All-Solid Li-S Batteries

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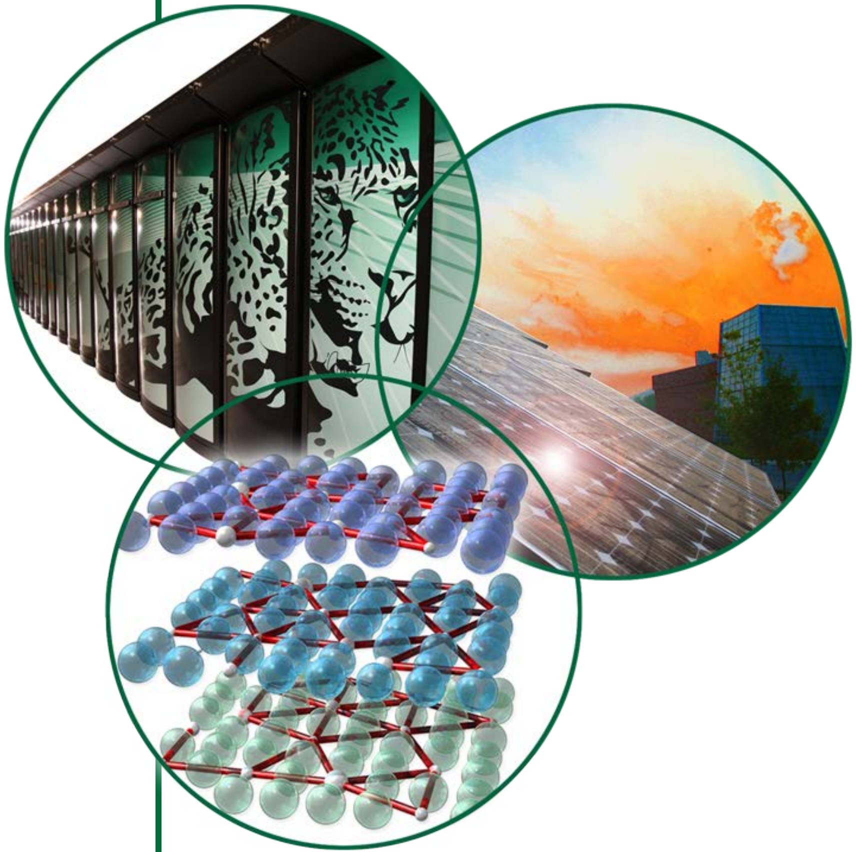

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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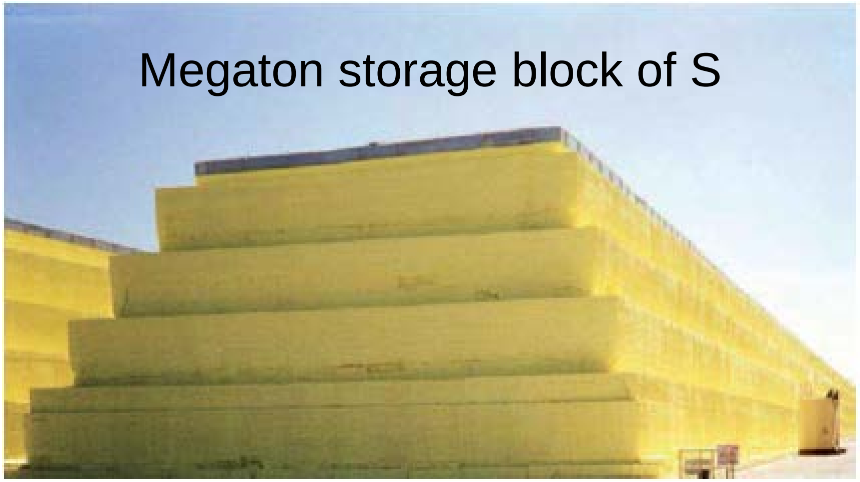
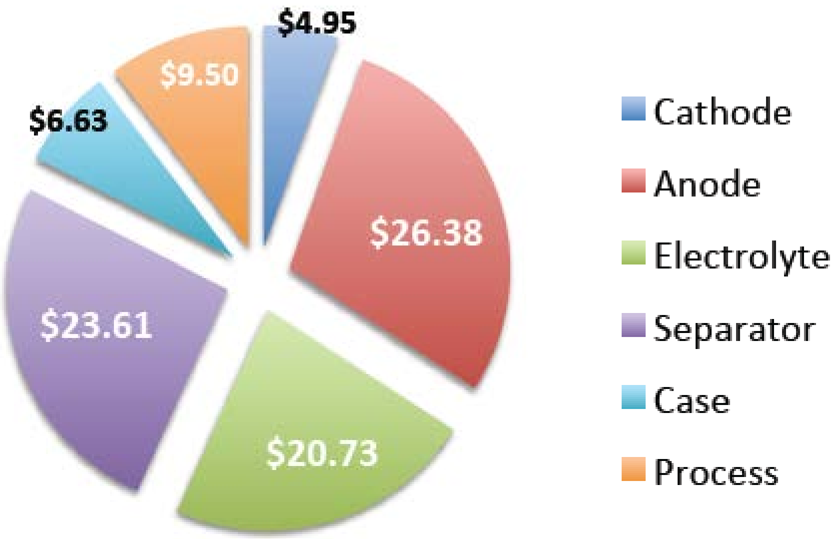
Li-S batteries meet both the cost and energy targets for EV

- High energy density
  - Theoretic: 2550 Wh/kg, 2862 Wh/l
- Low cost
  - Sulfur is free
  - Cell cost is low



courtesy of Alberta Sulfur Research Ltd



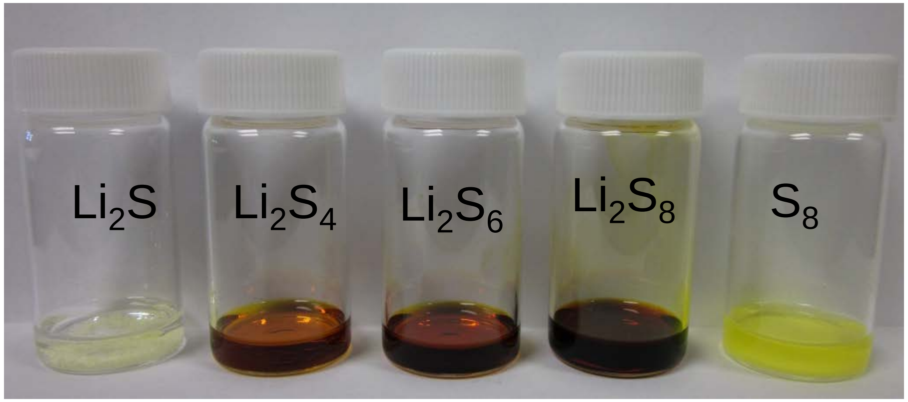
courtesy of Nohms

Estimated cost at cell level: $100/kWh

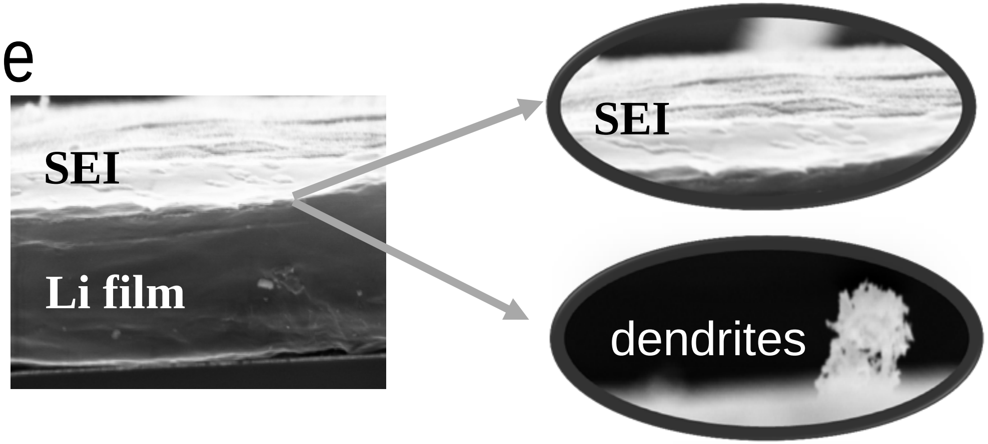
DOE, AEV, 2020 target: $100-150/kWh

Liquid electrolytes lead to short cycle life of Li-S batteries

- Dissolution of sulfur cathode
  - Loss of active material
  - Self discharge
  - Low energy efficiency (polysulfide shuttle)



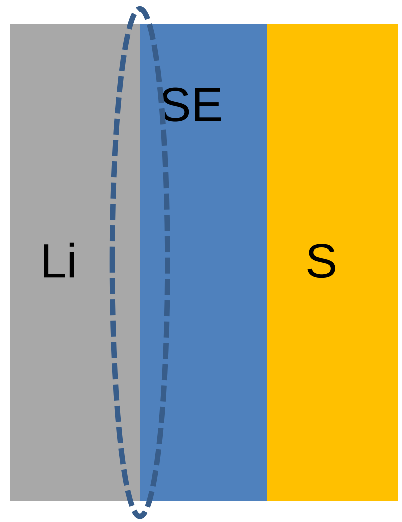
- Problematic cycling of Li anode
  - Dendritic growth of lithium
  - SEI formation
  - Safety



Using a solid electrolyte can solve all these problems!

Challenges for all-solid Li-S batteries

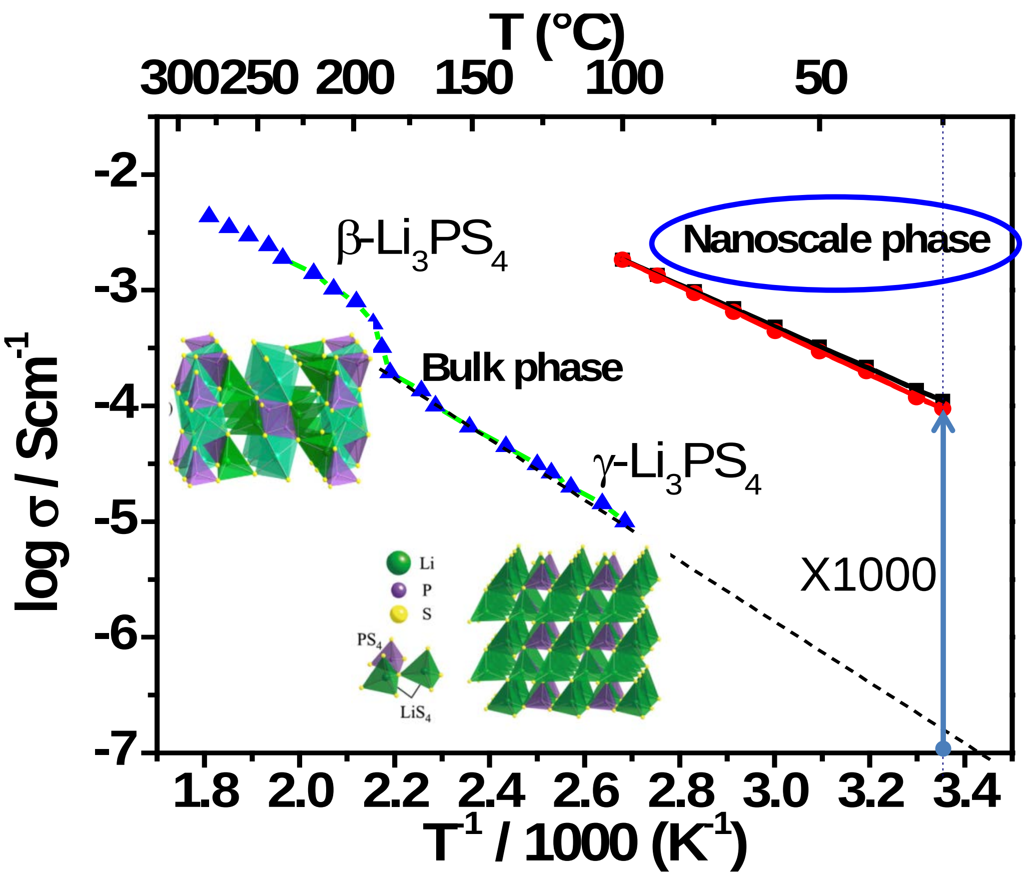
Solid Electrolyte:
High ionic conductivity

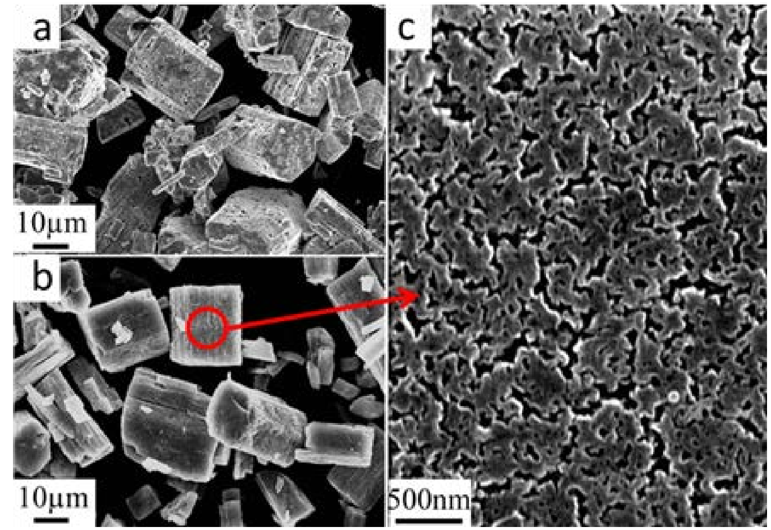


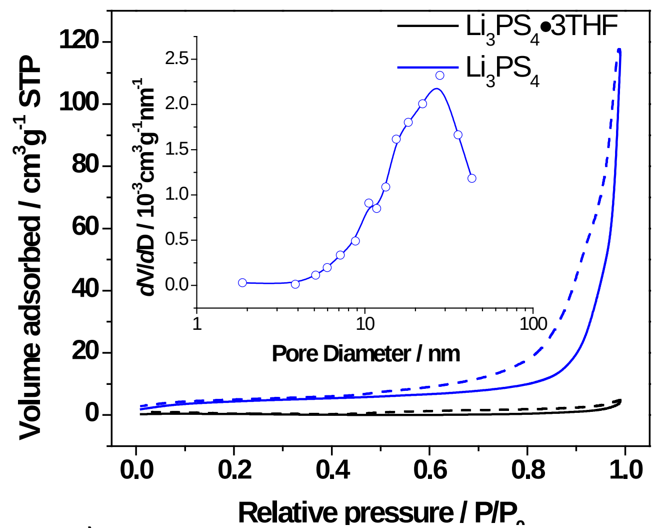
Lithium anode:
Chemical and electrochemical compatibility

Sulfur cathode:
- Ionic conductivity
- Electronic conductivity

Nanostructured Li_3PS_4 has a high ionic conductivity







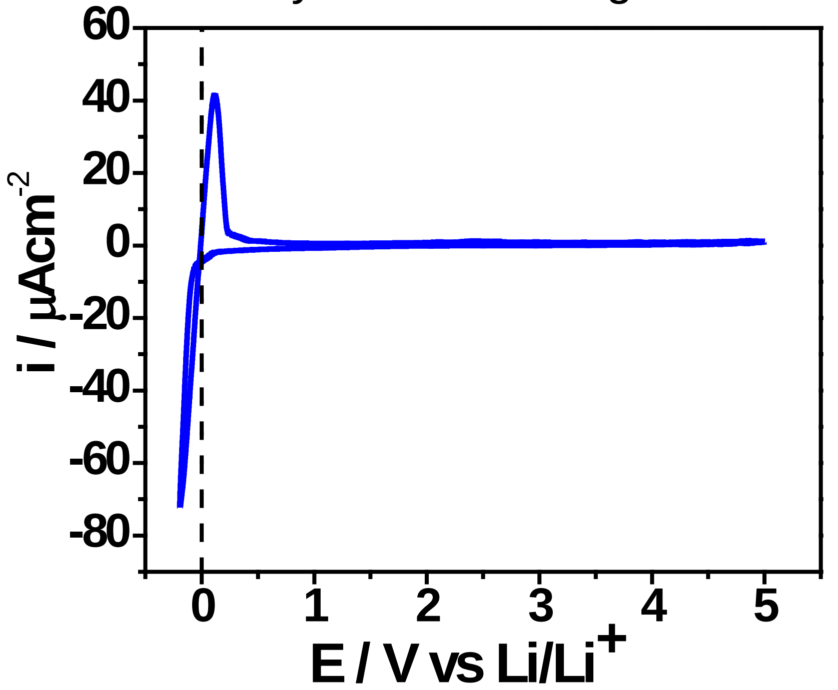
Mercier et al., Solid State Ionics (1984), Kanno et al., Solid State Ionics (2011)

*Liang et al., patent pending

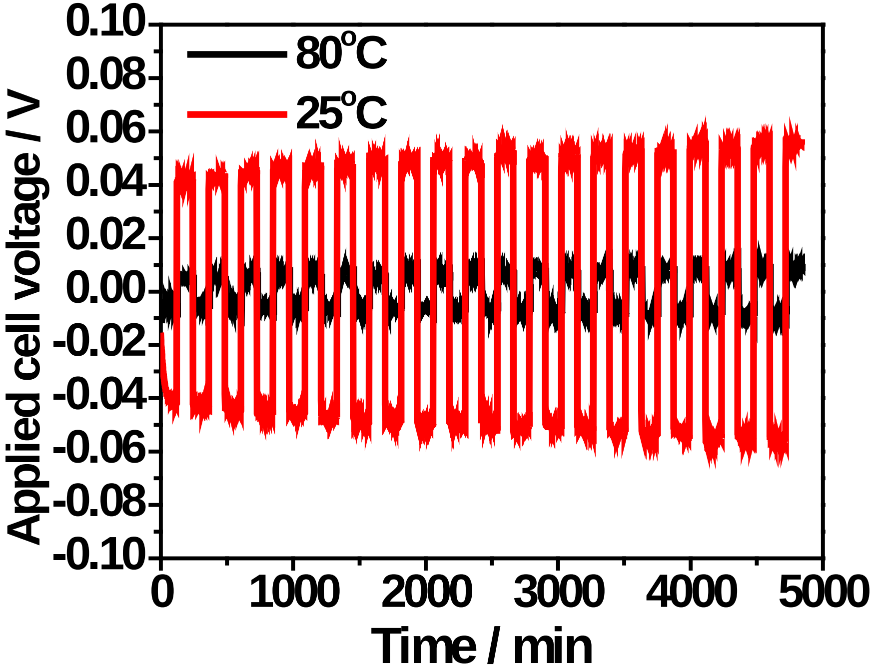
Liu and Liang, Nature Materials (under review)

Excellent compatibility of Li_3PS_4 with lithium metal anode

Cyclic voltammogram



Li|SE|Li symmetric cell test



Good electrochemical stability:

- Li deposition at 0V
- No redox peak up to 5V

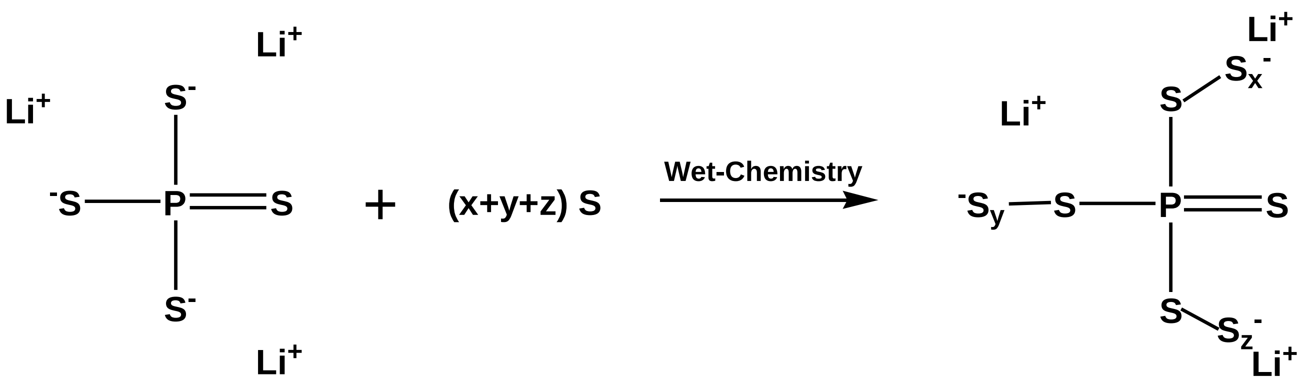
Excellent cyclability:

- No obvious interfacial reaction
- Reversible Li plating

Overcome the poor ionic conductivity of S cathode through chemical reactions

Key problem for S cathode: Poor ionic conductivities of S and its discharge products

a



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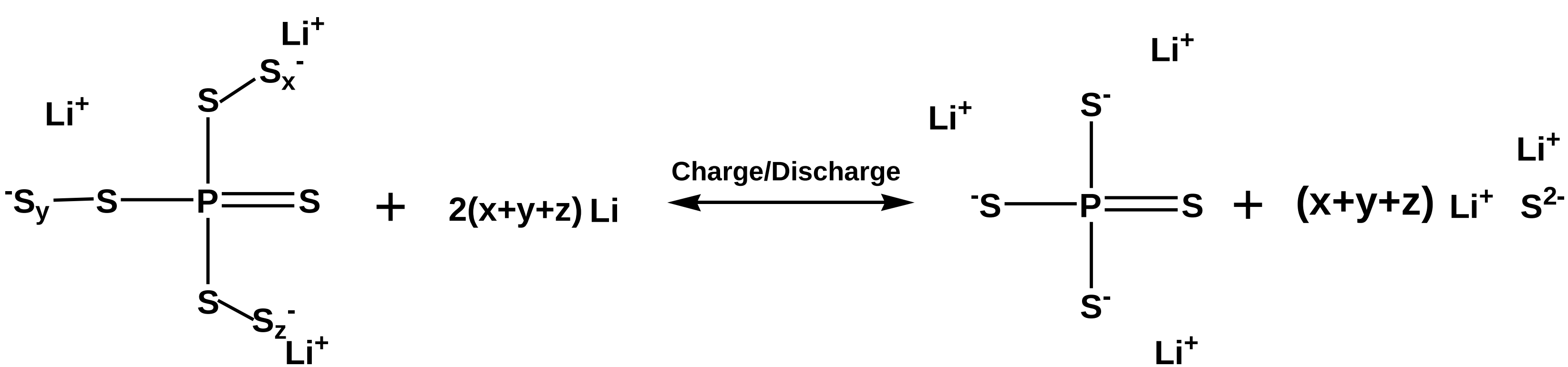
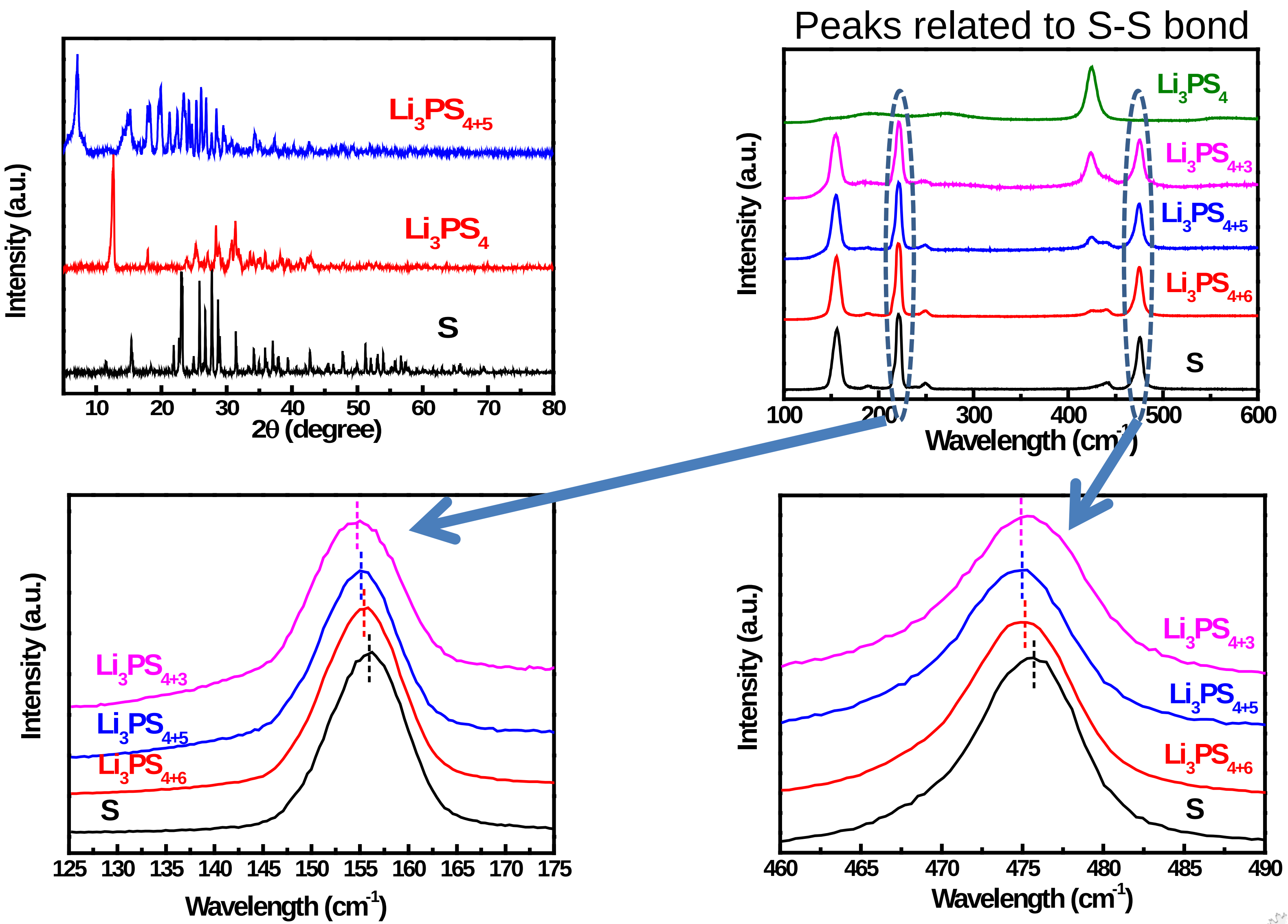


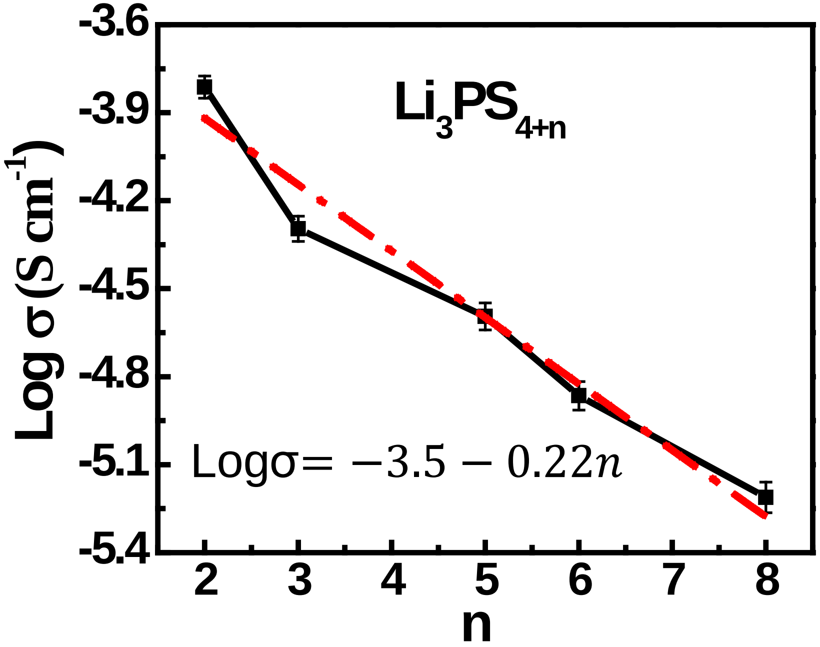
Lin and Liang patent pending

Raman spectra and XRD confirm the reaction of S with Li_3PS_4

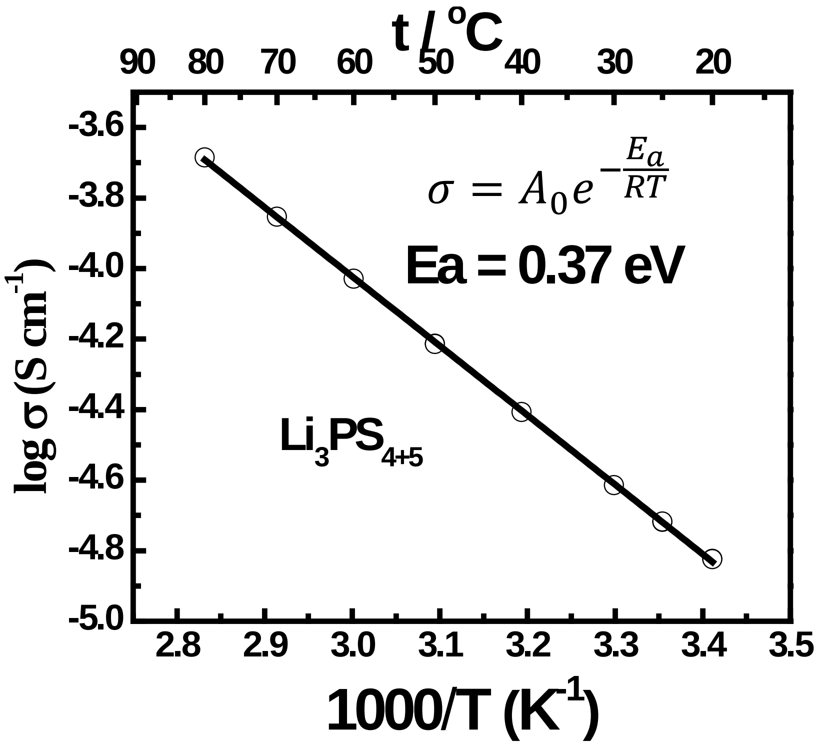


Ionic conductivity of the cathode is a function of S to Li_3PS_4 ratio

Room temperature conductivity as a function of sulfur in SE

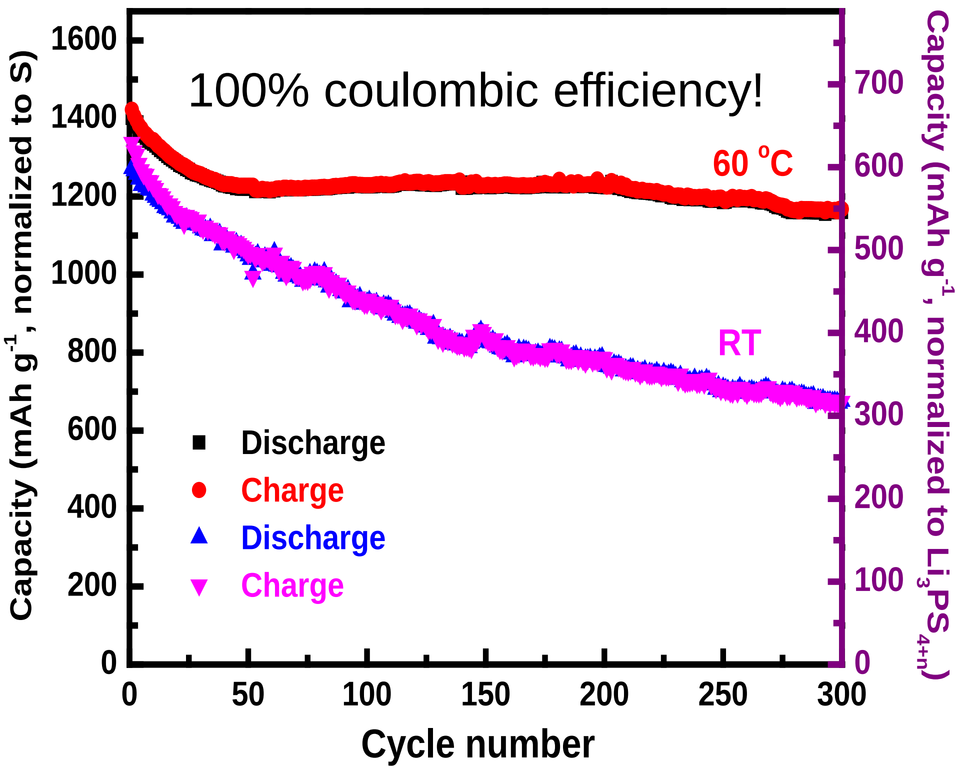


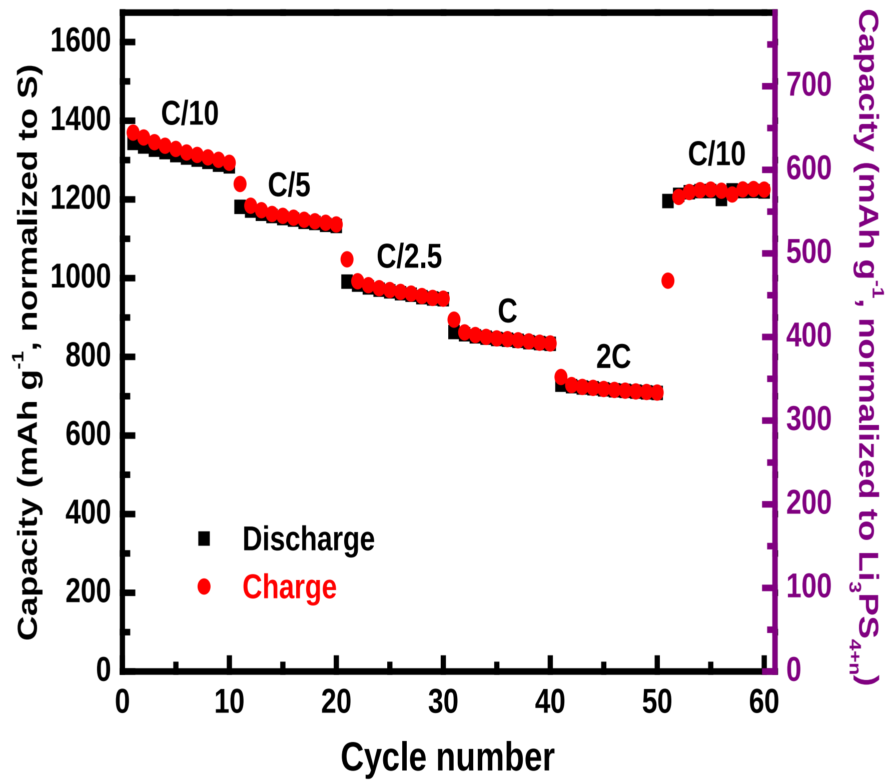
Arrhenius plot



Room temperature conductivity of Li_3PS_{4+5} is 100,000 times higher than that of Li_2S!

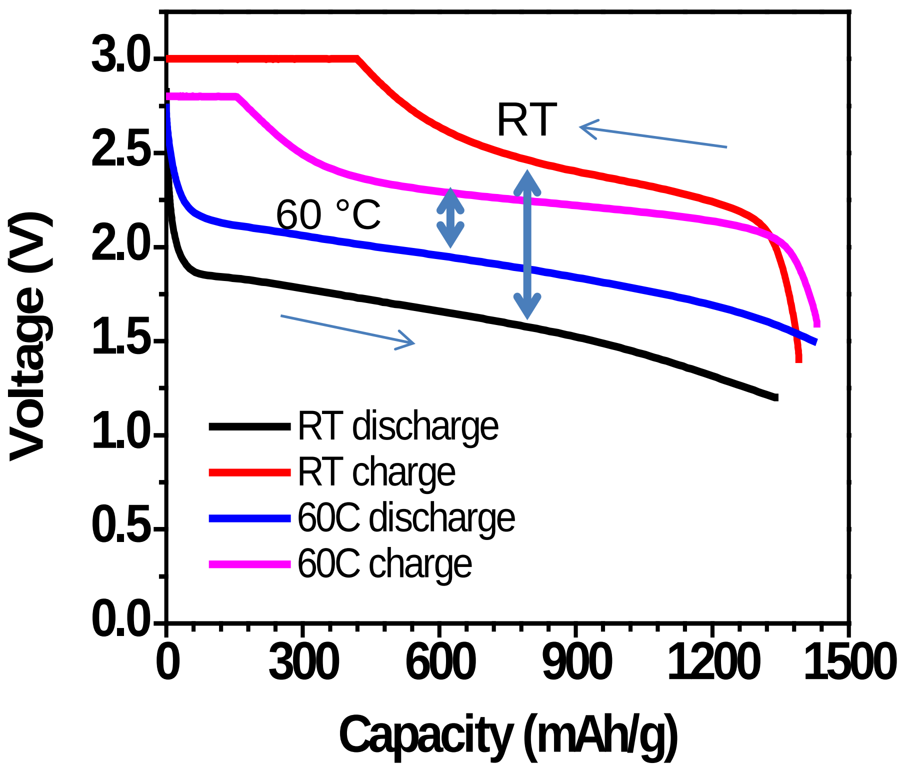
All-solid Li-S batteries have excellent cyclability and rate performance



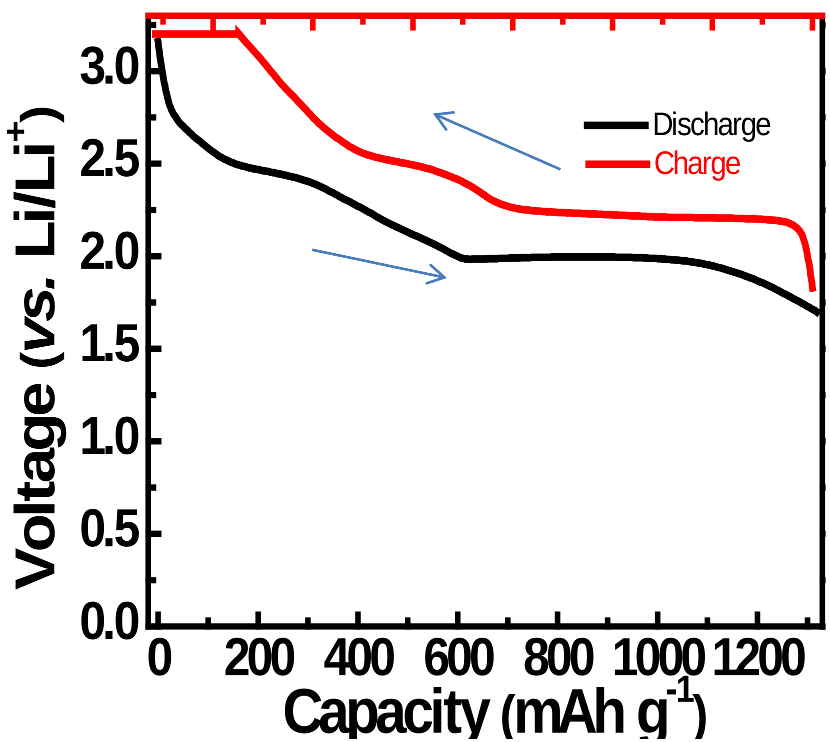


All-solid Li-S batteries have a different electrochemical reaction path

Solid electrolyte



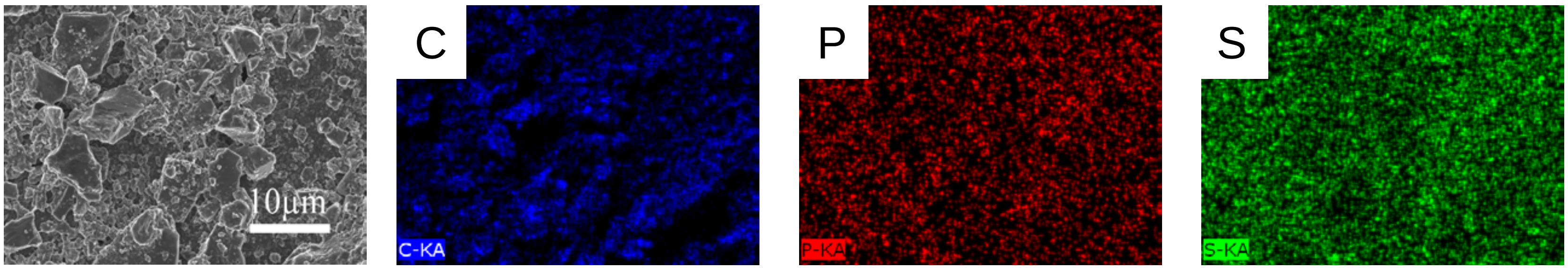
Liquid electrolyte



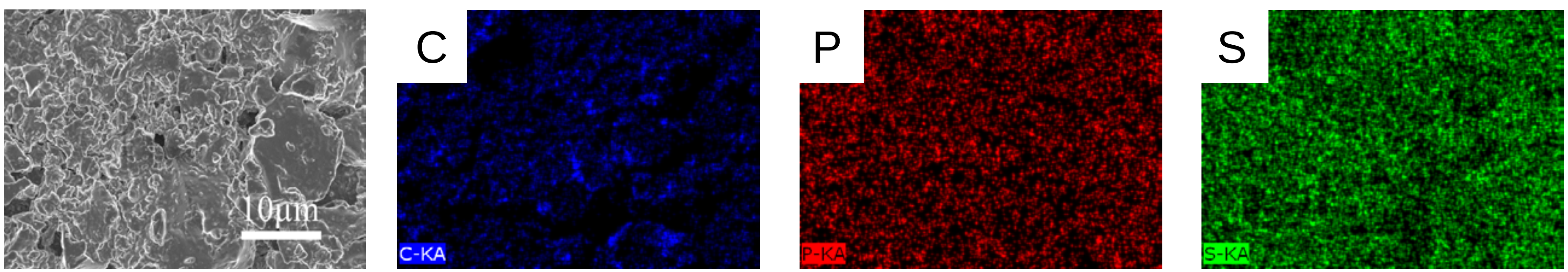
No polysulfide plateau presents in the all-solid cell

Cathode structure preserved after intensive cycling

SEM and elemental maps before cycling



SEM and elemental maps after 300 cycles at 60 °C



Conclusions

- Nanostructured Li_3PS_4 has superior electrochemical properties
  – High ionic conductivity ~10^{-3} Scm^{-1} at room temperature
  – Wide electrochemical window up to 5V
  – Compatible with lithium metal anode
- Cathode with a lithium-conducting sulfur compound
  – 5 orders of magnitude of improvement in ionic conductivity versus Li_2S
  – Good rate performance
  – Excellent cyclability
- All-solid battery overcomes the problems of conventional Li-S batteries
  – No PS shuttle, high coulombic efficiency, no self-discharge
  – Enabling metallic Li anode

Acknowledgements

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