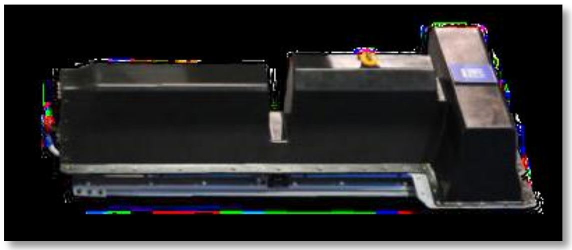
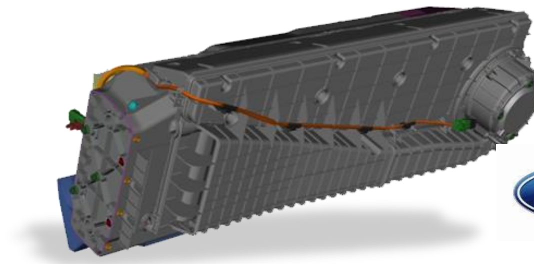
Keeping up with the increasing demands for electrochemical energy storage





Jeff Sakamoto

2015 **Top of the learning curve:** optimize current technology

2020 **Frontiers of Li-ion technology:** new materials

2030 **Frontiers of energy storage**: beyond Li-ion technology

Quantifying the demand for energy storage

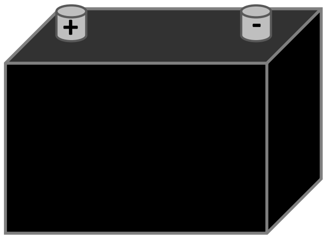
Power: Watts = current·voltage

Energy: Watts·time = Watt·hours

Specific Energy: Wh/kg

Energy Density: Wh/liter

Current and future energy storage tech



?

Wh/kg

Wh/kg

Batteries →

Wh/kg

Wh/kg

Lithium →

Beyond Lithium

Courtesy S. Whittingham

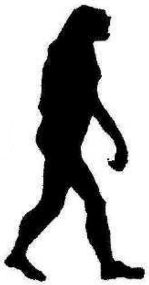
safety

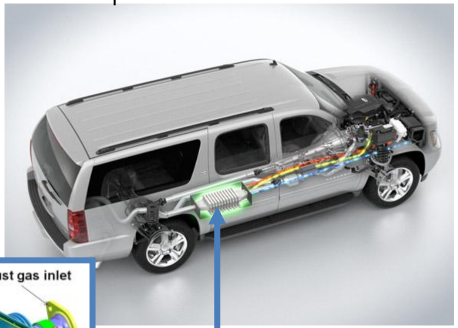
Li-ion

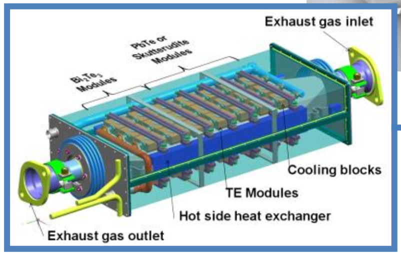
Li-sulfur

Li-air

Na, Mg, ?







Thermoelectrics

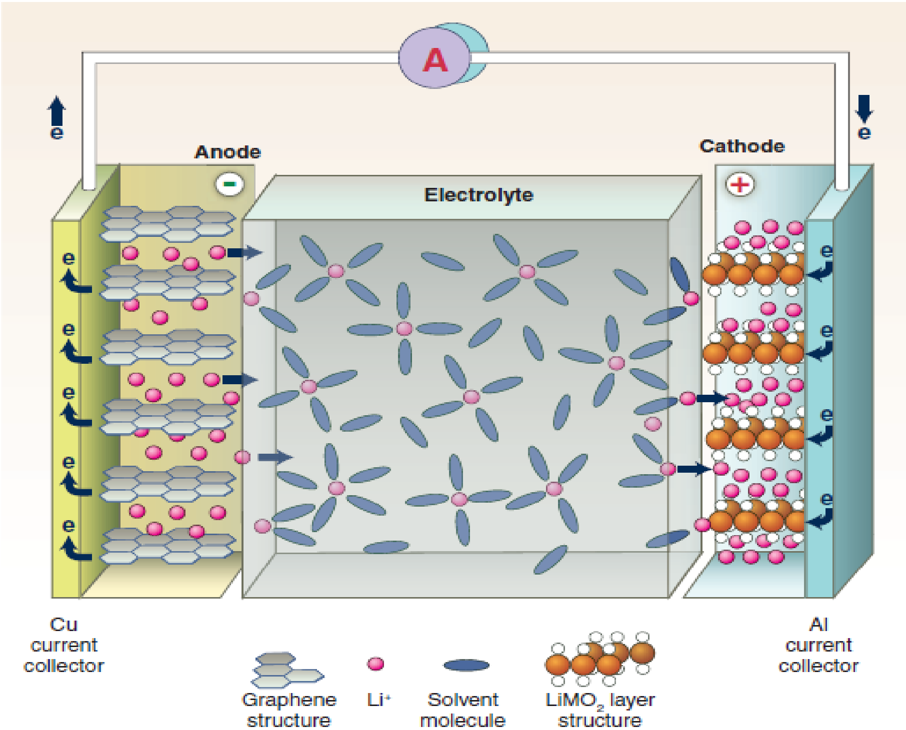
Is there enough lithium?

Courtesy of Ted Miller

Enough Li for:

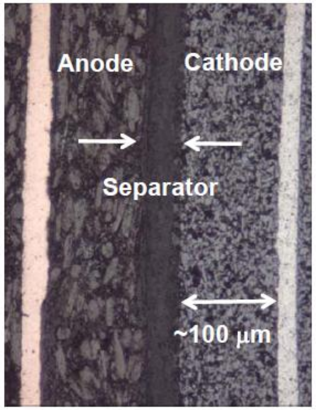
- 10^{12} HEV
- 10^{11} PHEV
- 10^{11} BEV

Current Li-ion: Nuts & Bolts

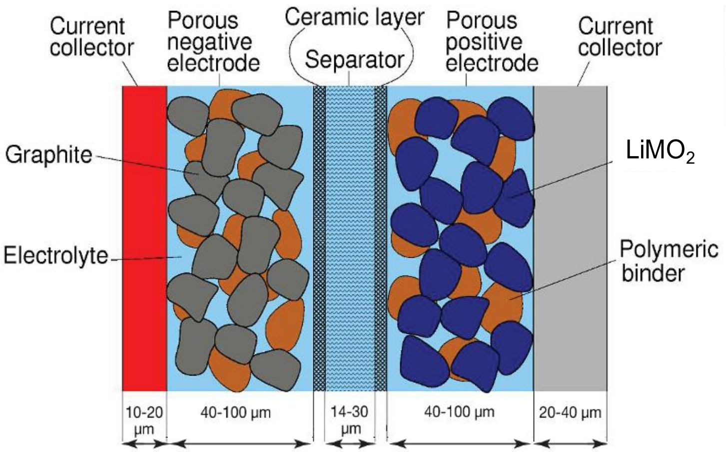


Dunn, B., Kamath, H. and Tarascon, J.-M. 2011.Science 334: 928-935.

Q.C. Horn and K.C. White, Abstract #318, 211th ECS Meeting, 2007



Typical Thickness of Li-ion cell components



Ponticel. P, 2012,, Society of Automotive Engineers: Vehicle Electrification: 6-28.

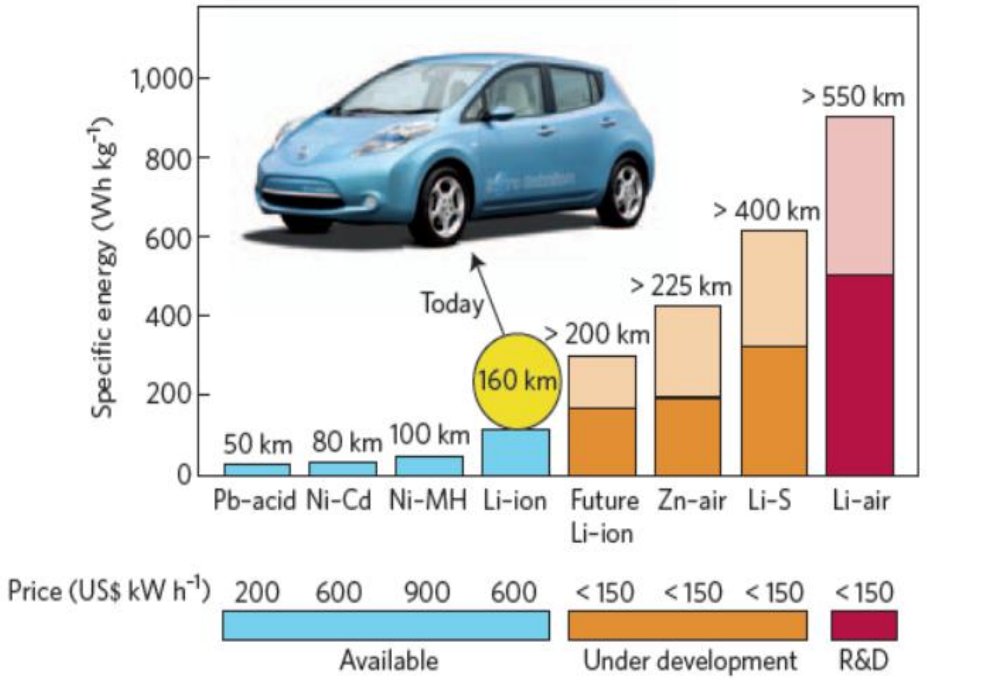
Frontiers of Electrochemical Energy Storage

	Current	2015	2020	2030	Post 2030
Specific Energy	100Wh/kg	150Wh/kg	250Wh/kg	500Wh/kg	700Wh/kg
Cost	1300$/kWh	400$/kWh	270$/kWh	130$/kWh	70$/kWh

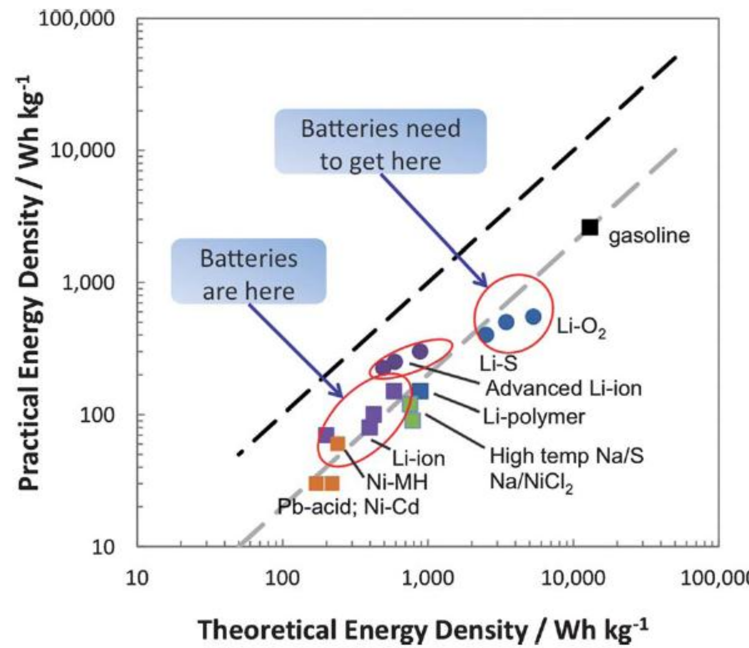
New Technologies

Climate Change Committee (2012) Final Report prepared by Element Energy Limited, Cambridge, UK .

Frontiers of Electrochemical Energy Storage



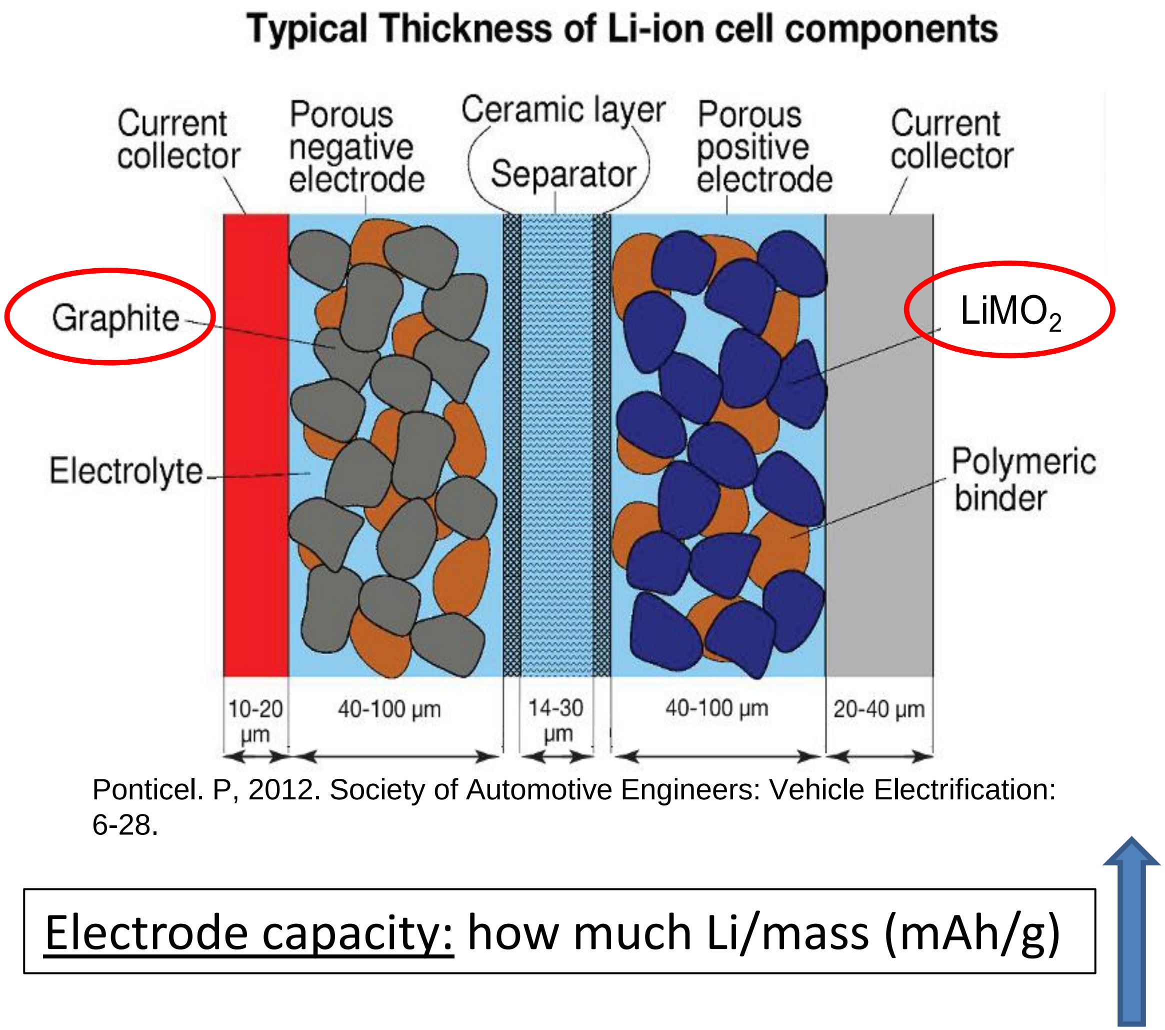
Bruce, P. G., Freunberger, S. A., Hardwick, L. J. and Tarascon, J.-M. 2012. Nature Materials 11: 19-29.



Thackeray, M., M., Wolverton, C. and Isaacs, E. D. 2012. Energy and Environmental Science 5: 7854-7863.

2020 Frontiers of Li-ion technology: new materials

(> 200km range, <$150/kWh)

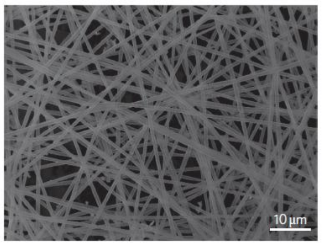


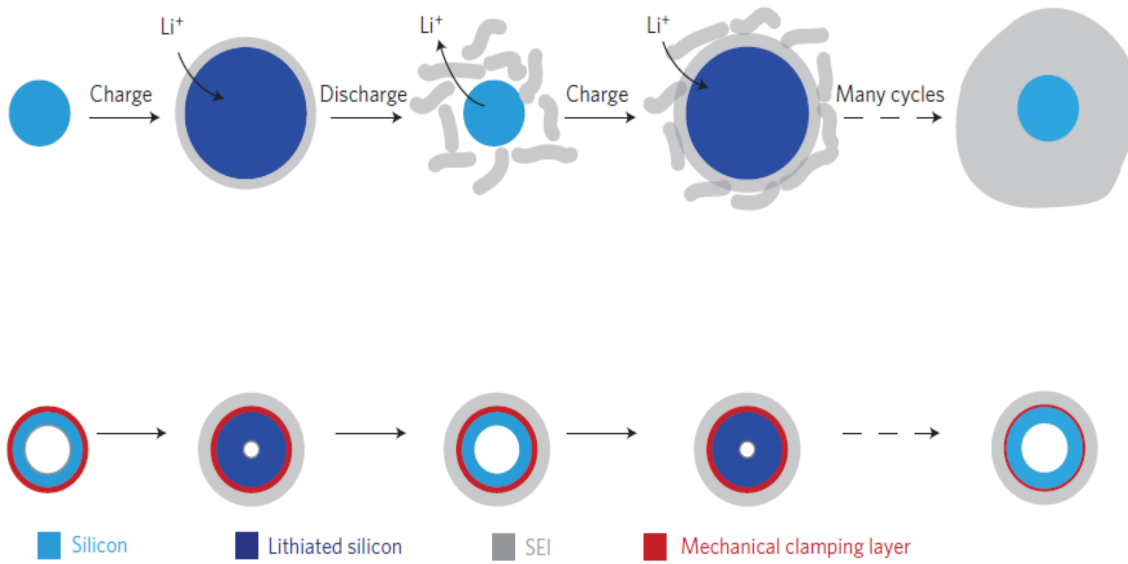
Ponticel. P, 2012. Society of Automotive Engineers: Vehicle Electrification: 6-28.

<u>Electrode capacity:</u> how much Li/mass (mAh/g)

2020 Anode: alloy vs. intercalate Li

Graphite anode = ~330 mAh/g (theoretical = 372 mAh/g)
Si anode = ~1000 mAh/g (theoretical > 4000 mAh/g)





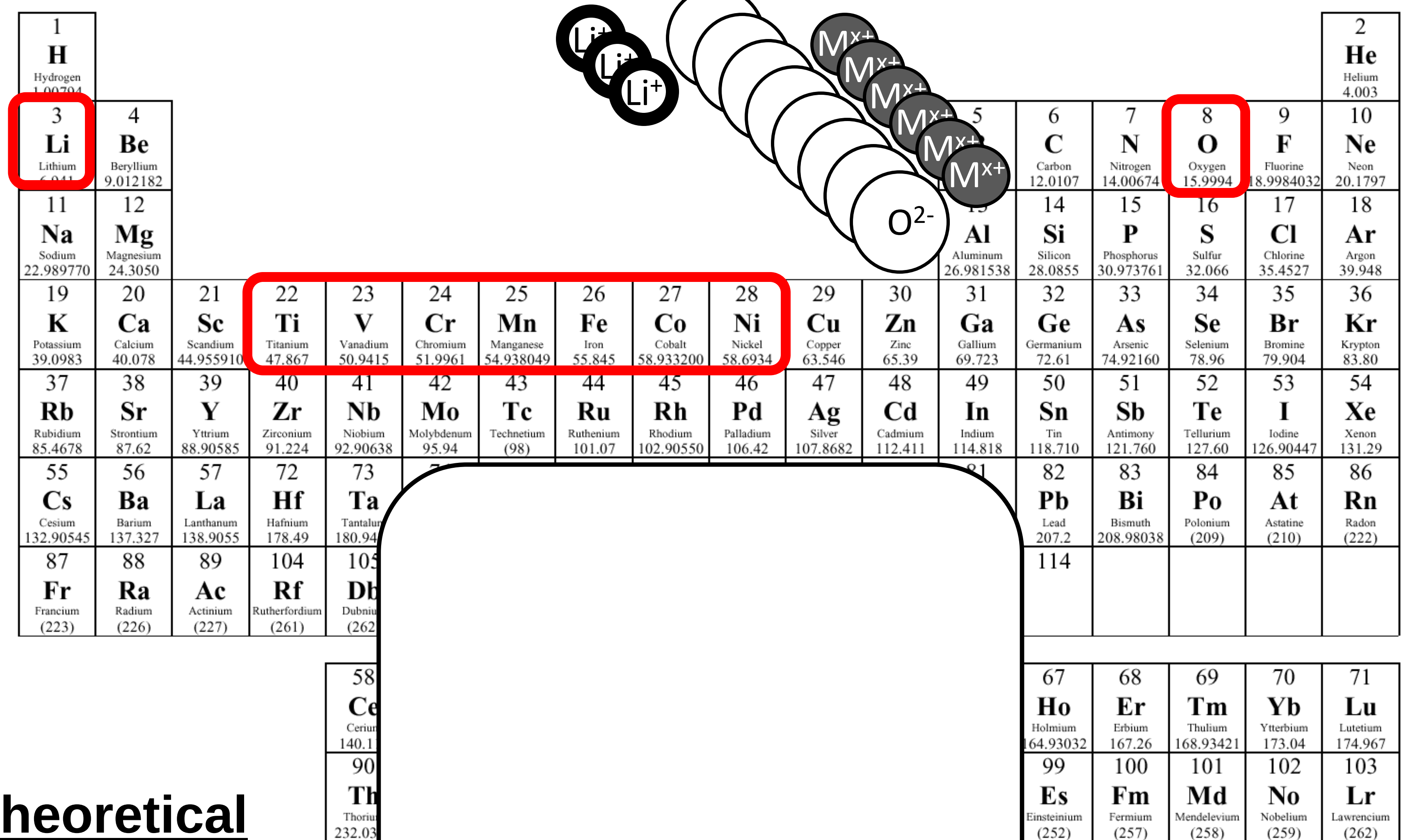
Cui *et al.* (2012) *Nature nanotechnology letters*.

Gorilla Glass®

+) Si is abundant & cheap
+) Increase in capacity
+) Low voltage

?) Cycle life; 300% volume change
?) Cost of manufacturing nano Si

The Periodic Table of the Elements



Theoretical

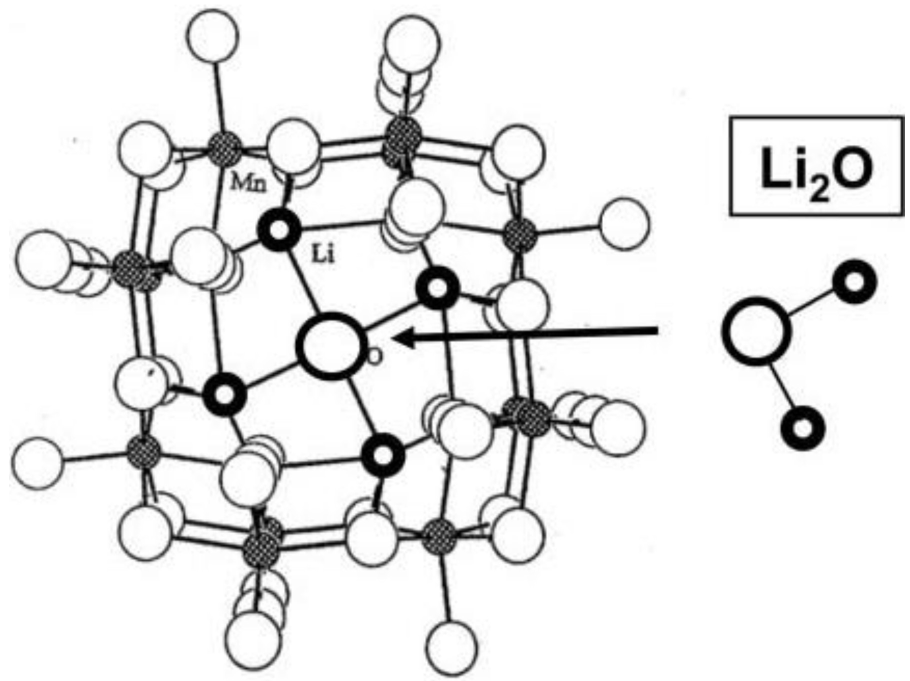
Li_1MO_2 ~ 280 mAh/g

Practical

$Li_{0.5}MO_2$ ~ 140 mAh/g

2020

Cathode: maximize Li utilization



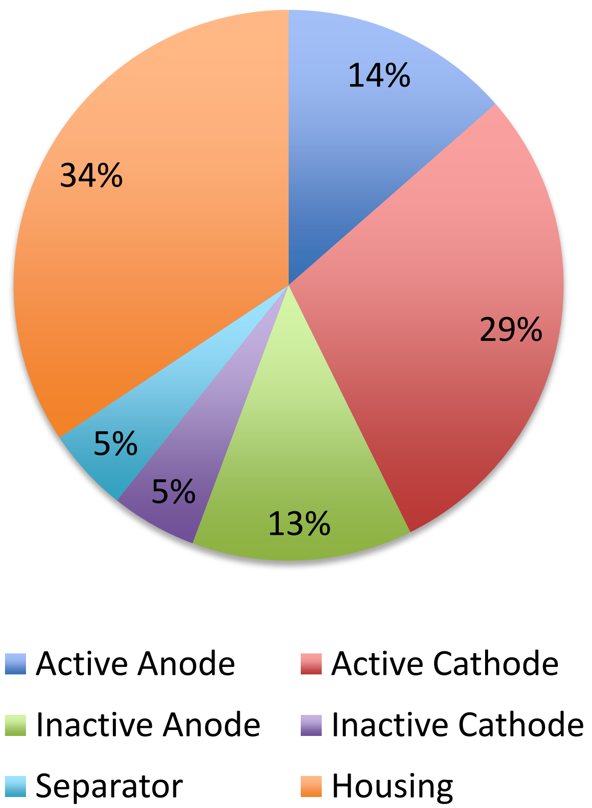
Li_2MnO_3-stabilized $Li_{\color{red}{1}}MO_2$: ~ 286 mAh/g

Layered cathodes: Thackeray *et al* Argonne National Lab.

+) Doubling of capacity
+) No new elements

?) Slow kinetic/power
?) Crystallographic stability
?) Charged @ > 4.5V: no electrolyte

2020 Impact of new materials

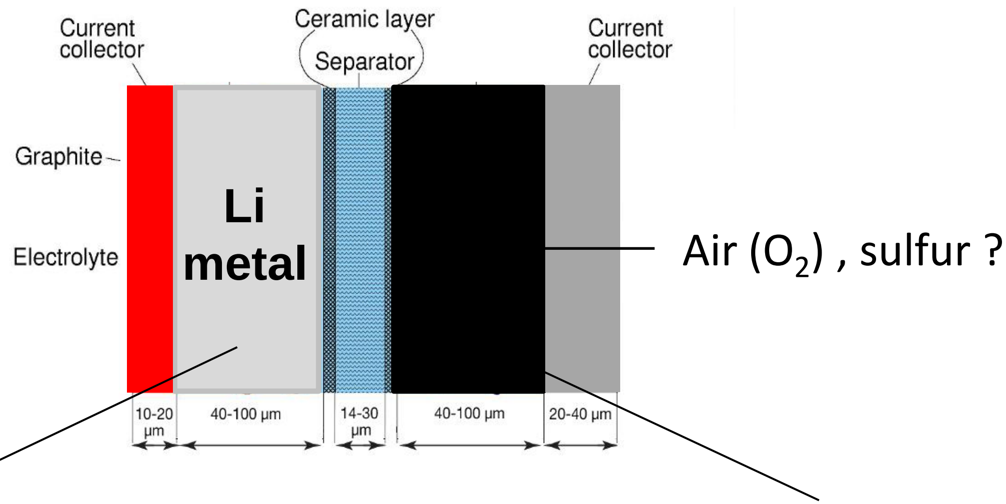


Adapted from: Johnson, B.A. & White, R.E.
Journal of Power Sources **70**, 48-54 (1998).

2030

Frontiers of energy storage: beyond Li-ion

(> 400km range, <$150/kWh)



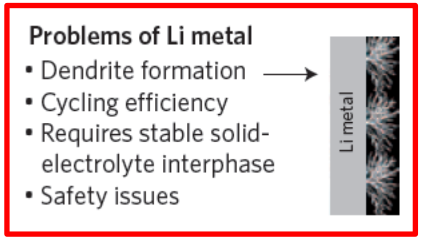
++) 3375 mAh/g (10X over graphite)

++) Li-Sulfur 2,500 Wh/kg Theoretical

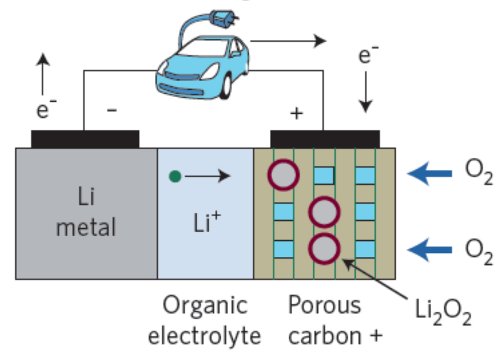
++) Li-O_2 3,500 Wh/kg Theoretical

2030 Li-O_2 dry (>500 km range, < $150 kWh)

Anode

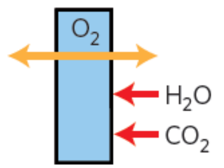


Discharge

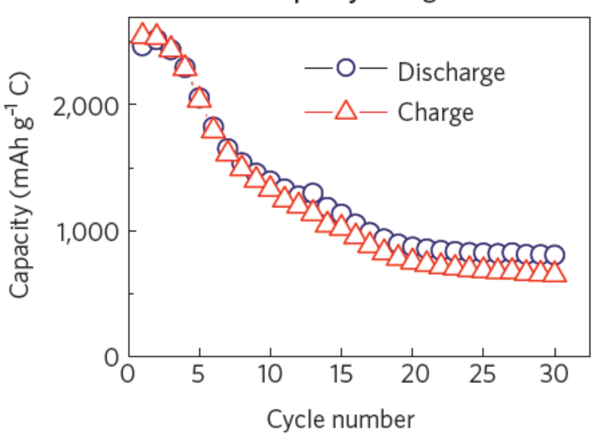


Cathode

Cathode needs a membrane to block CO_2 and H_2O, while allowing O_2 to pass.

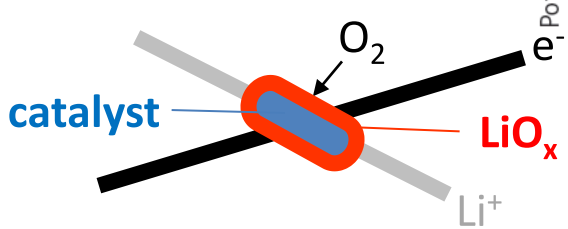


Capacity fading

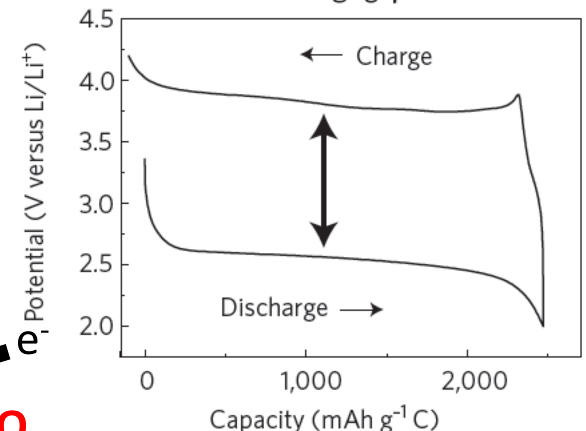


Bruce *et al*. 2012. Nature Materials 11: 19-29.

Electrolyte
- Stability
- Conductivity
- Volatility
- O_2 solubility, diffusivity



Voltage gap

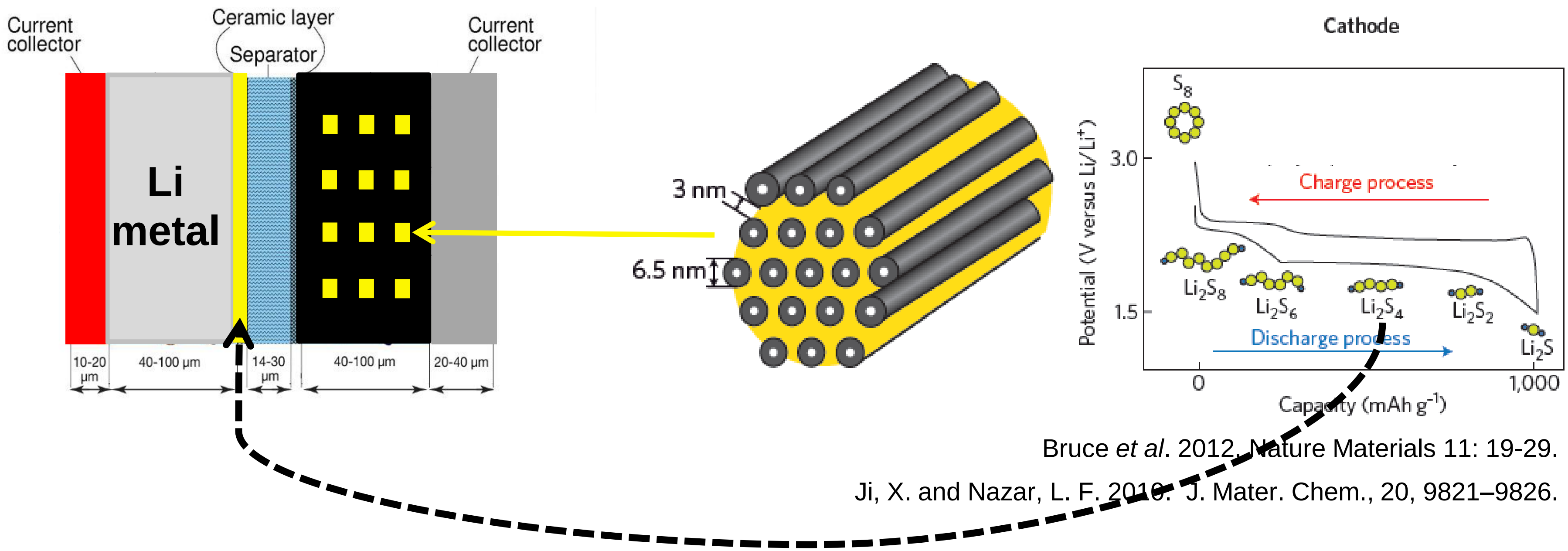


Porous cathode design
- Pore size, distribution
- Catalyst — type, distribution, loading

++) High Specific Energy
+) O_2 is ubiquitous

?) Must separate O_2
?) Kinetics/Power/Hysteresis
?) Li metal anode stability

2030 **Li-Sulfur** (>400 km range, < $150 kWh)



Bruce *et al*. 2012. Nature Materials 11: 19-29.

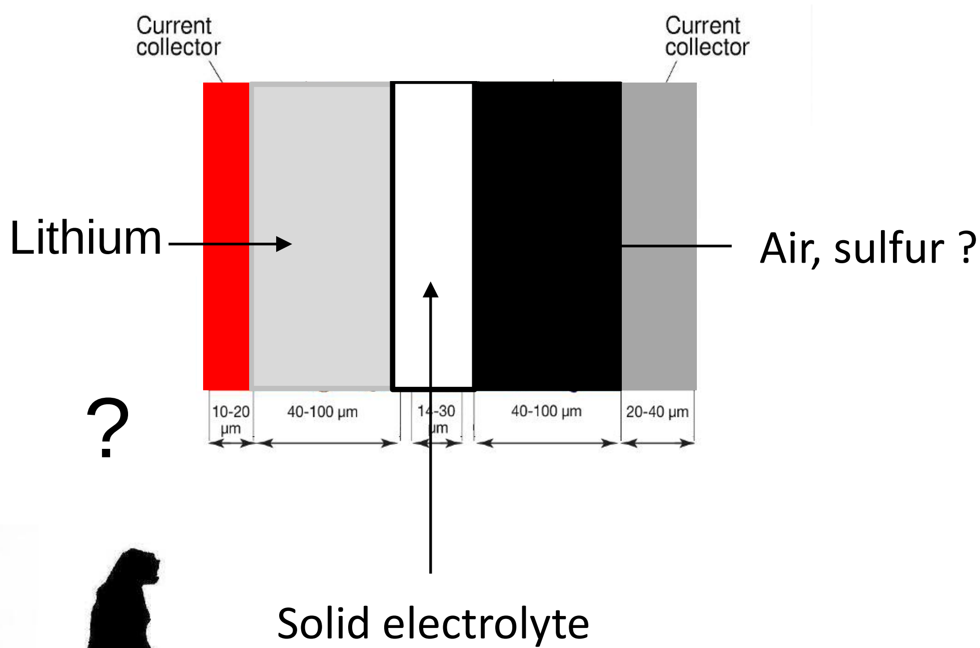
Ji, X. and Nazar, L. F. 2010. J. Mater. Chem., 20, 9821–9826.

+) High specific energy
+) Cheap, abundant
+) Light
+) 2 Li for every S (Li_2S)

?) cycling
?) Sulfur conductivity
?) Li metal anode stability

2030 Beyond Li-ion requires new electrolyte

Beyond Li-ion



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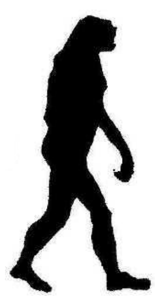
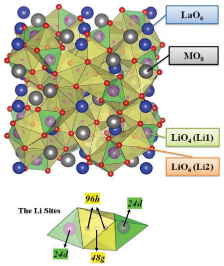


Sakamoto Group: *Engineering nothing*

Atoms

Å



Atomic-scale vacancies facilitate ion transport in ceramic electrolytes

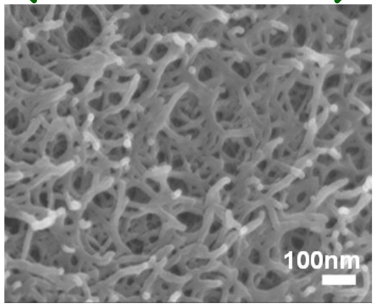
Gas molecules

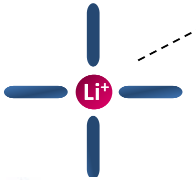
Å-2nm

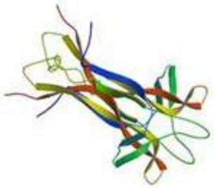
Micro pores impede gas transport

Solvated ions & proteins

2-50nm





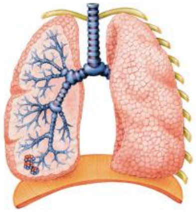


Meso pores connect molecular-scale phenomena to the macro-scale

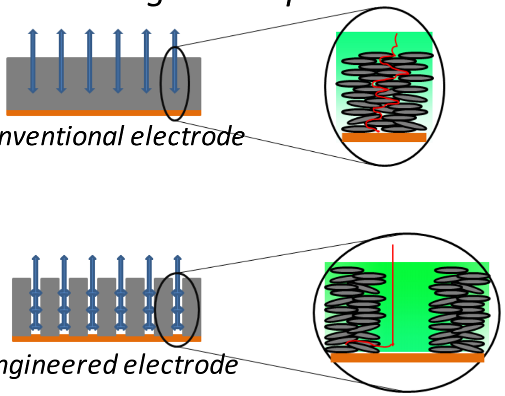
Macro scale phenomena

>50nm

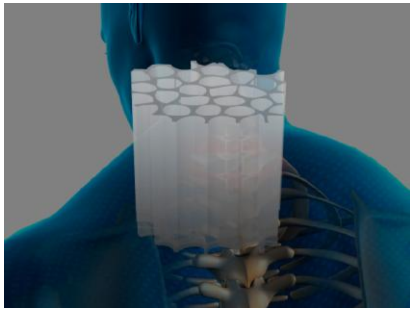
Li-ion "lung": Li-ions move from large linear to small orthogonal capillaries

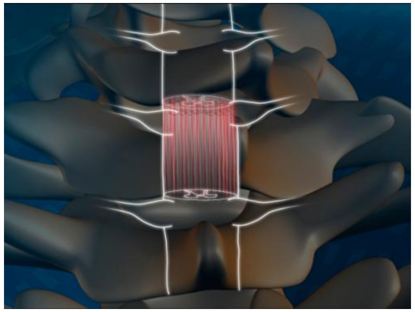


Oxford University Press: *Oxford Illustrated Science Encyclopedia*



Meso pores deliver proteins to linear macro pores that guide nerves





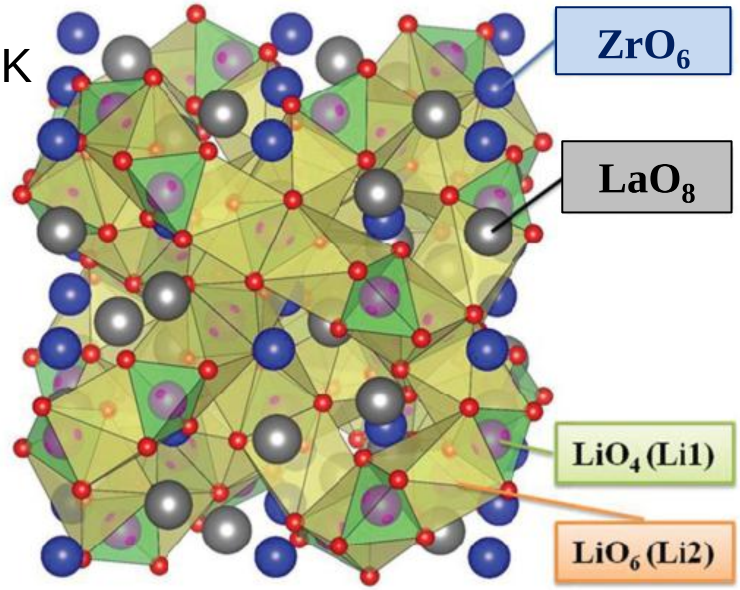
Ceramic electrolyte: $Li_7La_3Zr_2O_{12}$ garnet

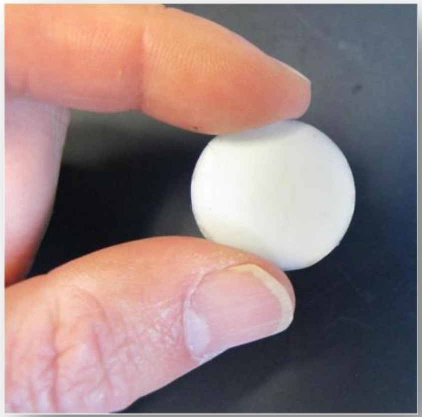
Advantages

- Li Conductivity similar to liquid electrolytes @ 298K
- First bulk, oxide electrolyte stable against Li
- Stable up to 9 V

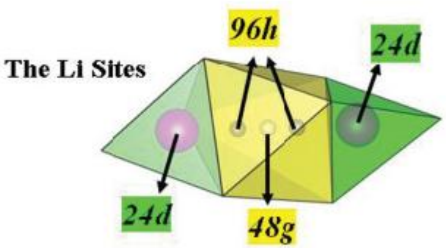
S. Ohta, T. Kobayashi, T. Asaoka, J. Power Sources 196 (2011) 3342.

- Can be synthesized/processed in ambient air





E. Rangasamy, J. Wolfenstine and J. Sakamoto, *Solid State Ionics*, **206**, 28-32 (2011).

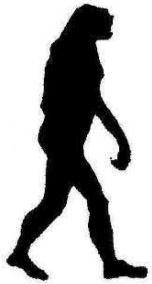


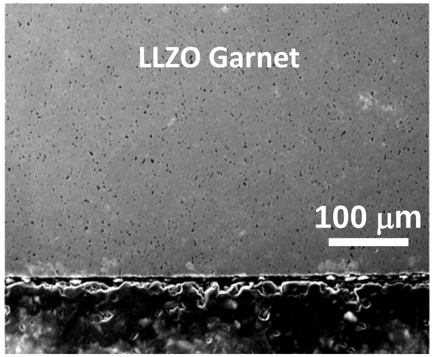
Xu *et al*. PHYSICAL REVIEW B 85, 052301 (2012)

First Report: R. Murugan, V. Thangadurai, W. Weppner, Angew. Chem. In. Ed. 46 7778 (2007).

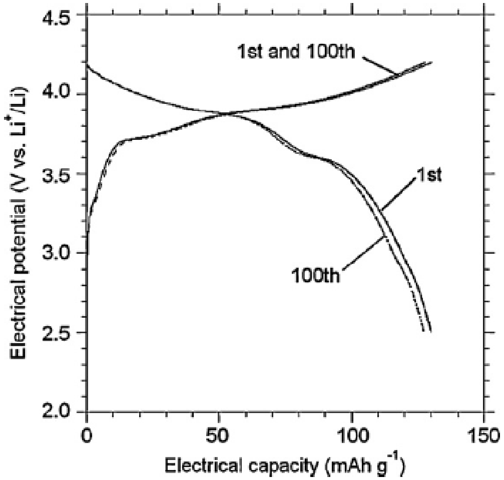
Towards cycling Li metal anodes

?



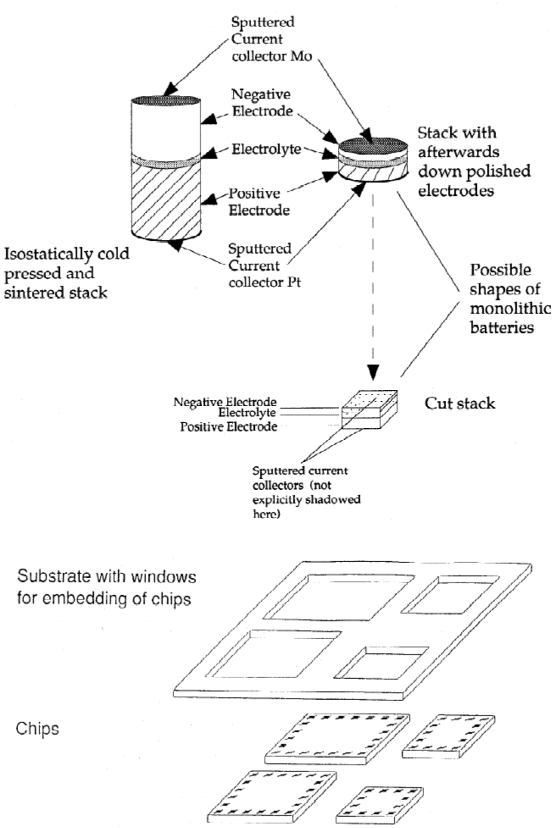


Sakamoto group, cycled LLZO

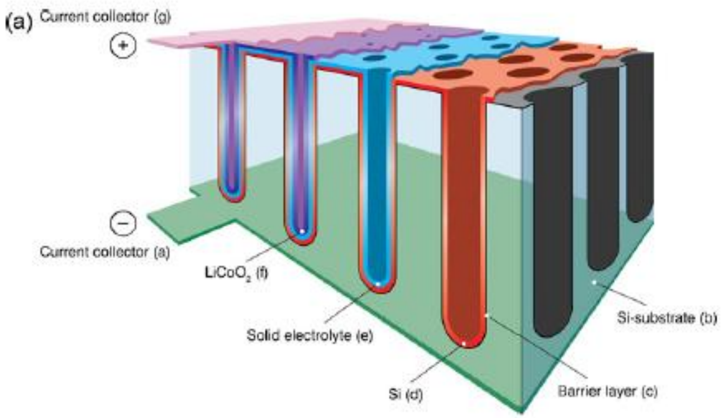


S. Ohta *et al*. , *Journal of Power Sources*, vol. 196, no. 6, pp. 3342-3345 (2011).

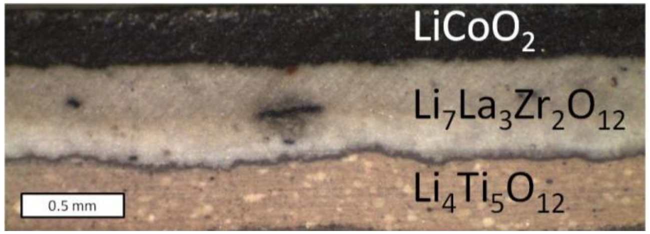
Solid-state, All Ceramic Batteries



Weppner *et al.* (1999)



Notten *et al.* Phillips (2009)



Sakamoto group (2011)

+) No organics to degrade
+) Synthesized and fabricated in air
+) Significant reduction in packaging
+) Non-flammable
+) Gets better with increasing temp

?) Interface integrity
?) Kinetics/Power
?) Thermomechanical stresses

Conclusions

1. Energy density (Wh/kg) must increase by ~4X
2. Cost ($kWh) must decrease by ~4X
3. 2020 goal: integrate new materials into current Li-ion
4. 2030 goal: must go beyond Li-ion requiring:
   - Li metal anodes
   - New cathodes
     - Li-O_2
     - Li-Sulfur
5. Opportunities
   - New solid and liquid electrolytes
   - Electrode and battery designs
   - Additive manufacturing
   - Predictive analysis
   - Packaging