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University of Utah, Seminar at Gentex, March 14, 2023

Li-ion batteries: current research, challenges and the future

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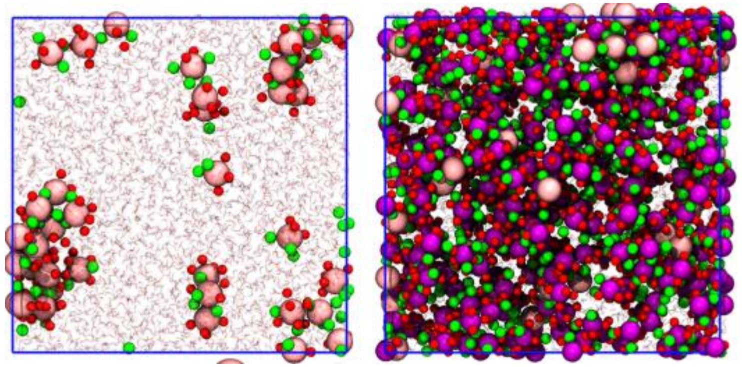
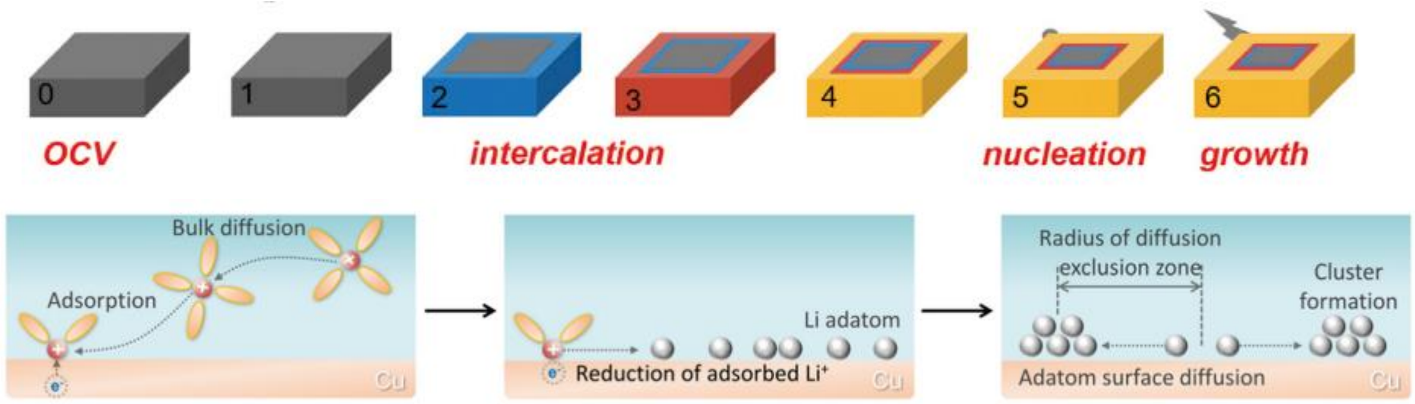
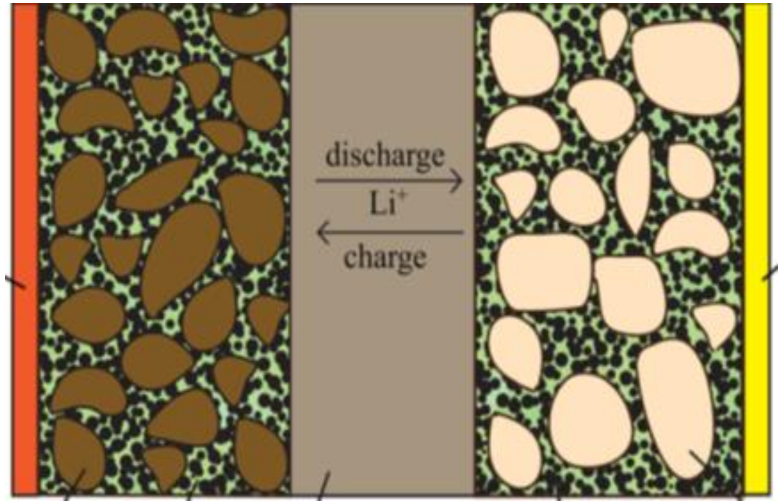




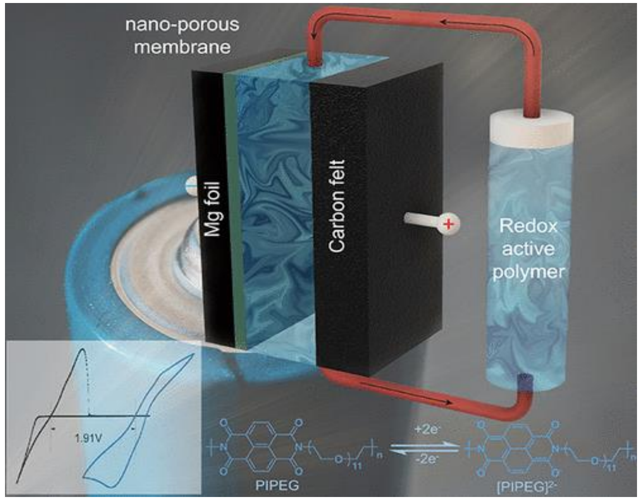
Multi-scale Electrochemical Engineering Lab

ME2 Lab

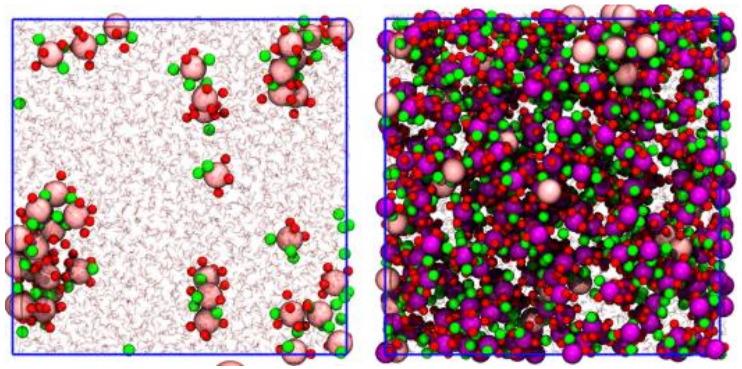
Li-ion batteries



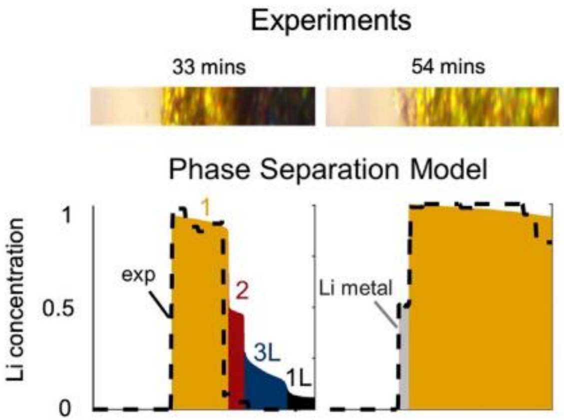
Electrochemical reactor



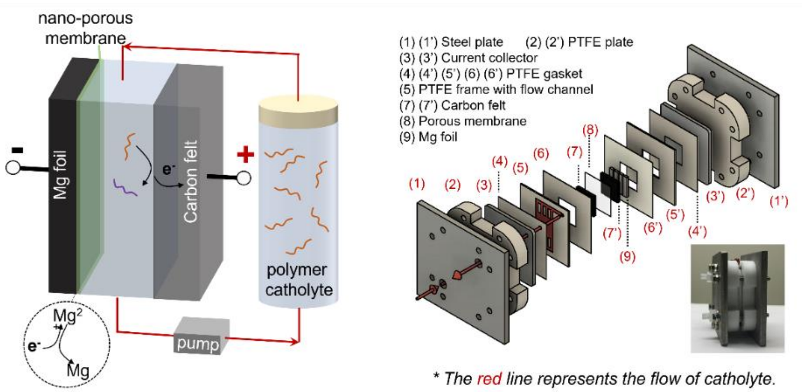
Atomic/molecular scale | Meso-scale | Device scale



Structure of electrolytes and electrodes



reaction, diffusion and phase transformation

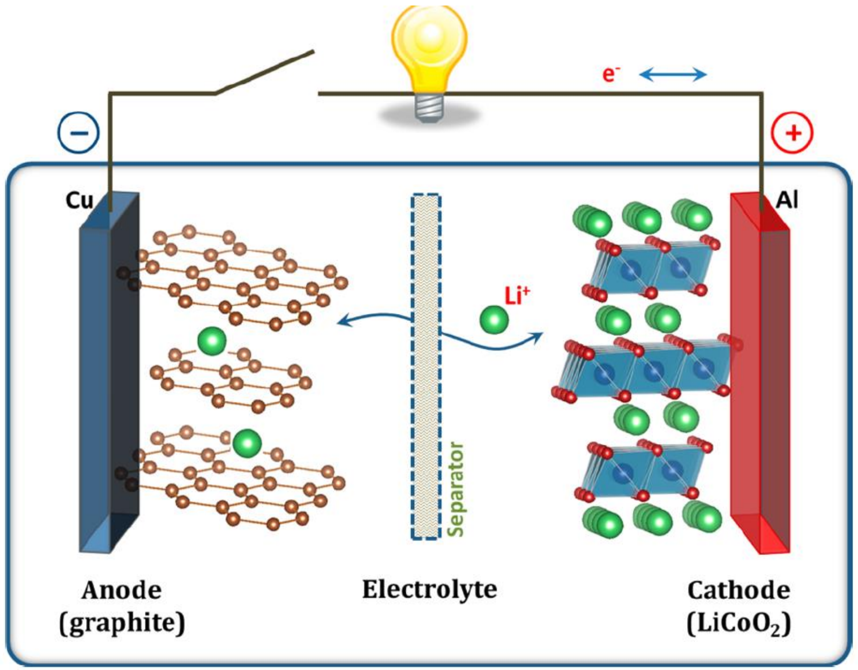


New device or process

Content

- Basics of Li-ion battery
- Electrolyte of Li-ion battery
- Safety of Li-ion battery
- Degradation of Li-ion battery
- Electrolyte for advanced performances
    - High-Energy Li battery
    - Fast-charging Li-ion battery

Principle of Li-ion batteries (LIBs)



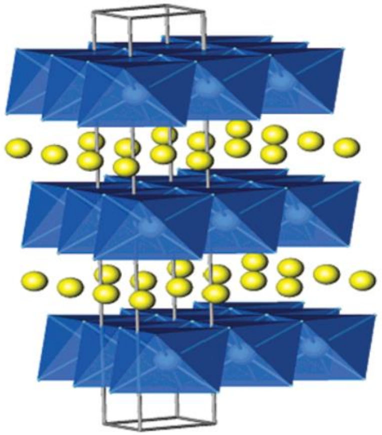
Basic requirement of electrodes

- High Li storage capacity
- High/low potential (for cathode/anode)
- Fast Li diffusion
- Reversible Li insertion/extraction

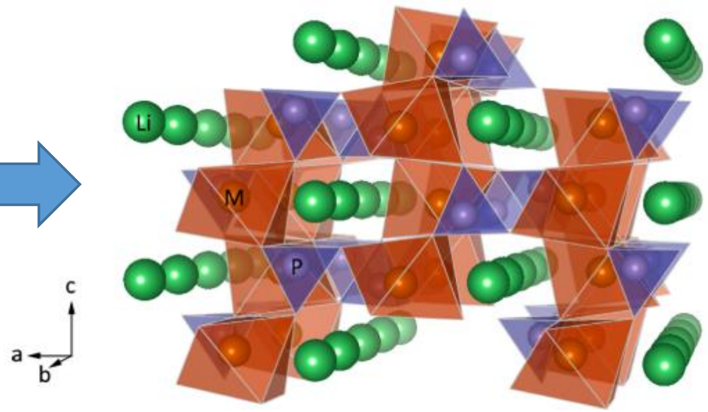
Basic requirement of electrolyte

- Transport property
  - Be a good ionic conductor and electronic insulator
- Electrochemical stable
  - Have wide electrochemical window
- Chemical stable
  - Inert to other cell components
- Thermal stable
- Environmentally friendly

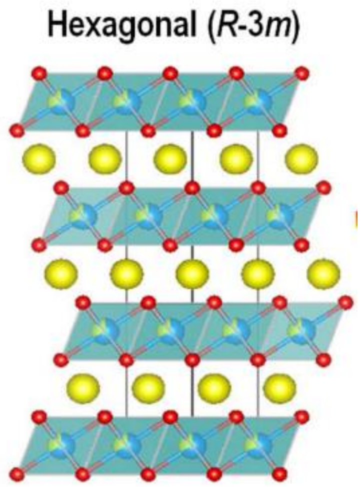
Cathode materials for LIBs



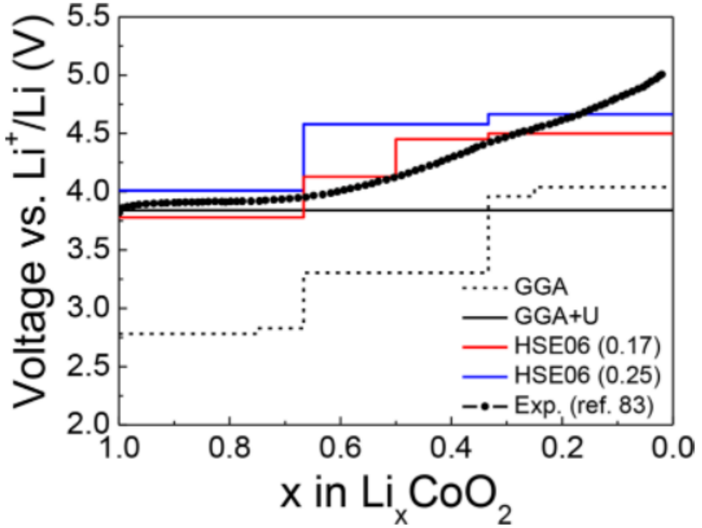
$LiCoO_2$



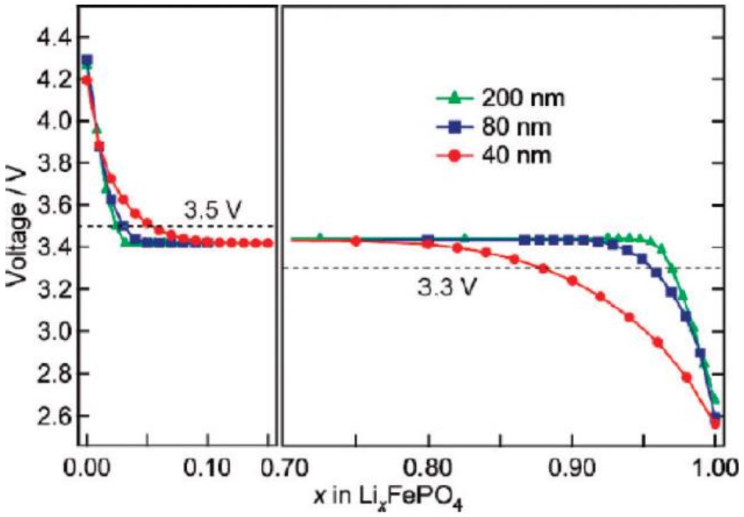
$LiFePO_4$



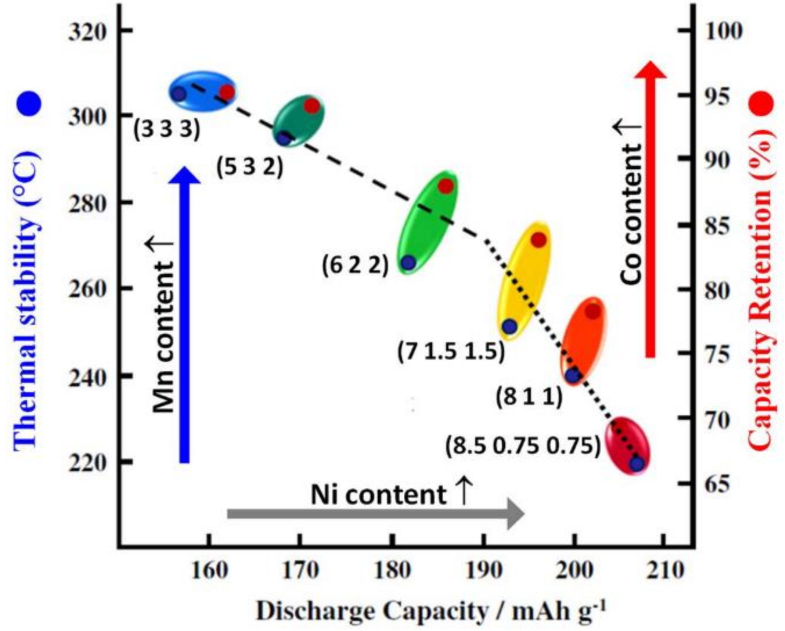
NMC



D. H. Seo, A. Urban, and G. Ceder, *Phys. Rev. B - Condens. Matter Mater. Phys.*, 2015,



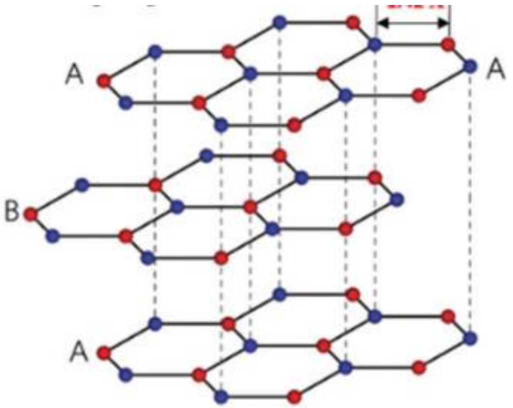
B. L. Ellis, K. T. Lee, and L. F. Nazar, *Chem. Mater.*, vol. 22, pp. 691–714, 2010

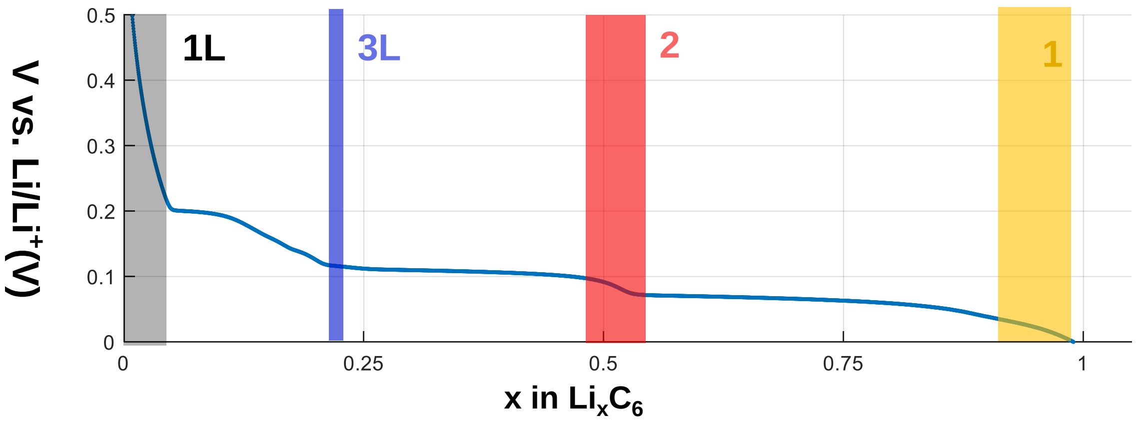


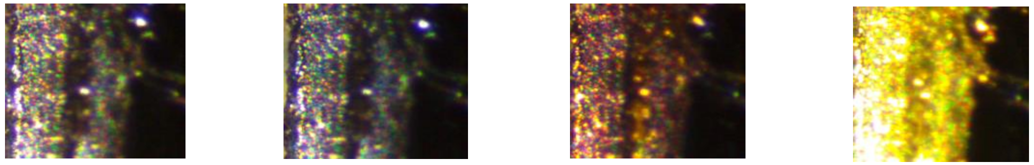
P. Rozier and J. M. Tarascon, *J. Electrochem. Soc.*, vol. 162, no. 14, pp. A2490–A2499, 2015

Anode materials for LIB

Graphite

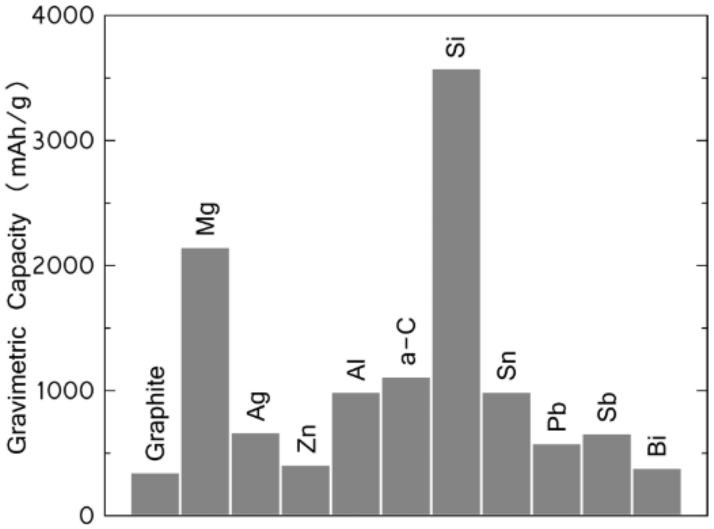




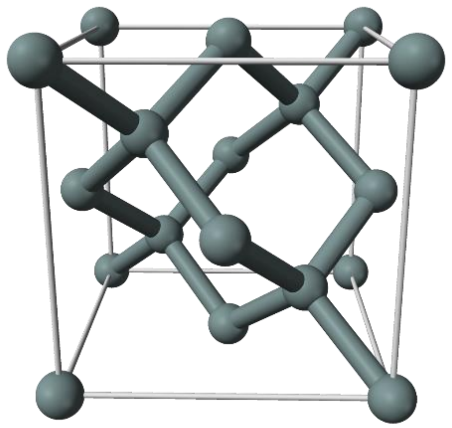


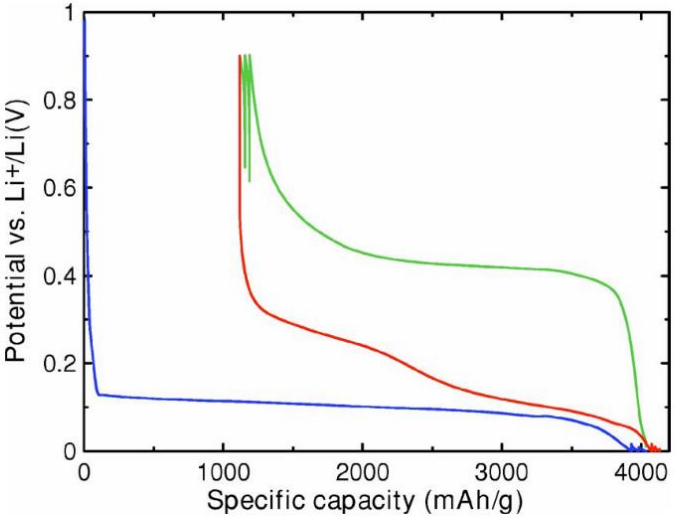
x<0.1 x=0.21 x=0.5±δ x=1-δ

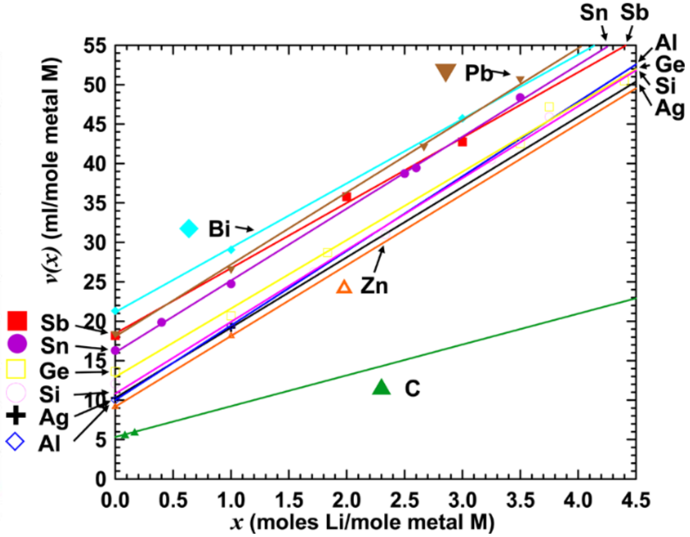
T. Gao, W. Chueh, J. Li, M.Z. Bazant, *et al. Joule, 2021*



Silicon







M. N. Obrovac, V. L. Chevrier, *Chem. Rev.* **2014**

Content

- Basics of Li-ion battery
- Electrolyte of Li-ion battery
- Safety of Li-ion battery
- Degradation of Li-ion battery
- Electrolyte for advanced performances
  - High-Energy Li battery
  - Fast-charging Li-ion battery

Electrolyte for Li-ion battery: solvent

A typical liquid electrolyte consists of

- Main solvent
- Co-solvent
- Li salt
- Additives

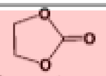
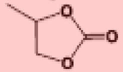
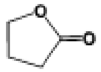
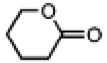
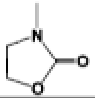
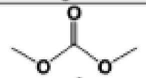
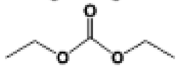
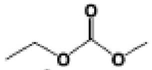
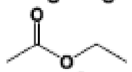
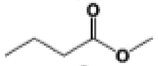
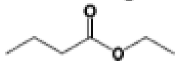
An ideal solvent should

- Have high dielectric constant
- Have low viscosity
- Resistant to oxidation/reduction
- Have a wide liquid temperature
- Have a high flash point
- Nontoxic and economical

Therefore

- Non-polar solvents ruled out
- Protic solvent ruled out
- Organic carbonates and esters of special interest due to their resistance to oxidation

Table 1. Organic Carbonates and Esters as Electrolyte Solvents

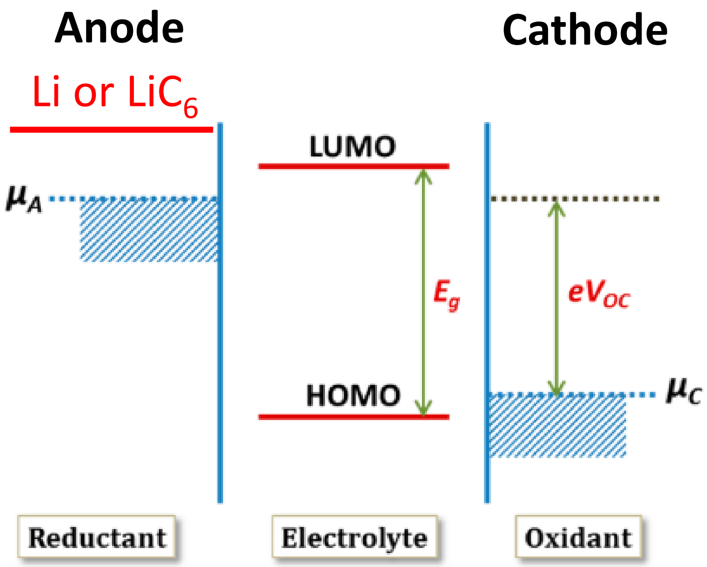
Solvent	Structure	M. Wt	T_m/ °C	T_b/ °C	η/cP 25 °C	ε 25 °C	Dipole Moment/debye	T_f/ °C	d/gcm^{-3}, 25 °C
EC		88	36.4	248	1.90, (40 °C)	89.78	4.61	160	1.321
PC		102	-48.8	242	2.53	64.92	4.81	132	1.200
BC		116	-53	240	3.2	53			
γBL		86	-43.5	204	1.73	39	4.23	97	1.199
γVL		100	-31	208	2.0	34	4.29	81	1.057
NMO		101	15	270	2.5	78	4.52	110	1.17
DMC		90	4.6	91	0.59 (20 °C)	3.107	0.76	18	1.063
DEC		118	-74.3 [a]	126	0.75	2.805	0.96	31	0.969
EMC		104	-53	110	0.65	2.958	0.89		1.006
EA		88	-84	77	0.45	6.02		-3	0.902
MB		102	-84	102	0.6			11	0.898
EB		116	-93	120	0.71			19	0.878

Kang Xu, Chemical Reviews, 2004, Vol. 104, No. 10

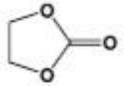
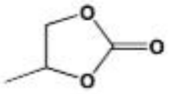
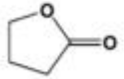
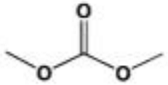
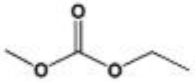
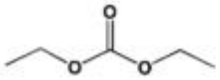
Reduction of solvent

An ideal solvent should

- Have high dielectric constant
- Have low viscosity
- Resistant to oxidation/reduction
- Have a wide liquid temperature
- Have a high flash point
- Nontoxic and economical



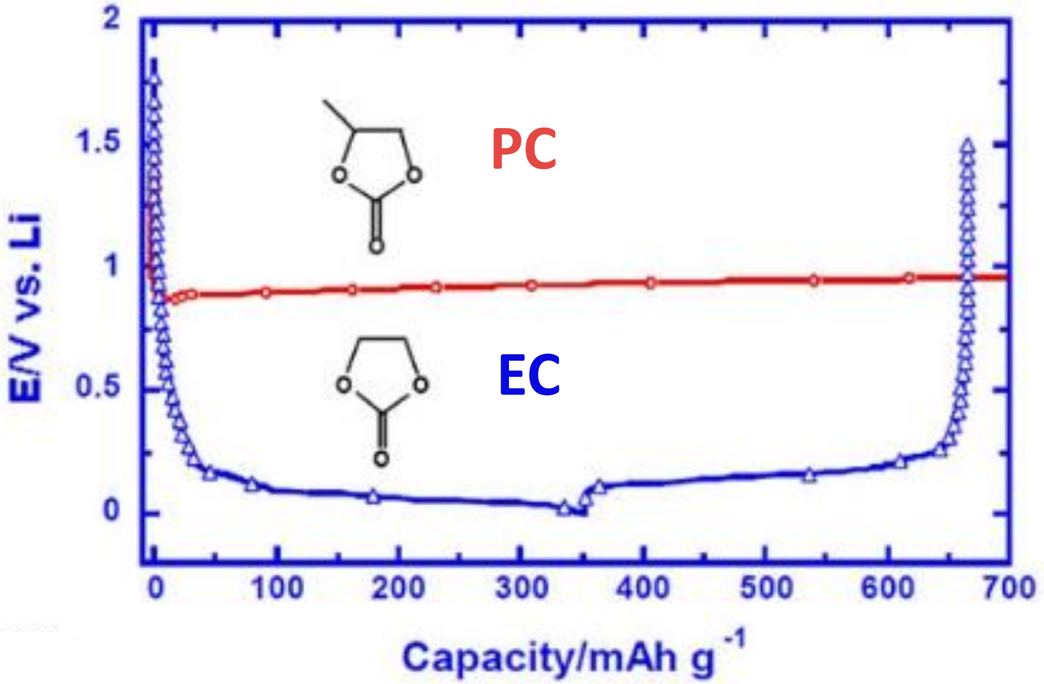
LUMO Energy Level and Reduction Potentials of Solvents and Additives

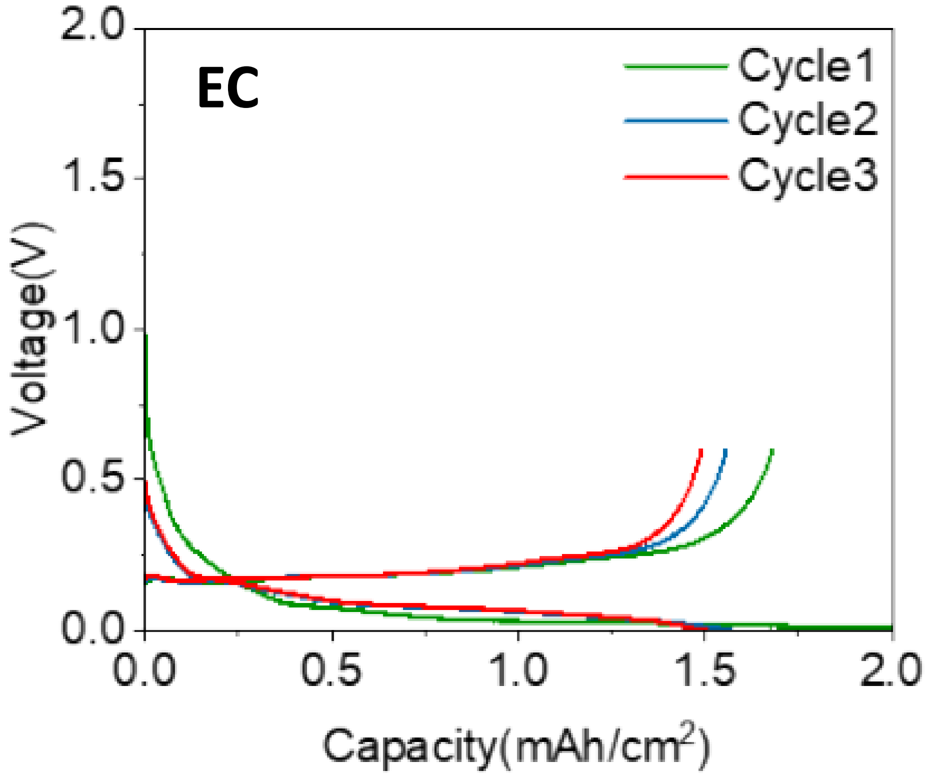
Solvent/Additive		LUMO/eV	Reduction Potential (vs. Li^+/Li) on GC	Reduction Potential (vs. Li^+/Li) on GR
	EC	1.175 0.97	0.9	0.8
	PC	1.235 1.02	1.0	0.78
	γBL	1.049 0.91		
	DMC	1.054	1.32	
	EMC	1.248 1.17		
	DEC	1.288 1.21	1.32	

Kang Xu, Chemical Reviews, 2004, Vol. 104, No. 10

Reduction of solvent during charging of graphite

Reduction of graphite in a Li electrolyte using EC or PC as the solvent





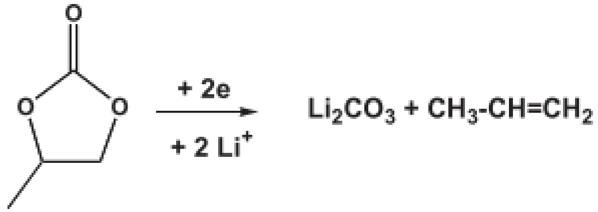
Kang Xu, Chemical Reviews, 2004, Vol. 104, No. 10

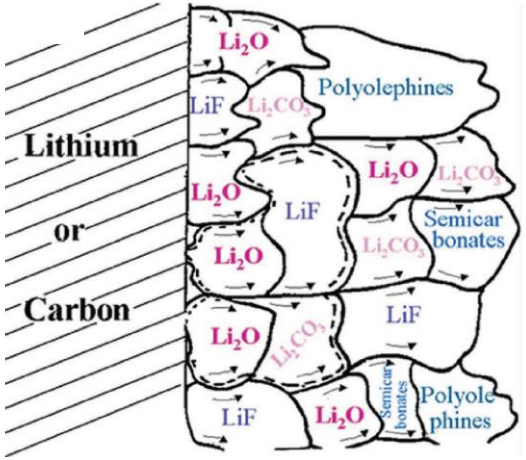
Gao. T, et al (2022) *ACS Applied Materials & Interfaces*. doi: 10.1021/acsami.2c04319.

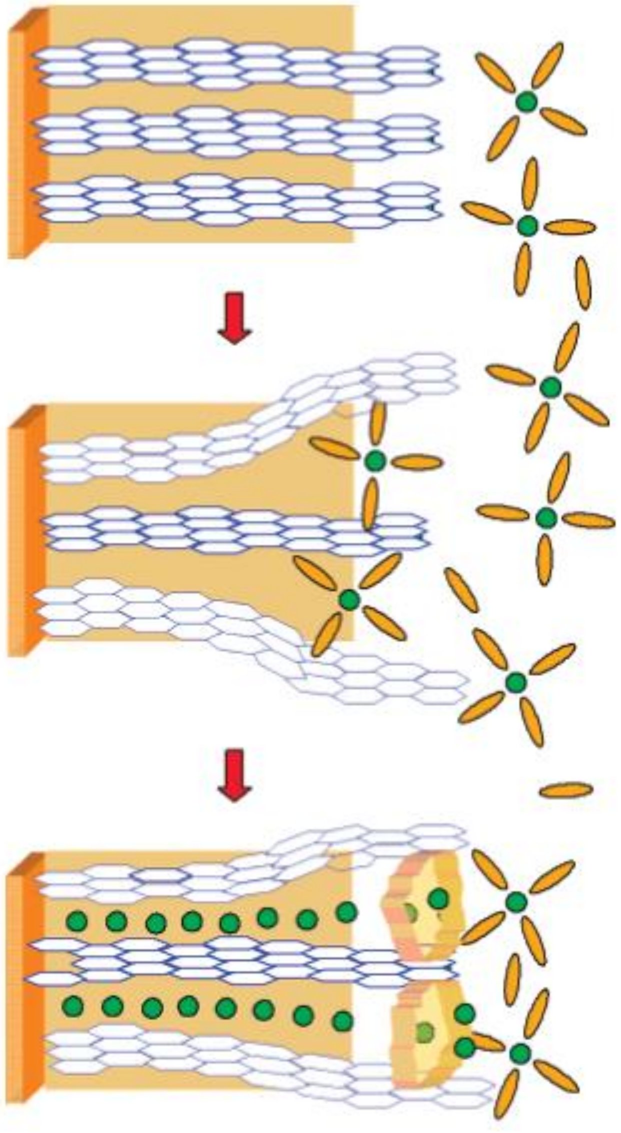
Solid electrolyte interphase (SEI)

- EC forms stable SEI, but PC can not

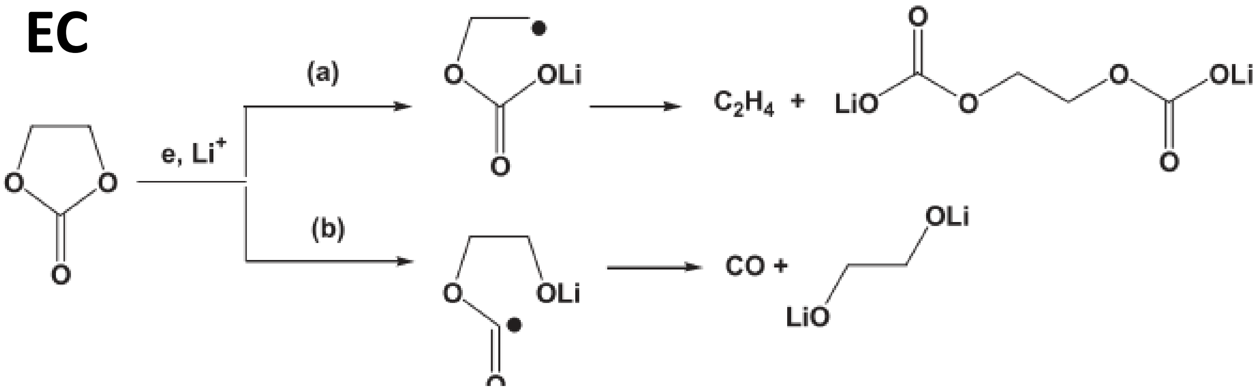
PC







EC



Xu, K.; Von Wald Cresce, A. *J. Mater. Res.* **2012**, *27* (18), 2327–2341.

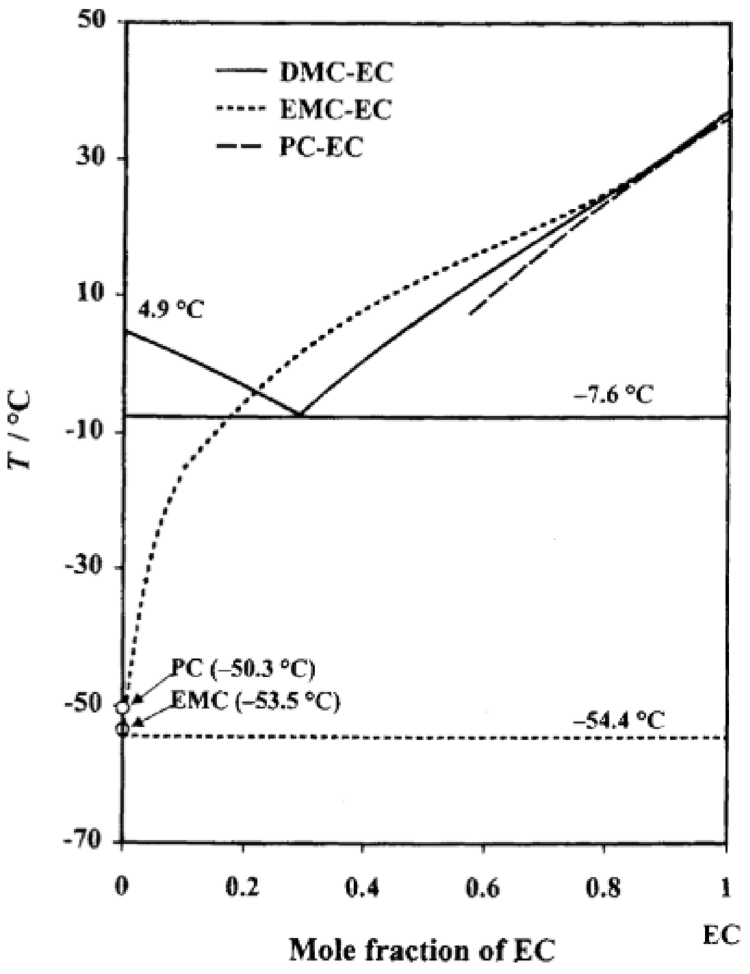
Co-solvent to expand the liquid range

An ideal solvent should

- Have high dielectric constant
- Have low viscosity
- Resistant to oxidation/reduction
  - EC is kinetically resistant to reduction
- Have a wide liquid temperature
- Have a high flash point
- Nontoxic and economical

EC is solid at RT

- MP= 36.4 ^{o}C



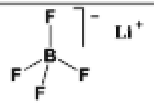
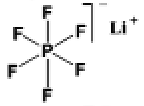
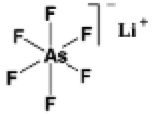
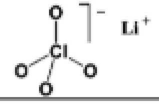
SOA LIB solvent composition:

- EC + linear carbonates
- linear carbonates
  - DMC
  - DEC
  - EMC
  - Or a mixture of them

Kang Xu, Chemical Reviews, 2004, Vol. 104, No. 10

Electrolyte for Li-ion battery: salts

An ideal salt should
- Completely dissolve and dissociate
- Electrochemical stable
  - Anion be stable against oxidation at the cathode.
- Chemically stable
  - inert to other components
- Thermally stable
  - Not decompose at high T
- Nontoxic and economical

Salt	Structure	M. Wt	T_m/ °C	$T_{decomp.}$, / °C in solution	Al-corrosion	σ /mScm^{-1} (1.0 M, 25 ° C) in PC	σ /mScm^{-1} (1.0 M, 25 ° C) in EC/DMC
$LiBF_4$		93.9	293 (d)	> 100	N	3.4 [a]	4.9 [c]
$LiPF_6$		151.9	200 (d)	~ 80 (EC/DMC)	N	5.8 [a]	10.7 [d]
$LiAsF_6$		195.9	340	> 100	N	5.7 [a]	11.1 [e]
$LiClO_4$		106.4	236	>100	N	5.6 [a]	8.4 [d]
Li Triflate	$Li^+ CF_3SO_3^-$	155.9	>300	>100	Y	1.7 [a]	
Li Imide	$Li^+ [N(SO_2CF_3)_2]^-$	286.9	234 [b]	>100	Y	5.1 [a]	9.0 [e]
Li Beti	$Li^+ [N(SO_2CF_2CF_3)_2]^-$				N		

Average ion mobility: $LiBF_4 > LiClO_4 >$ $\mathbf{LiPF_6} > LiAsF_6 > LiTf > LiIm$

Dissociation constant: $LiTf < LiBF_4 < LiClO_4 <$ $\mathbf{LiPF_6} < LiAsF_6 < LiIm$

$LiPF_6$ chosen due to the below features
- Good combination of mobility, dissociation, stability etc.
- Resistant to oxidation to 5.1V
- Can passivate Al substrate at high potential

Kang Xu, Chemical Reviews, 2004, Vol. 104, No. 10

Ion transport properties

- Ion Transport property
  - Conductivity
  - Transference number

$$\sigma = \sum n_i \mu_i Z_i e$$

$$\mu_i = \frac{1}{6\pi\eta r_i}$$

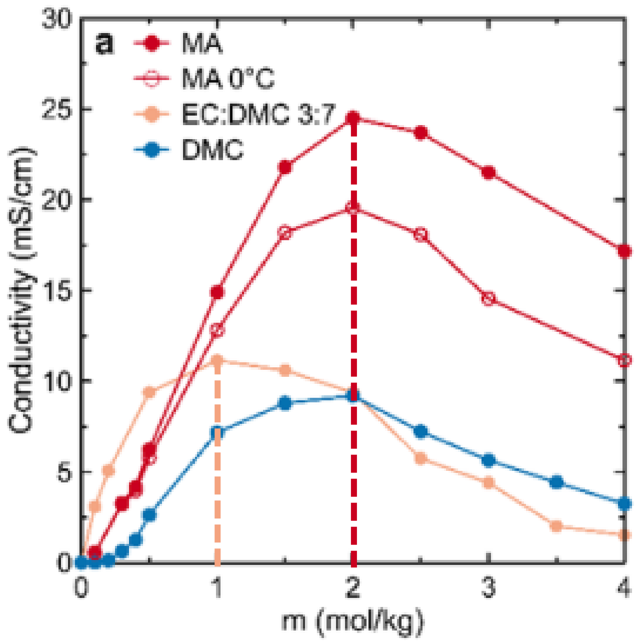
$$t_{\mathrm{Li}} = \frac{\mu_{\mathrm{Li}}}{\sum_i \mu_i}$$

- Depends on
  - Salt concentration
  - Solvent composition

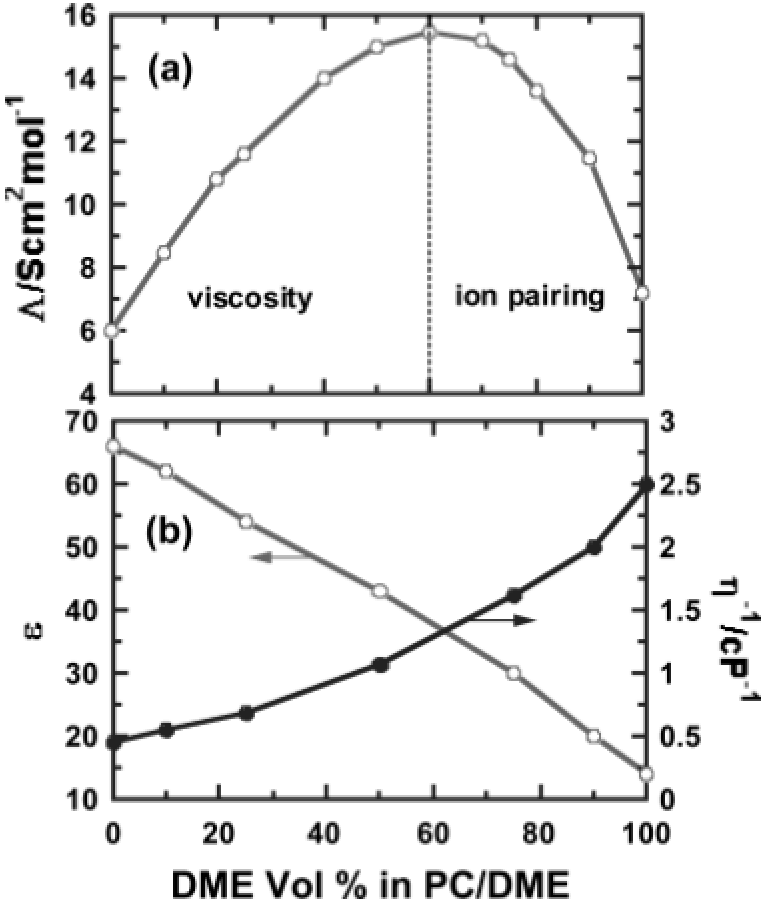
- SOA LIB electrolyte salt concentration: 1M

Ion concentration

viscosity



LiPF$_6$ in different solvents



1.0 M LiClO$_4$ in PC/DME

Logan, E. R., *Journal of Physical Chemistry C*, *124*(23), 12269–12280.
Kang Xu, Chemical Reviews, 2004, Vol. 104, No. 10

Summary for SOA LIB electrolyte

SOA LIB electrolyte:

- Solvent: EC + linear carbonates (DMC, DEC, EMC etc.)
  - Carbonate: Resistance to oxidation
  - EC: polarity, form stable SEI on graphite
  - Linear carbonate: reduce freezing point
- Salt: $LiPF_6$
  - Good combination of conductivity, compatibility and chemical stability
- Concentration: 1M
  - Highest conductivity

- Limitations
  - **Safety:** a high-temperature limit (50 °C) set by $LiPF_6$
  - **Fast-charging:** limited by the large interfacial resistance (SEI and desolvation) and low conductivity
  - **Low-T performance:** a low-temperature limit (-20 °C) set by EC

Tesla car battery 'spontaneously' catches fire on California freeway, requiring 6,000 gallons of water to put it out

Jan. 30, 2023, 9:47 AM MST

FORD · **Published** March 13, 2023 7:10am EDT

Ford recalling 18 F-150 Lightning electric pickups after battery fire

Manufacturing defect identified and fixed

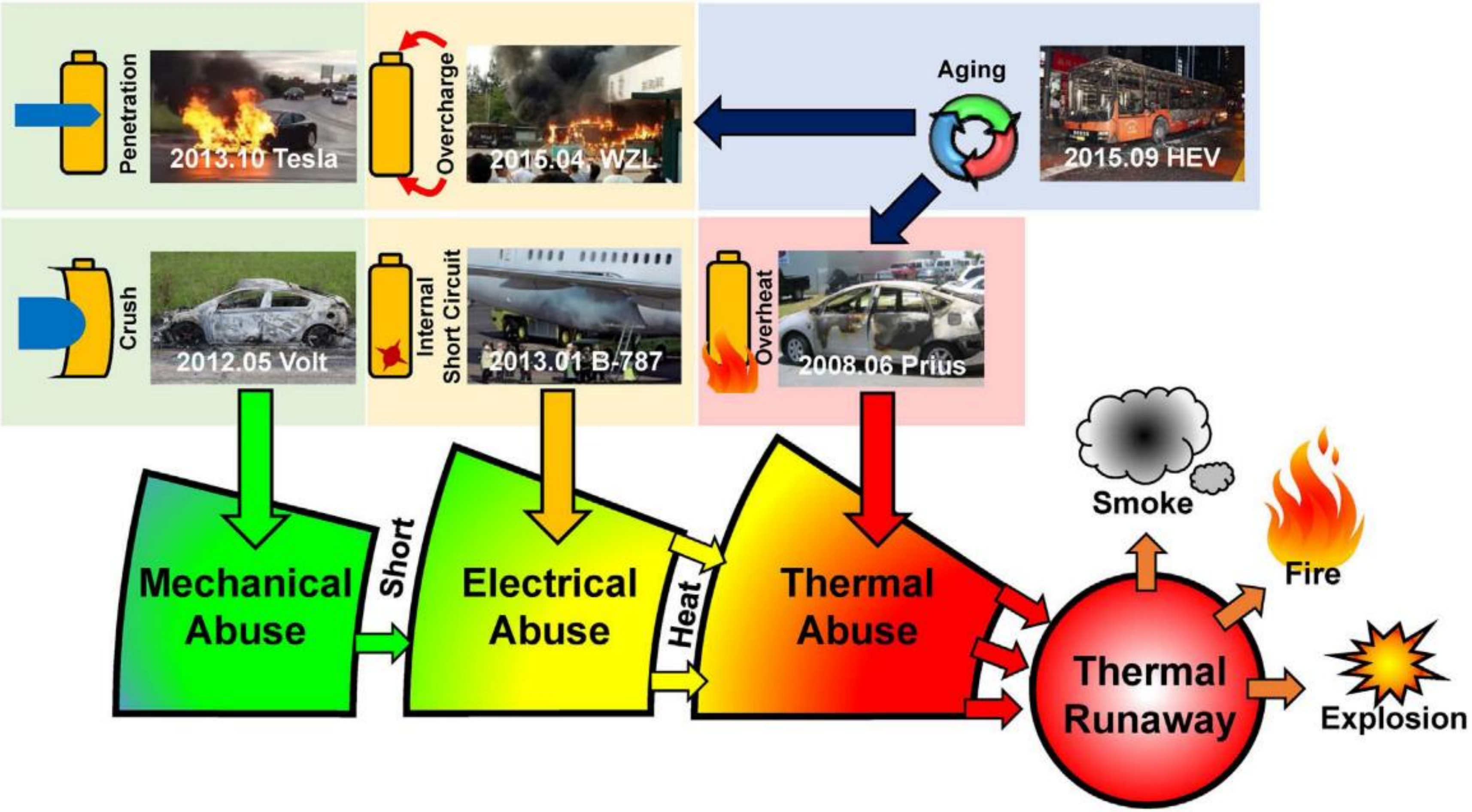
Content

- Basics of Li-ion battery
- Electrolyte for Li-ion battery
- Safety of Li-ion battery
- Degradation of Li-ion battery
- Electrolyte for advanced performances
  - High-Energy Li battery
  - Fast-charging Li-ion battery

How does a safety incident occur?

- Thermal runaway: uncontrolled release of battery energy in an abrupt manner
  - Temperature increases
  - Side reactions
    - Anion decomposes
    - SEI decomposes
    - Separator melts
  - Gassing and smoking
  - Fire and explosion

- Mechanical
  - Penetration
- Thermal
  - Overheat
- Electrical
  - Internal short-circuit



Feng, X. *et al.* (2018) *Energy Storage Materials*, 10(May 2017), pp. 246–267.

The root cause of internal short-circuit

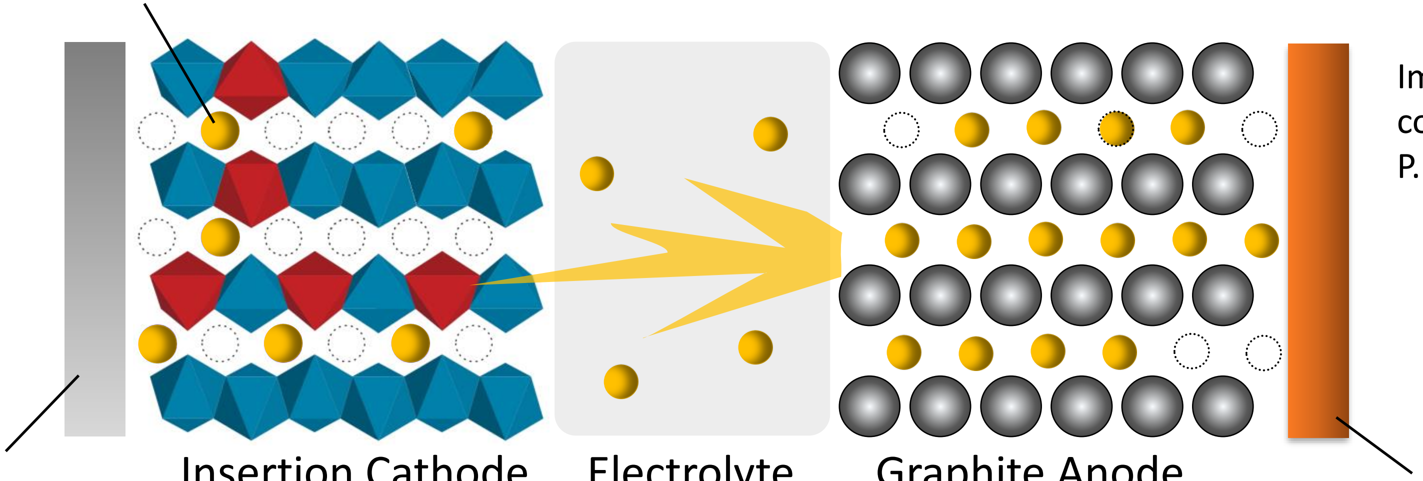
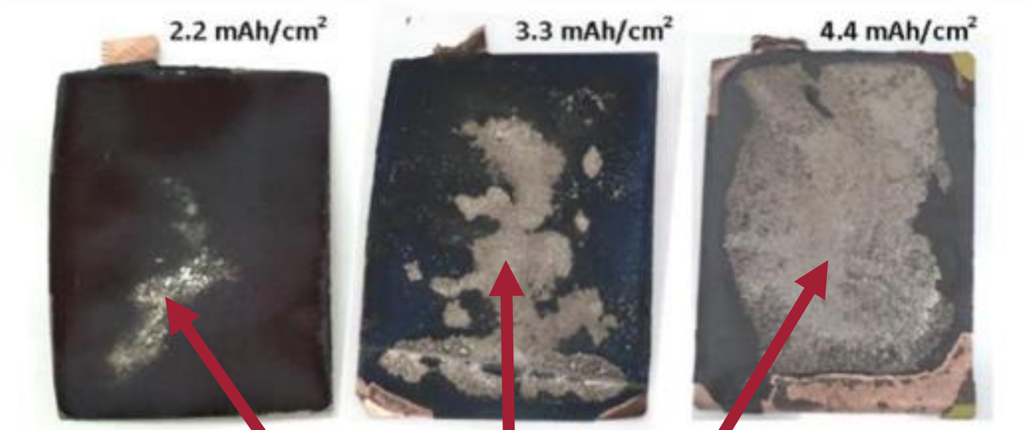
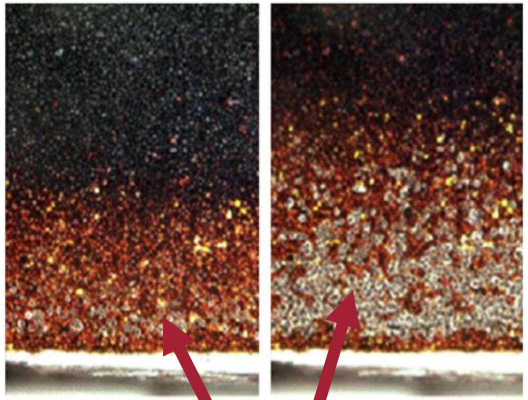


Image courtesy: P. Bai



Ahmed et al., Journal of power source, 2017

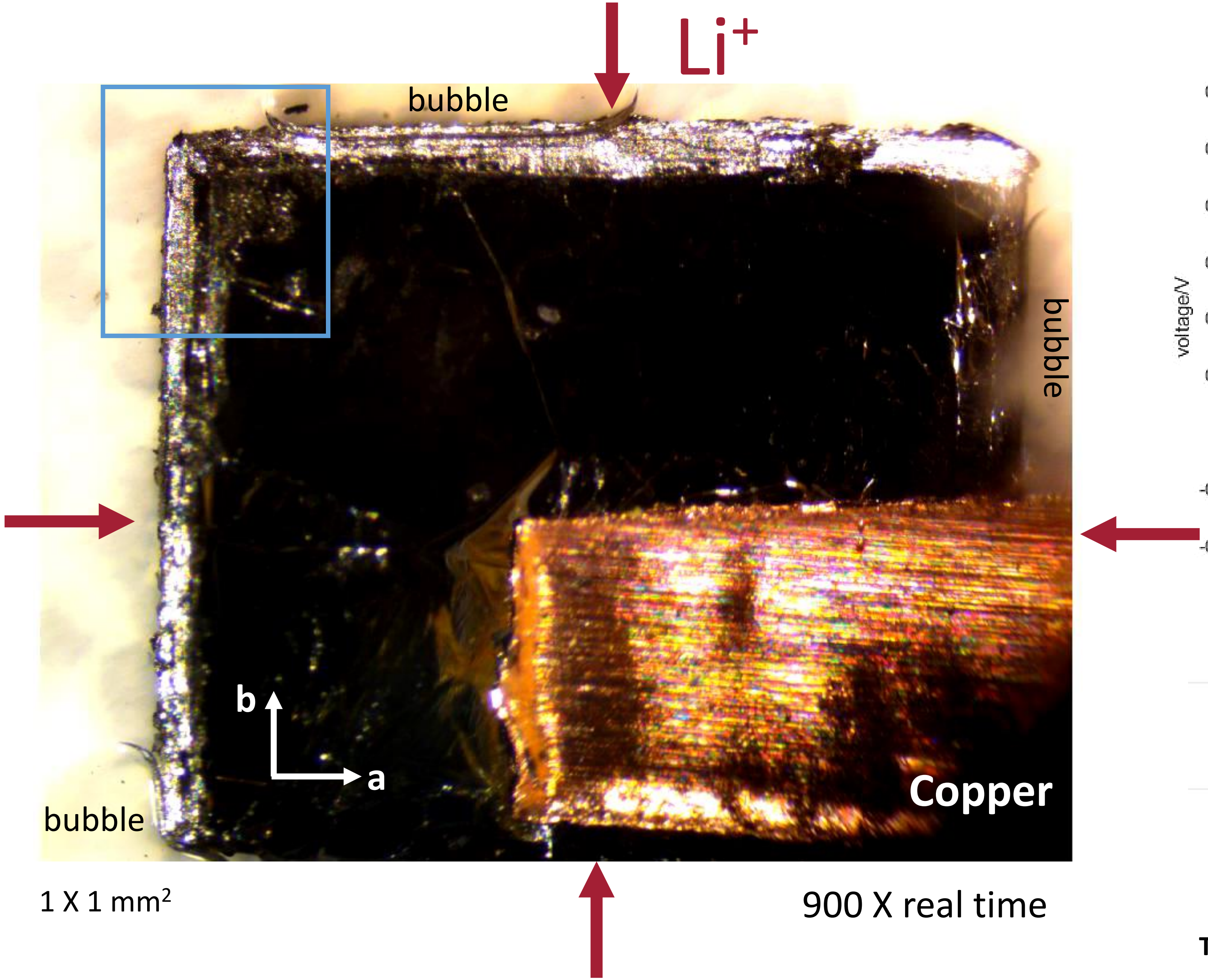
lithium plating



Harris et al, Chemical Physics Letter, 2010

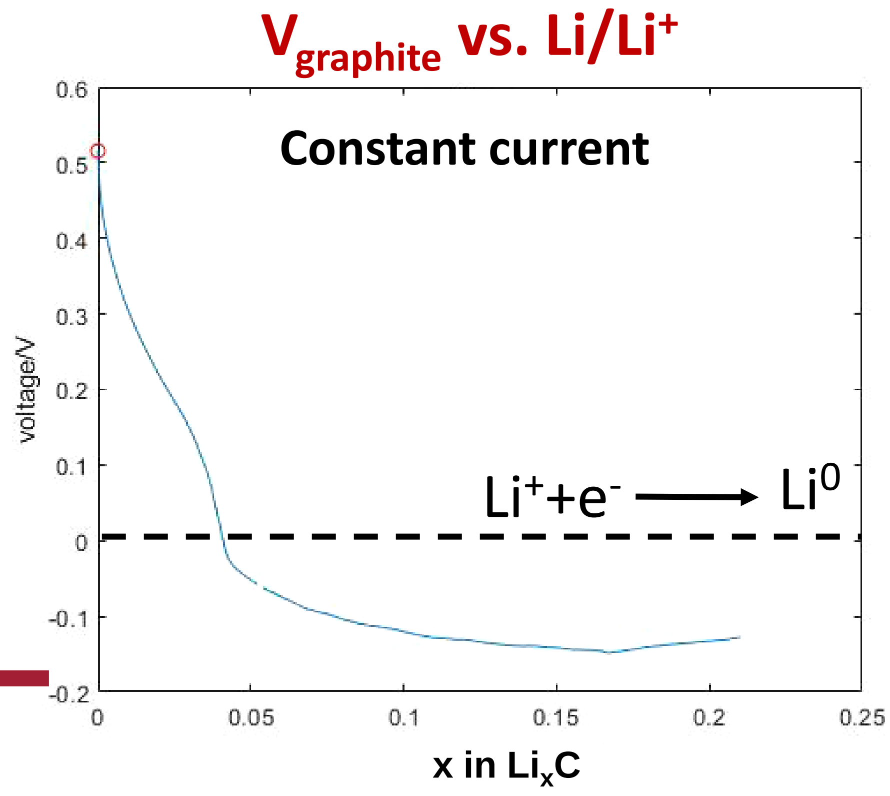
lithium plating

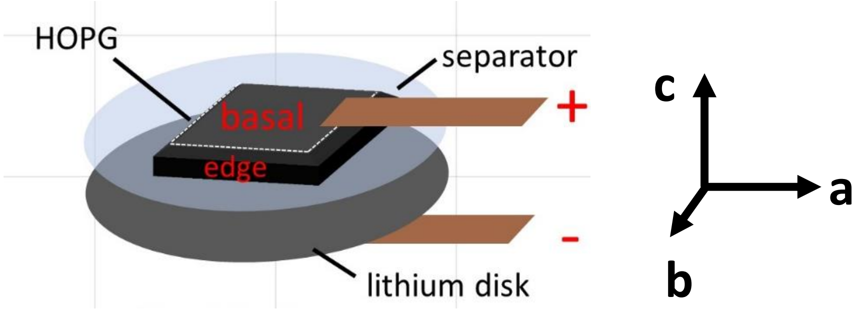
Experiment Results: Li insertion (video)



1 X 1 mm^2

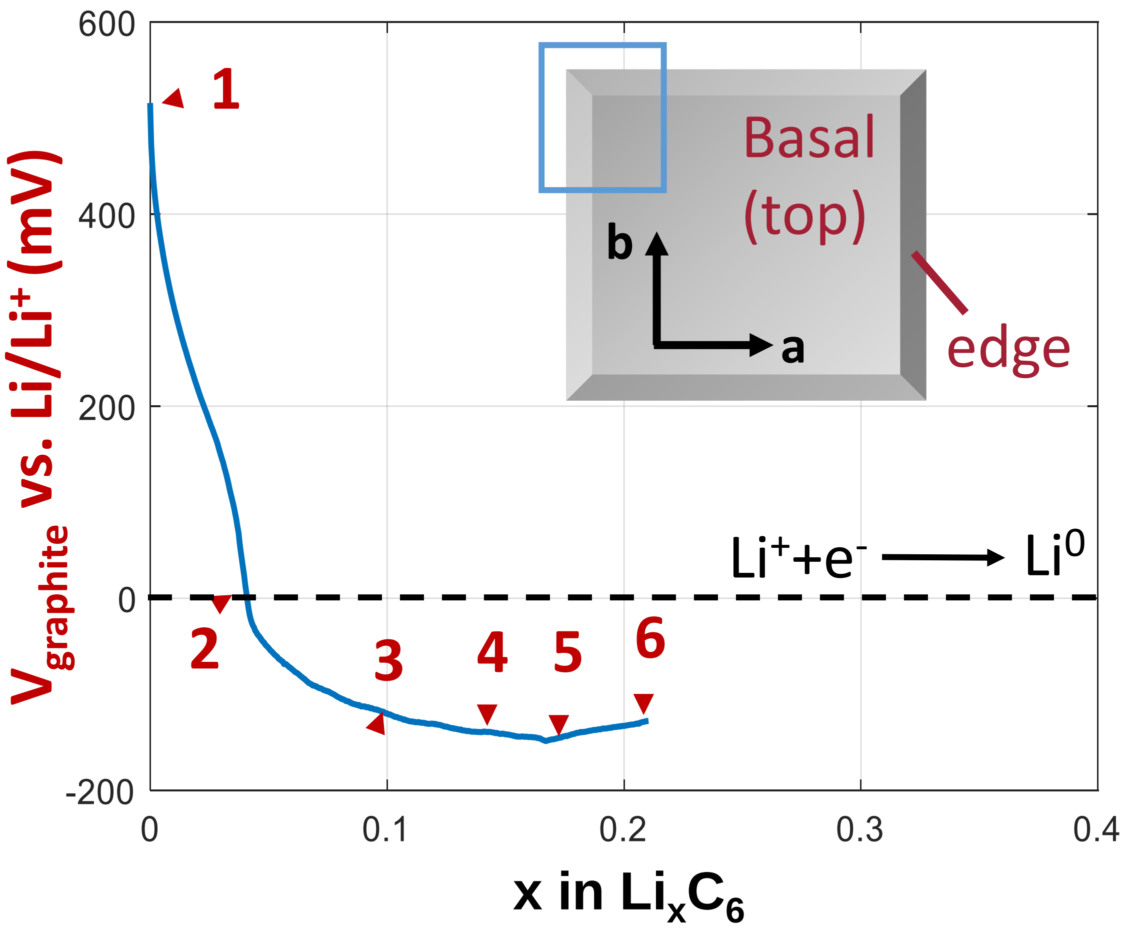
900 X real time

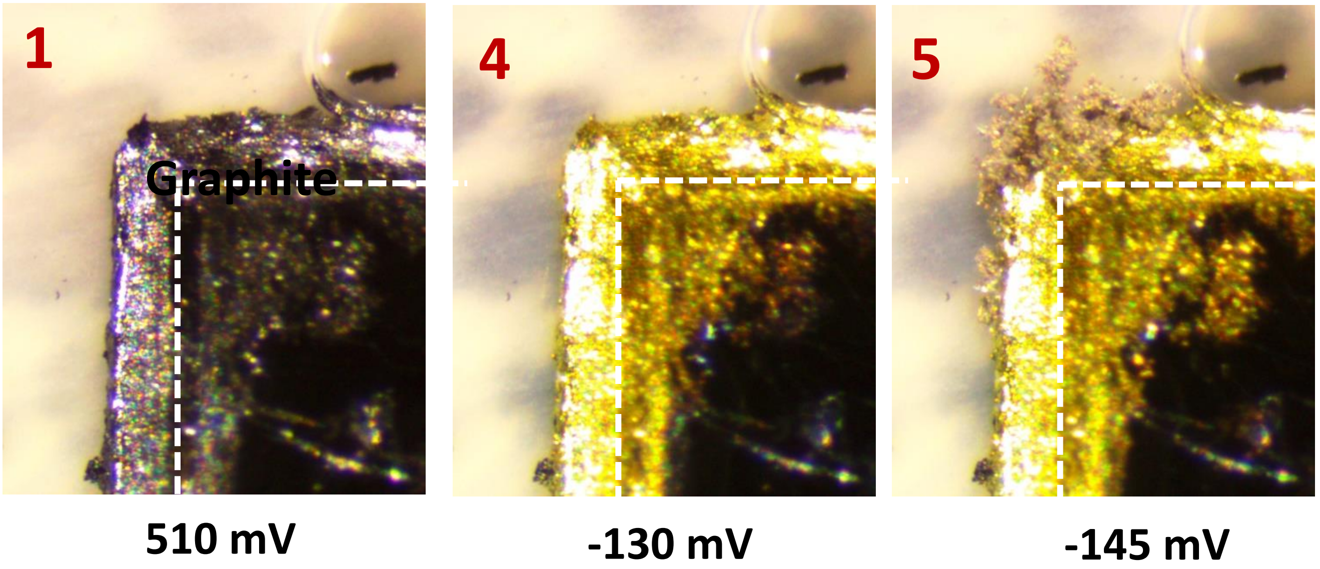


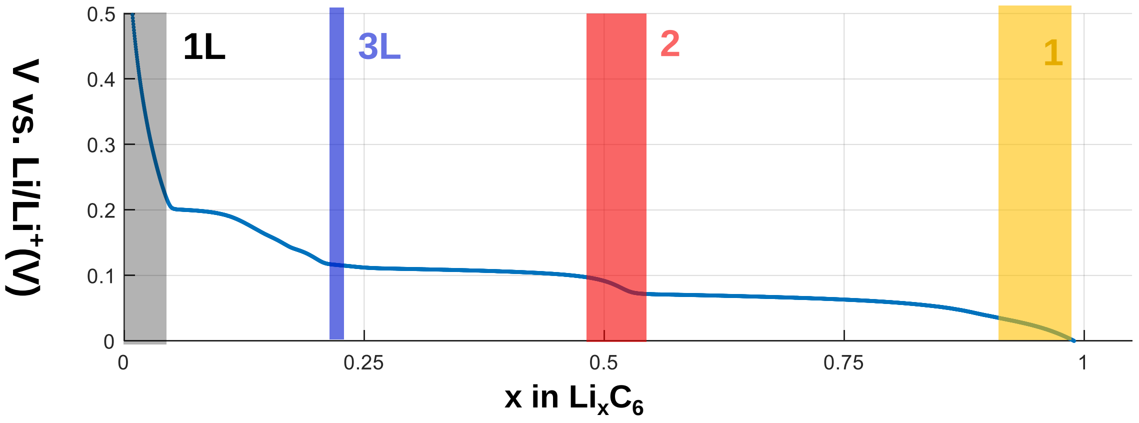


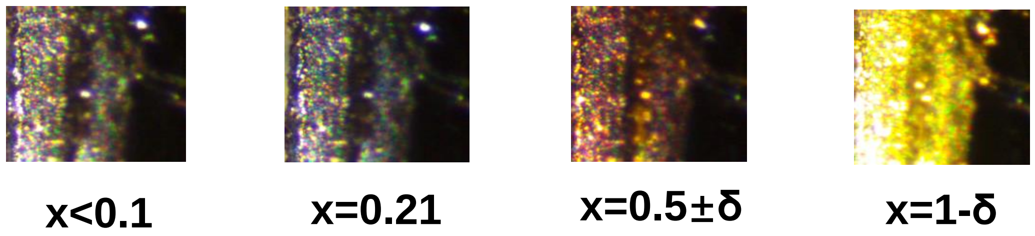
T. Gao, W. Chueh, J. Li, M.Z. Bazant, *et al. Joule, 2021*

Experiment Results: Li insertion (pictures)







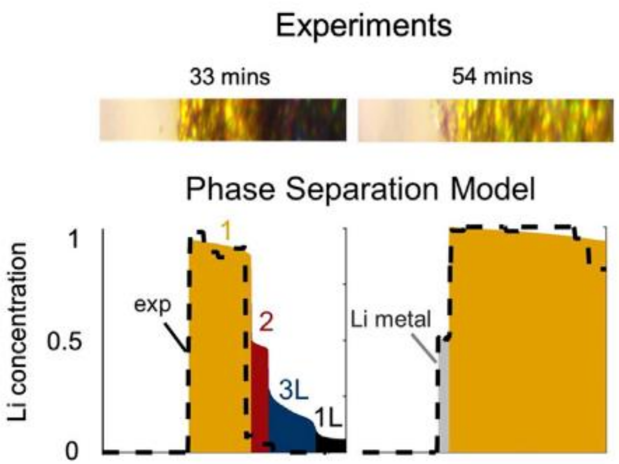


- **Li plating** can occur much early before graphite is fully charged
- **Li plating** due to surface saturation of graphite

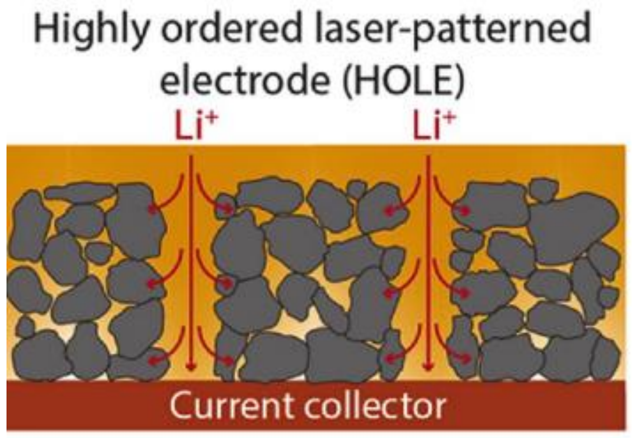
T. Gao, W. Chueh, J. Li, M.Z. Bazant**,** *et al. Joule, 2021*

How to avoid Li plating on graphite in LIBs?

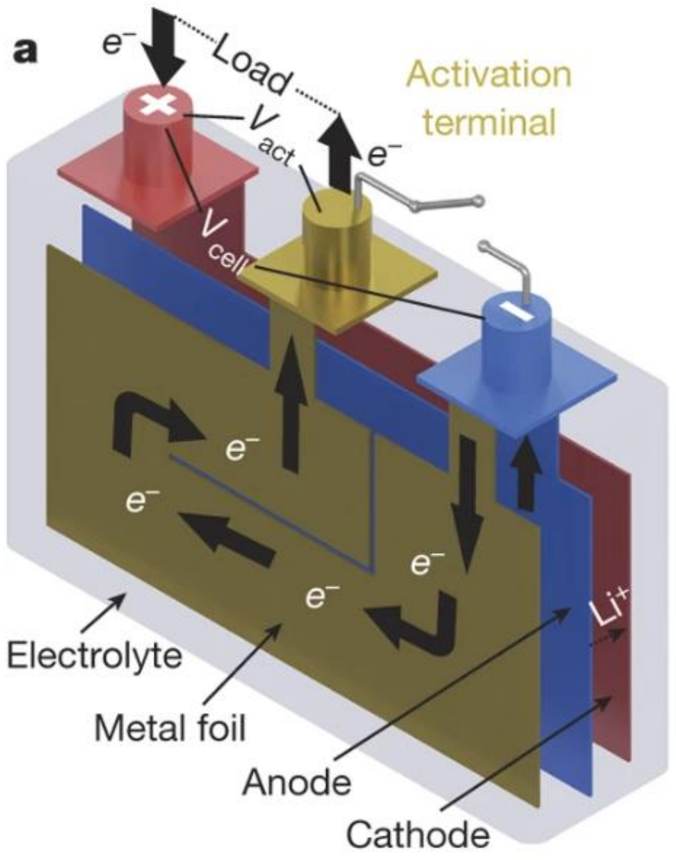
- DO NOT charge faster than graphite can tolerate.
  - Raise temperature for fast charging (Tesla, Wang CY)
  - Accurately predict Li concentration in graphite
  - Design better electrode structure to facilitate homogenous lithiation of graphite
  - Design better electrolyte to facilitate homogenous lithiation of graphite



T. Gao, W. Chueh, J. Li, M.Z. Bazant**,** *et al. Joule, 2021*



Chen, K. H. *et al.* (2020) *Journal of Power Sources*, 471(April), p. 228475.



Wang, C. Y. *et al.* (2016), *Nature*, 529(7587)

FORBES > INNOVATION > SUSTAINABILITY

Tesla Researcher Demonstrates 100-Year, 4-Million-Mile Battery

James Morris Contributor

I write about the rapidly growing world of electric vehicles

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May 28, 2022, 05:00am EDT

BUSINESS

Elon Musk expected to tout 'million-mile battery.' Here's what that means

Content

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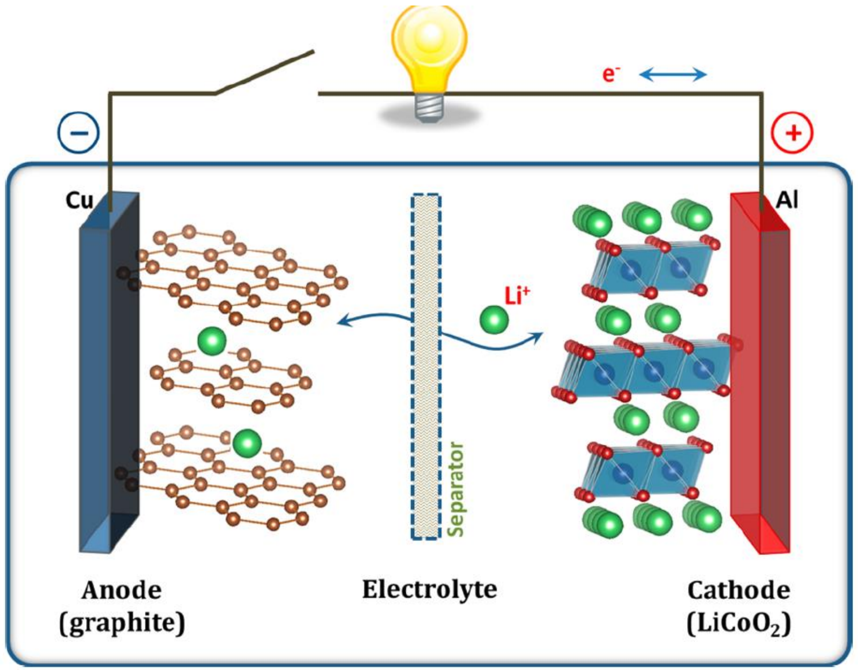
Degradation mechanisms of LIB



Performance degradation refers to:

- Loss of capacity and voltage as battery ages

In general, three reasons:

- Loss of lithium inventory (LLI)
- Loss of active material (LAM)
- Increase of resistance

Degradation occurs due to side reactions

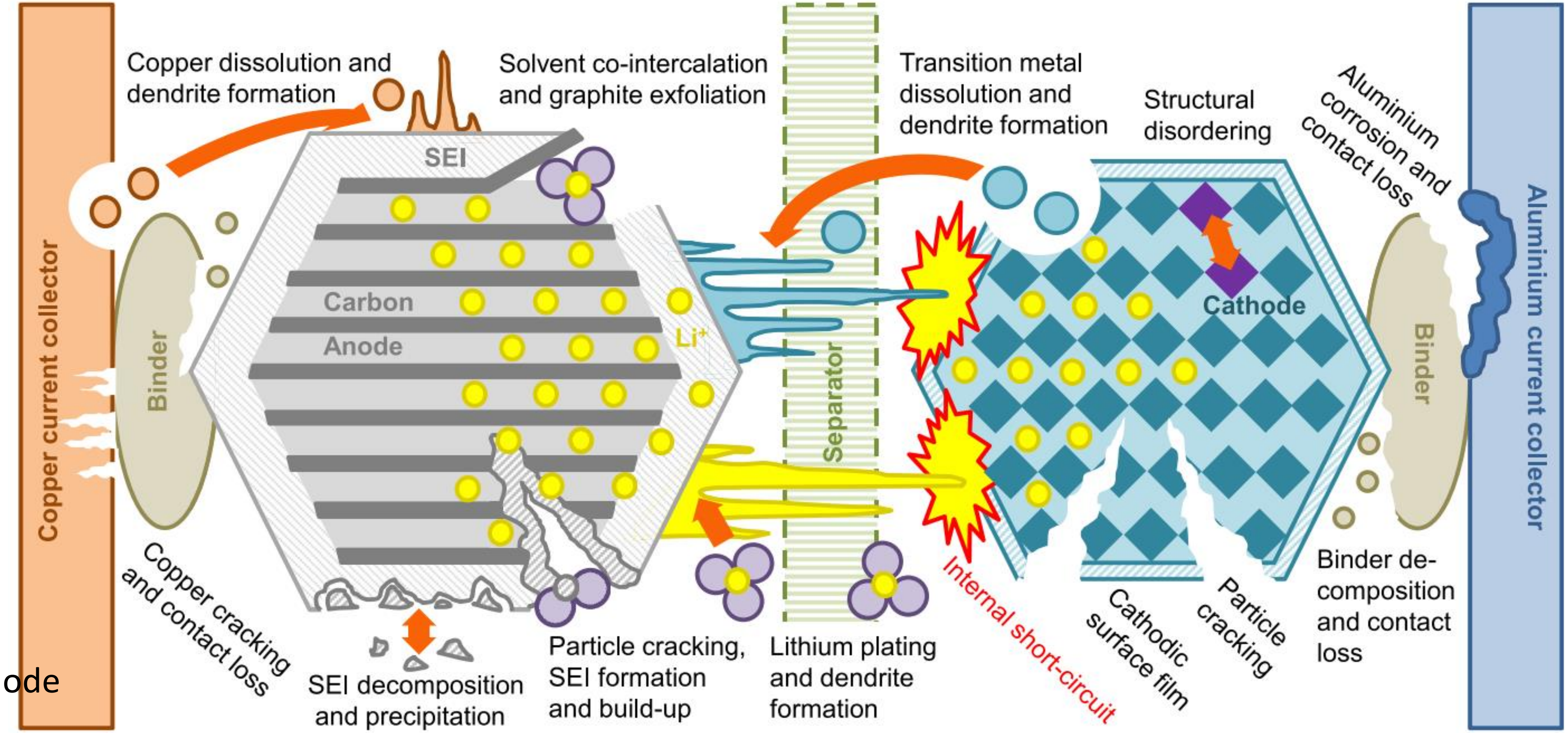
Dubarry, M. *et al.* (2011), *Journal of Power Sources*, 196(7), pp. 3420–3425.

Side reactions in LIBs

Loss of lithium inventory
- Li plating
- SEI healing and growth
- CEI growth

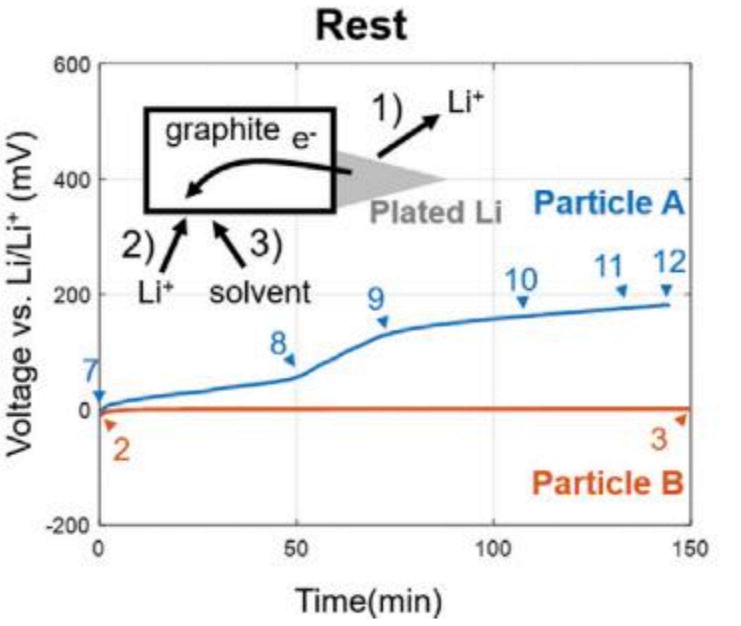
Loss of active material
- Particle cracking
- Graphite exfoliation
- TM dissolution

Increase of resistance
- Cu dissolution
- Al corrosion
- Binder decomposition
- TM precipitation on anode
- SEI/CEI growth

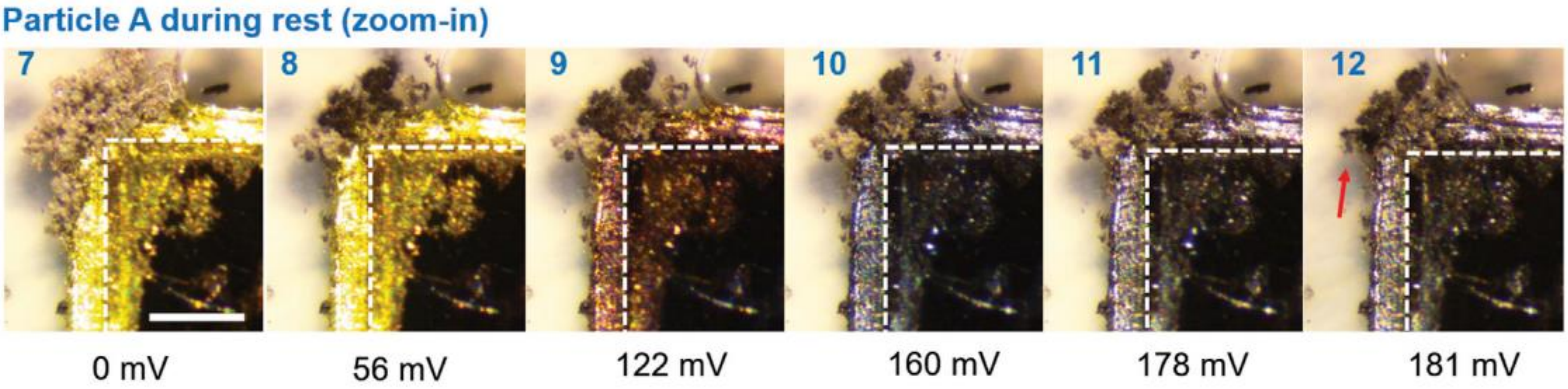


Birkl, C. R. *et al.* (2017) *Journal of Power Sources*, 341, pp. 373–386.

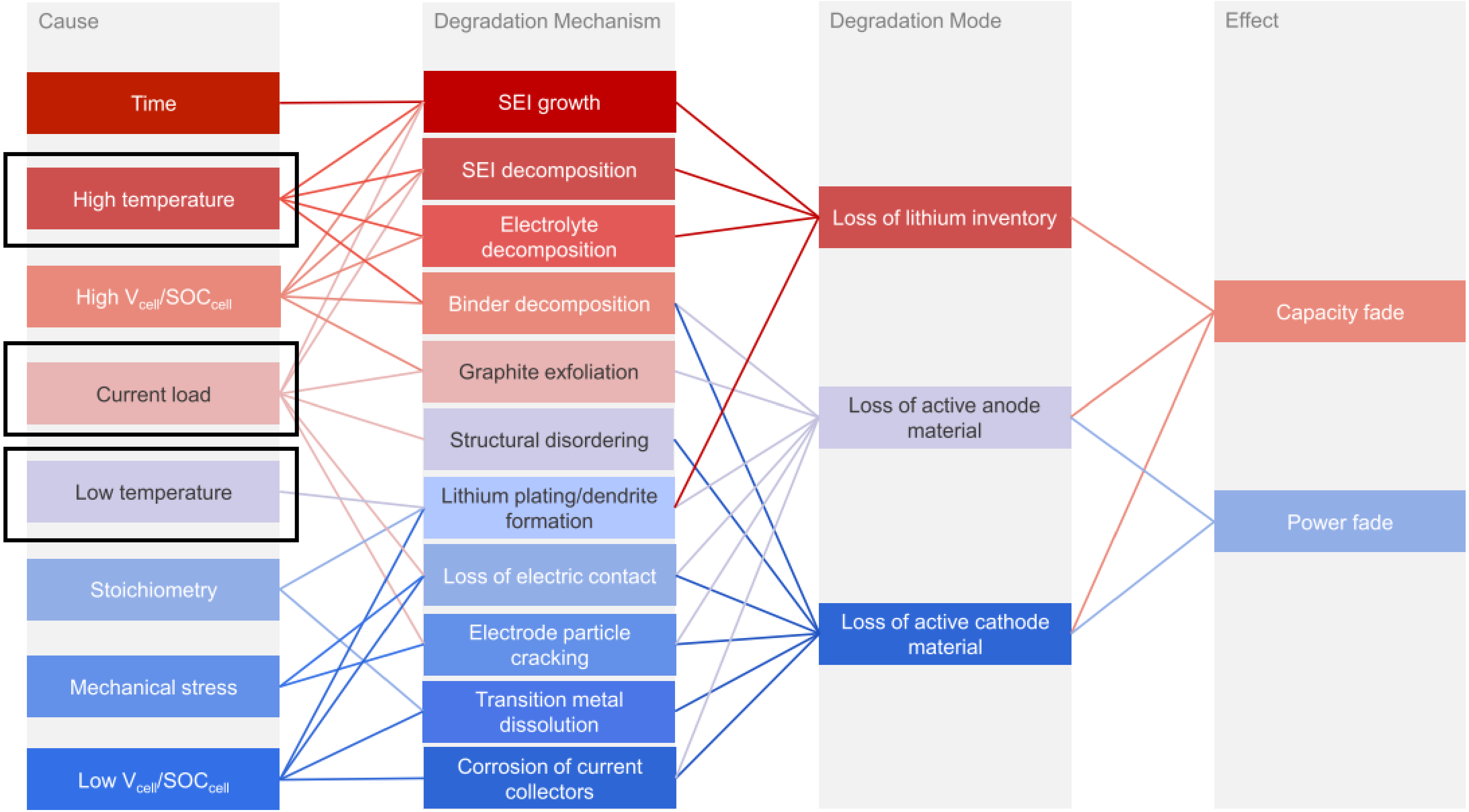
Li plating leads to loss of lithium inventory due to dead Li



T. Gao, W. Chueh, J. Li, M.Z. Bazant, *et al. Joule, 2021*



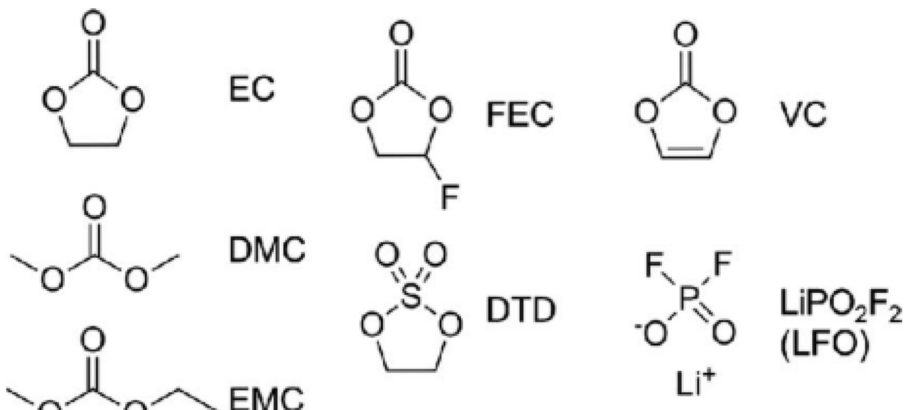
What causes the side reactions?

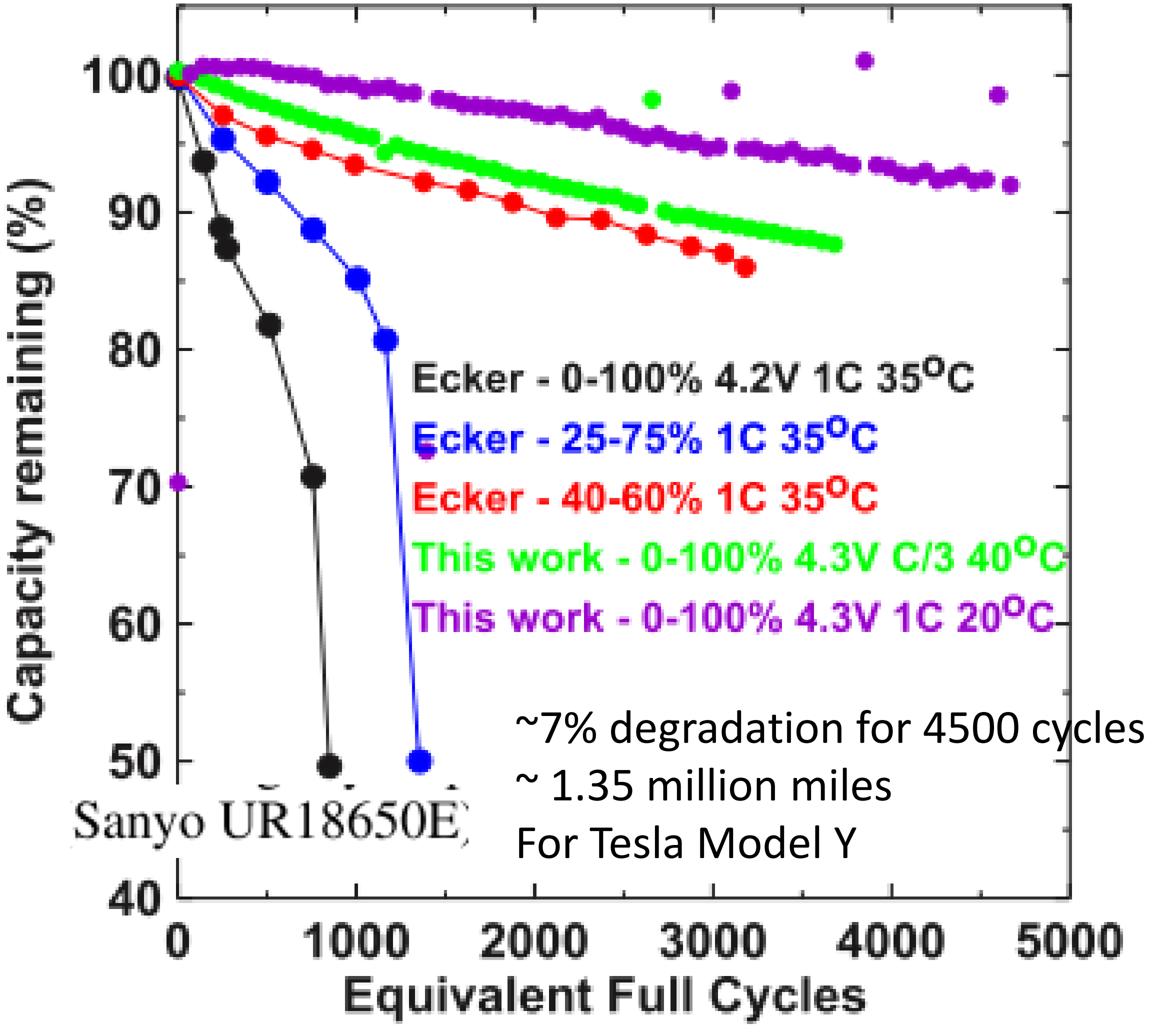


Birkl, C. R. *et al.* (2017) *Journal of Power Sources*, 341, pp. 373–386.

How to achieve a million-mile LIB?

- Avoid abusing the battery
  - Good battery management
    - Don't over charge/discharge
  - Good thermal management
    - Don't overheat
- Stable cathode/anode materials
    - Single crystal NMC
    - Artificial graphite
- Electrolyte to form stable SEI/CEI





J. R. Dahn, *J. Electrochem. Soc.* **2019**, *166*, A3031.


EVIATION ALICE
FIRST FLIGHT

General characteristics

- **Crew:** 2
- **Capacity:** 9 passengers
- **Length:** 17.4 m (57 ft 1 in)
- **Wingspan:** 19.2 m (63 ft 0 in)
- **Height:** 3.84 m (12 ft 7 in)
- **Max takeoff weight:** 8,346 kg (18,400 lb)
- **Commuter payload:** 1,134 kg (2,500 lb)
- **Cargo payload:** 1,179 kg (2,600 lb)[36]
- **Powerplant:** 2 × magniX 650 Electrical Power Unit , 700 kW (940 hp) each

Performance

- **Maximum speed:** 480 km/h (300 mph, 260 kn)
- **Range:** 460 km (290 mi, 250 nmi) VFR, 30 min. reserve, LRC, MTOW
- **Take-off field Length:** 840 m (2,750 ft)
- **Landing distance:** 620 m (2,040 ft)

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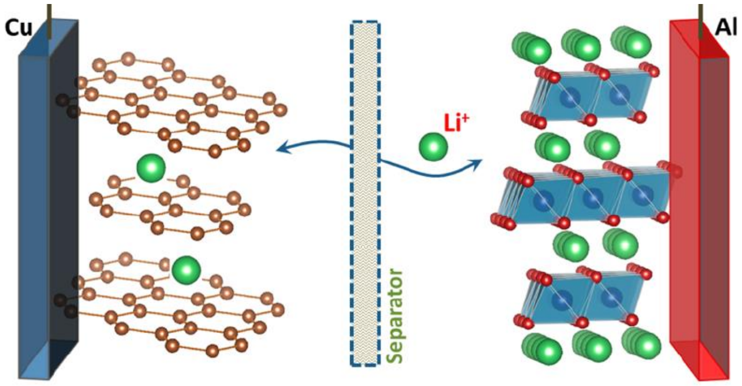
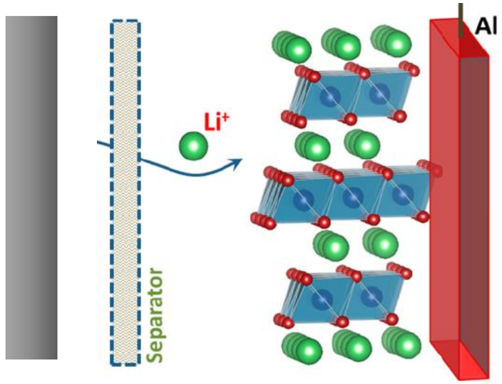
High-energy Li batteries: NMC/Li



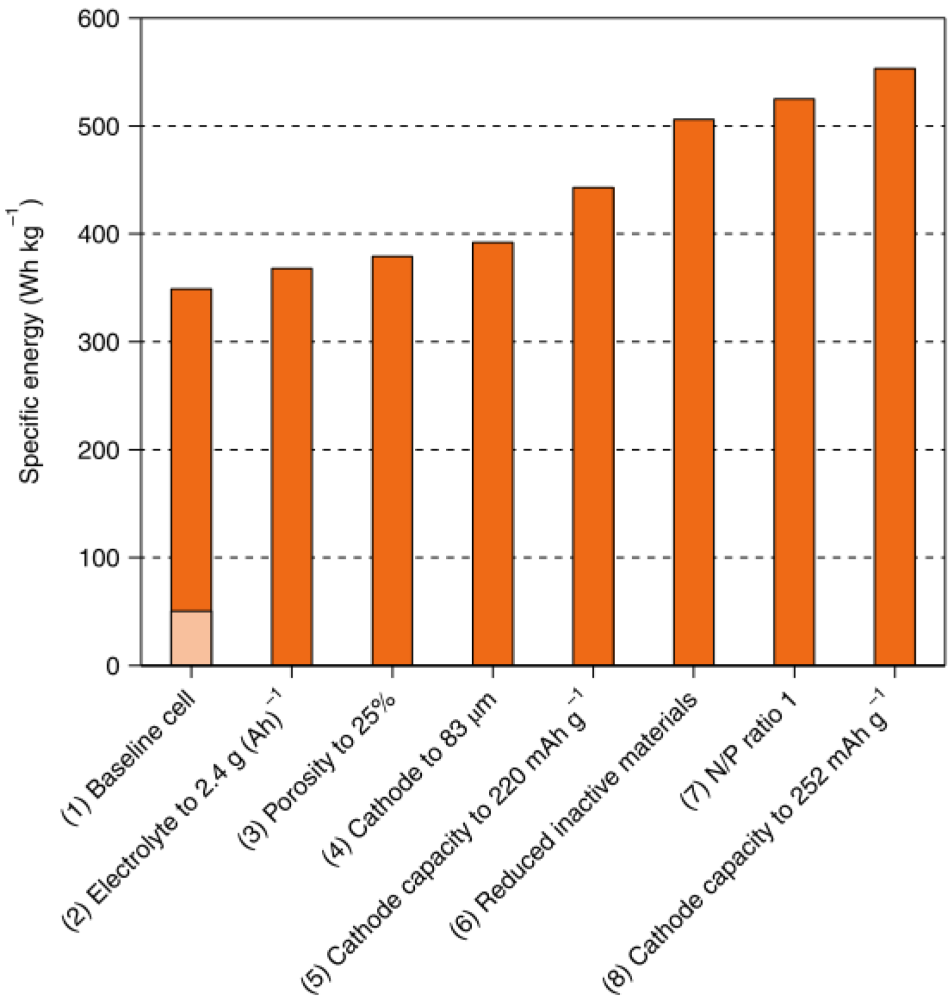
Li-ion battery: 250-300 Wh/kg



Li metal battery: 350-550 Wh/kg

Baseline:

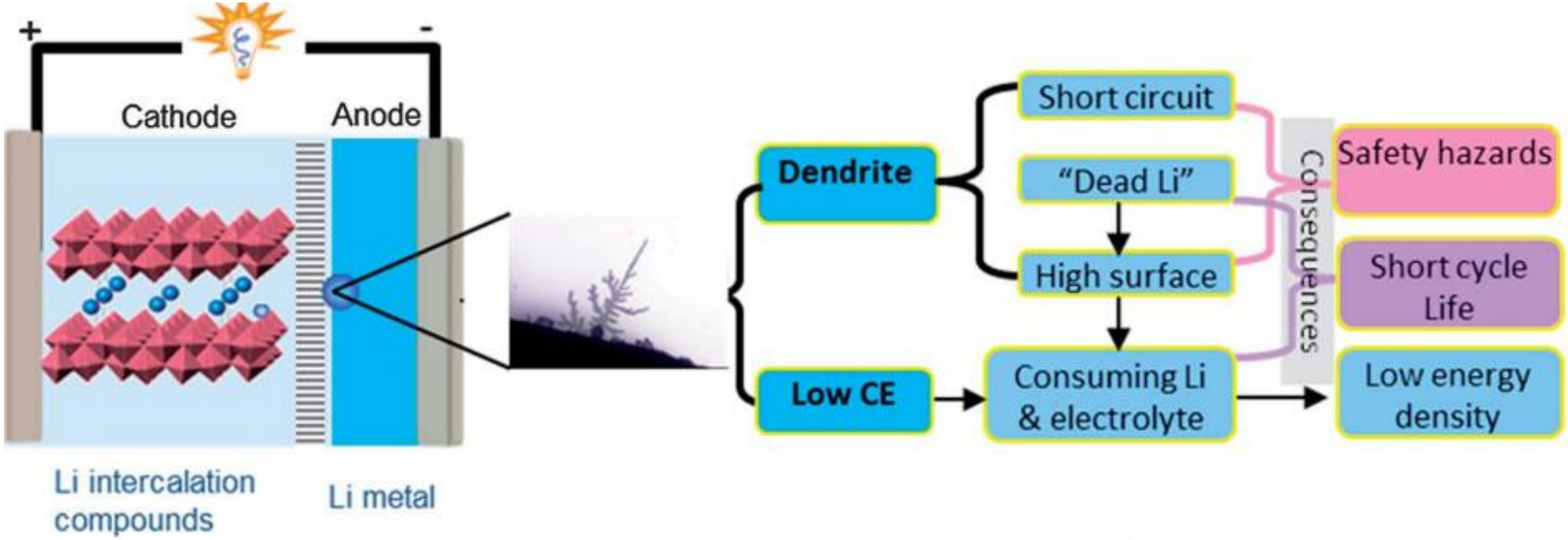
- NMC622 with 196 mAh/g
- 35% cathode porosity
- 22 mg/cm^2 mass loading
- N/P=2.6
- E/C=3.0 g/Ah.



Liu, J. *et al.* (2019) *Nature Energy*, 4(3), pp. 180–186.

Li metal anode: the challenges

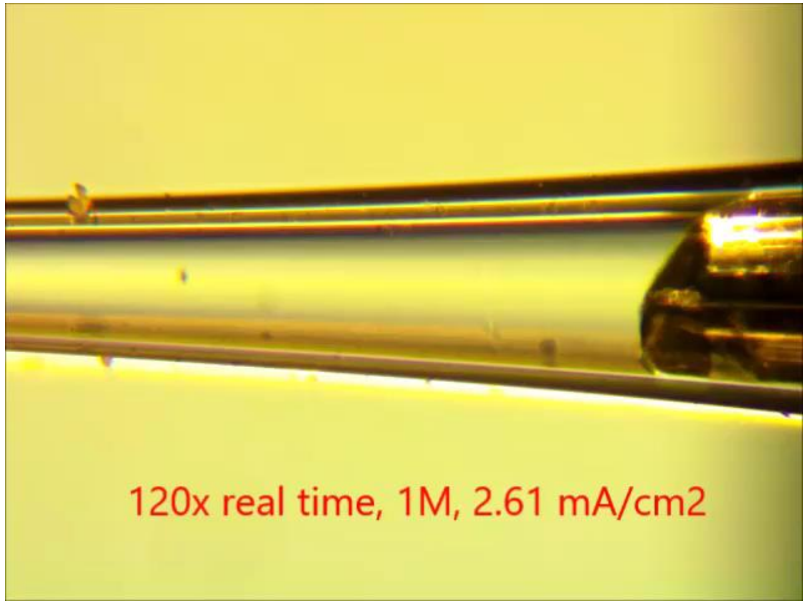
- High energy batteries, i.e., Li-S, Li-O_2, Li-NMC, all need to use Li metal as the anode.

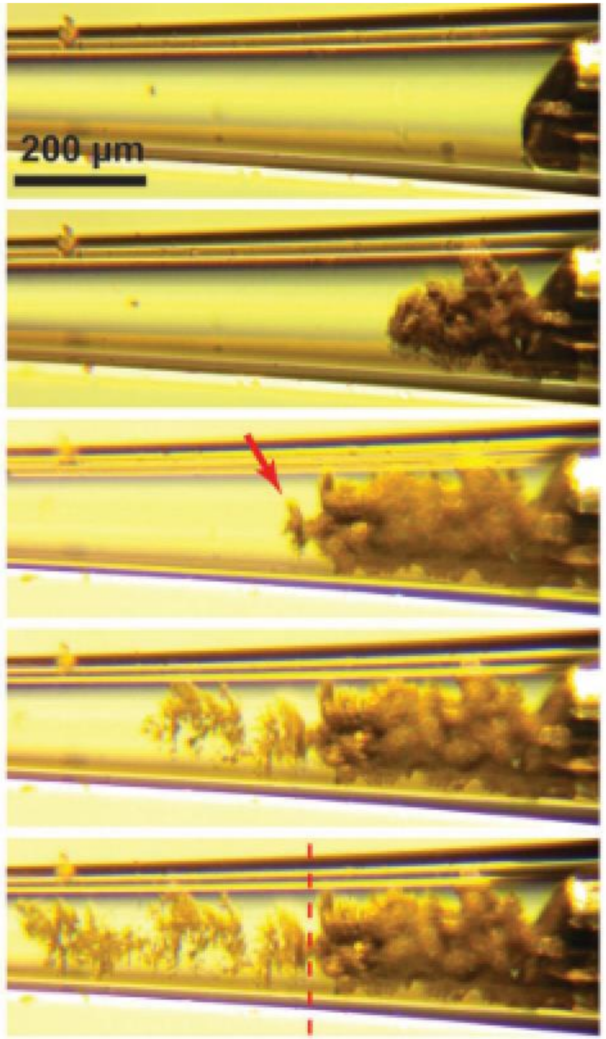


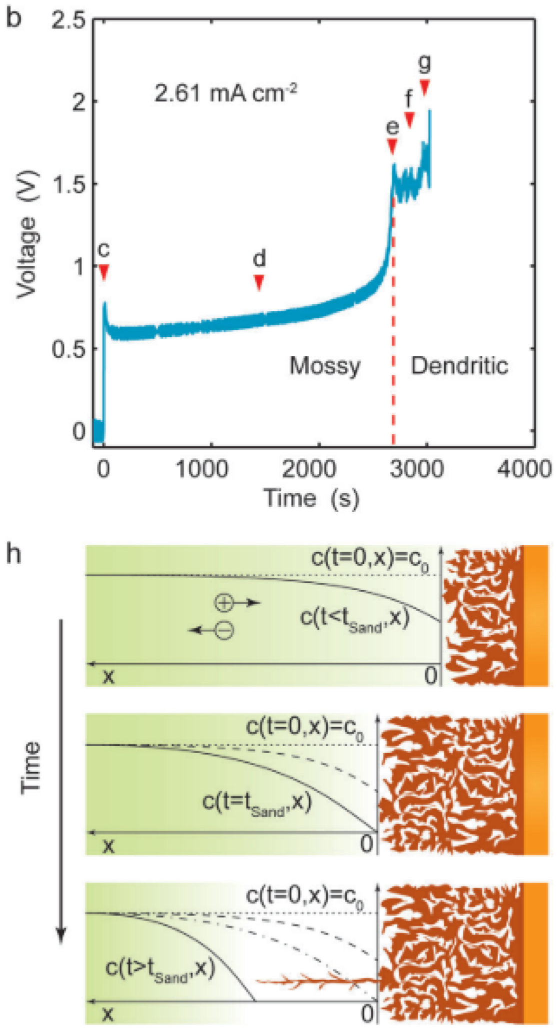
- **Internal short:** Li deposits can pierce the separator and shorts the battery from inside
- **Coulombic efficiency:** reflects how reversible the deposition/striping reaction is. There are two sources of lost Li
  - **SEI formation:** reactions between electrolyte with Li metal consumes Li, forming a Li^+ conducting electron insulating surface layer
  - **Dead Li:** the stripping can cut off the contact of some Li deposits from the base, rendering them floating Li that can not participate in following reactions

Dendrite and internal short-circuit

- Metal anodes are prone to form sharp deposits that can pierce the separator and short the battery from inside during charging





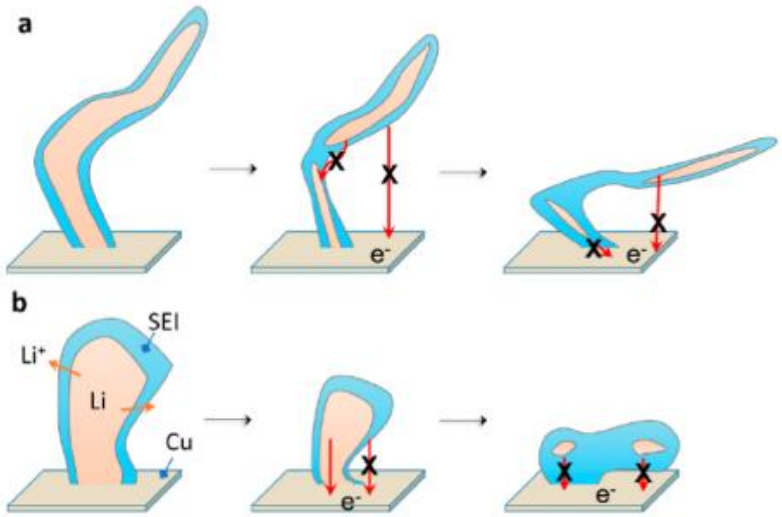


P. Bai, J. Li, F. R. Brushett, M. Z. Bazant, *Energy Environ. Sci.* **2016**, 13.

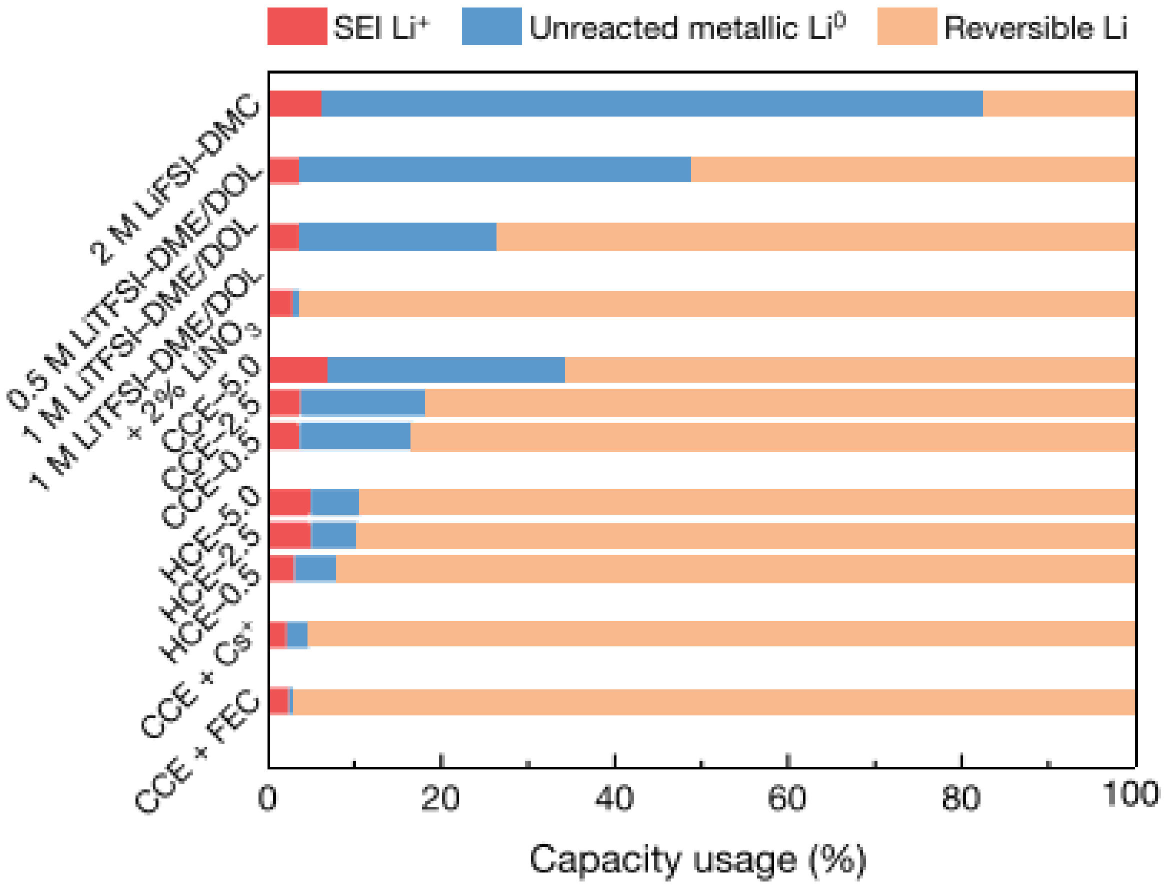
Coulombic efficiency (CE): dead Li and SEI contribution

CE directly correlates with the cycle life

- To keep 80% capacity after 500 cycles, CE needs to be > 99.96%
- To keep 80% capacity after 1000 cycles, CE needs to be >99.98%
- To keep 80% capacity after 10000 cycles, CE needs to be >99.998%



Xu, W. *et al.* (2014) *Energy & Environmental Science*.



Y. S. Meng et al, *Nature* **2019**, *572*, 511.

SOA Electrolytes for Li metal batteries

Electrolyte engineering has increased CE up to 99.3% at J ≤ 1 mA/cm2

Year	Composition	Substrate	CE	Current density (mA/cm2)	Capacity (mAh/cm2)	
2015	4M LiFSi-DME	Cu	99.1%	0.2	1	J.-G. Zhang, *Nat. Commun.* **2015**, *6*, 6362
2018	10M LiFSI-DMC	Cu	99.2%	0.2	1	C. Wang, *Chem* **2018**, *4*, 174
2018	1.2M LiFSI/DMC-BTFE	Cu	99.3%	0.5	5	J. G. Zhang, *Adv. Mater.* **2018**, *30*, 1.
2018	1 M LiPF6 in FEC/FEMC/HFE	Cu	99.2%	0.1	1	K. Xu, C. Wang, *Nat. Nanotechnol.* **2018**, *13*.
2019	1M LiPF6 carbonate	Ammonia treated carbon film		0.8		J. Liu, *Nat. Nanotechnol.* **2019**, *14*, 594
2019	LiFSI-1.2DME-3TTE	Cu	99.3%	0.5	1	J. G. Zhang, W. Xu, *Joule* **2019**, *3*, 1662.
2019	1 M LiFSI/DME-TFEO	Cu	97.74%	0.5	5	J. G. Zhang, *Nat. Energy* **2019**, *4*, 796.
2020	1M LiFSI/FDMB	Cu	99.3%	0.5	1	Y. Cui, Z. Bao, *Nat. Energy* **2020**, *5*, 526.
2020	LiPF6/EC-DEC-LiNO3-Sn(OTf)2	Cu	98.4%	1	1	Y. Lu, *Adv. Mater.* **2020**, *32*, 1.
2021	1M LiFSI-DMTMSA	Cu	99%	0.5	1	J. Li, *Nat. Energy* **2021**, *6*.

However,

- To keep 80% capacity after 1000 cycles, CE needs to be >99.98%
- High areal capacity (≥ 5 mAh/cm2) required to high energy Li metal batteries

Fundamental knowledge is required to guide the design of electrolyte and substrate

Content

- Basics of Li-ion battery
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- Degradation of Li-ion battery
- Electrolyte for advanced performances
  - High Energy
  - Fast charging

BUSINESS | AUTOS & TRANSPORTATION | AUTOS INDUSTRY

Tesla Drivers Worry About Wait Times as Elon Musk Opens Up Supercharger Network

Expanded user base for its charging infrastructure could generate more revenue for the EV maker

Charging speed for a Tesla Model S

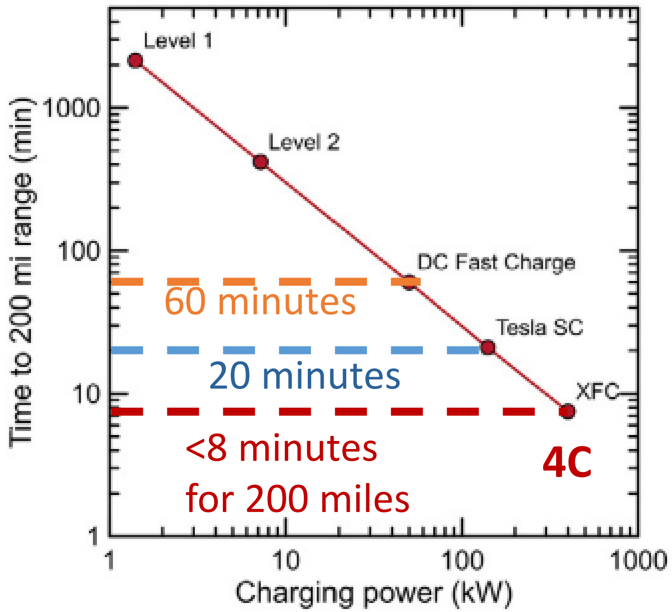
Charger level	Charging time
NEMA 5-15	3 miles of range per hour
NEMA 14-50	17 to 18 hours
Wall connector	9 hours
Supercharger	30 minutes

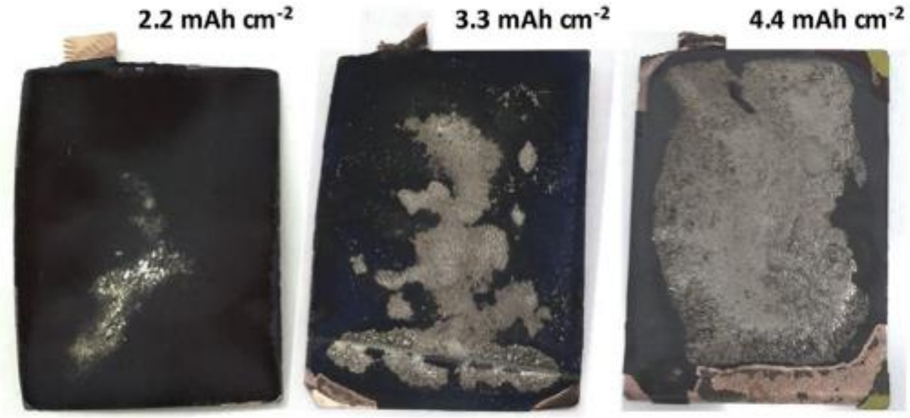
https://www.energysage.com/electric-vehicles/charging-your-ev/charging-a-tesla/

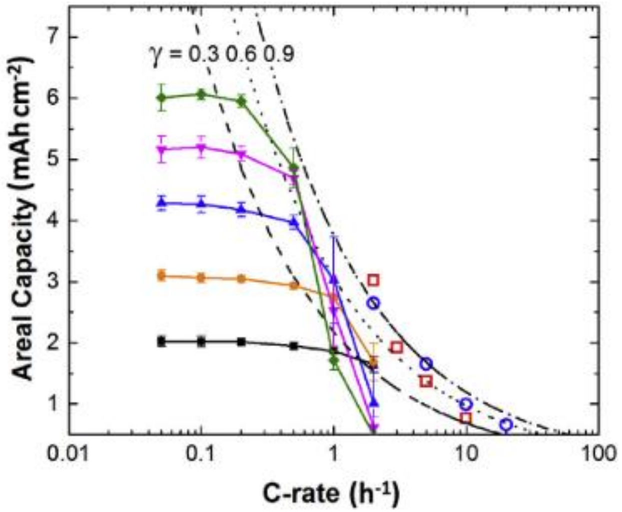
Fast-charging Li-ion batteries

- Motivation
  - Many US households do not have at-home charger
  - Long-distance travel: limited by EV charging time
  - Taxis requires fast turn-around for business operation
- Challenge 1: reduced capacity utilization
  - Ohmic overpotential
  - Interfacial overpotential (charge transfer, SEI)
  - Concentration overpotential
- Challenge 2: accelerated degradation
  - Anode: Li plating
  - Cathode: particle crack and fracture

Tesla model S: 100 kWh





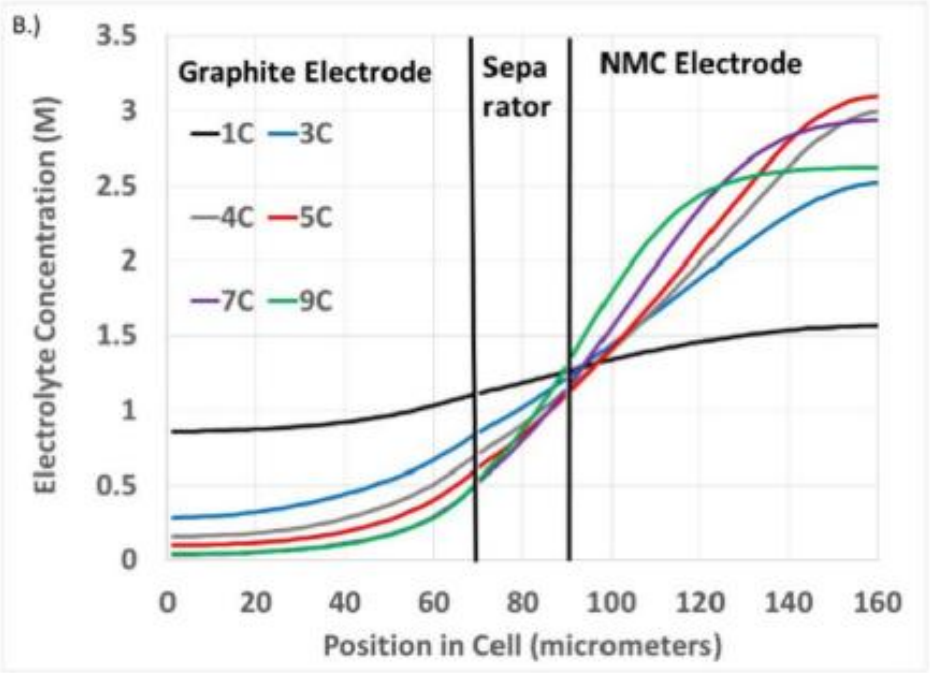


Logan, E. R. and Dahn, J. R. (2020) , *Trends in Chemistry*, 2(4), pp. 354–366.

US DOE, ARPA-e, *ELECTRIC VEHICLES FOR AMERICAN LOW-CARBON LIVING (EVs4ALL) program FOA*

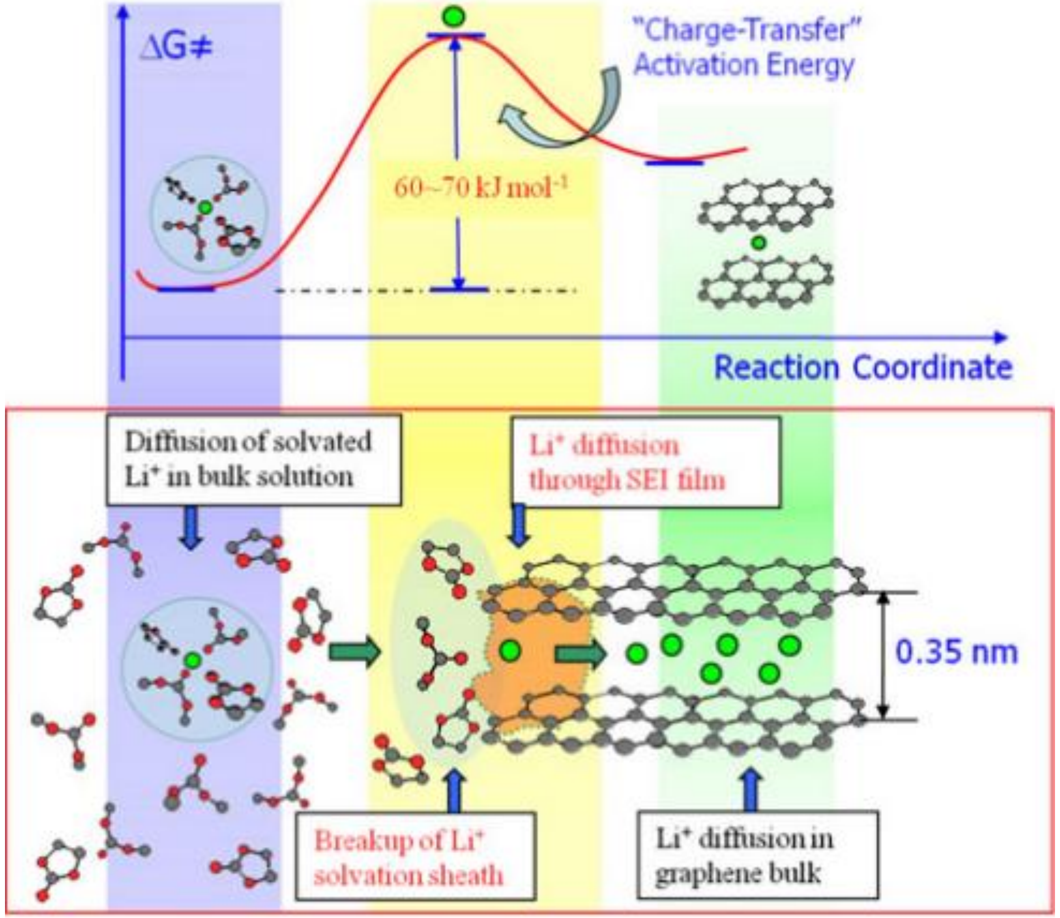
Fast-charging electrolyte should have

- Transport properties
  - High Li^+ diffusivity (conductivity)
  - High Li^+ transference number



Colclasure, A. M. *et al.* (2020), *Electrochimica Acta*, 337, p. 135854.

- Interfacial properties
  - Low SEI resistance
  - Low charge transfer resistance
    - Low de-solvation energy



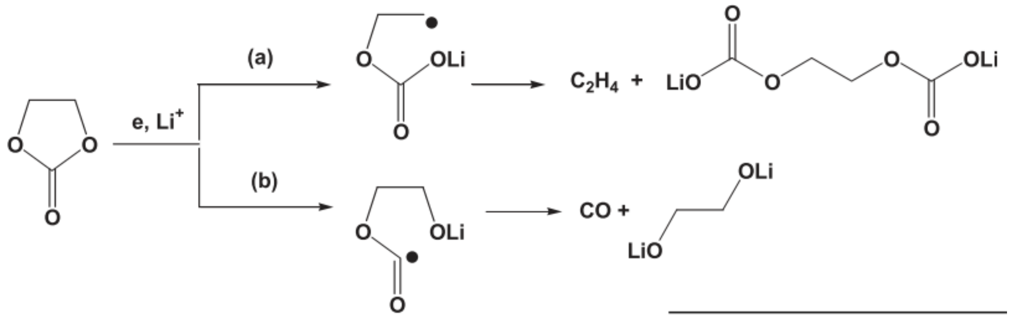
Xu, K. and Von Wald Cresce, A. (2012), *Journal of Materials Research*, 27(18), pp. 2327–2341.

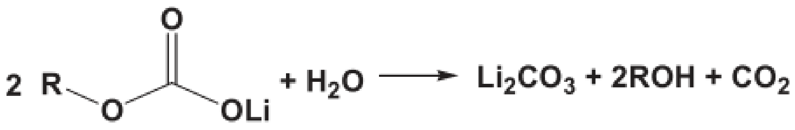
SOA LIB electrolyte has high interfacial resistance

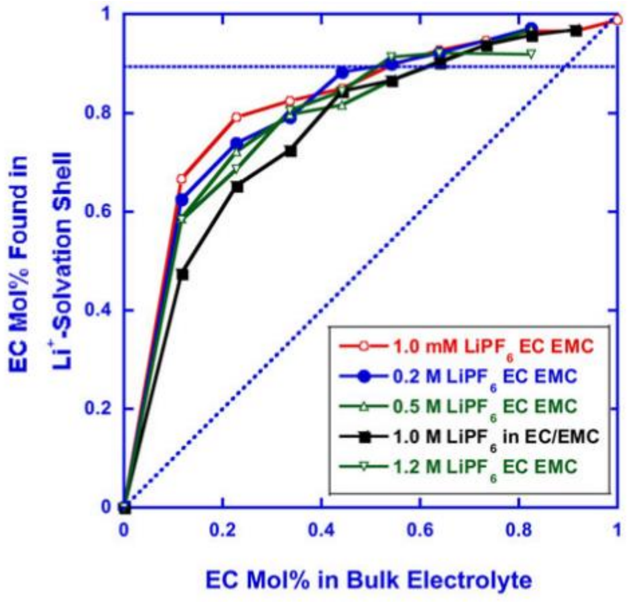
In commercial carbonate electrolytes

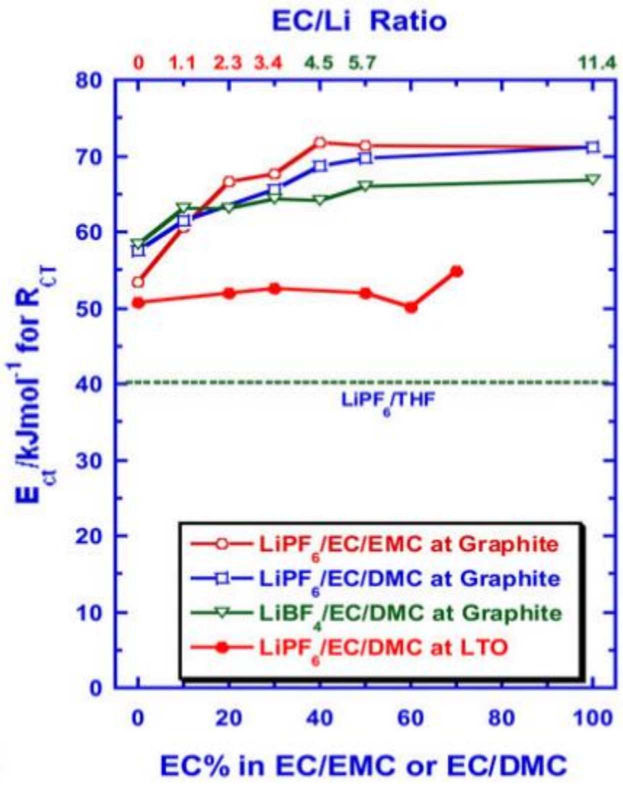
(e.g., 1M $LiPF_6$ EC DMC)

- Li^+ preferential solvated by EC
- EC strongly binds Li^+
- Energy barrier for intercalation: 50-70 kJ/mol
  - De-solvation dominates: 50 kJ/mol
- SEI dominated by EC decomposition
  - Alkyl carbonate, Li_2CO_3 and etc.





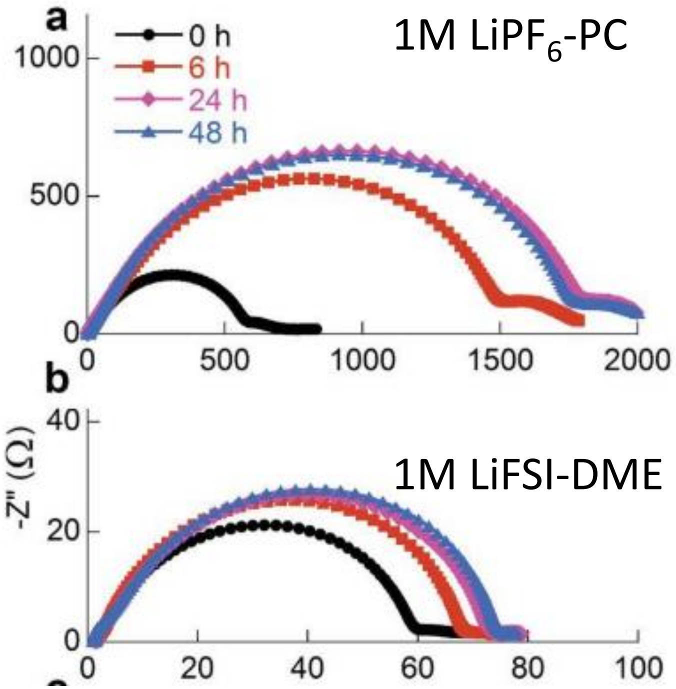




Xu, K. and Von Wald Cresce, A. (2012), *Journal of Materials Research*, 27(18), pp. 2327–2341.

Ether-based electrolyte has much lower interfacial resistance

EIS of Li|Li symmetric cell



Interfacial resistance:
> one order lower

Qian, J. *et al.* (2015), *Nature Communications*, 6, p. 6362.

Fast-charging in Li-Graphite half-cells

LP50
1M $LiPF_6$ EC-EMC

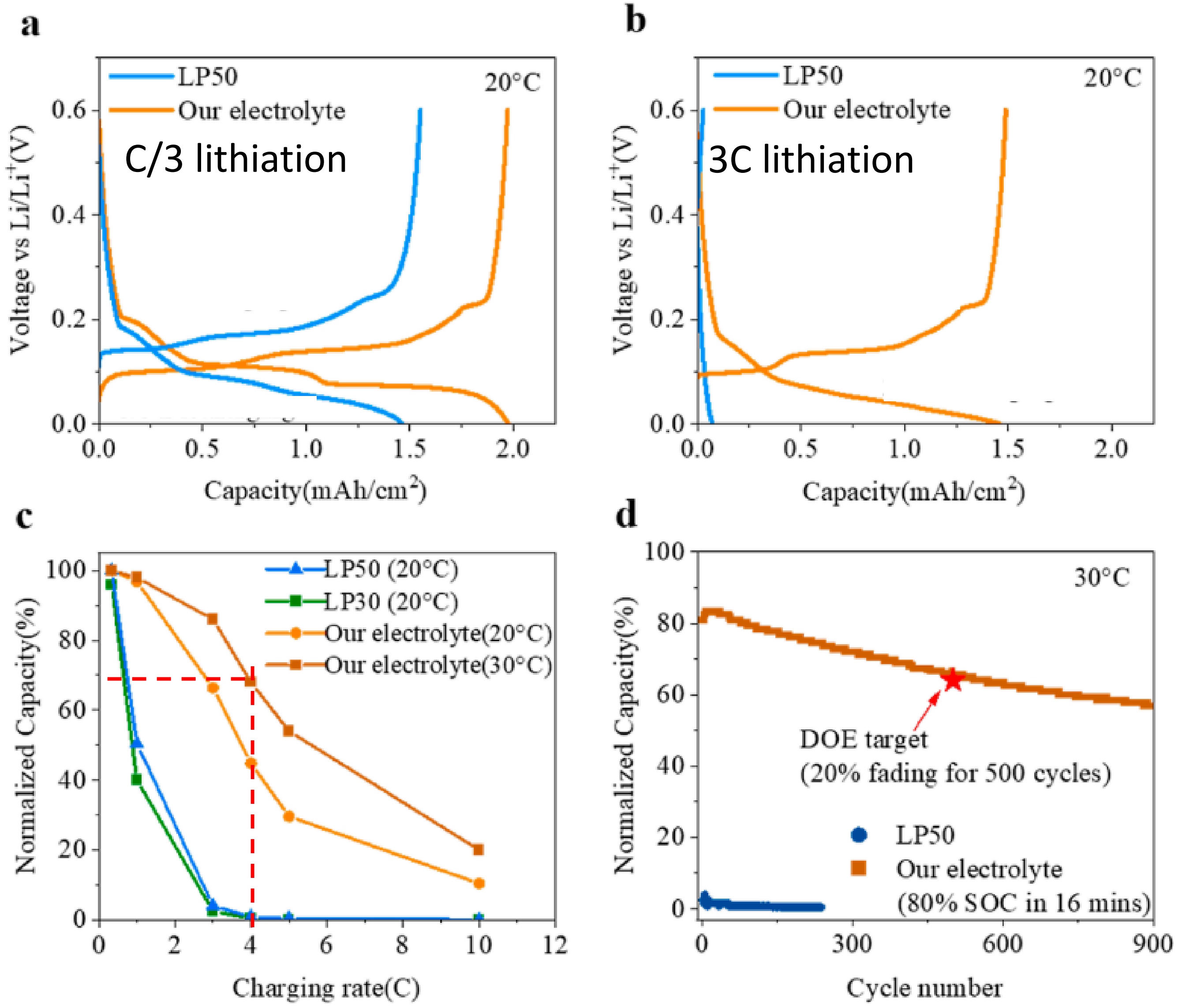
LP30
1M LiPF6 EC-DMC

C/3 de-lithiation

Graphite:
2.1 mAh/cm2

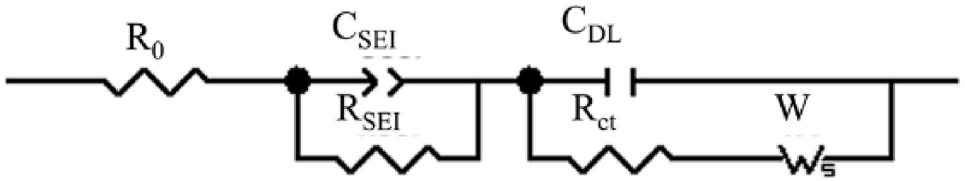
~70% SOC
in 10.5 minutes
(4C and 30 °C)

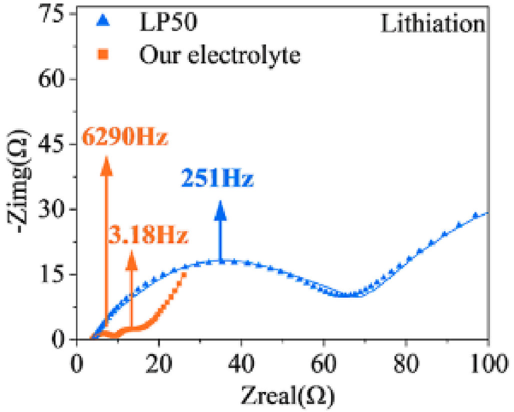
- 175 miles in 8 minutes

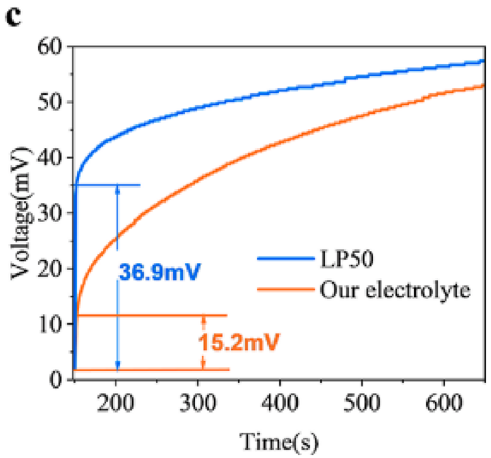


Li, Z. ***Gao, T***. (2022) 'Enhancing the Charging Performance of Lithium-Ion Batteries by Reducing SEI and Charge Transfer Resistances', *ACS Applied Materials & Interfaces*.

Reduced Interfacial Resistance







	fully lithiated state	
resistance	LP50	our electrolyte
R_o (Ω)	4.21	3.75
R_{SEI} (Ω)	60.3	5.27
R_{ct} (Ω)	174	8.01

Table S2. Conductivity of different electrolyte in 25°C

Electrolyte	Conductivity (mS/cm)
LiTFSI in DME (1M, 1.26m) [1]	16.9
LP30 (1M)	11.16
LP50 (1M)	13.25
Our electrolyte (1.9M, 3.5m)	14.04

Energy barrier for charge transfer reaction:
19 kJ/mol

Carbonate:
50-70 kJ/mol

Li, Z. ***Gao, T***. (2022) 'Enhancing the Charging Performance of Lithium-Ion Batteries by Reducing SEI and Charge Transfer Resistances', *ACS Applied Materials & Interfaces*.

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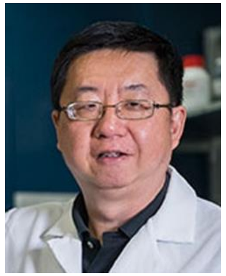
K.Xu

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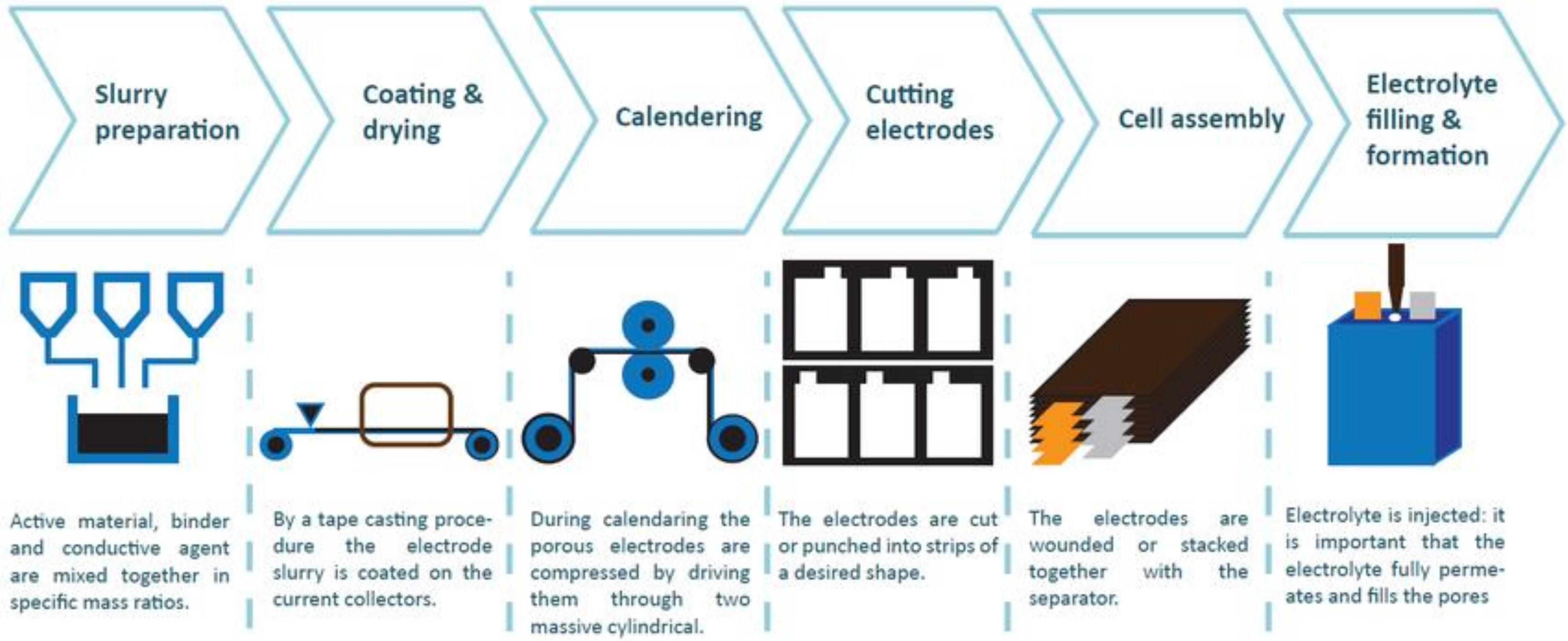
Manufacturing of LIB



The safety problem of LIBs

Hoverboard

Laptop

UPS Cargo Fire

Tesla Cars

On April 21, 2019, a Tesla Model S was exploded in an underground garage in Shanghai, China.

On May 4, 2019, Tesla Model S, not plugged in, with smoke observed near the rear right tire. [100]

On May 13, 2019 a Tesla Model S, caught on fire while parked in Hong Kong.[101]

On June 1, 2019, a Tesla Model S burned down while supercharging in Belgium.[102]

On August 10, 2019, a Tesla Model 3 collided with a truck on a high-speed road in Moscow, Russ

On November 12, 2019 a Tesla Model X from 2017 burst into flames while charging, leaving the v

Source: Wikipedia