Nanomaterials for Energy Storage

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Beckman Center, Irvine, CA, June 16, 2016

Batteries & Supercapacitors

Today's market of $25+Billion expected to grow to $1+Trillion by 2040

- Hybrid and Electrical Engines for Transportation

- Power Quality for National Grid

- Hybrid Engines for Energy Efficient Industrial Equipment

- Electric Planes & Drones

- Power Tools

- Department of Defense (DoD)

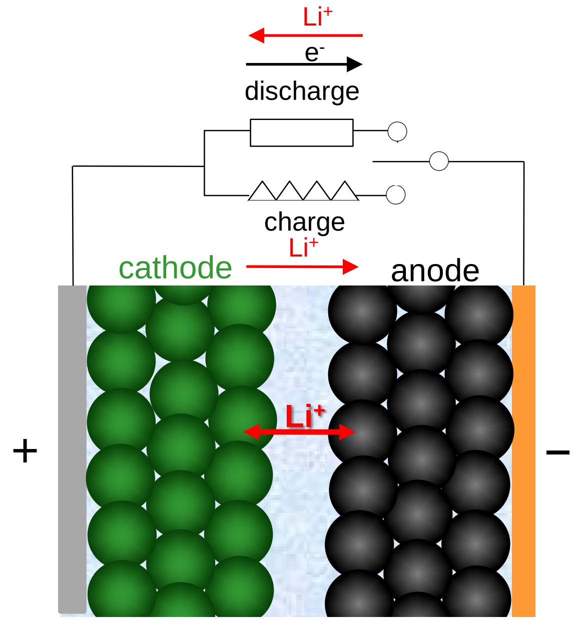
- Electronics

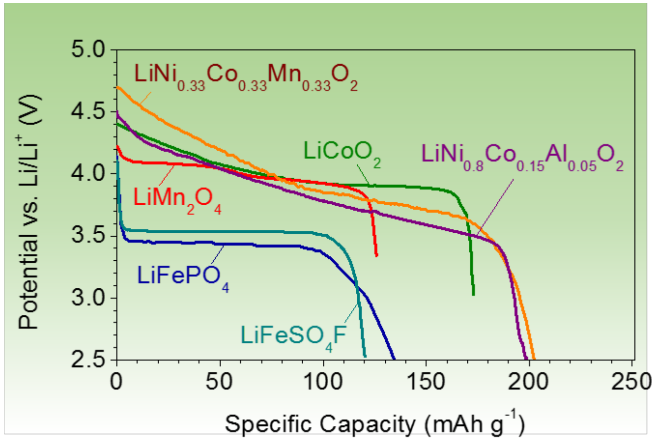
Operating Principle of Li-ion battery

- "Rocking-chair" or "shuttlelock" mechanism: **Li ions shuttle between the anode and the cathode**

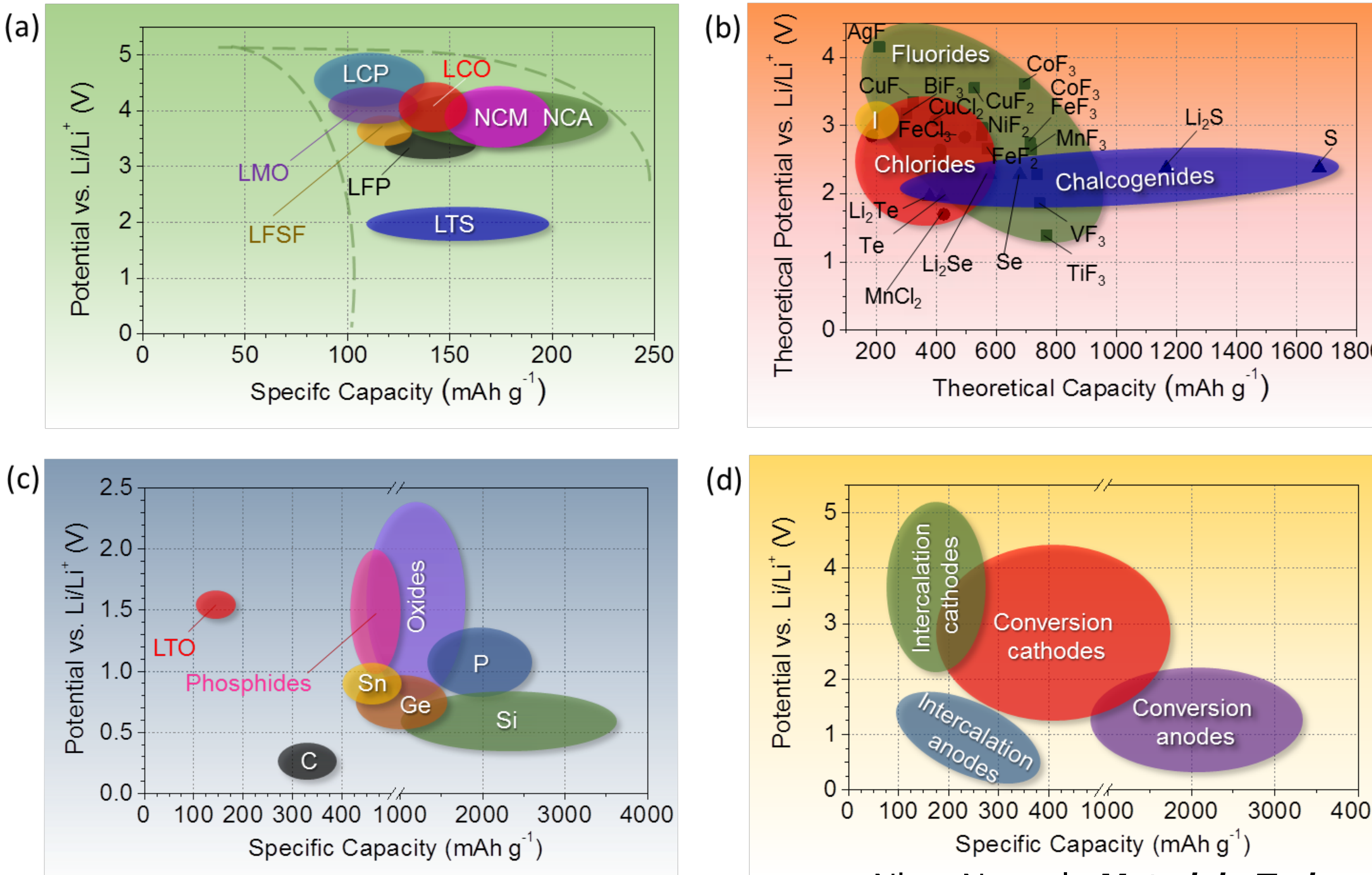
- Higher capacity of the cathode or the anode will lead to higher capacity of a battery

- For high battery voltage, a cathode should maintain high potential vs. Li/L$^+$ for the large range of Li concentrations, while an anode should maintain low potential vs. Li/Li+ for the large range of Li concentrations





Materials for Li-ion batteries



Nitta, N. et al., ***Materials Today***, 2015

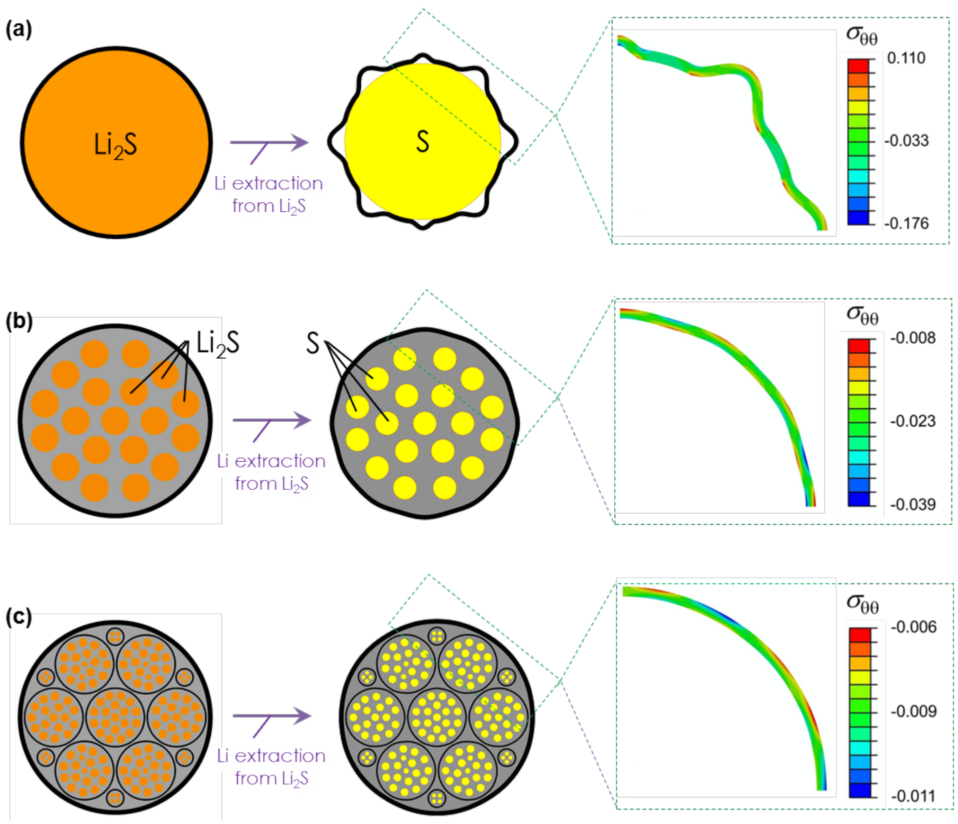
Challenges with Conversion Electrode Materials

- Significant mass transport (slow kinetics) ☹
- Large volume changes & electrode swelling ☹
- Fractures of individual particles ☹
- Electrode disintegration & disconnection from current collectors ☹
- Continuous irreversible decomposition of electrolyte ☹
- Dissolution of active materials (cathodes) ☹
- Many others ☹

Nanotechnology is needed
to overcome such challenges

Conversion-Type Cathodes: Li_2S and S

➢ Hierarchical Li_2S-C Nanocomposites: Overcoming Dissolution



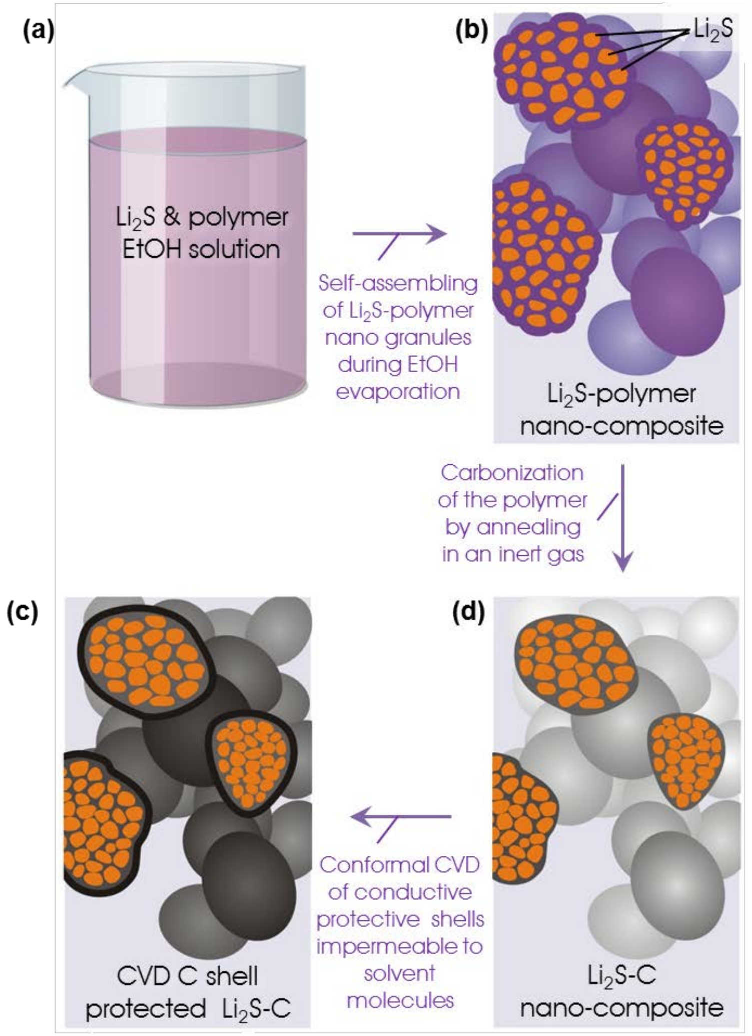
- Shells may protect dissolution of cathodes during cycling, but typically fail due to repeated volume changes
- Hierarchical particles' shelling for enhanced mechanical stability of volume-changing active materials
- Significant reduction of the hoop stress within the outer shells achieved in hierarchical particles

Patent pending

Wu, F. et al., ***Adv. Mater.***, 2015

Conversion-Type Cathodes: Li_2S and S

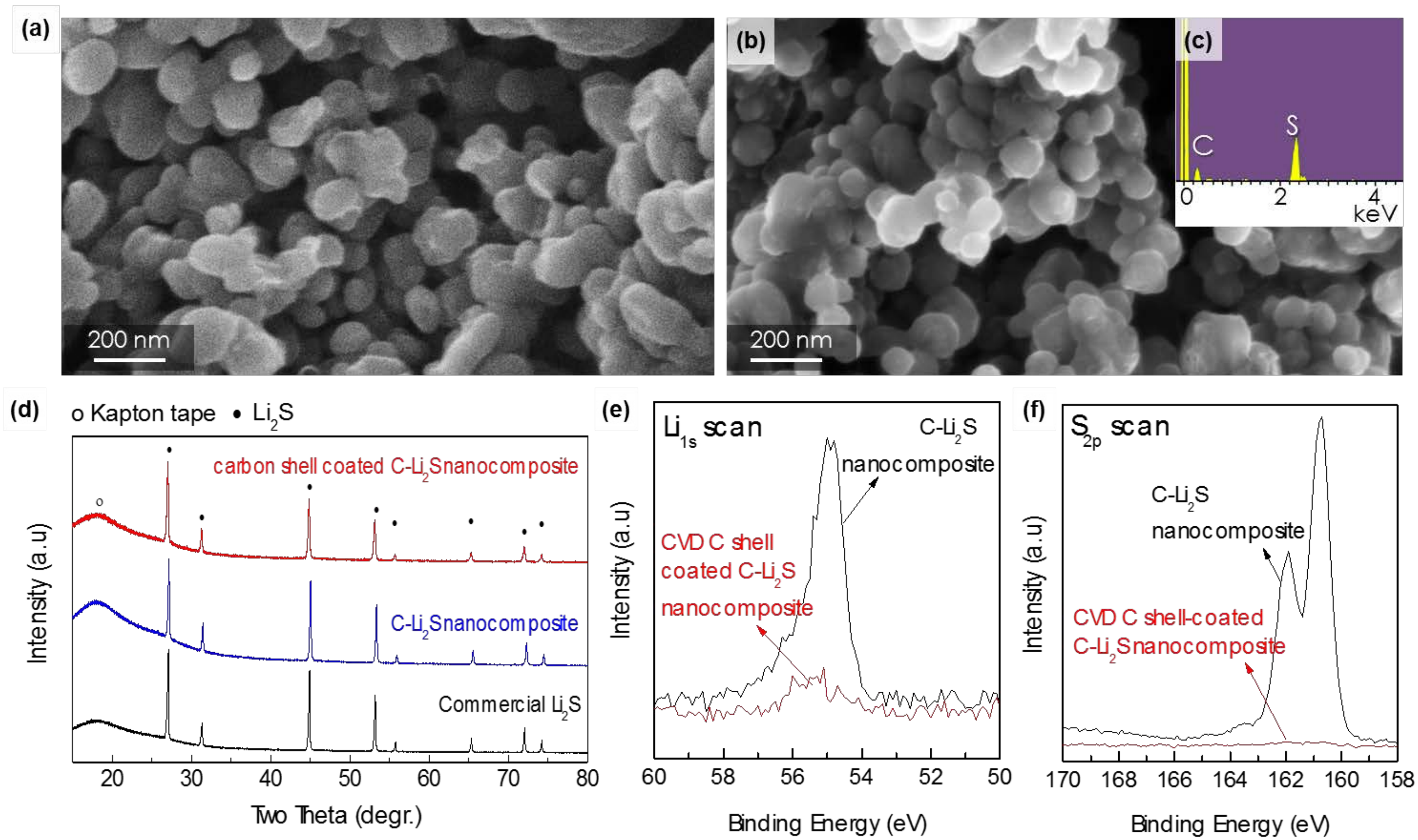
Patent pending



- Hierarchical Li_2S-C Nanocomposite Preparation:
  - Ideally would like to have a narrow distribution of Li_2S nanoparticles within conductive C matrix
  - Conventional approach (formation of Li_2S nanoparticles and coating it with carbon) does not work: (1) nanoparticles tend to agglomerate in solutions; (2) solution-solvable organic carbon precursors dissolve Li_2S
  - Our solution: employ (i) steric separation of freshly nucleated Li_2S particles, (ii) their self-assembling, (iii) polymer carbonization due to high MP of Li_2S

Wu, F. et al., ***Adv. Mater.***, 2015

Conversion-Type Cathodes: Li_2S and S



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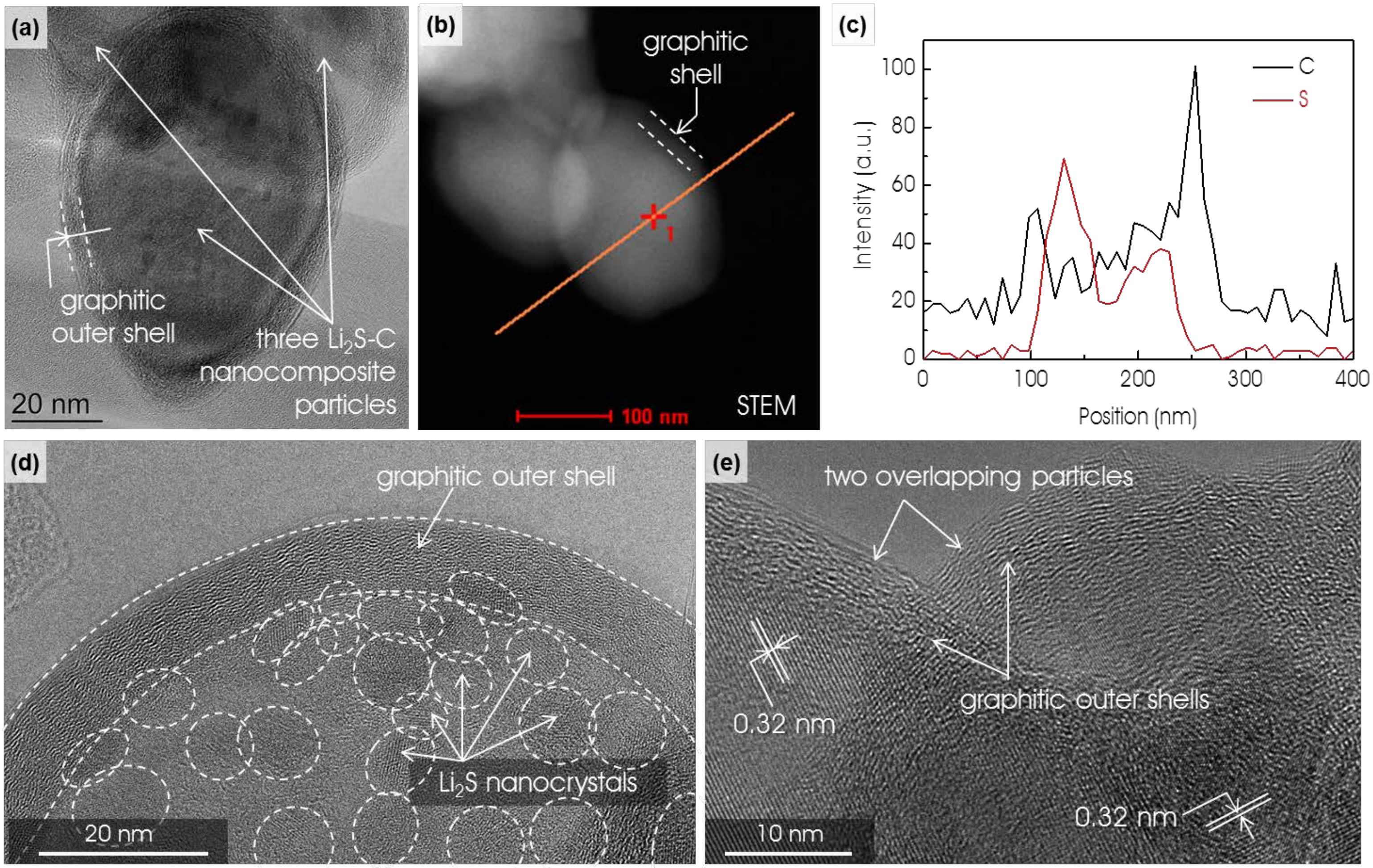

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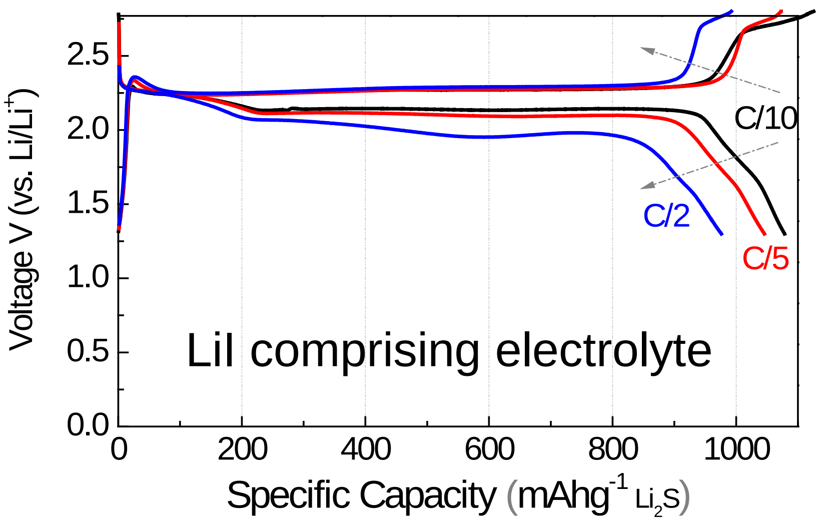
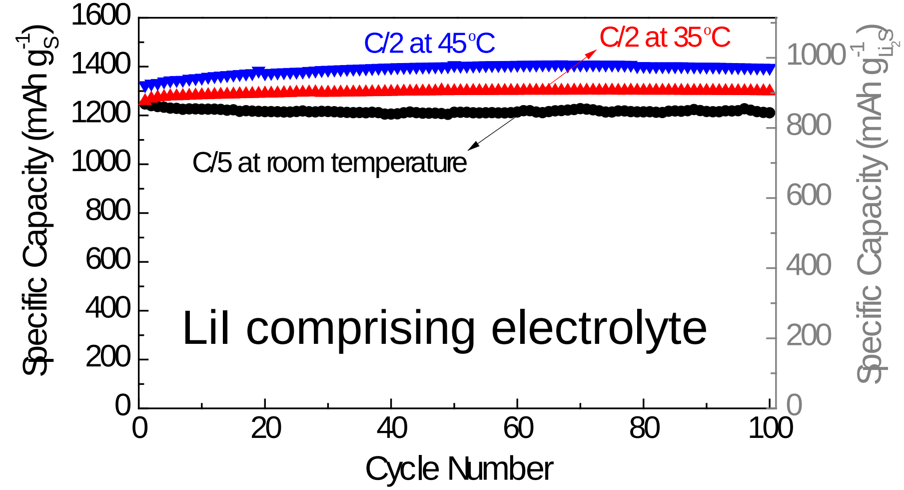
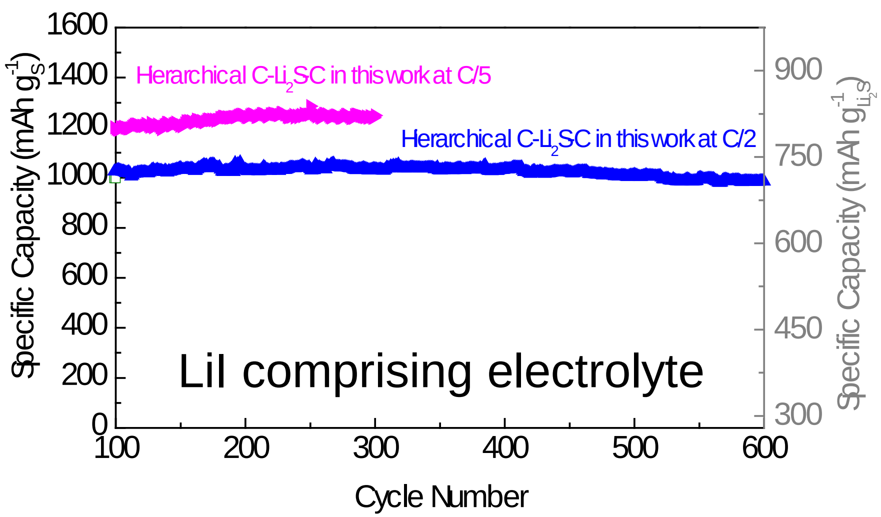
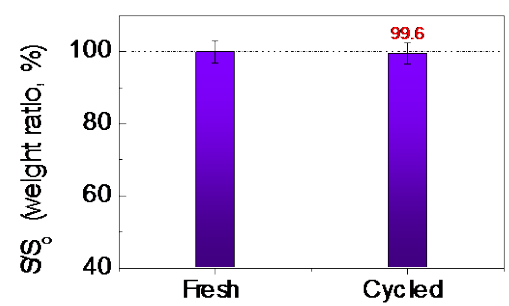
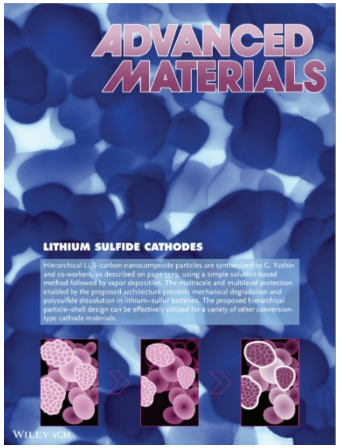




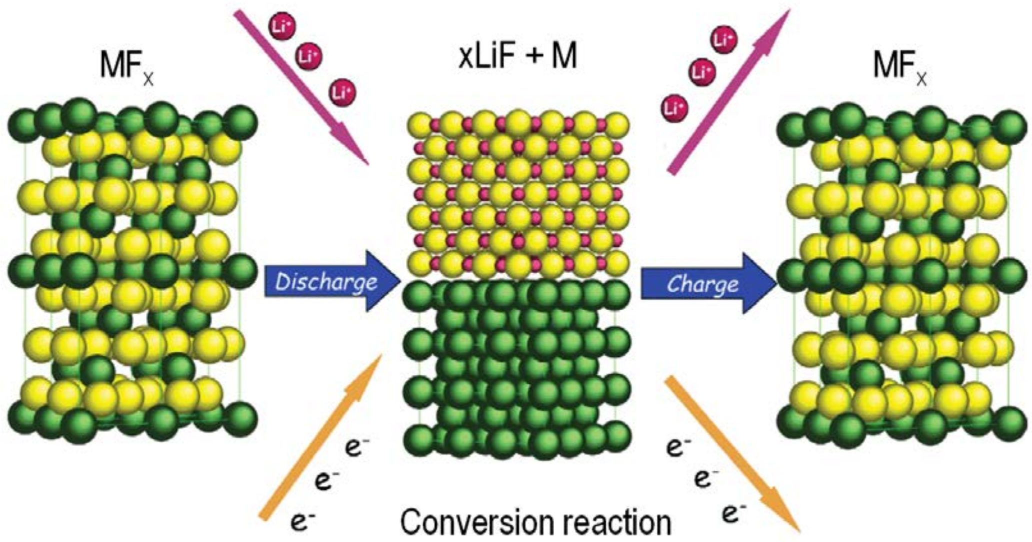






Wu, F. et al., ***Adv. Mater.***, 2015

“True Conversion”-Type Cathodes: MFx



- $xLi^+ + xe^- + MF_x \leftrightarrow xLiF + M$
  M – is a fluoride-forming element

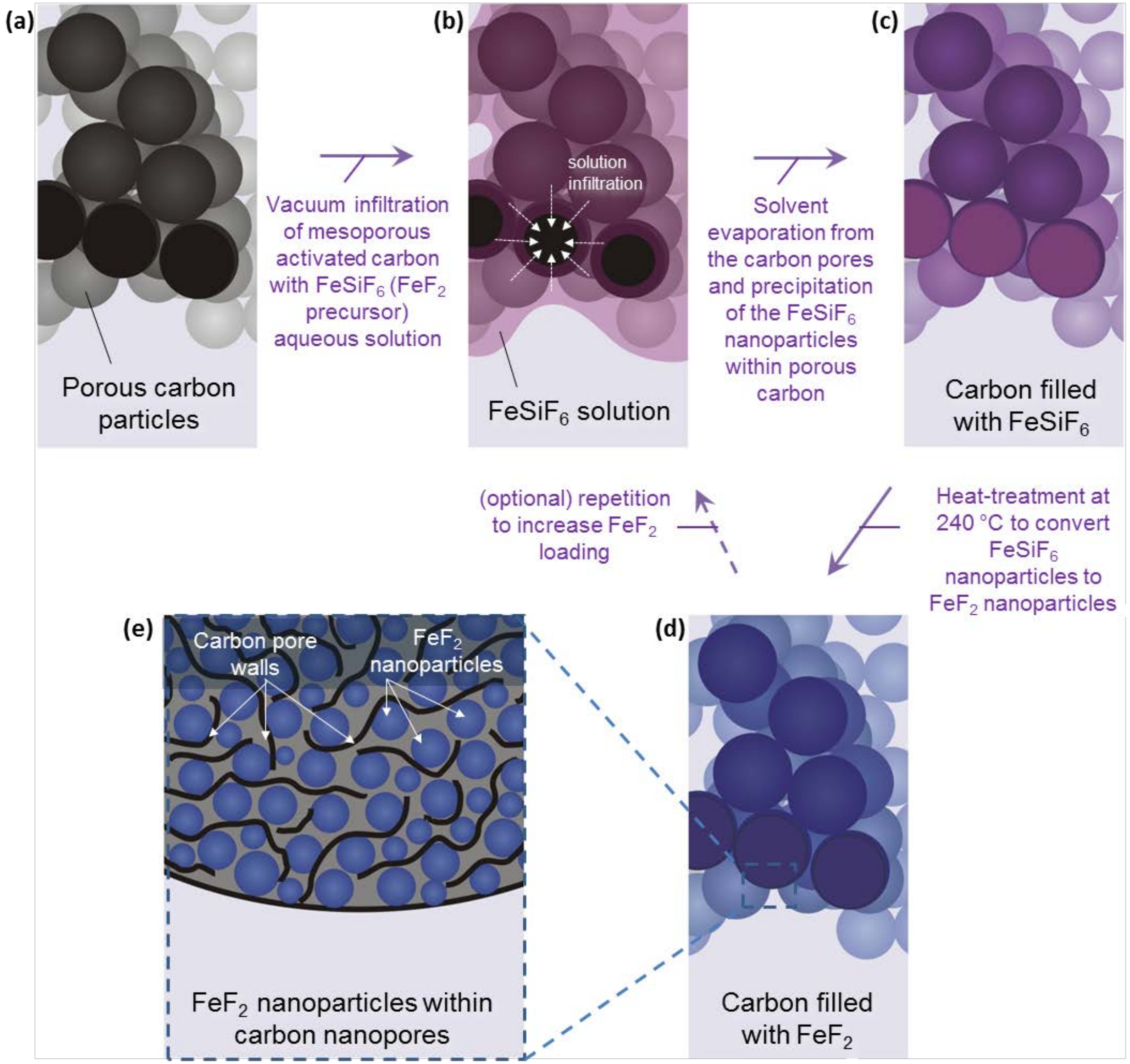
- Volumetric capacity of most metal fluorides: up to ~2200 mAh/cc – similar to that of S/Li_2S

- Due to higher V: higher energy density

- Challenges with MFx:
  - Metal dissolution
  - Irreversible separation of LiF and M clusters

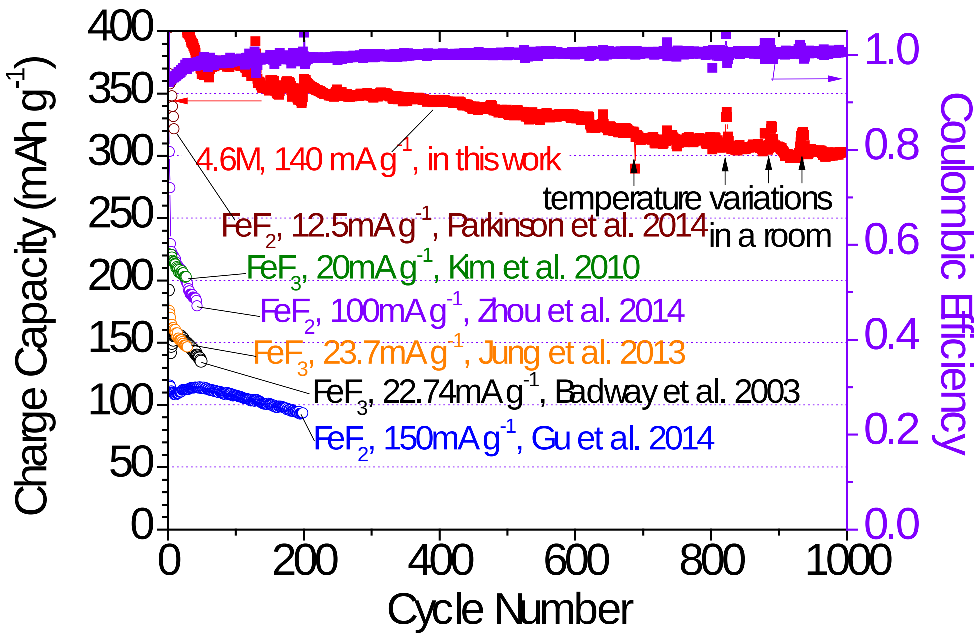
Schematic: reproduction from G.G. Amatucci, N. Pereira, Journal of Fluorine Chemistry, (2007)

“True Conversion”-Type Cathodes: MFx



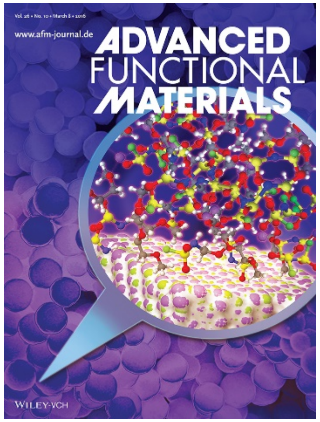
- To prevent agglomerations of LiF and M clusters we confine MFx in carbon nanopores
- Conductive carbon pore walls will additionally provide pathways for electron transport (so we don’t rely on interconnectivity of M clusters)

"True Conversion"-Type Cathodes: MF_x with *in-situ* formed protective shell



- The longest stability of MF_x demonstrated thus far
- Extremely small (for this chemistry) hysteresis @ RT and 140 mAh/g (C/3) current density
- Unique MFx-electrolyte combination

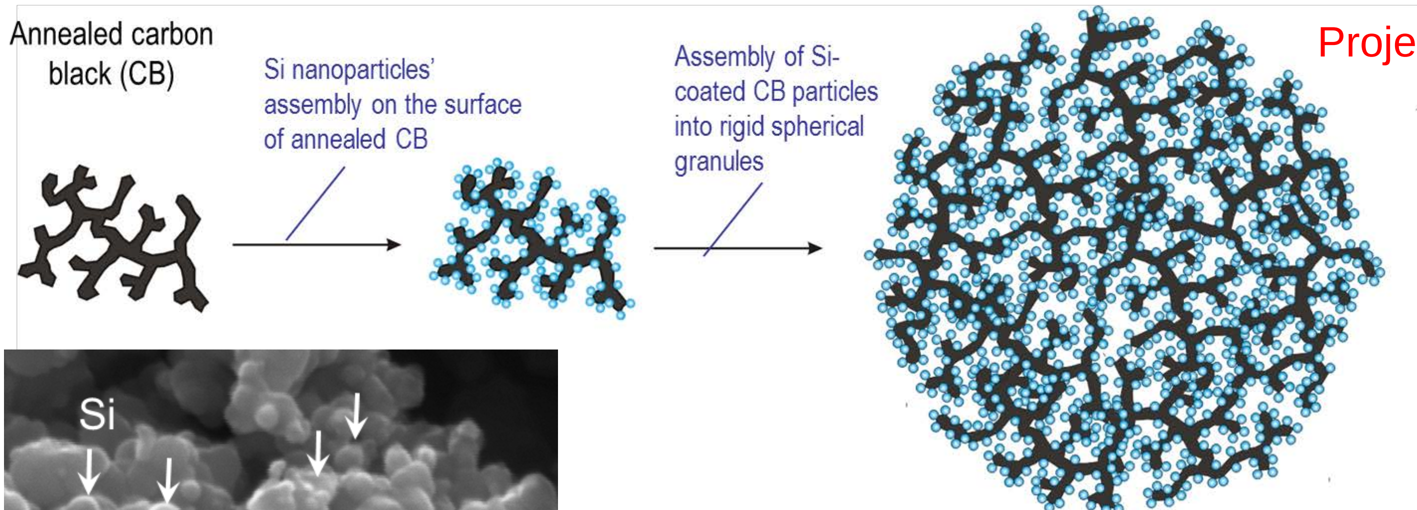
Gu, W. et al., ***Advanced Funct Mater***, 2016

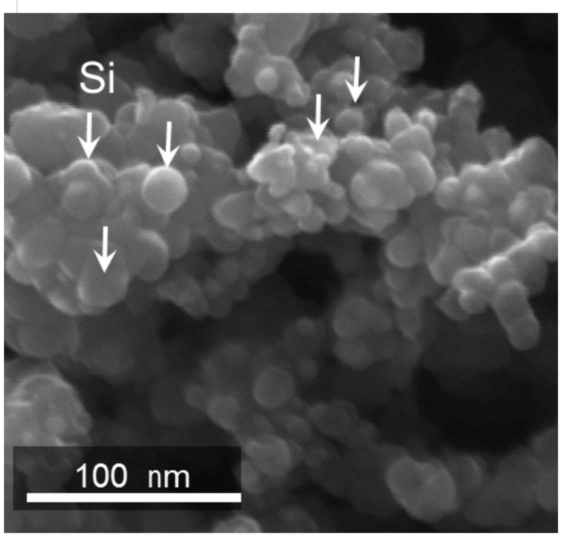


Silicon Anodes

➢ **Minimizing volume changes using nanocomposites**
(note: 300%+ volume increase in Si upon lithiation)

Project started in 2008





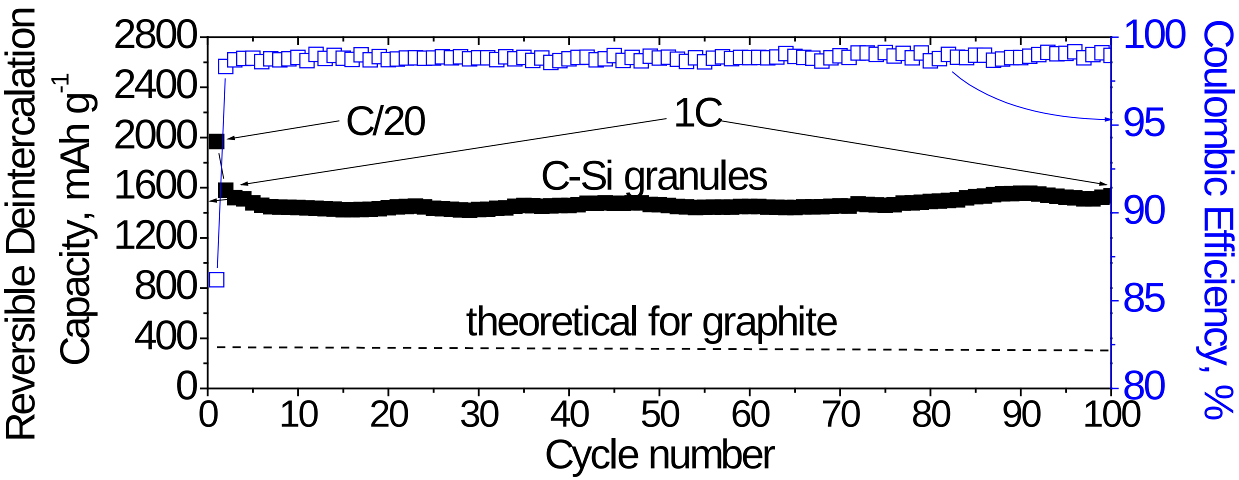
- Uniformity of the deposited Si nanoparticles
- No volume changes during Li insertion/extraction
- Compatibility with existing manufacturing technologies (drop-in replacement)
- High electrical & thermal conductivity

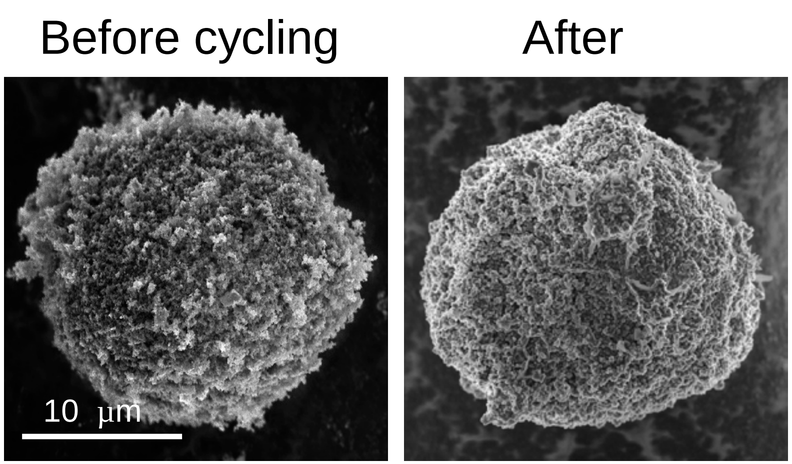
Patent pending

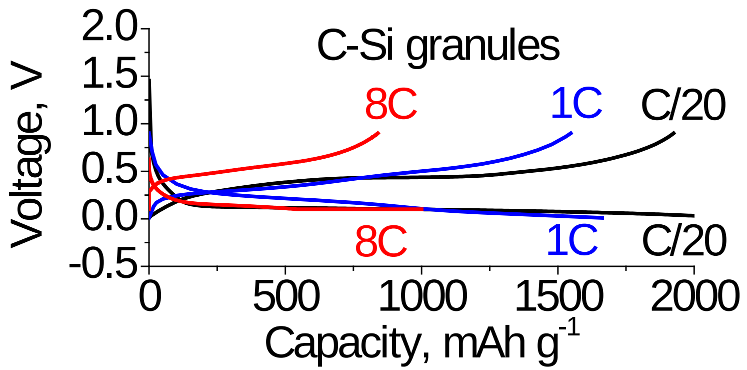
G. Yushin et. al, ***Nature Materials***, 2010

Silicon Anodes

- **Small volume changes at the nanocomposite particle level**





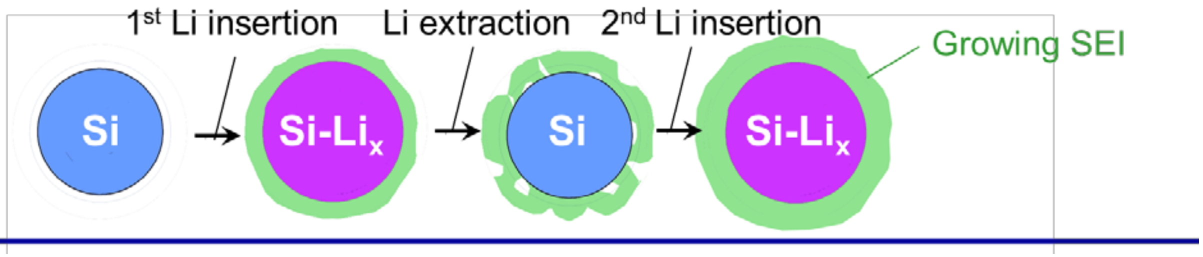


Patent pending

G. Yushin et. al, ***Nature Materials***, 2010

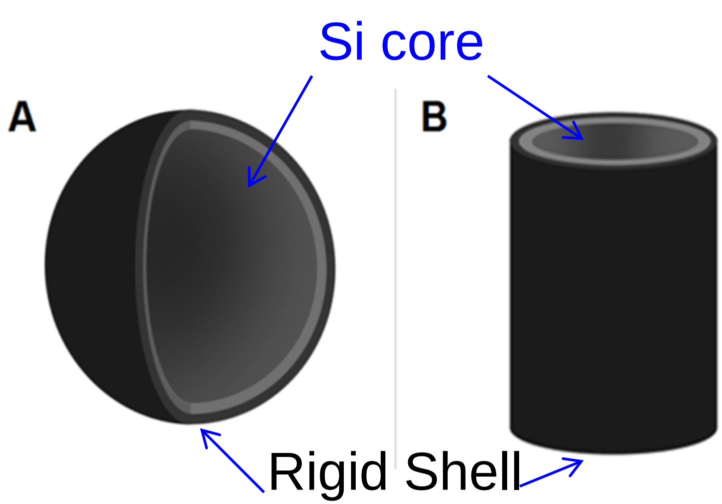
Silicon Anodes

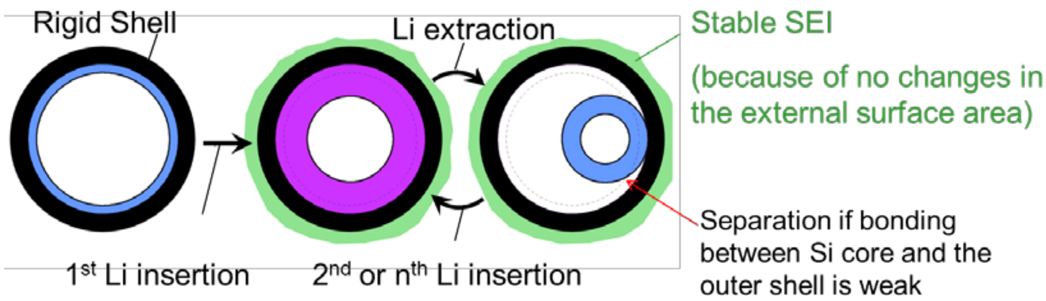
- **SEI stabilization**



Our proposal: porous core-shell structure.
Simplest Design – Single Pore

Georgia Tech Invention Disclosure, Jan 2008

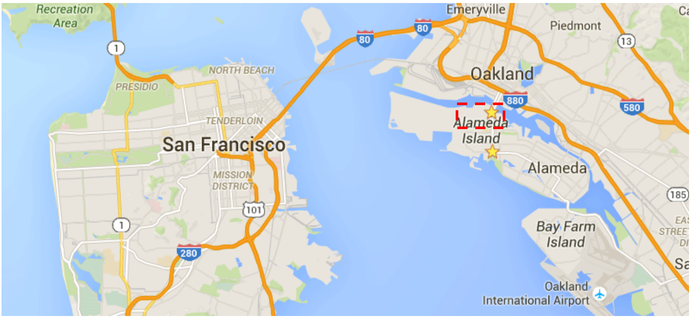




Patent pending

G. Yushin et al., ***JACS*, 2010**

Where we are now?



R&D and Pilot Plant Building: 31,500 sq. ft building

- In 2011 formed Sila Nanotechnologies Inc., a **Georgia Tech startup**
- **Sila is a Materials company** that develops & manufactures breakthrough engineered materials for smaller, lighter, longer-lasting batteries.
- **Drop-in solution** to existing battery manufacturing processes
- Sila is backed by Tier I investors**,** Public Sector & Industry Partnerships

Credit: Sila Nanotechnologies, Inc., web: www.silanano.com; email: info@silanano.com

Market Opportunity

Wearables


- More features and elegant form factors, with improved battery life to drive mass adoption

Portable Electronics

- Add capabilities, reduce size, increase battery life

Drones

- Extended flight time and advanced on-board capabilities

Electric Vehicles

- Mass market EVs: sub-$40,000, 300+ mile range

Renewable Energy

- Enable integration of renewable energy sources at grid-scale

Credit: Sila Nanotechnologies, Inc., web: www.silanano.com; email: info@silanano.com

Sila Products Roadmap: Double Energy Density of Li Batteries by 2022

- Micron-scale electrode powders
- Low volume changes @ very high capacity
- Complex nanostructured materials are produced in bulk reactors

Phase I: Anode Materials

2017: +20% *(vs. 2015 state of the art Li ion batteries)*
2018: +30%
2019: +40%

Phase II: Cathode Materials

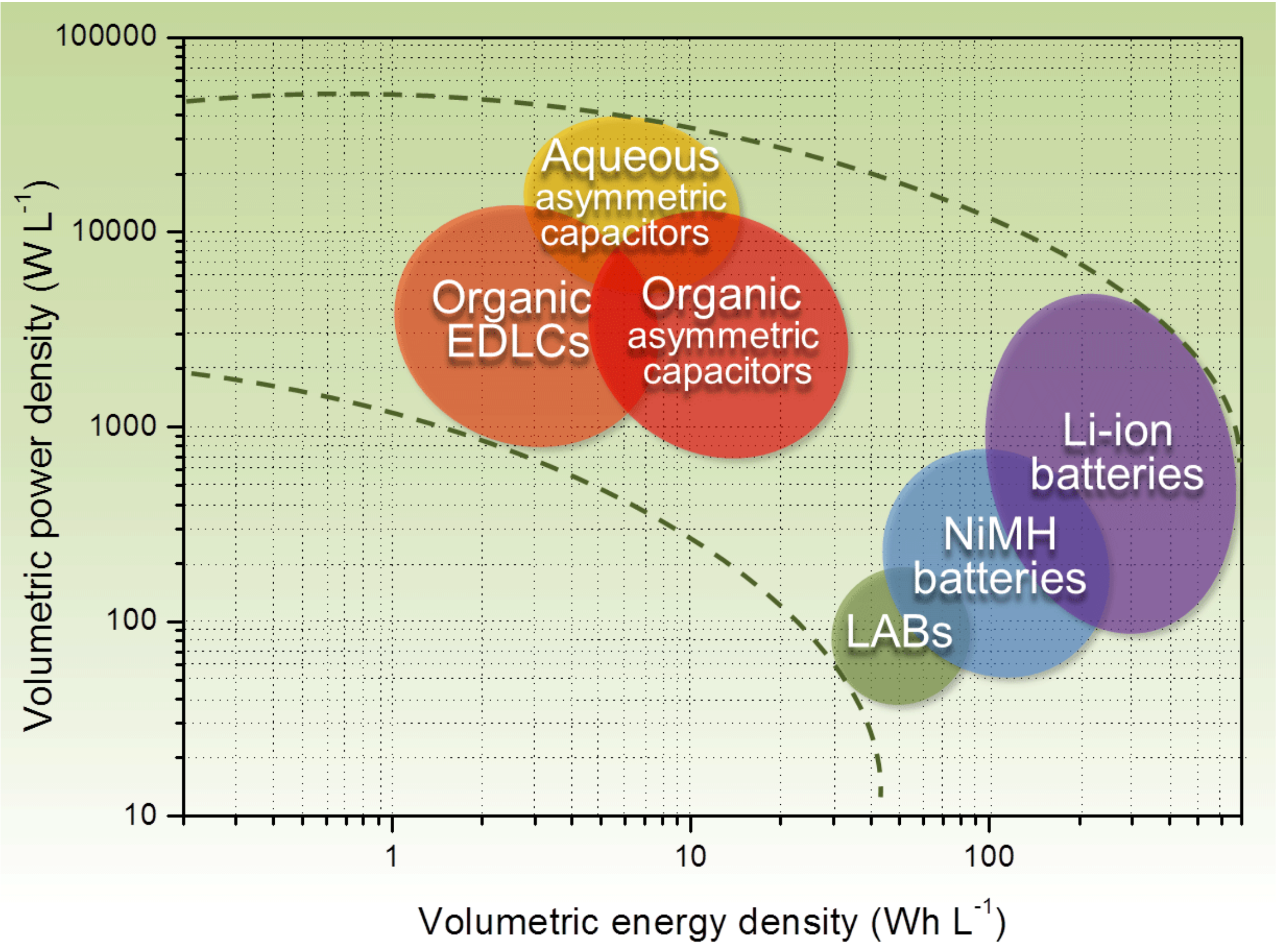
2020: +60%
2021: +80%
2022: +100%

Phase III: Other Energy Storage Tech

SILA NANOTECHNOLOGIES

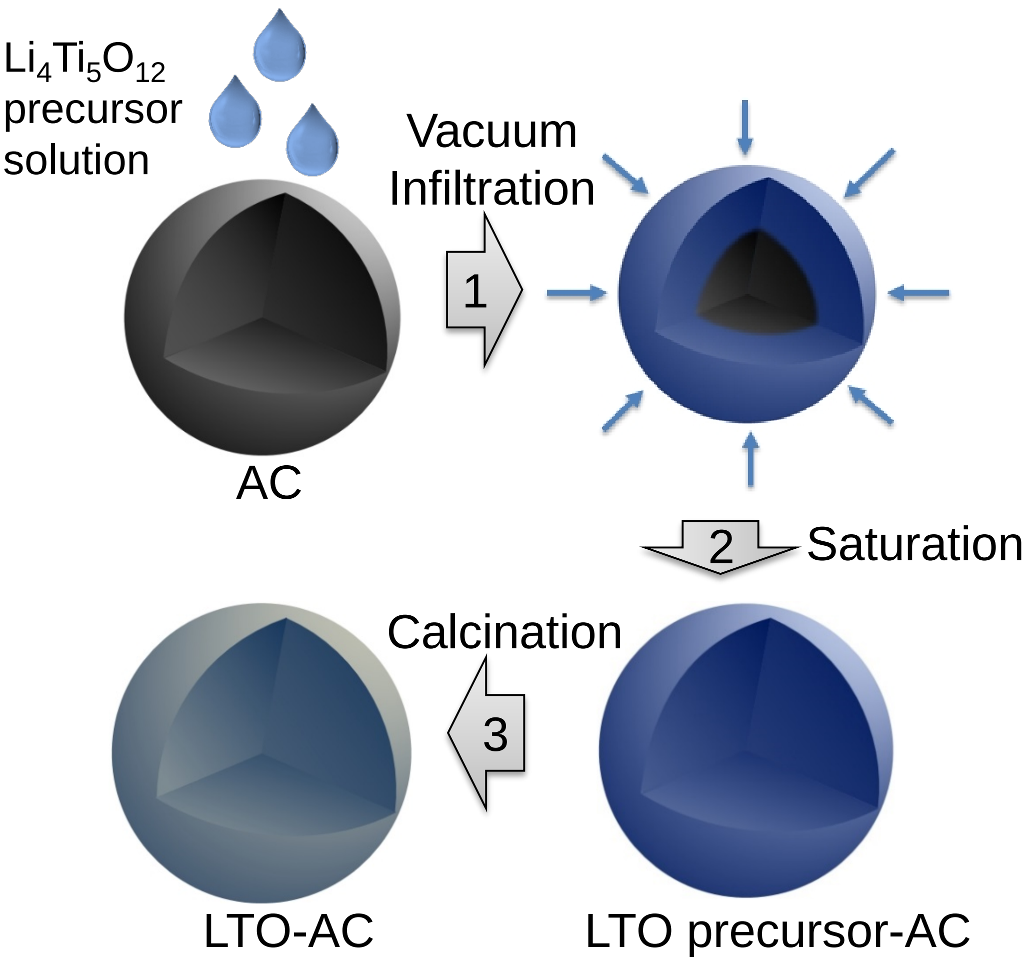
Credit: Sila Nanotechnologies, Inc., web: www.silanano.com; email: info@silanano.com

Energy Storage Technologies: High Power & Ultra-Fast Charging Capabilities

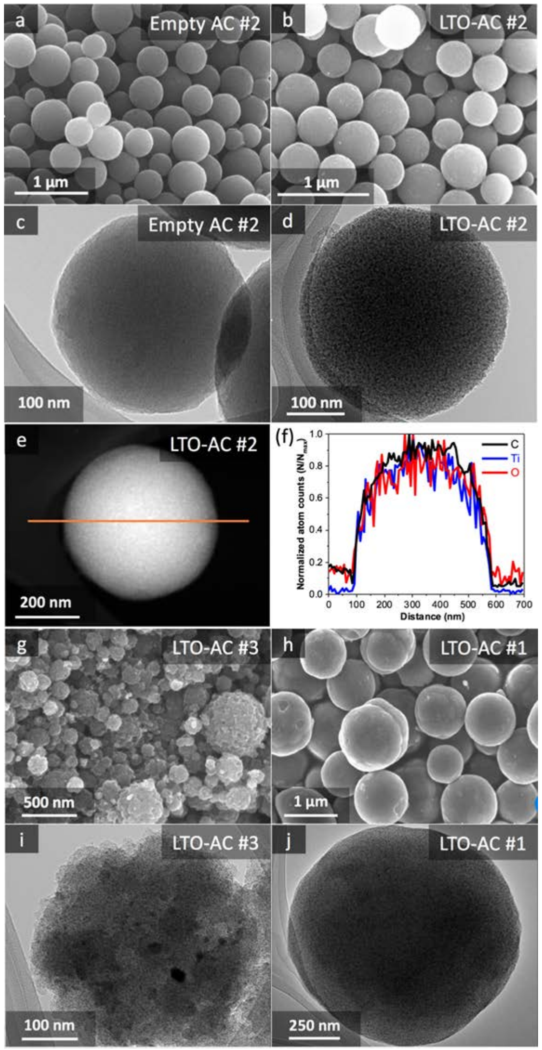


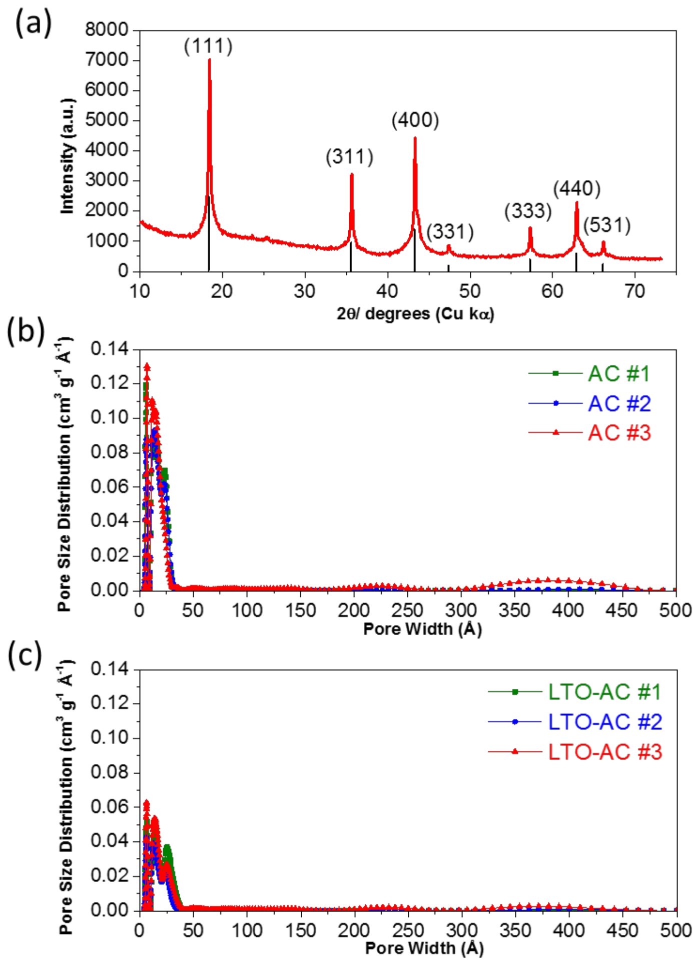
AC- $Li_4Ti_5O_{12}$ Nanocomposites for Ultra-Fast Charging:
Aiming to Approach Energy Density of Batteries, while Retaining Power Density of Supercapacitors

- Battery active materials (such as LTO) store ions in the bulk and thus offer much higher energy storage than supercapacitors
- But… they suffer from low electrical conductivity and slower ion transport. As a result – the power performance is poor
- Our approach: porous carbon-active material nanocomposites, where porous carbon provides high conductivity & porosity for rapid ion transport & LTO provides high capacity for Li ion storage



AC- $Li_4Ti_5O_{12}$ Nanocomposites for Ultra-Fast Charging

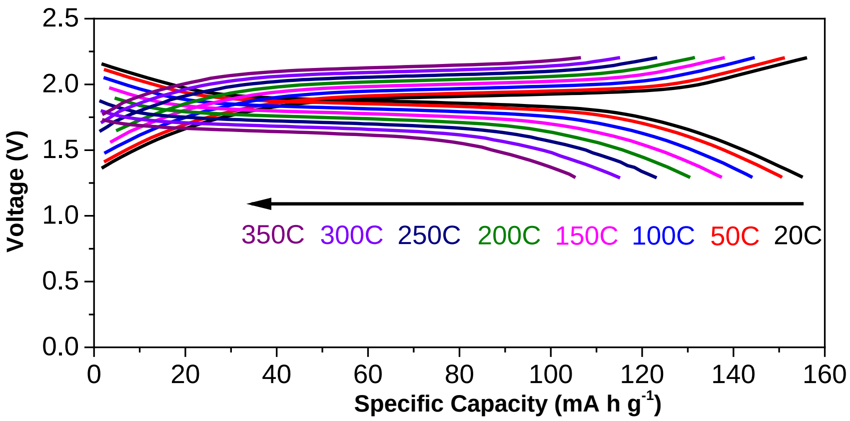


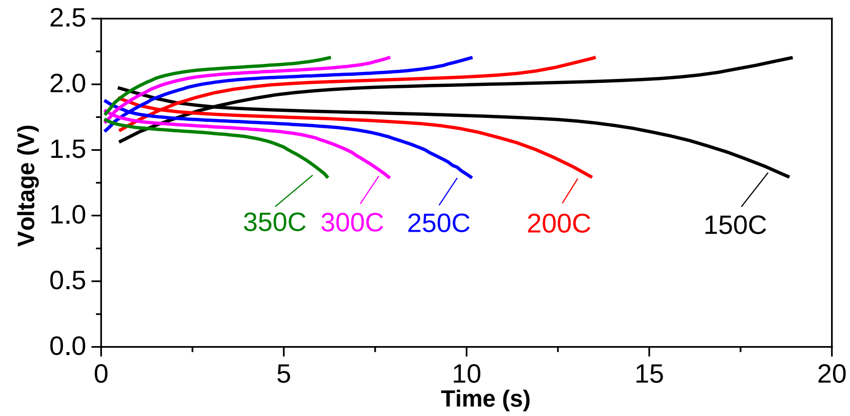


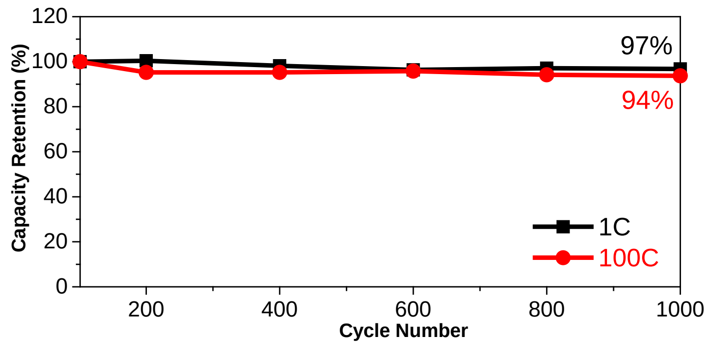
- Uniform infiltration of LTO into 3 types of porous carbons: AC#1, AC#2, AC#3
- Similar distribution of micropores and small mesopores

Zhao, E. et al., ***ACS Nano***, 2016

AC- $Li_4Ti_5O_{12}$ Nanocomposites for Ultra-Fast Charging







- AC#3-LTO composite have charge-discharge rates comparable to double-layer capacitors (seconds), while offering much higher specific and volumetric capacities

Zhao, E. et al., ***ACS Nano***, 2016

Summary

- Nanocomposites may help to overcome challenges of conversion-type materials for ultra-high energy density Li-ion batteries
- Nanocomposites may also lead to dramatic increase in the charge or discharge rates of electrochemical energy storage technologies utilizing conventional intercalation-type materials

Thank you!

SILA NANOTECHNOLOGIES NASA ARPA-E ARO AFOSR

- GT patents have been licensed to Sila Nanotechnologies, Inc.,
- G. Yushin & Georgia Tech are stock holders in Sila Nanotechnologies, Inc.