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ARRADIANCE[®]

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ALD – Enabling the Frontiers of Energy Research



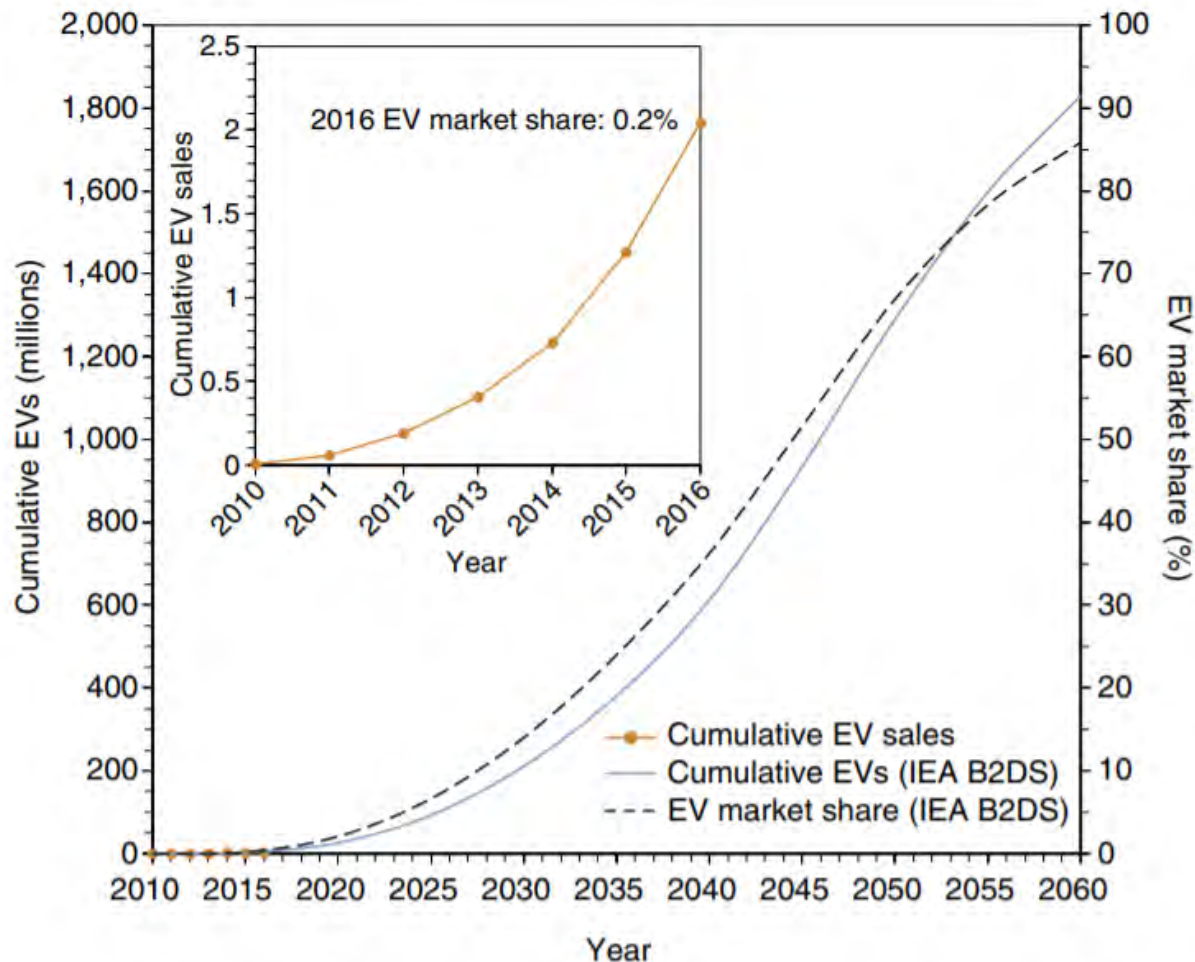
Europäische Forschungsgesellschaft Dünne Schichten e. V.
European Society of Thin Films



- ◀ ALD - Energy Storage
- ◀ ALD - Catalyst Research
- ◀ Summary

Energy Storage – Growing Electric Vehicle Market

Total automotive market

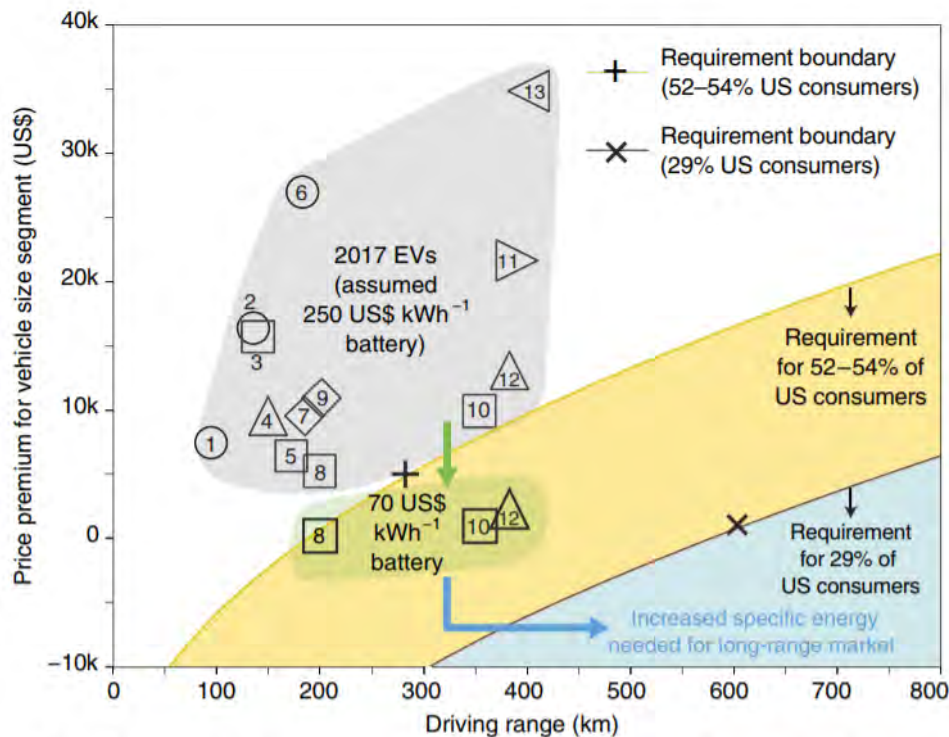


Public demand for electric vehicles is expected to grow.

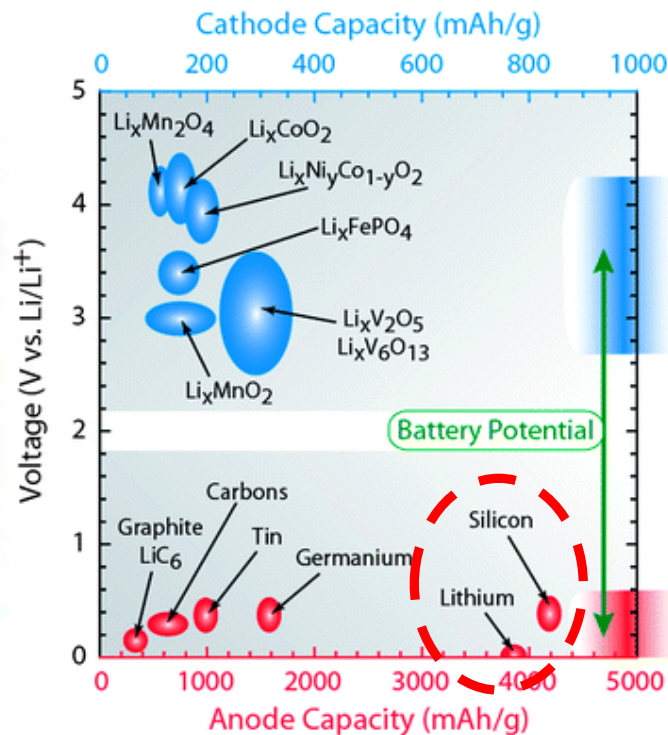
Cano, Zachary P., et al. "Batteries and fuel cells for emerging electric vehicle markets." *Nature Energy* 3.4 (2018): 279.

The Future of Energy Storage Requires New Materials

To meet future demand and extend EV range, adoption of new materials is required.

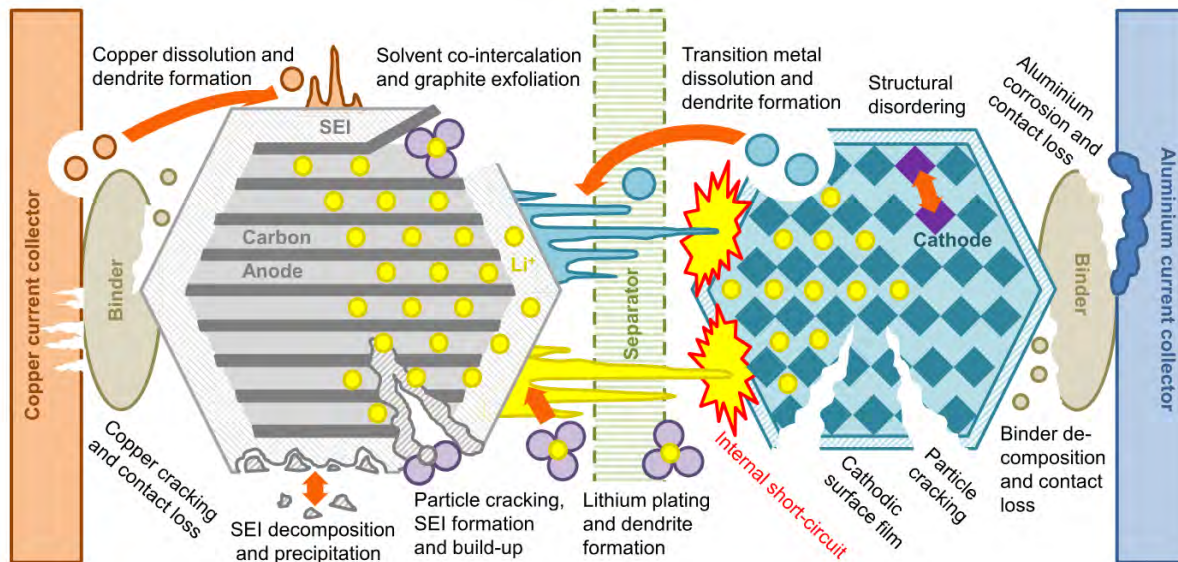


- | | | |
|----------------------------|------------------------|---------------------------|
| ○ Subcompact car | 1. Mitsubishi I-MiEV | 8. Hyundai Ioniq electric |
| ◇ Compact car | 2. Fiat 500e | 9. Volkswagen e-Golf |
| □ Mid-size car | 3. Mercedes-Benz B250e | 10. Tesla Model 3 |
| △ Full-size car | 4. Kia Soul electric | 11. Tesla Model X 75D |
| △ Subcompact SUV/crossover | 5. Nissan Leaf | 12. Chevrolet Bolt |
| △ Full-size SUV/crossover | 6. BMW i3 | 13. Tesla model S 75 |
| | 7. Ford Focus electric | |



A number of challenges plague the commercialization of these materials – Primarily at the interface between electrodes and electrolyte

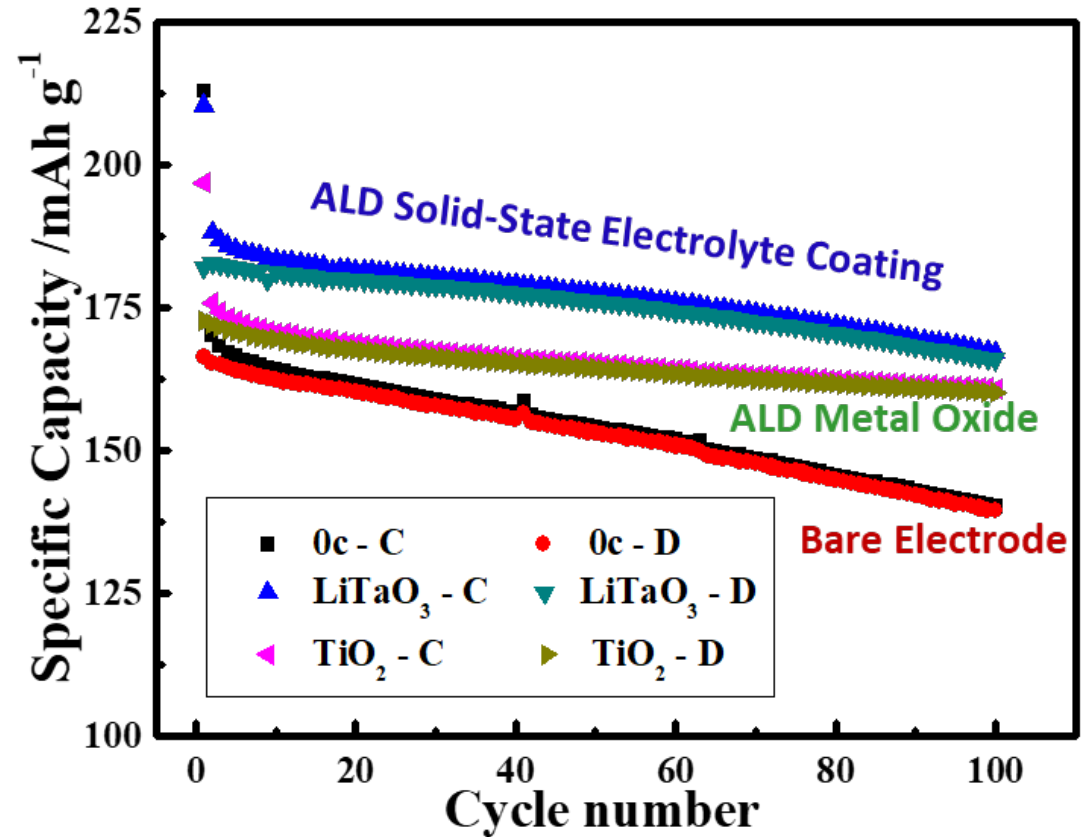
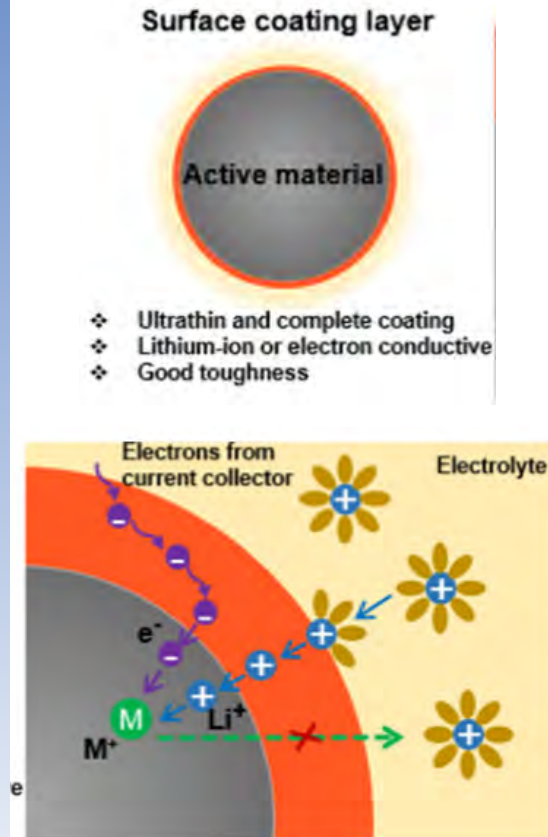
Challenges at the Interface



ALD is one coating strategy that can be used to address challenges at both the anode and cathode of lithium ion batteries.

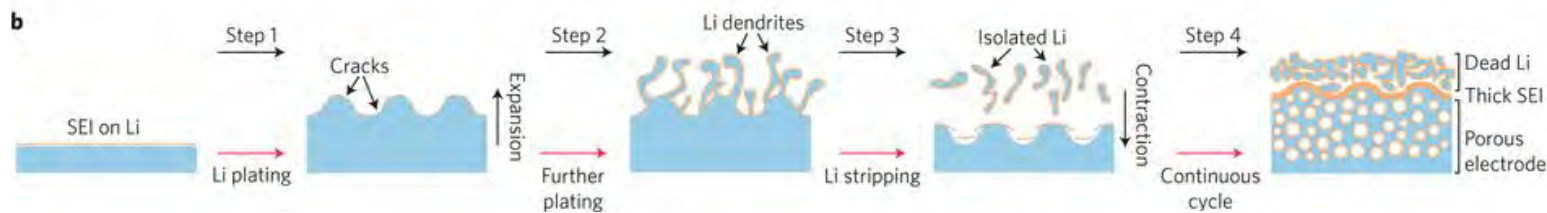
Required Coating properties	Anode	Cathode
Uniform Coverage	✓	✓
Lithium-ion Conductive	✓	
Electronically Conductive		✓
Chemical stability	✓	✓
Prevent Metal Dissolution	✓	✓
Provide Mechanical Stability	✓	✓

Example of ALD Enhancing Cathode Performance

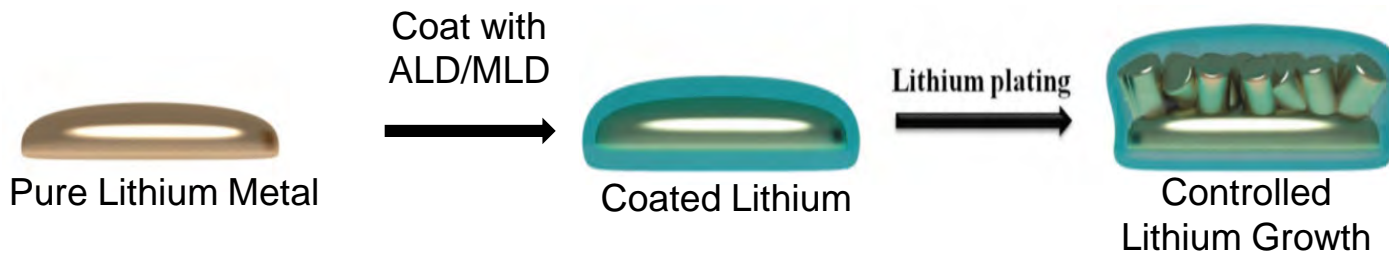
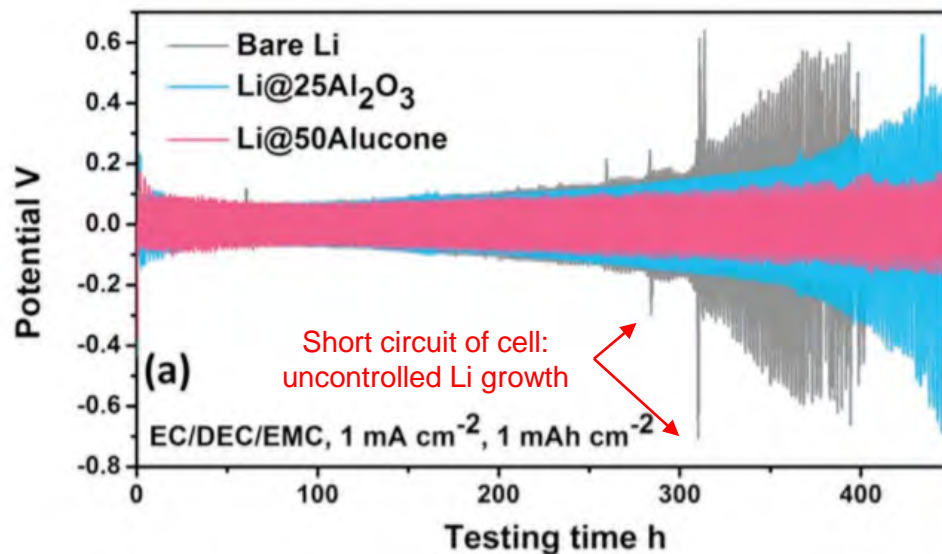


- ⚡ ALD provides unique surface coverage required to mitigate metal dissolution
- ⚡ ALD nanolaminates used to tune film properties, such as lithium ion diffusion.

Example of ALD/MLD Application to Anode



Recharging battery made using pure lithium metal results in uncontrolled growth of lithium dendrites which degrade cell performance and can cause short circuits

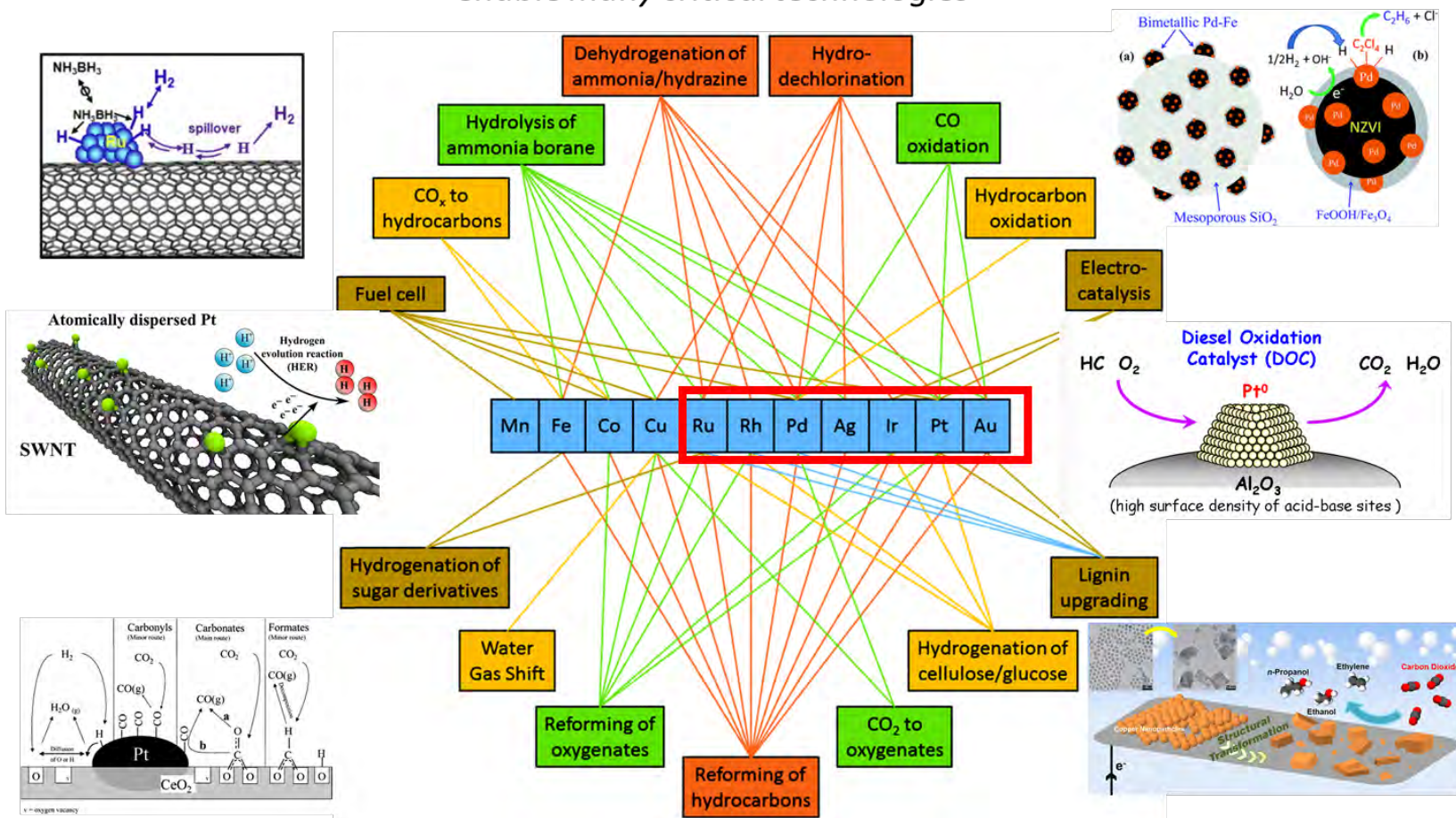




- ◀ In order to meet future consumer demand for electric vehicles, lithium ion batteries need to adopt new materials
- ◀ Several engineering challenges impede the commercialization of these materials – primarily at the interface between the electrode and the electrolyte
- ◀ ALD is a unique coating strategy that can tackle many interface problems
- ◀ At the cathode, ALD can prevent dissolution of metals while enhancing electrical conductivity and lithium conduction
- ◀ At the anode, ALD/MLD can help to stabilize the surface of pure lithium metal

Nobel Metals Empower Catalyst Reactions

Supported noble metal catalyst nanoparticles are among the most important catalyst that enable many critical technologies

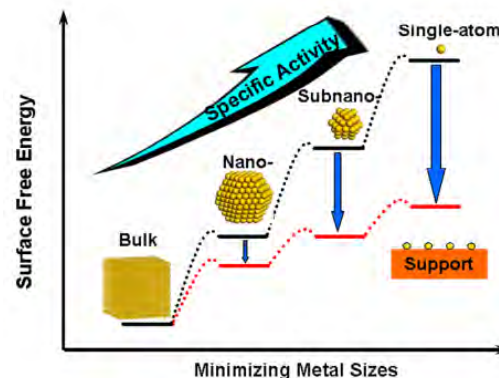
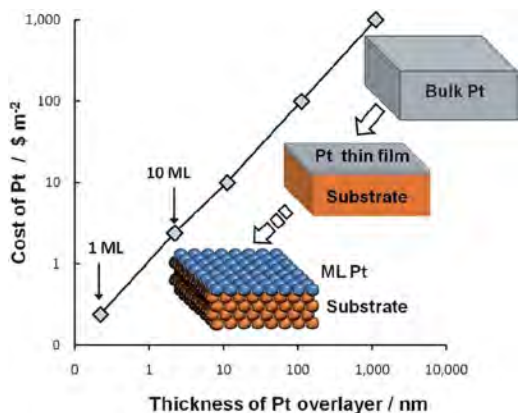


De, S., Zhang, J., Luque, R., & Yan, N. (2016). *Energy & Environmental Science*, 9(11), 3314-3347.
 Tavakkoli, M., Holmberg, N., Kronberg, 2017). *ACS Catalysis*, 7(5), 3121-3130.

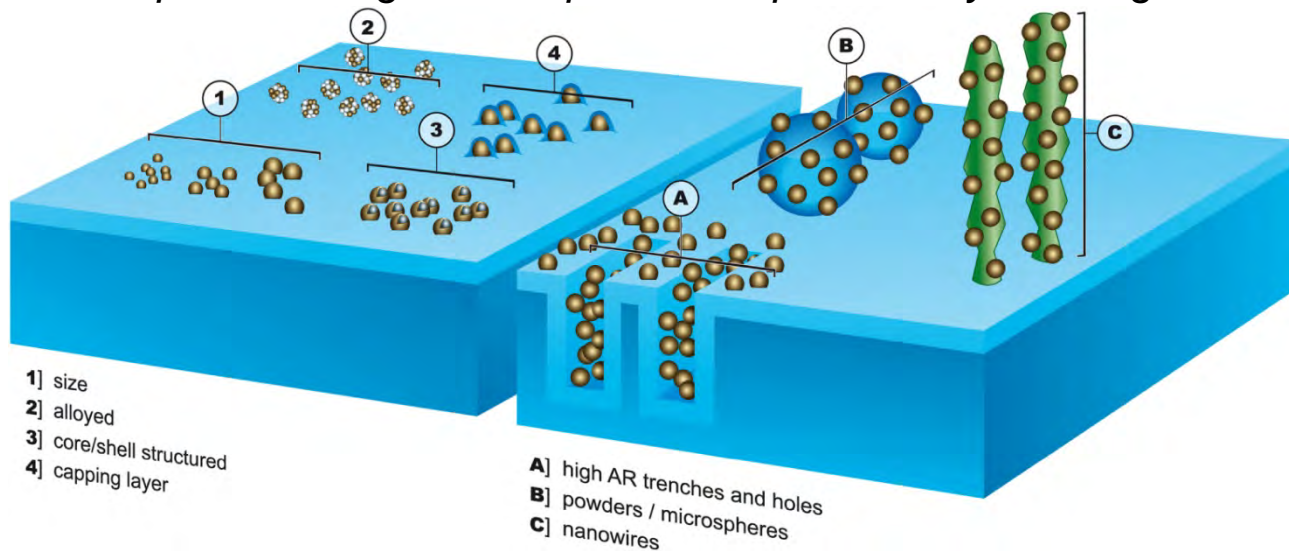
Reducing Size of Catalyst Particles

High price and low natural abundance of noble metals is an issue.

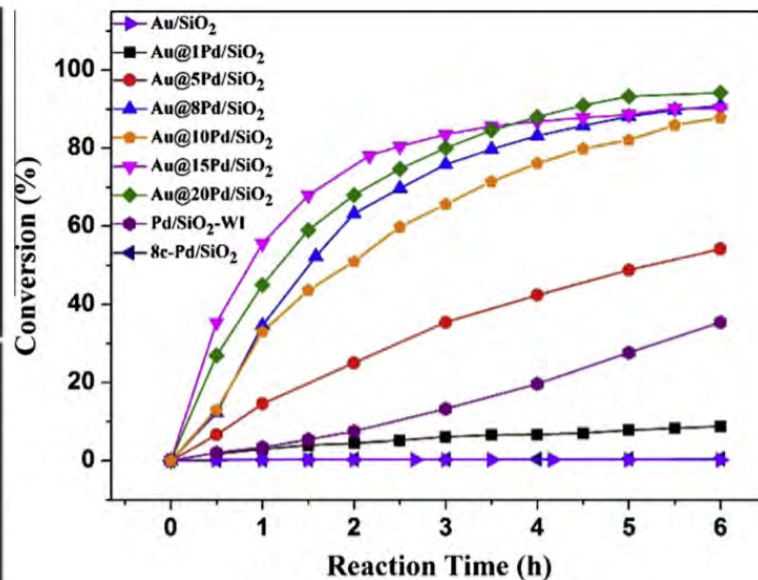
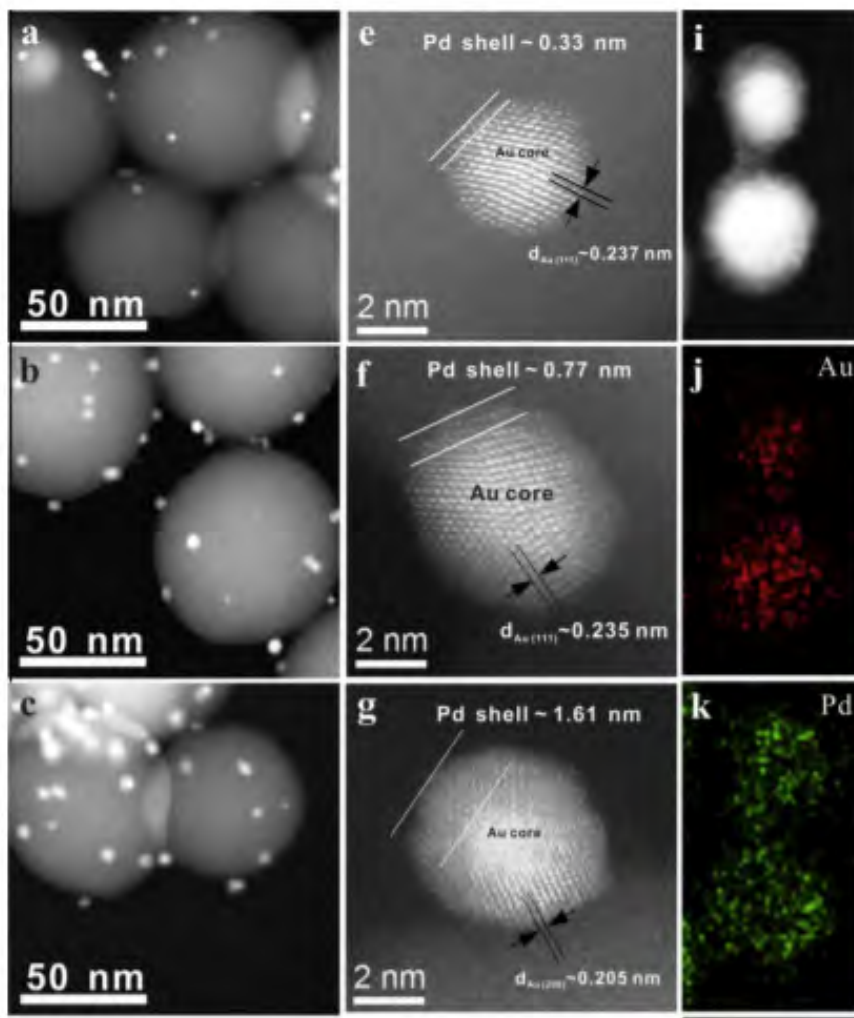
Important aspect that determines catalytic performance is nanocatalyst size



ALD has unique advantages for deposition of particles by allowing control over:



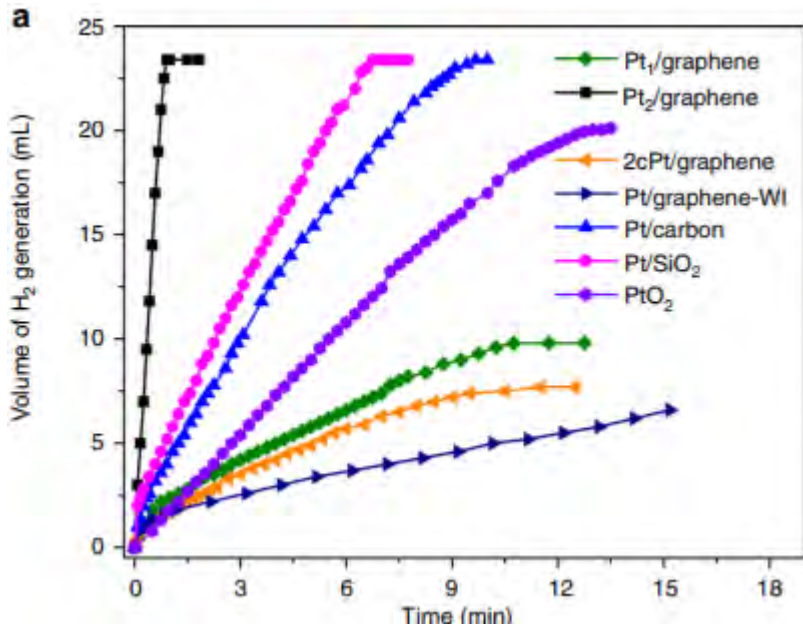
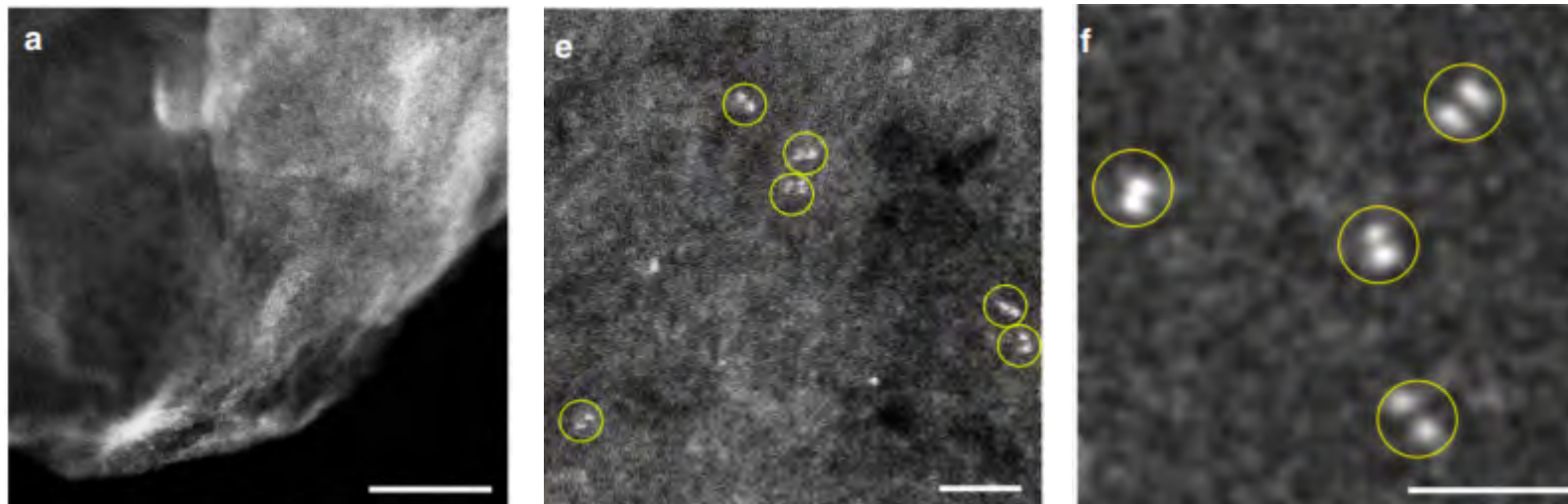
Example of ALD deposited Pd Nanoparticles



ALD used to precisely controls metal concentration, directly influencing catalytic activity

Merge slides 11 and 12 together

Atomic Control Over Particle Size



By controlling both surface chemistry and gas phase chemistry, deposition of single or double atoms of platinum are possible



- ◆ Many critical technologies require the use of noble metals as catalyst.
- ◆ Unfortunately, these metals are very expensive therefore their use must be maximized
- ◆ One way to accomplish this is to shrink the size of the particles, while also using high surface area substrates
- ◆ ALD is an ideal technology in both reducing noble metal particle size while being able to deposit on high surface area materials
- ◆ ALD accurately controls average size of noble metal particles



- ◀ ALD - key enabler for energy research
- ◀ ALD addressed some of the challenges in lithium ion battery devices
- ◀ ALD thin films improve battery technology safety
- ◀ ALD particle coatings increase catalytic performance

