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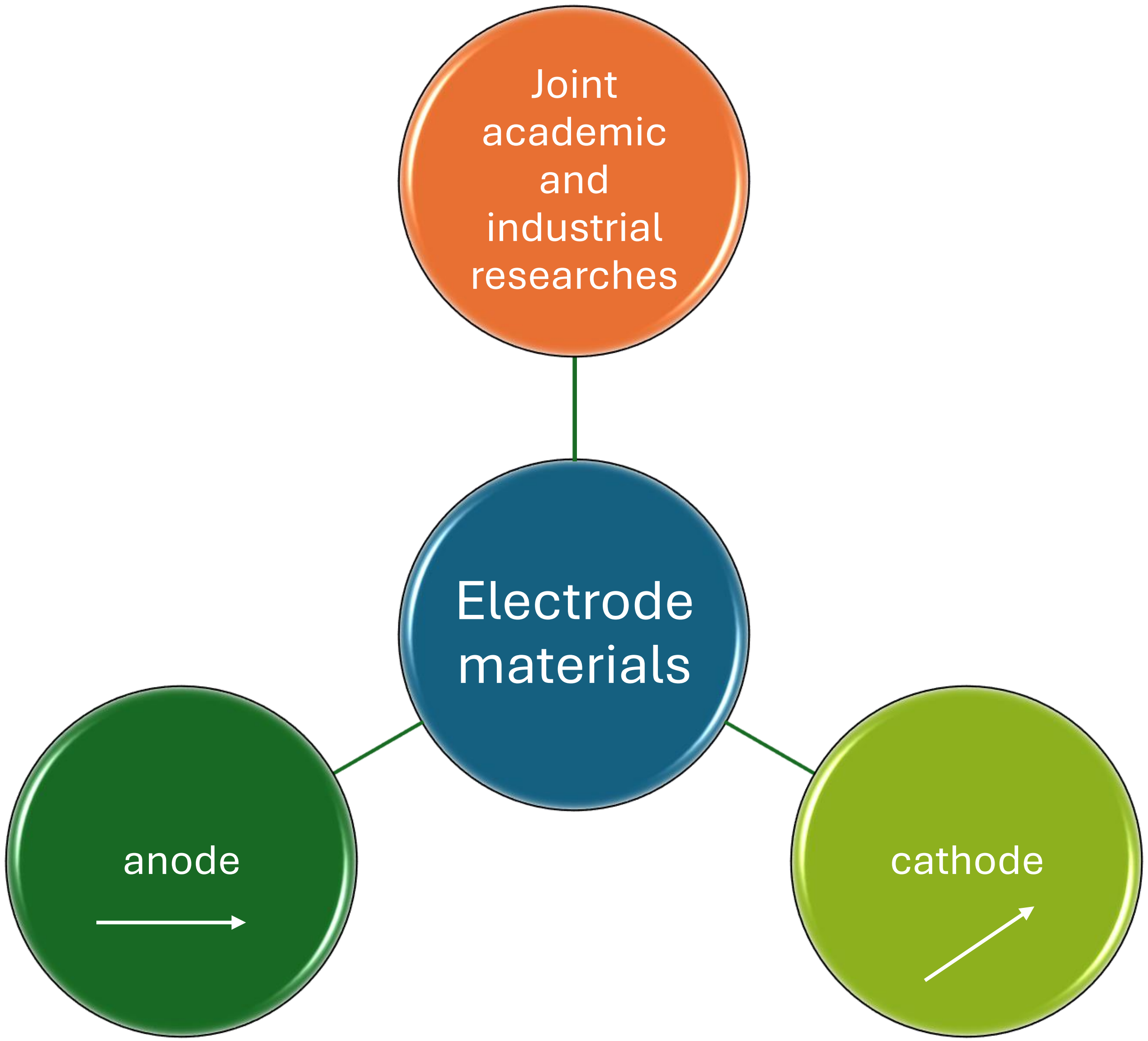
Advancements and Challenges of Silicon Anodes in Lithium-Ion Batteries

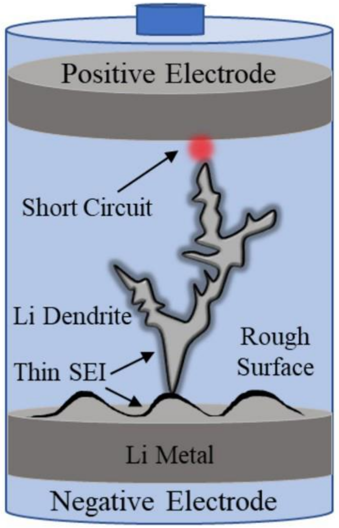
28th March 2025.


Joint academic and industrial researches
Electrode materials
anode
cathode

Nature offers us **two possibilities** for anode material:

deposit lithium as metal

replacing graphite with silicon



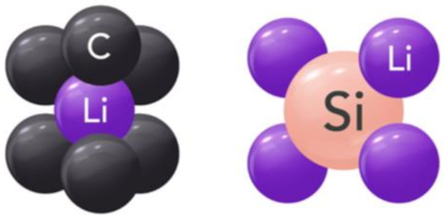
-natural tendency to deposit in dendrites
-short circuit—and possibly a fire

-1/1000000 cell need **fail** to force a recall

T. Foroozan, S. Sharifi-Asl, R. Shahbazian-Yassar, Mechanistic understanding of Li dendrites growth by in- situ/operando imaging techniques, J. Power Sources. 461 (2020) 228135. https://doi.org/10.1016/j.jpowsour.2020.228135.

1 Si atom – 4.4 Li C_s=**4200** mAh/g

6 C atoms – 1 Li C_s=**372** mAh/g



-10-fold higher "specific capacity"
-an equivalent capacity anode will be thinner
-lower electrical resistance
-fast charge and discharge

Recharge time ↓
Si cell widely regarded as a technology with R_t<10 min

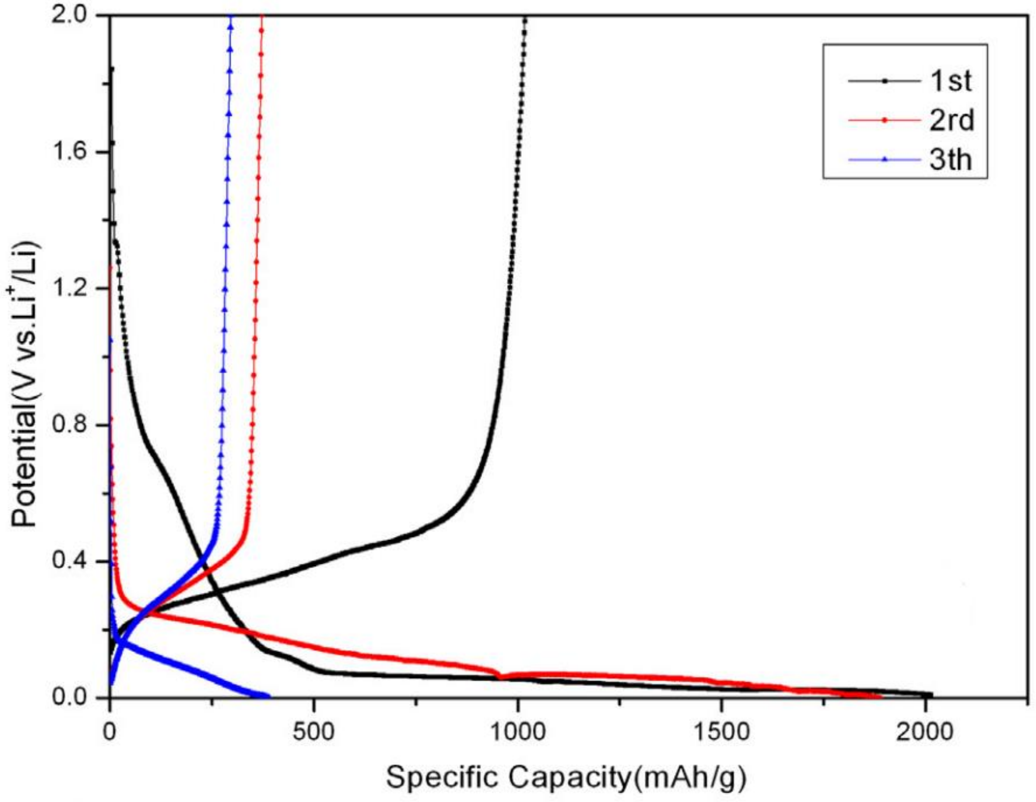
Cycle life?

A graphite anode cell over **800** full charges.

Operation mechanism

Conventional silicon anodes

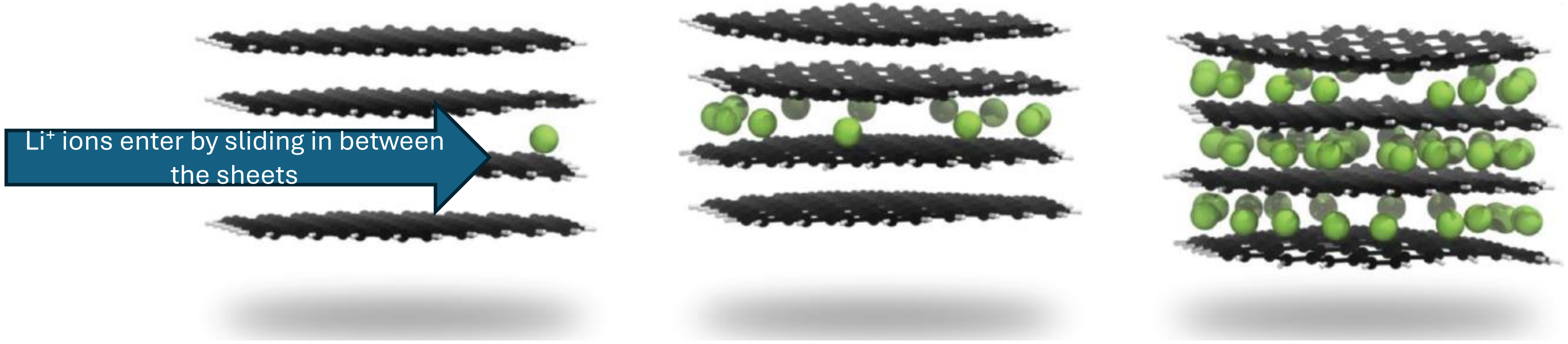
50-200 cycles.



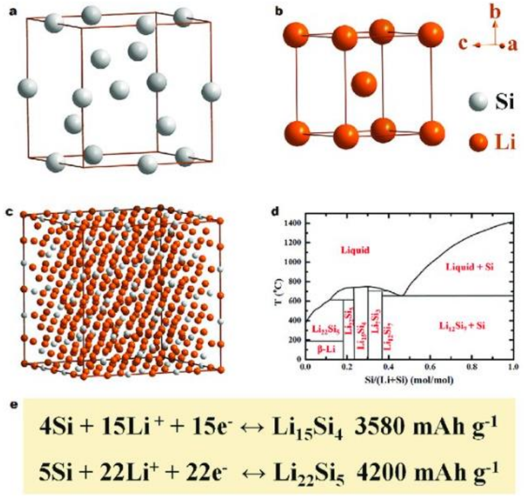
Initial capacity of nano silicon anode are **2013.8 mAh/g** and **1017.0 mAh/g**, respectively, the first columbic efficiency is only **50.5%** and the **specific capacity decays rapidly** in the following two cycles.

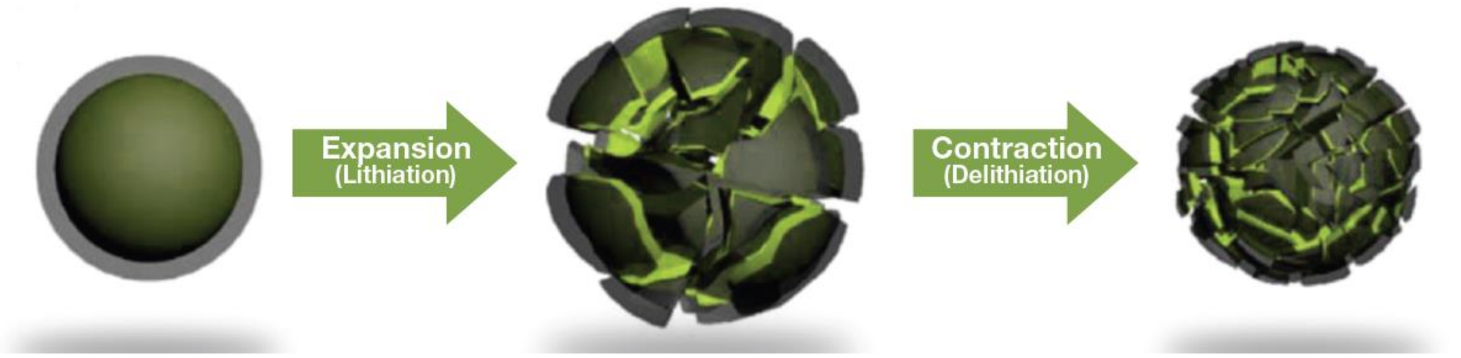
L. Gan et al. / Electrochimica Acta 104 (2013) 117–123

-Graphite's excellent reversibility
-**"intercalation"** material
-**expands by about 10%** when it's **fully lithiated** and then decreases back to its original size when delithiated.



-Silicon is a **"conversion"** material.



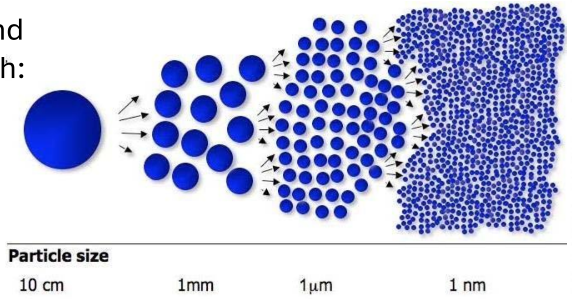


expands by 300% → formation of cracks → loose of electrical contact → loss of active silicon → rapidly capacity fading

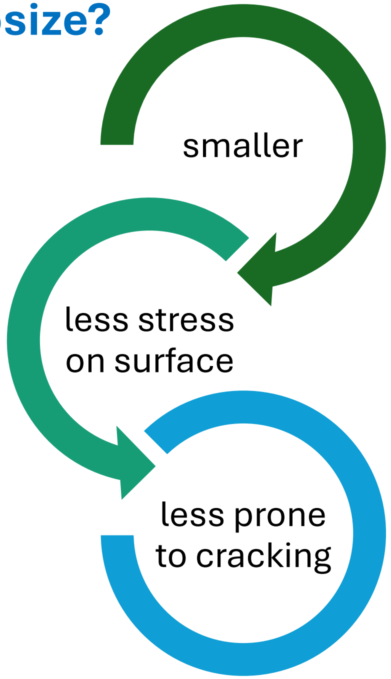
This **cycle life limitation** in turn limits the **amount of silicon** that can be added to an EV battery cell.

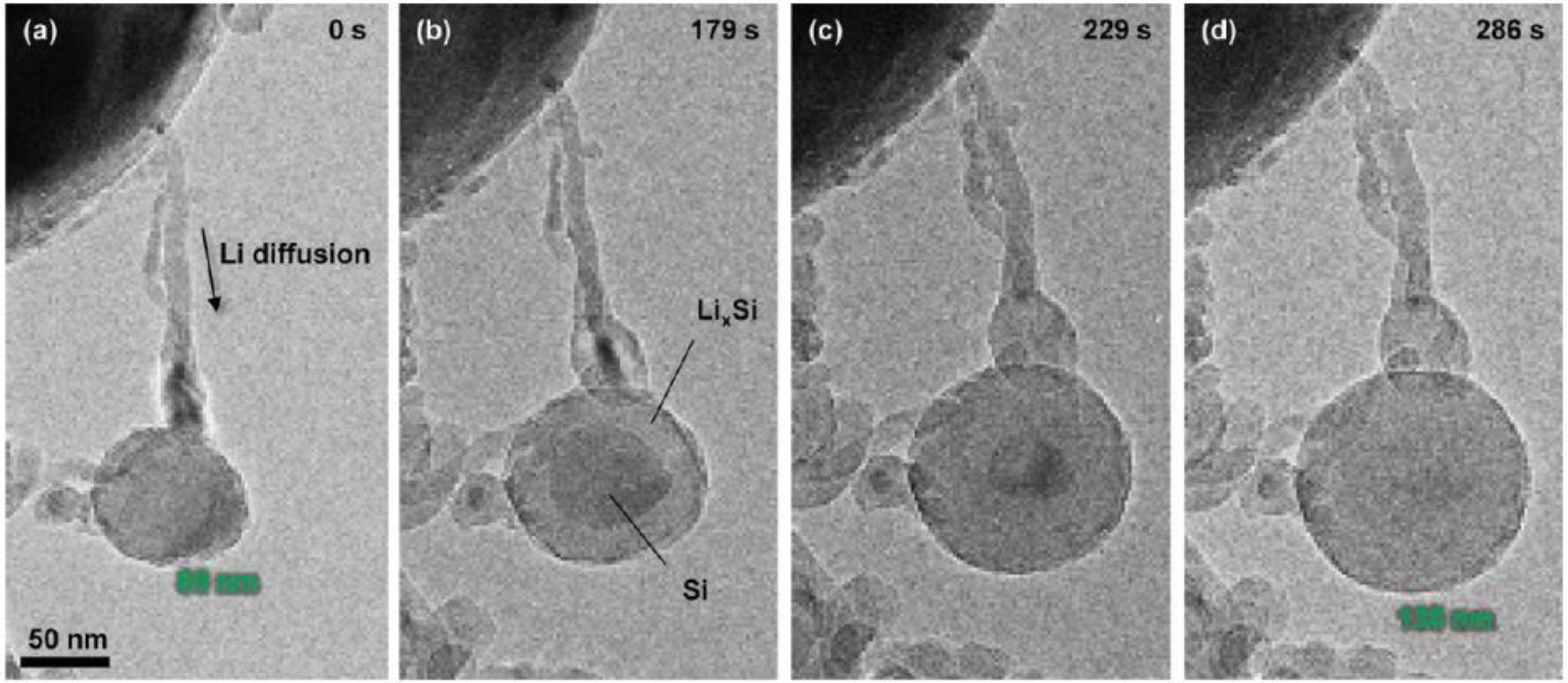
Challenge: **to prevent the expansion and contraction of silicon** from undermining battery life.

The most **popular** and **successful** approach:



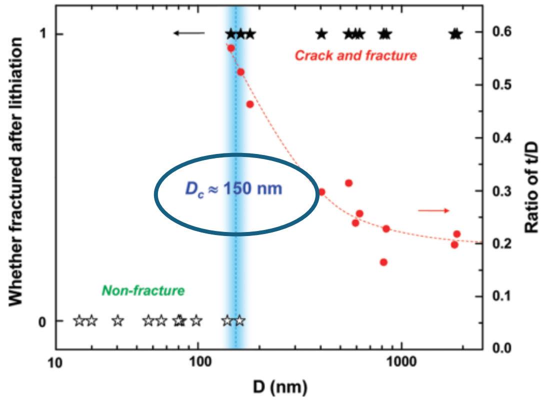
Nanosize?





-**80-nm SiNP** uniformly expanded to **130 nm** after lithiation

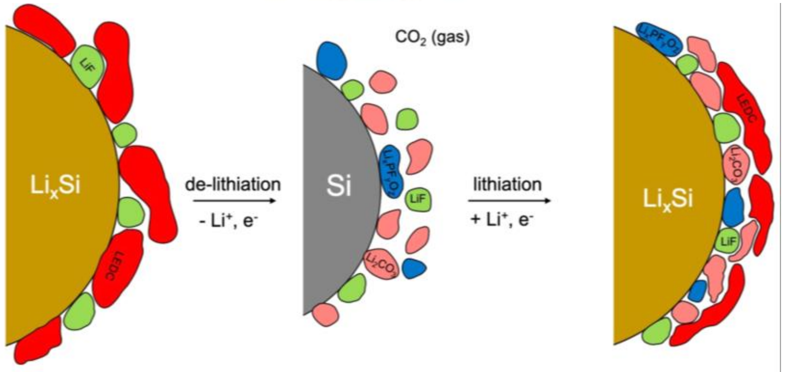
-despite the volumetric expansion of around **300%.**

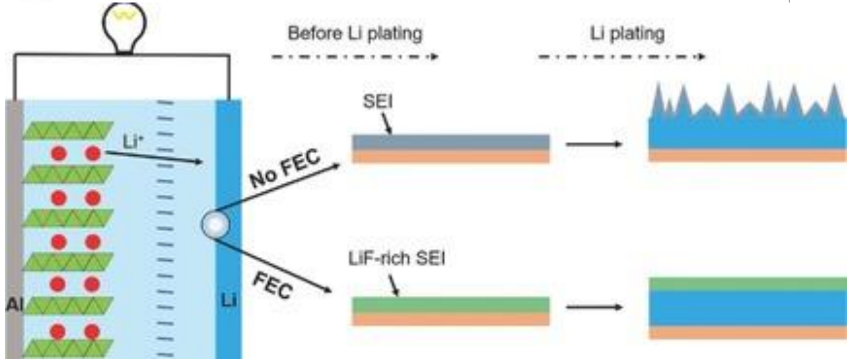


The **critical particle size** below which structural failure does not occur.

Liu, X. H., Zhong, L., Huang, S., Mao, S. X., Zhu, T., & Huang, J. Y. (2012). Size-Dependent Fracture of Silicon Nanoparticles During Lithiation. ACS Nano, 6(2), 1522–1531. doi:10.1021/nn204476h

Approach	Challenges	Improvements
Silicon-Oxide (SiOx) Anodes	- Low conductivity - Initial capacity loss due to lithium consumption	- **Pre-lithiation** to compensate for lithium loss - **Doping with metal oxides** to enhance conductivity - **Nano-engineering** to reduce stress from volume expansion
Silicon-Carbon (Si-C) Composite	-High volume expansion (~300%) - Pure carbon has lower capacity	- **Graphene/carbon nanotube integration** for better conductivity - **Porous carbon frameworks** to accommodate expansion - **Advanced polymer binders** (e.g., PAA, alginate) for better flexibility
Coated Silicon Nanoparticles	-Minimize silicon exposure to electrolyte -inhibit SEI formation	- **Conductive coatings** - **Core-shell structures** (SiO_2, Al_2O_3) to stabilize SEI formation - **Hollow/yolk-shell designs** to allow silicon expansion without breaking
Including Additives in the Electrolyte	-Formation of stable SEI layer - Electrolyte decomposition reduces efficiency	- **Fluoroethylene Carbonate (FEC)** for stable SEI formation - **Lithium Nitrate ($LiNO_3$)** to enhance SEI stability - **Self-healing polymers** to dynamically repair SEI





*Holland, Julian, et al. "Ab initio study of lithium intercalation into a graphite nanoparticle." Materials Advances 3.23 (2022): 8469-8484.
*Zhou, Xiaozhong, et al. "Research progress of silicon suboxide-based anodes for lithium-ion batteries." Frontiers in Materials 7 (2021): 628233
*X.Q. Zhang, X.B. Cheng, X. Chen, C. Yan, Q. Zhang, Fluoroethylene Carbonate Additives to Render Uniform Li Deposits in Lithium Metal Batteries, Adv. Funct. Mater. 27 (2017)
*J. Wang, C. Gao, Z. Yang, M. Zhang, Z. Li, H. Zhao, Carbon-coated mesoporous silicon shell-encapsulated silicon nano-grains for high performance lithium-ion batteries anode, Carbon Vol. 192 (2022) 277–284.

BENCHMARK

COMPANY	CHARACTERISTICS
SilaNano	C/Si composite Panansonic Energy Mercedes Benz- C/Si=50:50 wt% 1600-1900 mAh/g
Group14	C/Si composite Porshe 1800-1850 mAh/g
IonBlox	Silicon oxide anode
Amprius	Si nanowires-expensive Sold under brand SiCore >500 cycles
Enovix	C/Si composite-high pressure-dense packing
Enevate	Flexible glassy C/Si layer Binder free

COMMERCIAL CONSIDERATIONS OF SILICON ANODES

- Synthetic graphite today has a market price of $7.00-$7.50/kg
- Cost of **raw metallurgical silicon** is less than $5/kg at scale.
- A commonly discussed short-term market price range for **silicon/carbon anode** material is between **$50-75/kg**.

synthesized from **expensive silane gas** and are combined with relatively expensive **carbon scaffolding and specialized coatings**

- SCIENTIFIC APPROACH

EXAMPLE OF SCIENTIFIC APPROACH

Journal of Power Sources 588 (2023) 233720

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Cost-competitive manufacture of porous-silicon anodes via the magnesiothermic reduction: A techno-economic analysis

Maximilian Yan [a,b], Sarah Martell [b], Mita Dasog [b], Solomon Brown [a], Siddharth V. Patwardhan [a,*]

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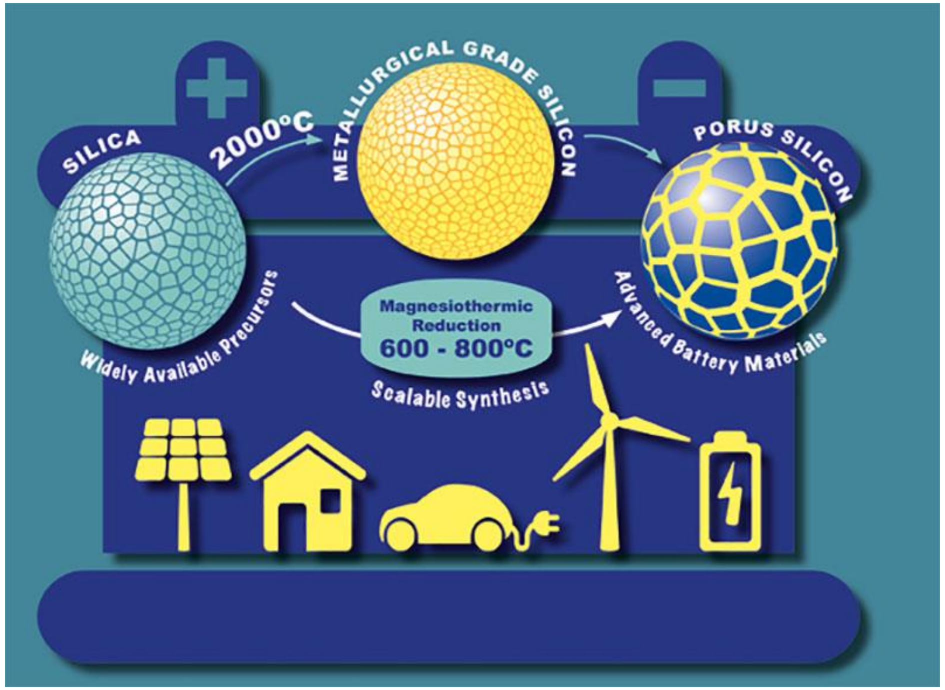
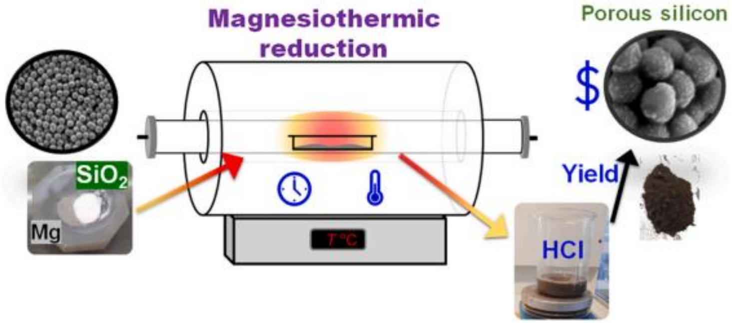
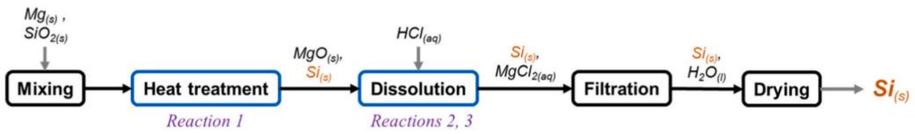
[b] Department of Chemistry, Dalhousie University, 6274 Coburg Road, Halifax, NS, B3H 4R2, Canada



J. Mater. Chem. A, 2018, 6, 18344

-low-cost method for silicon anode production
-abundant silica sources
-operating at **lower temperatures (~600-700°C)** compared to traditional methods



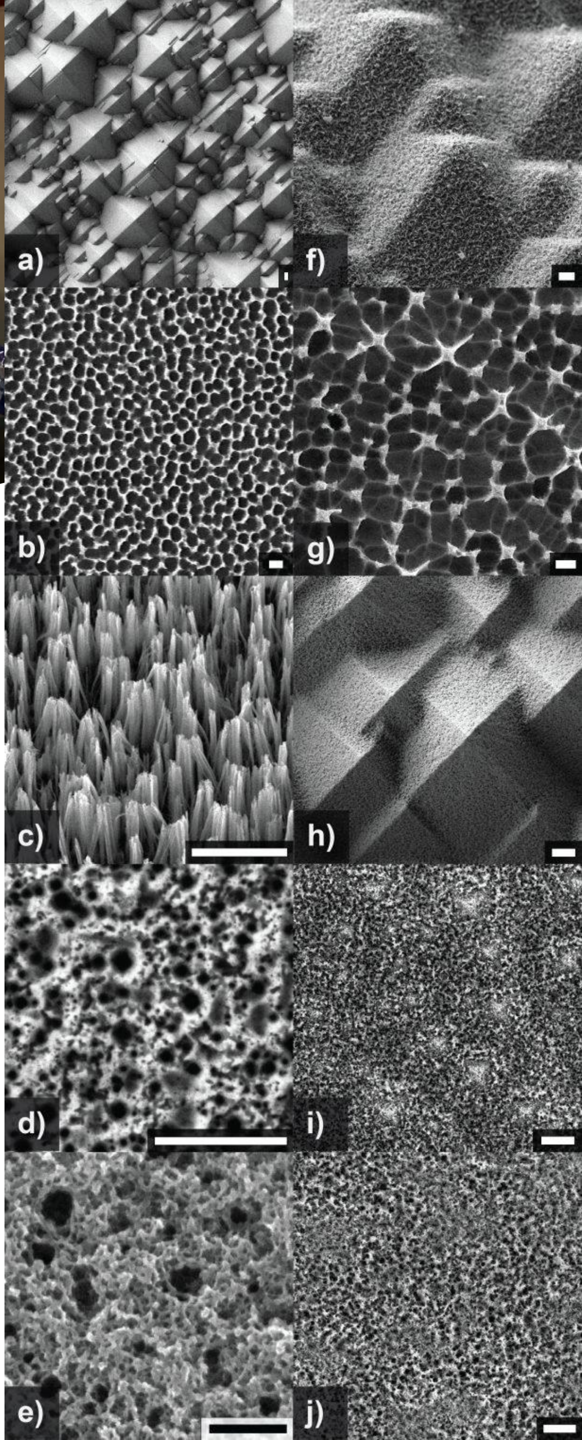


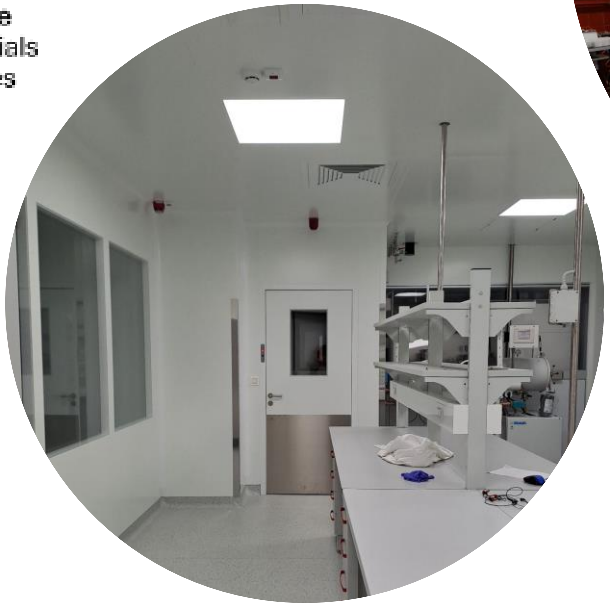
reduces energy costs → reduces raw material expenses → scalable and profitable approach

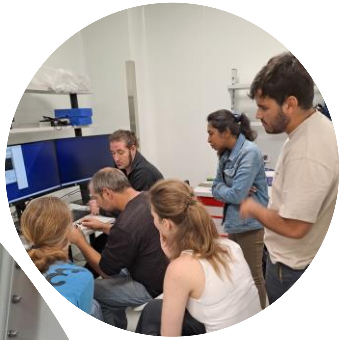
RB

CEMS

Center of Excellence for Advanced Materials and Sensing Devices







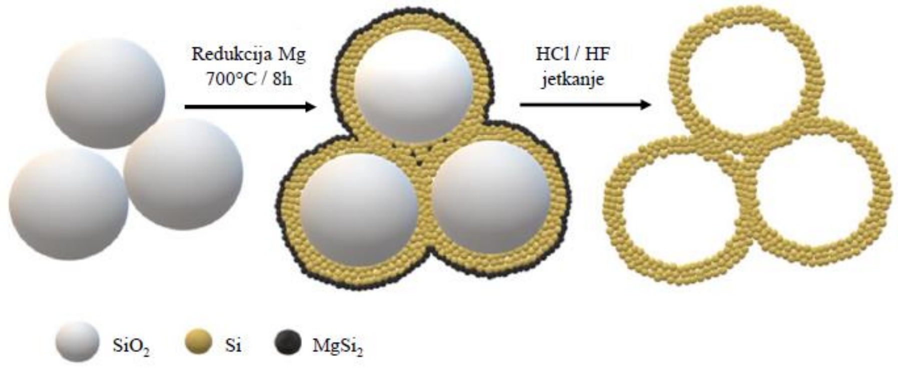
Laboratory for molecular physics and synthesis of new materials

head: dr. sc. Mile Ivanda

Research focus:

synthesis of silicon-based materials for various applications

Magnesiothermic reduction → Nanoporous silicon → Decorated with Ag nanoparticles



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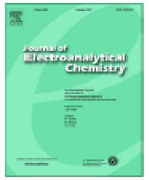

Ag decorated porous Si structure as potential high-capacity anode material for Li-ion cells

Matea Raić [a,b], Lara Mikac [a,b], Marijan Gotić [a,b], Marko Škrabić [c], Nikola Baran [a,b], Mile Ivanda [a,b,*]

[a] Laboratory for Molecular Physics and Synthesis of New Materials, Ruđer Bošković Institute, Bijenička c. 54, 10000 Zagreb, Croatia
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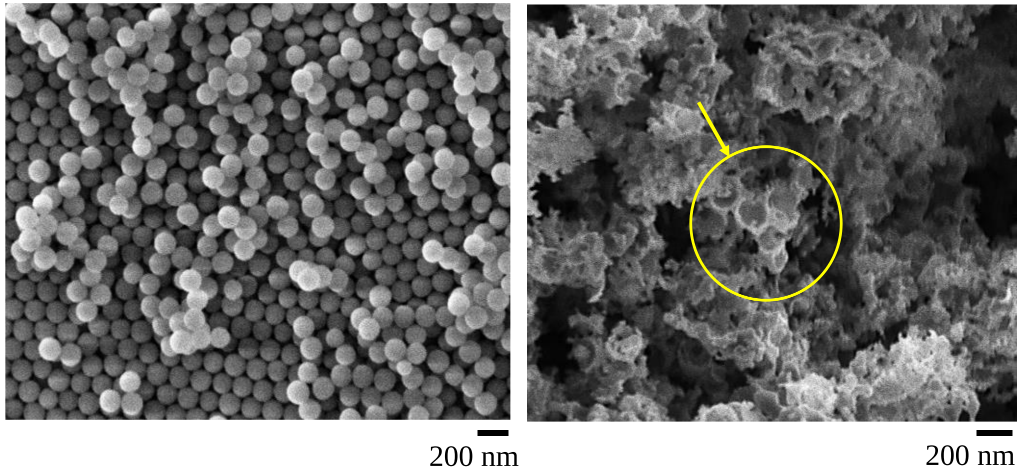
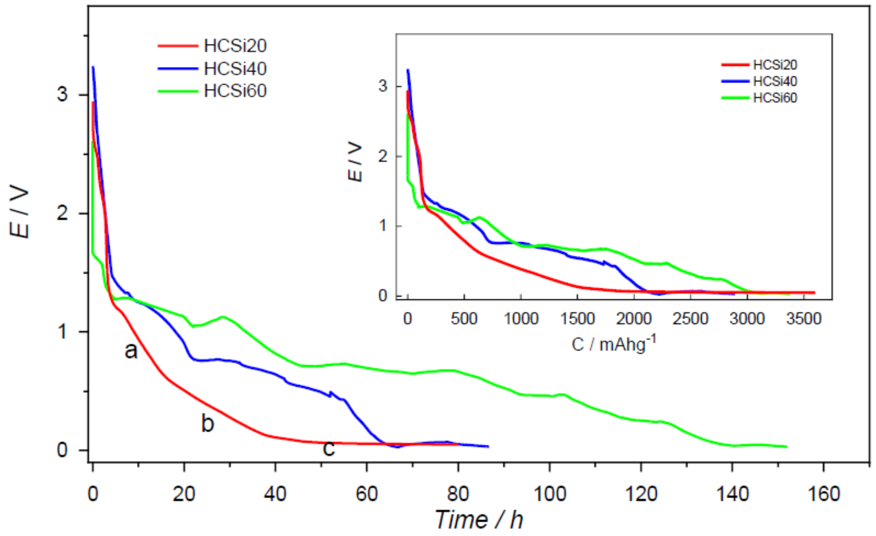


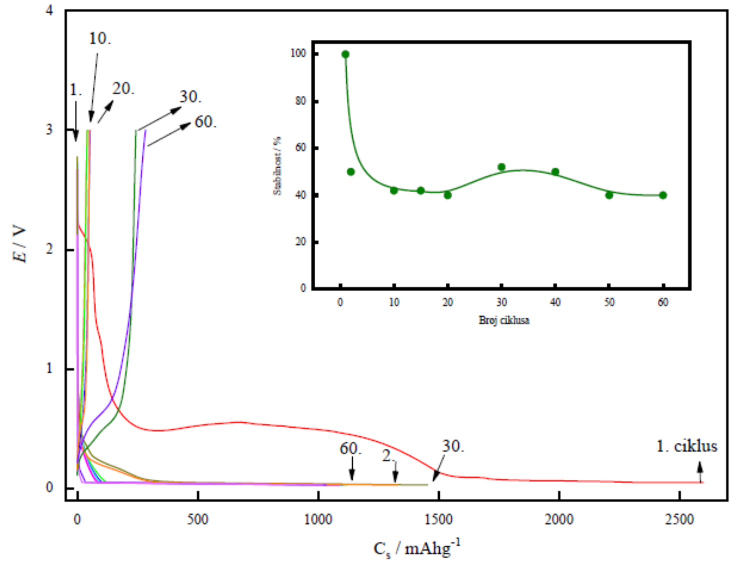
High Surface Area
•more lithium-ion storage and faster charge/discharge rates

Accommodates Volume Expansion
•prevents electrode degradation

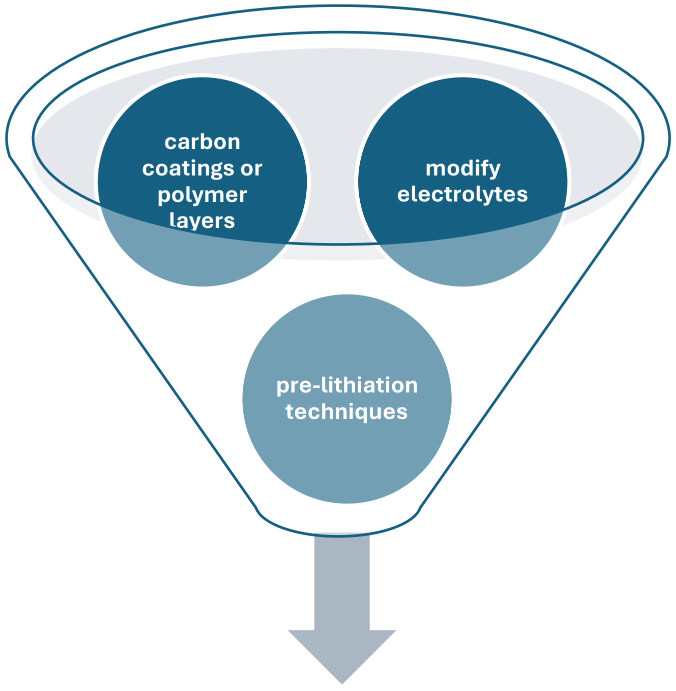


-High capacity in 1st cycle (≈**3500 mAh/g**)
-Capacity drops to **20% in 50 cyles**
-Additive increases up to **80** cycles

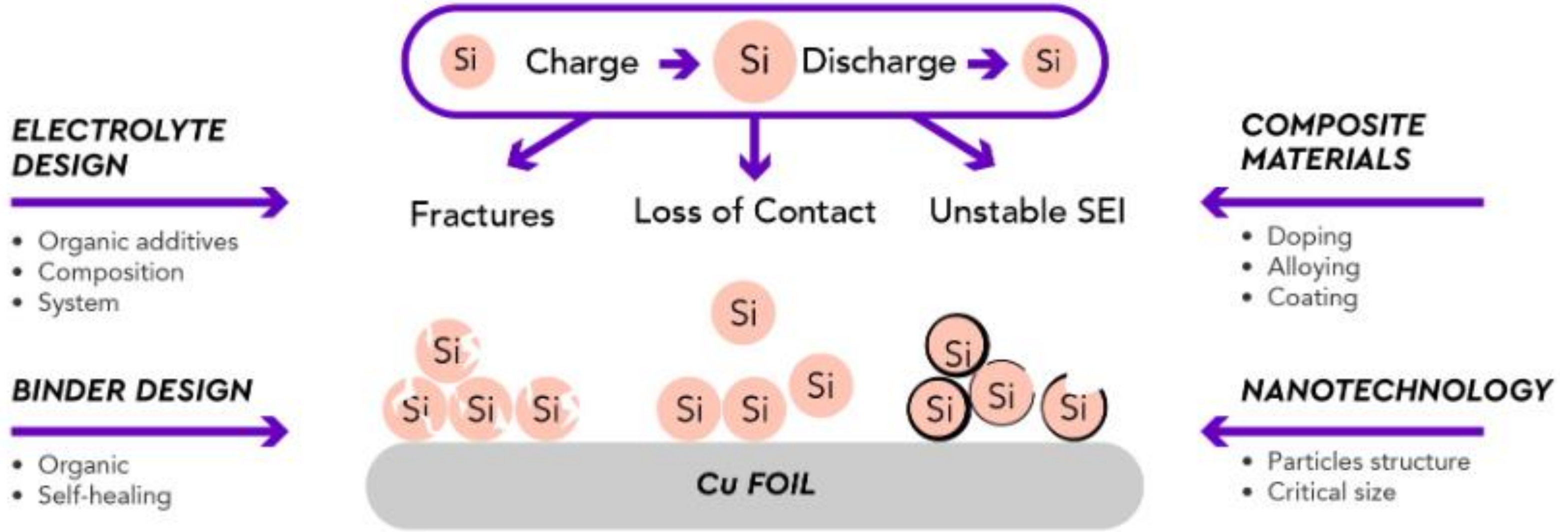
+FEC



Future plans:



Improve cyclability



Future perspectives

Innovation in the **chemistry of materials** to improve Li-ion battery components.

Thank you for attention!