Next Generation Anodes for Li-Ion Cells: How to Achieve Both High Capacity and Cycle Stability When Using Silicon Metal

Michigan - 50 TPA - 2018 → 150 TPA Q1 2019
>2,000 TPA China 2019

Jeff Norris
CEO
+1.803.528.0941
JNorris@ParacleteEnergy.com
Is High Capacity Silicon Metal Commercially Viable?

Agenda

- The Problem
  - Is High Capacity Si Metal Commercially Viable?
    - The Problem & The Solution

- Demonstration & Analytical Proof of **SM-Architecture™** Capabilities

- Surface Modification
  - Covalent bonding
  - Cross linking
  - Organic/Inorganic hybrids

- Physical Properties
  - Surface Properties
  - Size Distribution
  - Morphology
  - Crystallinity

- Electrochemical Processing/Properties
  - Slurry Processing
  - Reversible Capacity
  - Rate Performance
Is High Capacity Silicon Metal Commercially Viable?

Please Send me a 100g to 1kg Sample of your Silicon
Is High Capacity Silicon Metal Commercially Viable?

• "Coming together is a beginning; keeping together is progress; working together is success."
  – Henry Ford

• "If everyone is moving forward together, then success takes care of itself.” – Henry Ford
SM-Architecture™ Enables Commercial Viability of Silicon Metal

Silicon metal for use in Li-Ion batteries is not yet a one-size-fits-all product. In order to achieve high capacity and cycle stability, there must be a flexible material architecture that allows for extensive optimization of silicon’s properties to a battery’s specific design and the creation of a sustainable conductive network between all the battery’s internal systems.
Paraclete Collaborative Business Model

"Coming together is a beginning; keeping together is progress; working together is success."

– Henry Ford

**SM-Architecture™** provides the flexibility and control to manipulate the properties of **SM-Silicon™** so that material variables are enhanced and optimized to a battery’s specific design and systems.

“In the world of electrification Paraclete Energy has one of the most creative business models I have seen in 4 decades of business by working across the spectrum of OEM, through battery manufacturer and the raw materials manufacturers. This cross spectrum approach increases the success of implementation by a huge margin.”  

**Bob Galyen – CTO CATL**
### Examples of Collaborative Business Model Objectives

<table>
<thead>
<tr>
<th>Percentage SM-Silicon/C™</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>0% SM-Silicon™</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Theoretical Capacity of SM-Silicon™</strong></td>
<td>3590 mAh/g</td>
<td>3590 mAh/g</td>
<td>3590 mAh/g</td>
<td>372 mAh/g</td>
</tr>
<tr>
<td><strong>SM-Silicon™ Purity Metal Basis</strong></td>
<td>99.50%</td>
<td>99.50%</td>
<td>99.50%</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>First Cycle Efficiency</strong></td>
<td>88-93%</td>
<td>88-93%</td>
<td>88-93%</td>
<td>88-93%</td>
</tr>
<tr>
<td><strong>Reversible Capacity (mAh/g)</strong></td>
<td>480-521 mAh/g</td>
<td>615-683 mAh/g</td>
<td>760-843 mAh/g</td>
<td>340-360 mAh/g</td>
</tr>
<tr>
<td><strong>Energy Density</strong></td>
<td>650-752 Wh/L 250-305 Wh/kg 6.2Ah</td>
<td>718-830 Wh/L 265-320 Wh/kg 6.2Ah</td>
<td>770-890 Wh/L 273-330 Wh/kg 6.2Ah</td>
<td>534-650 Wh/L 230-280 Wh/kg</td>
</tr>
<tr>
<td><strong>$/kWh</strong></td>
<td>Same or Less Than Graphite From a $/kWh at Production Quantities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cycle retention</strong></td>
<td>300-600 cycles &gt;80% at 100% DoD with SM-Silicon/C™*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Purpose of Surface Modification

- Provides the Adaptable and Flexible “Dials” for Augmentation and Optimization to the Variables of a Specific Battery’s Systems and Designs.
- Thereby Successful Implementation of High Capacity SM-Silicon™ in Li-Ion Batteries

Paraclete’s **SM-Architecture™** Enables:
- Unparalleled control of reactivity at the surface of silicon
- Flexibility to adjust the physical properties and composition of silicon metal
- Enabling desirable processing and electrochemical characteristics

“Paraclete Energy has created the most unique scientific approach to battery technology by modifying metal surface chemistry via modifications to match specific chemistry systems.” - Bob Galyen CTO CATL
Covalent Bonding of the Surface Modifier

No surface modifiers are used and contributions from surface oxides dominate the surface chemistry.

With surface modification the surface chemistry is dominated by the surface modifier.

Lack of oxides and surface modification enables higher reversible capacities than conventional oxide coated silicon.
Surface Modification for Cross Linking Applications

- Multi or Bifunctional surface modifier can be bound on one end to the silicon enabling cross-linking with binder and carbon and other systems

- Cross-linking combined with electrode design & the innate porosity of SM-Silicon™ mitigates issues caused during lithiation

- FTIR & NMR confirm that SM-Architecture™ enables control over how multi-functional surface modifier reacts with silicon
Uniformly Distribute Hybrid, or Organic or Inorganic SM Evenly across the Surface of the SM-Silicon™

Optimization for Multi Functional Cross Linking To Carbon and Binder Systems

<table>
<thead>
<tr>
<th>Element</th>
<th>Particle A</th>
<th>Particle B</th>
<th>Particle C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.07</td>
<td>11.50</td>
<td>11.01</td>
</tr>
<tr>
<td>2</td>
<td>03.39</td>
<td>03.95</td>
<td>03.58</td>
</tr>
<tr>
<td>3</td>
<td>83.09</td>
<td>81.80</td>
<td>82.86</td>
</tr>
<tr>
<td>4</td>
<td>02.45</td>
<td>02.75</td>
<td>02.55</td>
</tr>
</tbody>
</table>

Elemental distribution amongst different particles shows uniformity of mixed inorganic/organic surface modifier.

SEM-EDS of hybrid surface modifier
Can Be Made to Work in Either Aqueous or Non-Aqueous Systems

Properties of surface modifier transferred to surface of silicon particles

- Hydrophobic SM
- Hydrophilic SM

Time = 0 min  Time = 60 min
**SM-Architecture™** allows for downstream processing for incorporation into other composite materials.

TEM image showing the outer, artificial SEI, stabilizing shell of SM-Silicon™

Downstream processed SM-Silicon™
Control of Unique Particle Morphologies

Control of particle morphologies wherein higher aspect ratios allow increased rate capability compared to spherical particles.

SM-A
Jagged nano flakes

SM-B
Rounded nano particles
Customize Morphology– Mixed Amorphous/Crystalline Phase

Mixed amorphous/crystalline structure within each nanoparticle makes silicon less prone to fracture

<table>
<thead>
<tr>
<th>Composition (%)</th>
<th>Crystalline</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amorphous</td>
<td>65</td>
</tr>
</tbody>
</table>

HRTEM illustrates mixed amorphous/crystalline phases
Advantageous Slurry Processing

- Easy integration into existing slurry processes
- Air stable, dry powder with tap density similar to graphite
- Easily dispersible with graphite

Oxidized Silicon  $\text{SM-Silicon}^{TM}$ Graphite

$0.08 \text{ g/cm}^3 \quad 0.8 \text{ g/cm}^3 \quad 1.1 \text{ g/cm}^3$

$\text{SM-Silicon}^{TM}$ dispersed with graphite

200nm
SM-Silicon™ has two times the reversible capacity of SiOx and other Si-Alloys.
High Reversible Capacity

- Mixed silicon/graphite anode formulation shows full utilization of 3590 mAh/g silicon capacity

- High FCE: 15% SM-Silicon™ Composite anode with 76% graphite demonstrates high reversible capacity with FCE similar to that of graphite only electrodes

As little as 15% SM-Silicon™ increases anode specific capacity by over 2 times compared to graphite

Electrode Formulation
15% SM-Silicon™
76% Graphite
9% Binder/additives

Mass Loading: 2.8 mg/cm²
Areal Capacity: 2.5 mAh/cm²
SM-Silicon™ demonstrates similar rate capability to that of graphite even at fast rate charging/discharging.
SM-Silicon™ Thinner Anode Developed for 5Ah Pouch

5Ah Pouch Cell developed by Paraclete for one of its customers with 15% SM-Silicon™

Anode: Graphite only, 140 µm Thickness
Anode: SM-Silicon™, 90 µm Thickness

Cell with SM-Silicon™ containing 35% thinner anode demonstrates 30% more capacity than a cell with identical cathode versus pouch thickness with graphite only anode.

Graphite only anode, 140 µm
SM-Silicon™ containing anode, 90 µm
SM-Silicon™ 18650 Anode “drop-in” Replacement

Incorporating only 20% SM-Silicon™ results in 18650 with > 300 Wh/kg specific energy
Consistency From Benchtop to Mass Production

- Identical PSD & EC-Chem Data Between Research to Ton Production Quantities Proves Product Consistency for High Volume Manufacturing

15% SM-Silicon™ 76% Graphite
9% Binder/additives
2.8 mg/cm²
2.5 mAh/cm²

15% SM-Silicon™ 76% Graphite
9% Binder/additives
2.8 mg/cm²
2.5 mAh/cm²
Paraclete SM-Architecture™ & Collaborative Business Model
Enable Commercial Viability of Silicon Metal

**SM-Architecture™**

- Custom APS
- Optimized Amorphous
- Vis. Crystalline
- Adjust Conductivity
- Hydrophilic
- Covalently Bond
- Bond Chemistry
- Organic Inorganic
- Air Stable
- Oxide Free
- Not SiOx
- >99.5% Si Metal
- >92% FCE

**Collaborative Business Model**

**SM-Architecture™** provides the flexibility and control to manipulate the properties of **SM-Silicon™** so that material variables are enhanced and optimized to a battery's specific design and systems.

---

**Examples of Collaborative Business Model Objectives**

<table>
<thead>
<tr>
<th>Percentage SM-Silicon/C™</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>0% SM-Silicon™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Capacity (mAh/g)</td>
<td>3,500</td>
<td>3,500</td>
<td>3,500</td>
<td>372/1839</td>
</tr>
<tr>
<td>First Cycle Efficiency</td>
<td>88 - 93%</td>
<td>88 - 93%</td>
<td>88 - 93%</td>
<td>88 - 93%</td>
</tr>
<tr>
<td>Reversible Capacity (mAh/g)</td>
<td>480 - 521</td>
<td>615 - 683</td>
<td>760 - 845</td>
<td>548 - 560</td>
</tr>
<tr>
<td>Energy Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wh/L</td>
<td>650 - 790</td>
<td>718 - 850</td>
<td>770 - 890</td>
<td>534 - 650</td>
</tr>
<tr>
<td>Wh/kg</td>
<td>250 - 365</td>
<td>265 - 320</td>
<td>273 - 330</td>
<td>230 - 289</td>
</tr>
<tr>
<td>Ah</td>
<td>6.2Ah</td>
<td>6.2Ah</td>
<td>6.2Ah</td>
<td>6.2Ah</td>
</tr>
<tr>
<td>$/kWh</td>
<td>Same as or Less Than Graphite at $ 1.5kWh at Production Quantities -10 Ton. Year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle Retention</td>
<td>300 - 600 Cycles &gt;80% at 100% DoD with SM-Silicon/C™</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swelling at the Cell Level</td>
<td>&lt;16%</td>
<td>&lt;16%</td>
<td>&lt;16%</td>
<td>&lt;16%</td>
</tr>
</tbody>
</table>

---

Silicon metal for use in Li-Ion batteries is not yet a one-size-fits-all product. In order to achieve high capacity and cycle stability, there must be a flexible material architecture that allows for extensive optimization of silicon's properties to a battery's specific design and the creation of a sustainable conductive network between all the battery's internal systems. **SM-Architecture™** enables optimization of **SM-Silicon™** material variables.
Is High Capacity Silicon Metal Commercially Viable?

Paraclete’s **SM-Architecture™ & Collaborative Business Model**
Enable Commercial Viability of High Capacity Silicon Metal

“Experts in the battery industry agree that the breakthroughs to put electrified vehicles on an even par with petroleum fueled vehicles is advanced Lithium batteries utilizing Silicon.

The key element in achieving this milestone is Silicon created in a form that minimizes the volumetric swelling during cycling, which Paraclete Energy has such technology in its **SM-Silicon™**

Paraclete also has achieved this feat by increasing energy densities substantially without increased cost."

*Bob Galyen – CTO CATL*