Carbon Nanotubes for Li^+ Batteries

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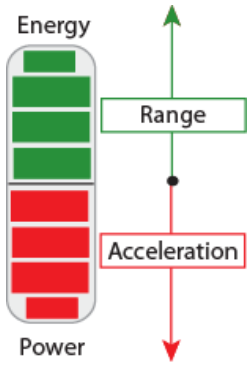
Portable Energy Challenge

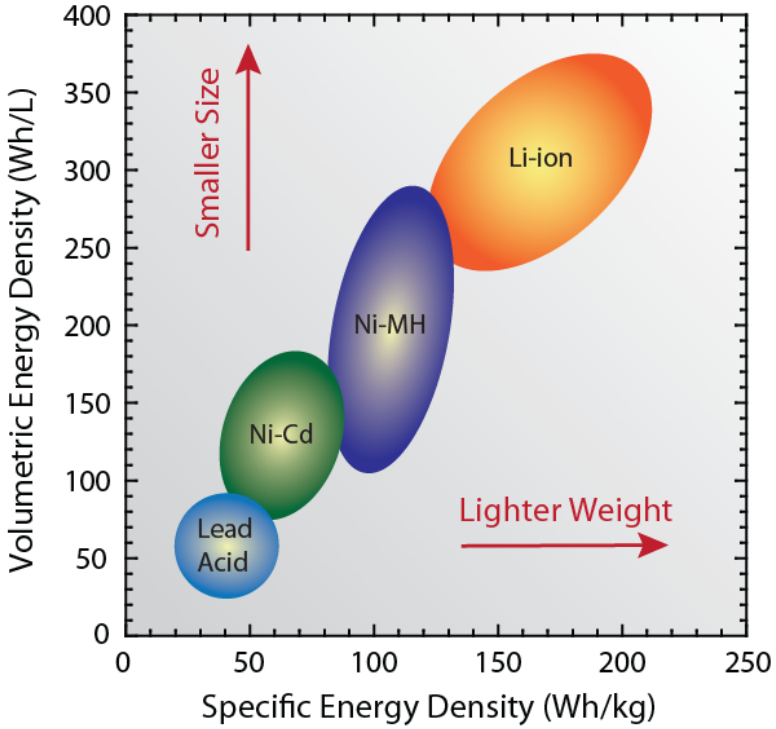
Energy demand generally exceeds supply

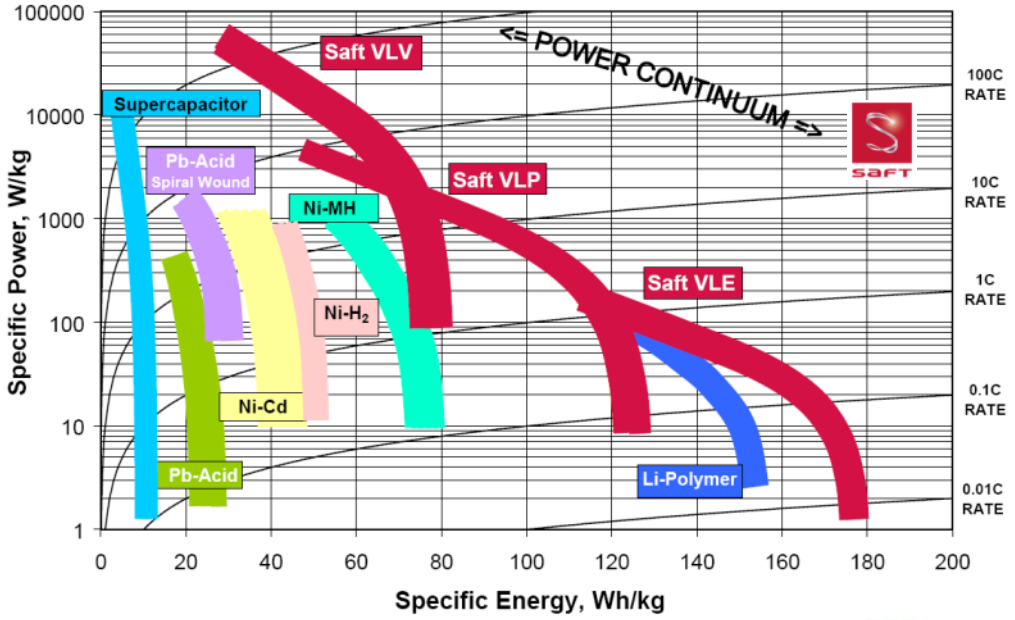
- Increase Energy Density (carry more)
- Fast Recharge (refill often)
- Device Energy Efficiency (use wisely)



HEV: P/E = >15
PHEV: P/E = 3-10
EV: P/E = <3

Source: US DOE, 2008

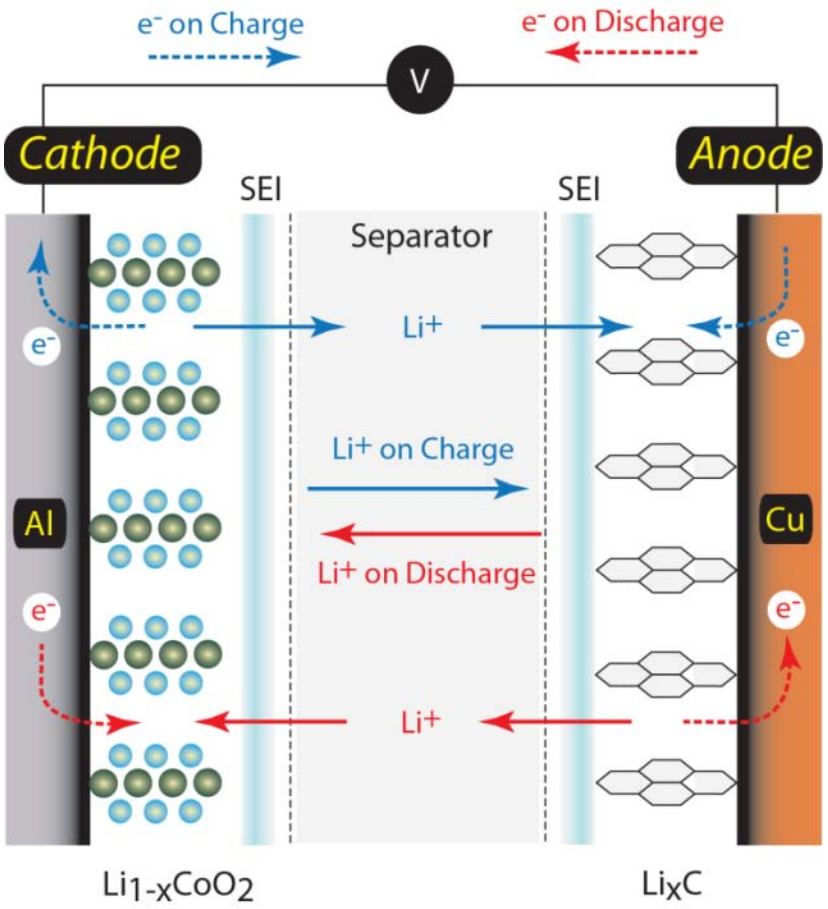


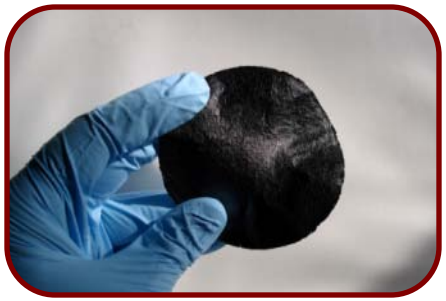


Lithium ion batteries are optimized either for high energy or high power

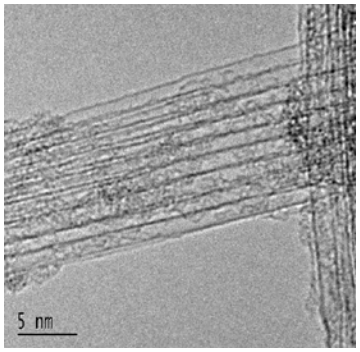
Can nanomaterials address this limitation?

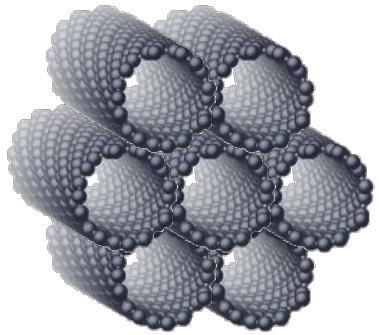
Application of CNTs in Li+ Batteries





Carbon Nanotube Properties





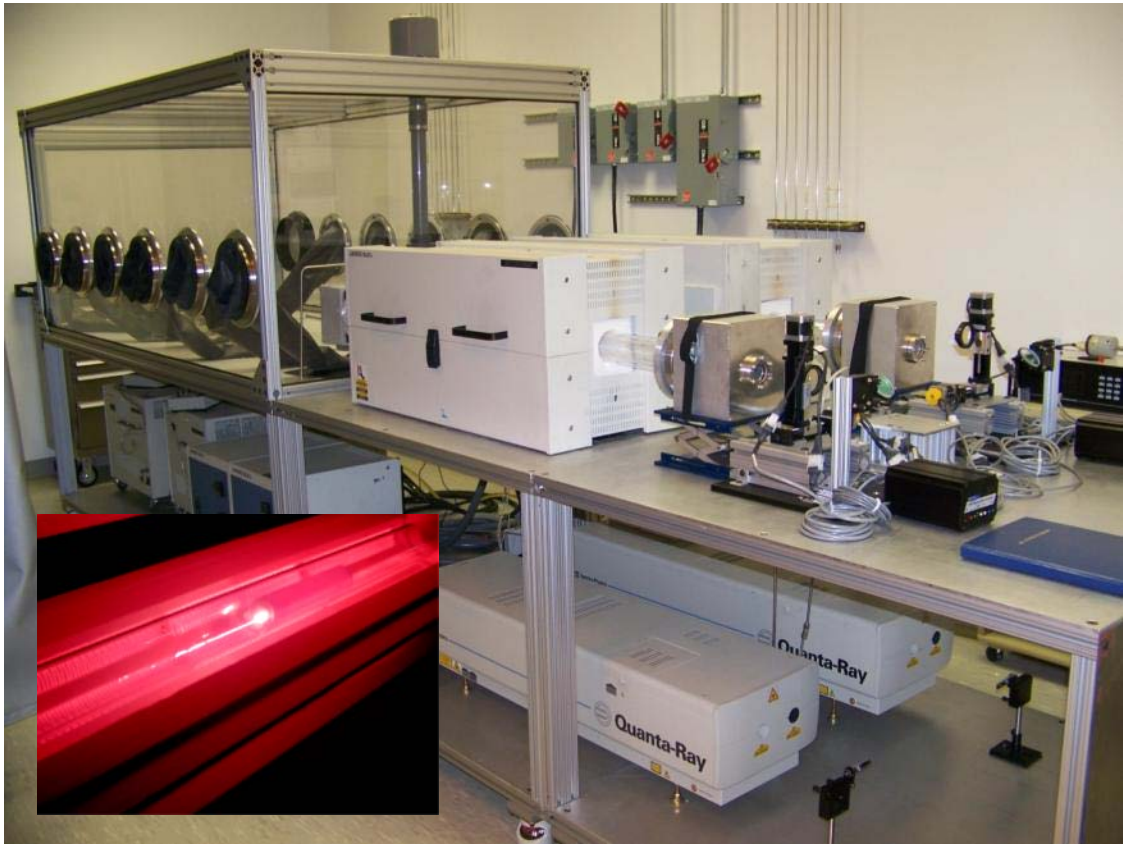
- High electricaly conductivity
- Nanoscale porosity
- Electrochemical and thermal stability

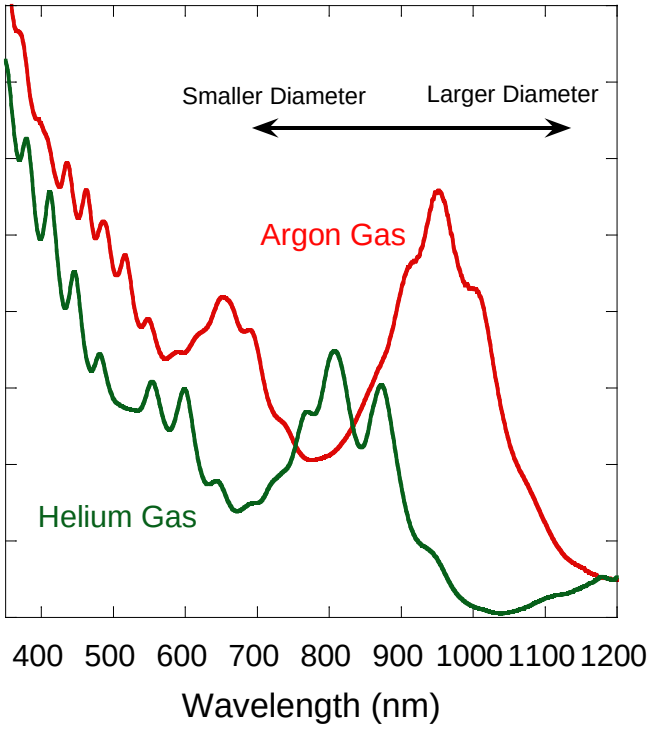
Application of Carbon Nanotubes

CNTs can be used as an additive material due to high aspect ratio and conductivity: percolation network at low wt. loadings

CNTs can be fabricated into free-standing electrodes: current collector, active material support, and anode – lithium ion storage

Laser Vaporization Synthesis of SWCNTs





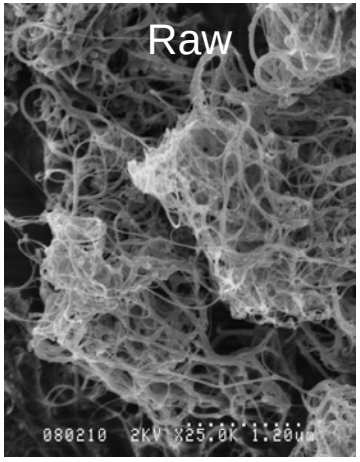
Control of SWCNT Properties
Quality of raw soot for purification

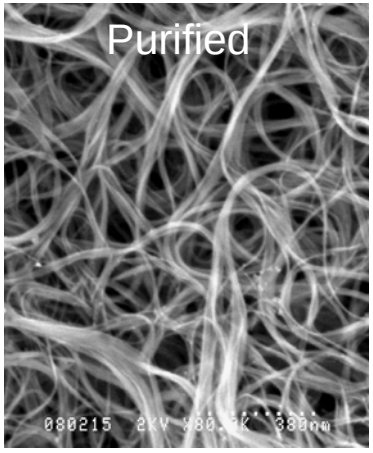
B.J. Landi, et al. *J. Phys. Chem. B* **2004**, *108*, 17089.

B.J. Landi, et al. *J. Phys. Chem. B* **2005**, *109*, 9952.

B.J. Landi, et al. *Chem. Mater.* **2006**, *17*, 6819.

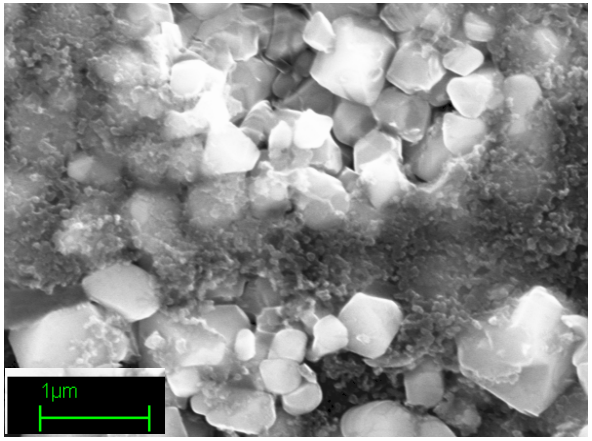
B.J. Landi, et al. *J. Nanosci. & Nanotechnol.*, **2007**, *7*, 883-890.



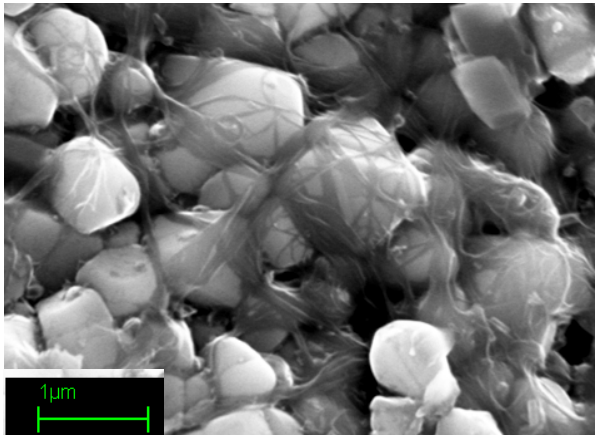


CNT Conductive Additives in Li+ Batteries

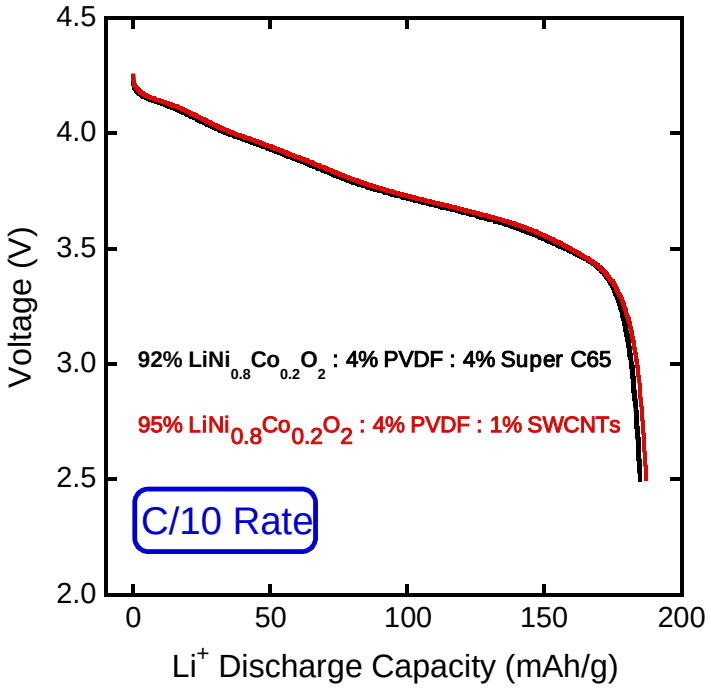
Typical Conductive Carbon Additive



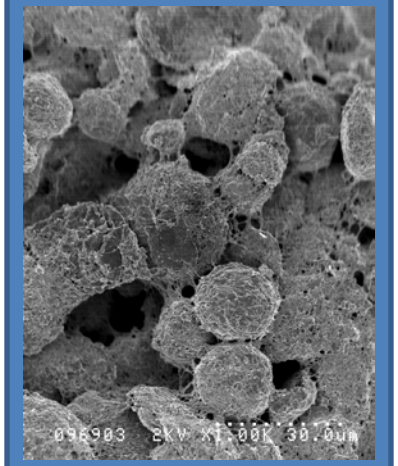
SWCNT Additive Replacement

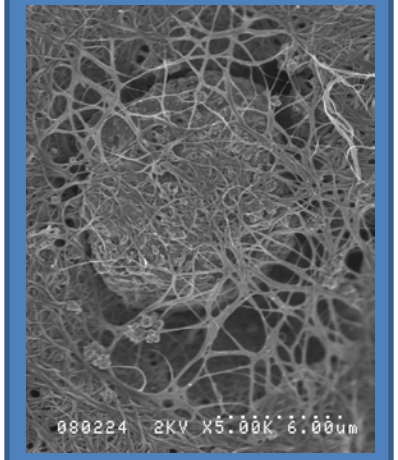


- Can achieve equivalent conductivity to conventional additives with <1% CNTs
- Comparable capacity for $LiNiCoO_2$ cathode and MCMB anode, but more active material is present.
- The SWCNT additive electrode shows a significantly higher retention of capacity at higher discharge rate and can lead to enhanced cyclability

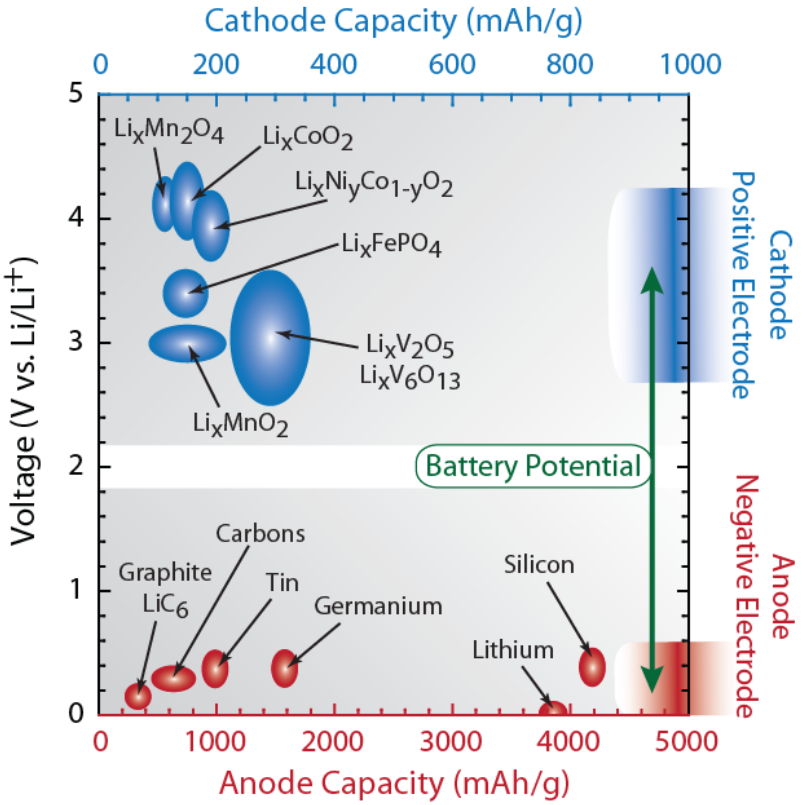


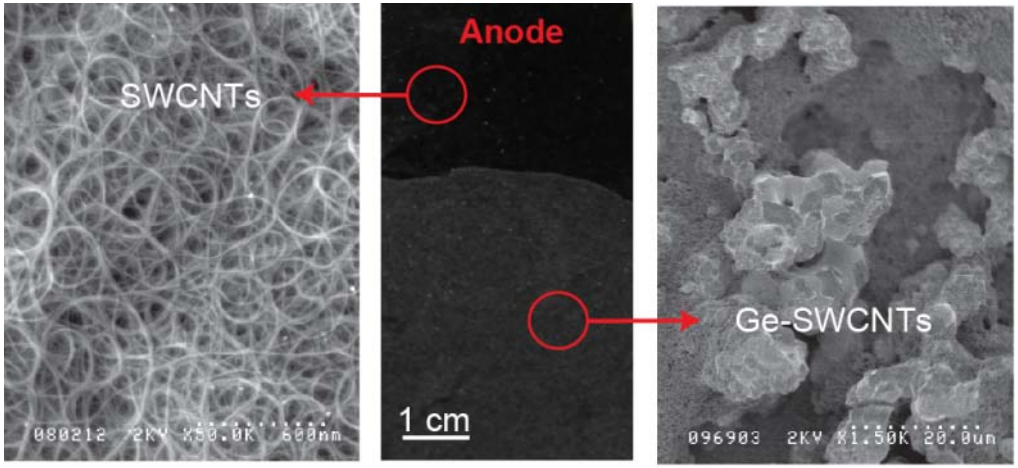
Anodes





RIT Approach to High Energy Density Anode





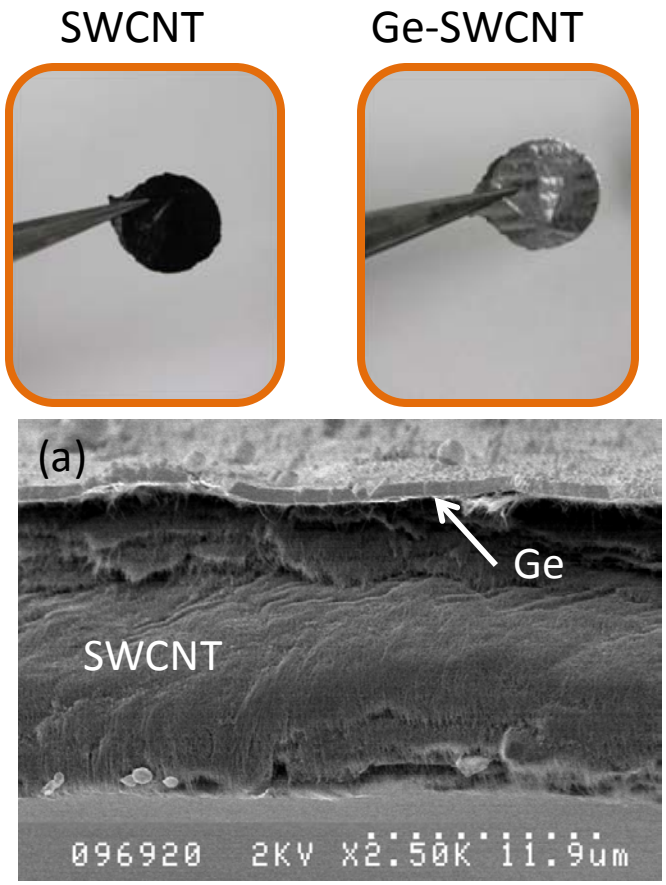
Battery Metric	Proposed Advantage
Energy Density	Physical support for high capacity lithium alloys (Si, Ge) Elimination of heavy inactive copper current collector High lithium ion storage capacity in CNTs
Power Density	Nanoscale electrical percolation network Potential for ballistic conduction with metallic CNTs Nanostructures offer higher electrolyte wetting
Performance	Flexible electrode design Elimination of copper promotes zero volt storage Enhanced cyclability due to particle entanglement

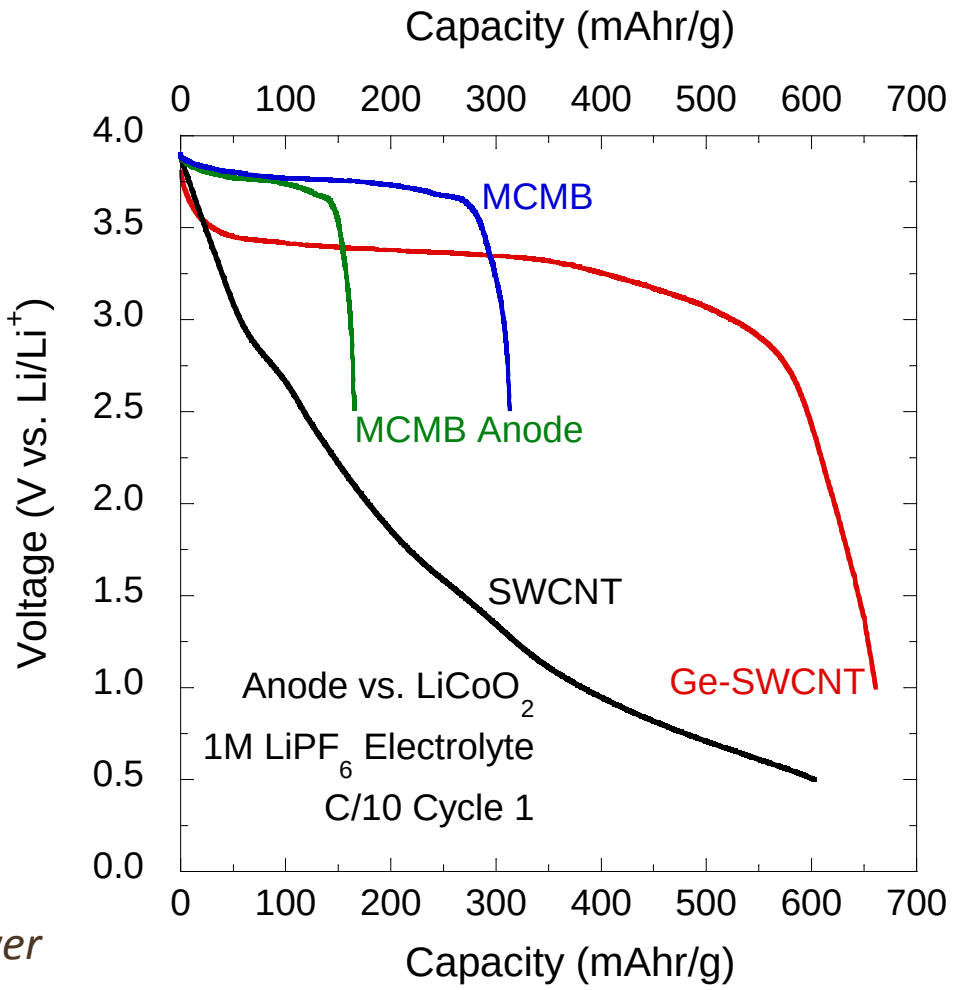
Silicon vs. Germanium

- Silicon has higher capacity
- Germanium has a higher density (5.35 vs. 2.33 g/cm^3) – volumetric capacity nearly equal
- Germanium has higher electronic conductivity (217 S/m vs. 1.2 E-3 S/m)

Landi, B.J.; et al. "Carbon Nanotubes for Lithium Ion Batteries." *Energy & Environ Sci.* **2009**, *2*, 549.

Thin Film Ge-SWCNT Anodes



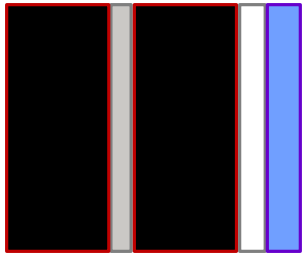


» *Paired with $LiCoO_2$*
» *Increased energy density by ~3x over MCMB anode and >>CNT electrode*

R.A. DiLeo, et al. *J. Mater. Res.* **2010**, *25*, 1441.

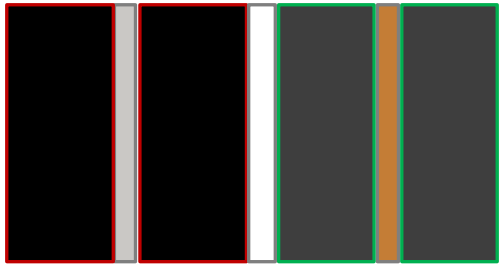
Modeling of High Energy Density Anodes

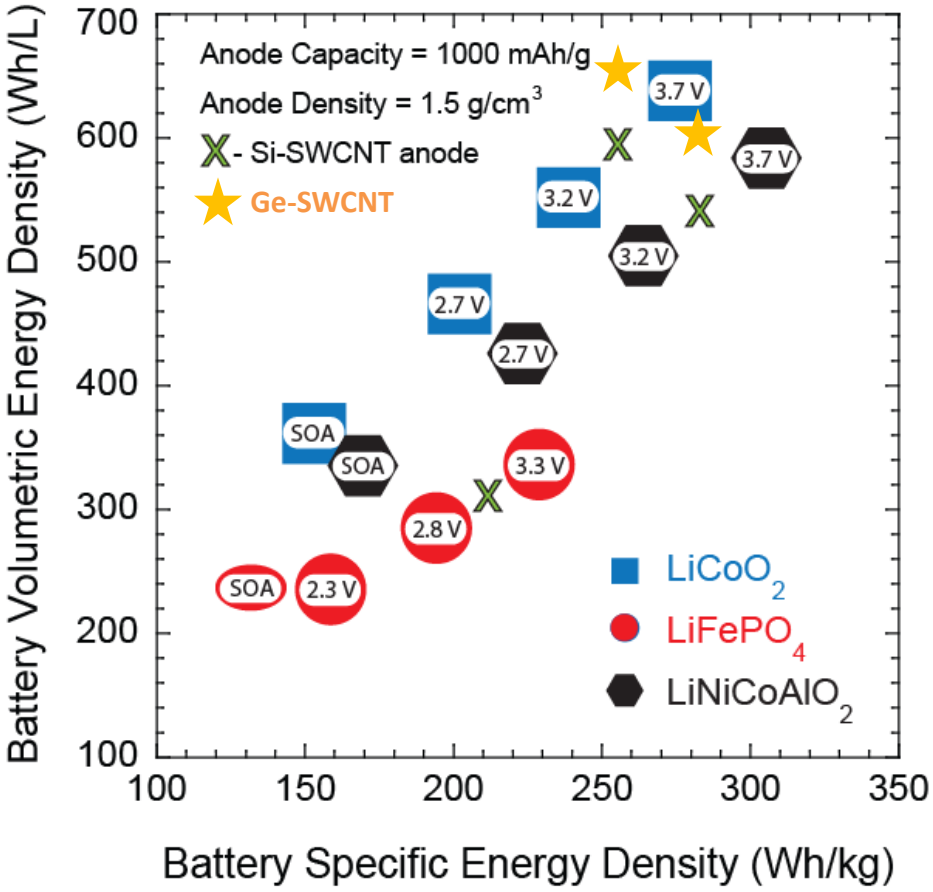
Cathode Ge-SWCNT



Free-standing anode thickness can be optimized to account for higher capacity

Cathode MCMB Anode

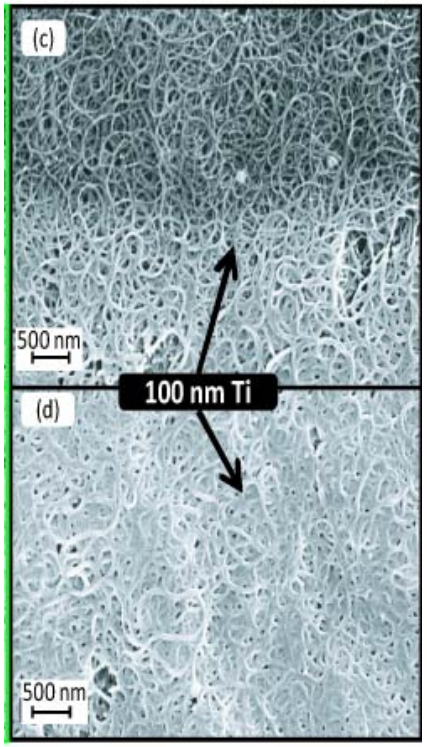


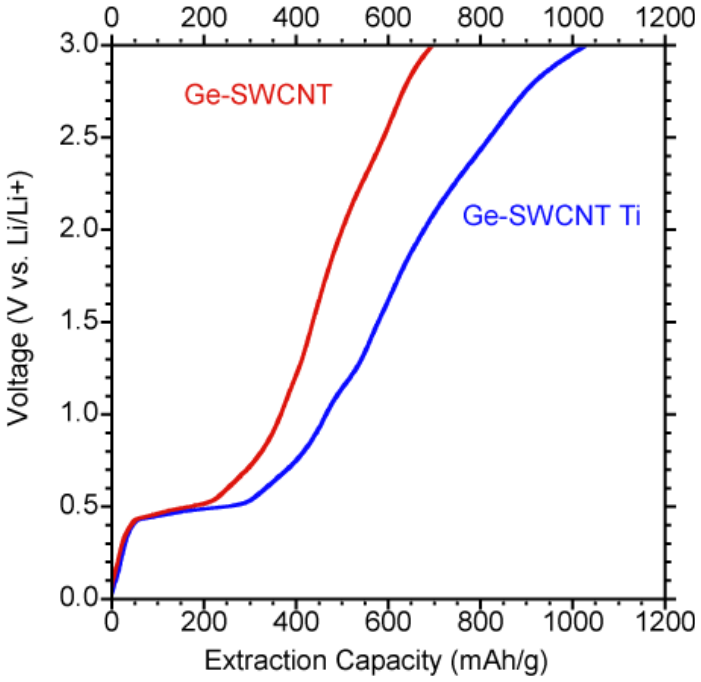


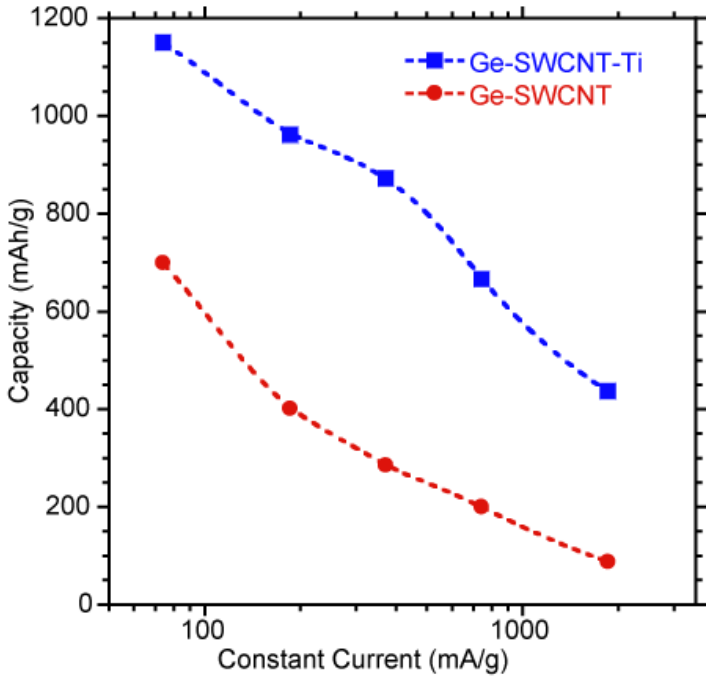
- Significant improvement over SOA with conventional cathode designs
- Improvements in high voltage cathodes can increase approach further

B.J. Landi, et al. *J. Mater. Res.* **2010**, *25*, 1636.

Ti-enhanced SWCNT electrodes



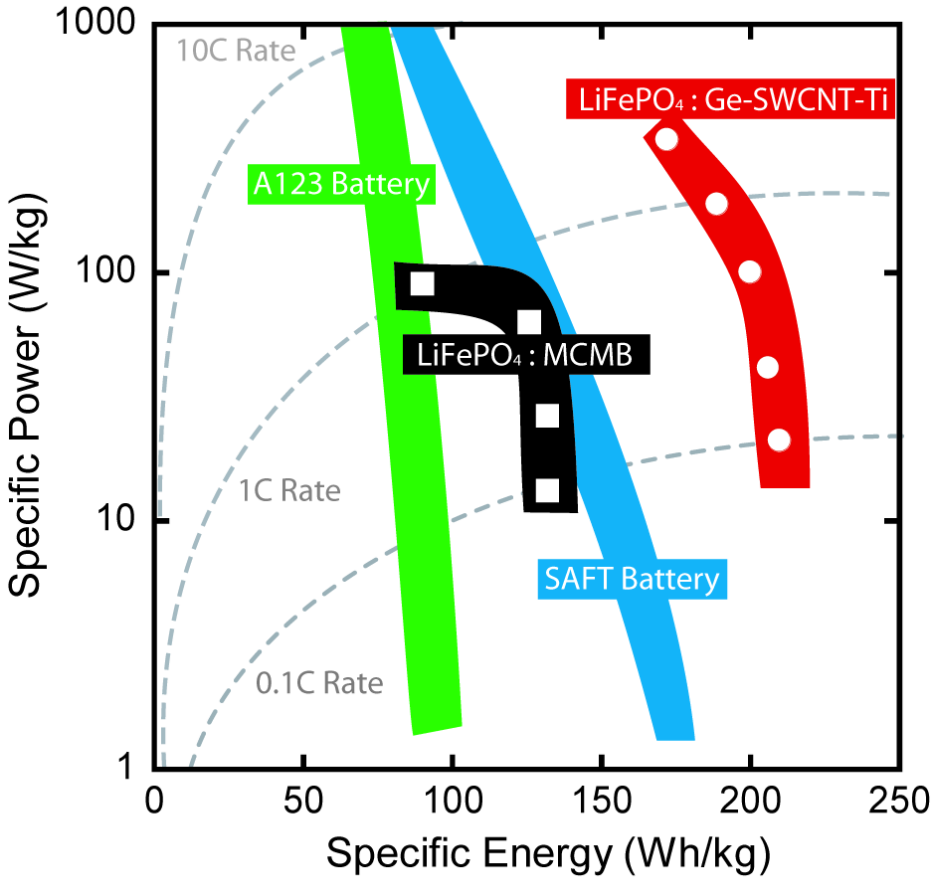




- Both Nickel and Titanium "wet" the surface of SWCNT electrodes through e-beam evaporation
- The use of a Ti layer with Ge-SWCNT anodes shows the ability to have a higher capacity for both the Ge and SWCNT contributions over a range of constant currents
- No evidence of reversible lithium ion capacity from TiOx compounds which occur at 1.5 V vs. Li/Li+

R.A. DiLeo, et al. *ACS Nano.* **2010**, *ASAP*.

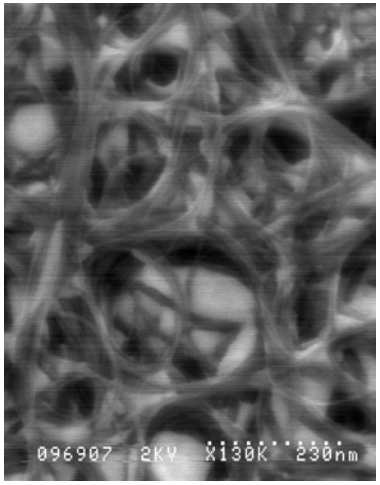
Conclusions and Impact



Carbon Nanotubes offer the potential to create a unique lithium ion battery with both ***high energy and power density***

Incorporation of high purity SWCNTs as a direct replacement of the conductive carbon in a typical cathode has maintained equivalent capacity with an improved rate capability

Advancement in titanium contacting of high capacity Ge-SWCNT anodes has shown the ability to maintain both high energy and power (>1C) capability; promising candidate to pair with $LiFePO_4$ for a balanced cell design.



R.A. DiLeo, et al. *ACS Nano.* **2010**, *ASAP*.