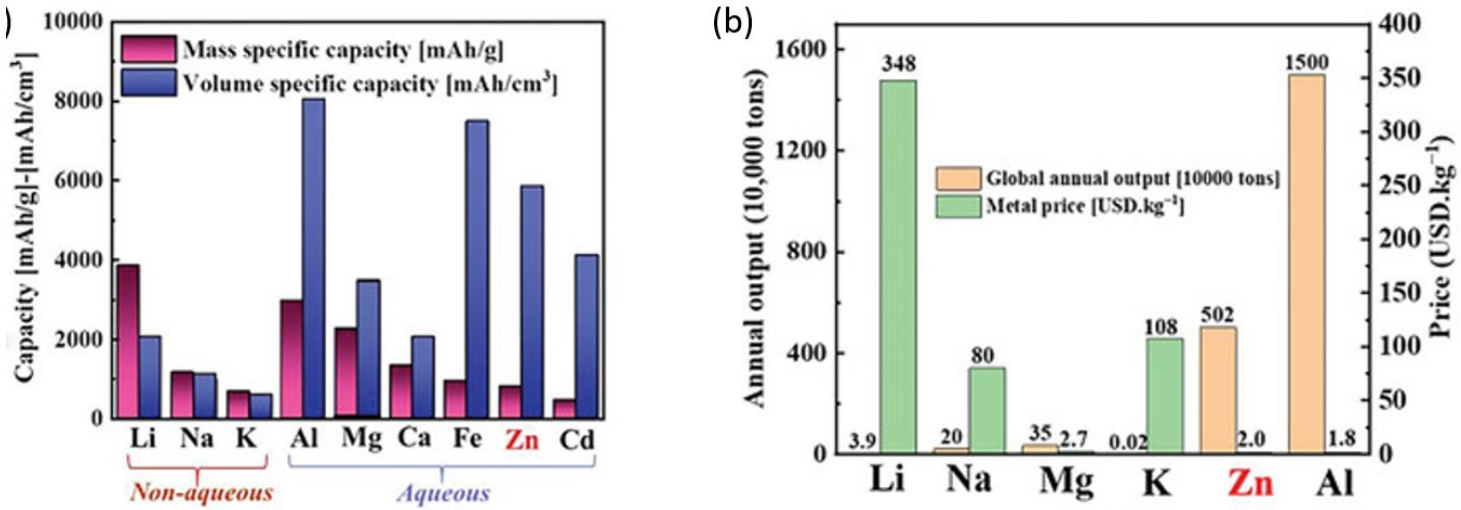
Our hypothesis 2: Encapsulation can slow down the escape of zincate

Assembly process of Ni-Zn AA cylindrical batteries



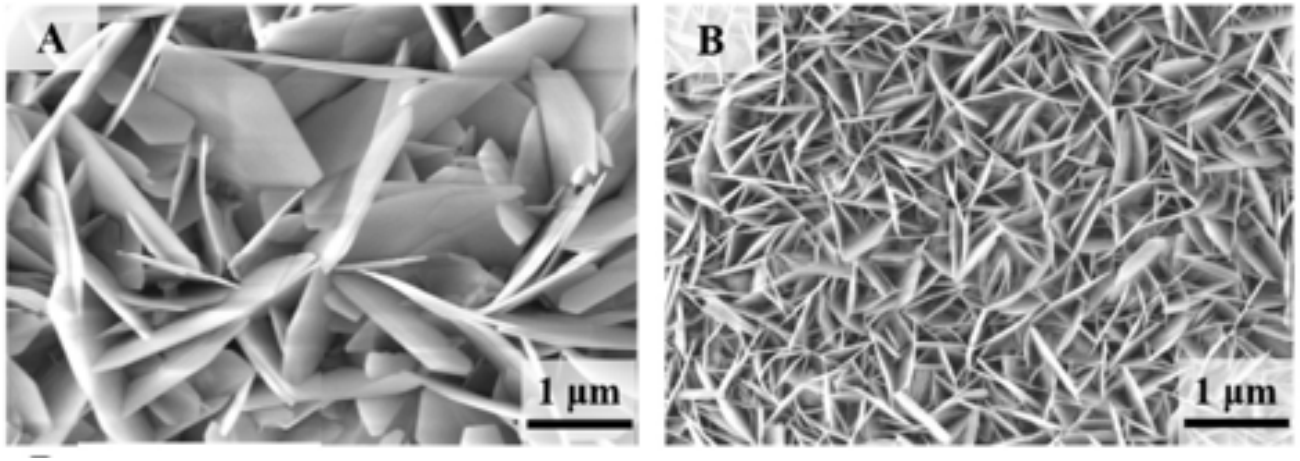
L. Gu et al, J. Power Sources 641 (2025) 236842

Zinc anode in neutral/mildly acidic electrolytes



Small **16**, 2000730-2000758 (2020)

Morphology of electrodeposited zinc:



ACS Appl Mater Inter **13**, 32930-32936 (2021)

Zinc anode:

- **Nonflammable aqueous electrolyte**
- **Low (but not too low) redox potential (slightly under HER)**
- **High theoretical specific capacity (820 mAh/g, 5854 mAh/cm³)**
- **Low cost**

Challenges:

- **Water reduction (HER)**
- **μm-scale: non-uniform deposition**
  Solutions:
  - Electrolyte additives
  - Electrode coating & doping (e.g. In, Sb)

- **mm-scale: migration of active materials**
  (thick electrodes, high areal capacity)