A variety of materials are under investigation for use as anode materials in lithium-ion batteries, of which, the most promising are those containing silicon.\(^\text{10}\) One such material is a composite formed via the dispersion of silicon in a resorcinol-formaldehyde (RF) gel followed by pyrolysis. Two silicon-carbon composite materials, carbon microspheres and nanofoams produced from nano-phase silicon impregnated RF gel precursors have been synthesized and investigated. Carbon microspheres are produced by forming the silicon-containing RF gel into microspheres whereas carbon nano-foams are produced by impregnating carbon fiber paper with the silicon containing RF gel to create a free standing electrode.\(^\text{1-4,9}\) Both materials have demonstrated their ability to function as anodes and utilize the silicon present in the material. Stable reversible capacities above 400 mAh/g for the bulk material and above 1000 mAh/g of Si have been observed.
Carbon Cryogel Silicon Composite Anode Materials for Lithium-Ion Batteries

James Woodworth
NASA Postdoctoral Program Fellow
Electrochemistry Branch Glenn Research Center

Richard Baldwin and William Bennett
Electrochemistry Branch Glenn Research Center
Lithium Ion Basics

Cathode
- Transition Metal Oxide
- LiCO₂

Capacity is dependent on number of Li⁺ ions that can be shuttled back and forth

Anode
- Most Commonly Carbon
- Graphite
- Hard Carbon

- LiMO₂ → Li₁₋ₓMO₂ + xLi⁺ + xe⁻
- Li₁₋ₓMO₂ + xLi⁺ + xe → LiMO₂

- C + xLi⁺ + xe⁻ → LiₓC
- LiₓC → C + xLi⁺ + xe⁻
NASA Goals

- Future missions of the National Aeronautics and Space Administration (NASA) require advanced energy storage systems
  - High specific energies (Wh/kg)
  - High energy densities (Wh/l)
- Develop advanced lithium ion cells
- Anode development is a key component
- The anode represents 24% of cell mass and additional opportunity for cell mass reduction
- Key performance parameters
  - Threshold value of 600 mAh/g
  - Goal of 1000 mAh/g

Estimates for component weight fraction in 30 Ah cell
Anode Materials

- **Graphite**
  - Excellent cycling characteristics
  - Theoretical capacity of 372 mAh/g ($\text{LiC}_6$)

- **Silicon**
  - Theoretical capacity of 4200 mAh/g ($\text{Li}_{15}\text{Si}_4$)
  - Expands 400% upon lithiation
  - High irreversible capacity loss
  - High fade rate
  - Poor coulombic efficiency

- **Silicon carbon composites**
  - Carbon matrix absorbs expansion of the silicon and maintains electrical contact
  - Carbon matrix prevents direct electrolyte contact

---

**Estimates for cell specific energy and energy density**

![Graph showing energy density and specific energy for different materials](image-url)
In-House Anode Synthesis

- Silicon containing carbon gel microbeads
- Carbon fiber paper supported silicon containing carbon nanofoam
- Based on resorcinol-formaldehyde gel precursors containing nano-silicon
- Porous carbon matrix will absorb the expansion of the silicon and prevent direct silicon-electrolyte contact
- Makes use of traditional cost-effective laboratory techniques
Carbon Cryogel Anode Materials

Carbon-Silicon Microbeads

Carbon Nanofoam with Nano-Silicon Supported on Carbon Paper

Originally investigated by Hasegawa, Mukkai, Shiratu and Tamon *Carbon* 42, 2004 pp. 2573-2579

Carbon nanofoams are currently under investigation by J. Long at NRL for use in electrochemical capacitors and as electrode support materials.
Carbon-Silicon Microbeads

Mix microbeads with binder and cast onto copper foil current collector

- **Advantage**: Uses conventional manufacturing techniques
- **Disadvantage**: Requires heavy copper current collector

Carbon Nanofoam with Nano-Silicon Supported on Carbon Paper

- **Advantage**: “Stand Alone” electrode that does not require the use of a current collector (Lighter)
- **Disadvantage**: Would require development of new electrode and cell manufacturing techniques

Estimates for Component Weight Fraction in 30 Ah Cell

Anode copper current collector represents a significant weight fraction (8%)
Copper vs. Carbon

Copper Foil  2g  
• Not electrochemically active towards lithium

Carbon Paper  0.2 g  
• Electrochemically active towards Li (250 mAh/g)

Theoretical Specific Capacities at the Active Material and Electrode Levels

<table>
<thead>
<tr>
<th>Electrode</th>
<th>mAh/g Active Material</th>
<th>mAh/g Electrode</th>
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<tbody>
<tr>
<td>Nanofoam</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Graphite With Cu</td>
<td>350</td>
<td>170</td>
</tr>
<tr>
<td>Si With Cu</td>
<td>1000</td>
<td>312</td>
</tr>
</tbody>
</table>
Carbon Microbead Testing

- Carbon microbeads were slurried with NaCMC
- 0.005” film cast onto copper foil
- Anodes placed in coin cells using lithium as the counter electrode
- Electrolyte: 1M LiPF$_6$ 1:1:1 ethylene carbonate, diethyl carbonate and dimethyl carbonate
- Cells formed at C/10 and cycled from 10mV to 1.5 V
Electrochemical Cycling of Carbon Microbeads

**Specific Capacity**
- Graph showing specific capacity (mAh/g) vs. cycle number.
- Three cells labeled: Cell 1, Cell 2, Cell 3.
- C/10 and C/5 markers.

**Coulombic Efficiency**
- Graph showing % coulombic efficiency vs. cycle number.
- Three cells labeled: Cell 1, Cell 2, Cell 3.

**Silicon Contribution to Specific Capacity**
- Graph showing specific capacity (mAh/g) vs. cycle number.
- Two contributions: Bulk Capacity and Si Only.
- Si Contribution labeled.
Carbon-Silicon Microbead Electrodes

As Cast Nano-Silicon Carbon Gel Microbead Electrode

Cast Nano-Silicon Carbon Gel Microbead Electrode After Cycling
Carbon Nanofoam Half Cells

- Pouch cells
- Nanofoam material placed on copper foil current collectors
- Nickel tab spot-welded instead of the copper foil
- Lithium counter electrode
- First formation at approximately C/5
- Second formation at C/20
Electrochemical Cycling of Carbon Nanofoam Electrodes

Graphs showing specific capacity and coulombic efficiency for various carbon nanofoam electrodes.
Si-Carbon Microbeads Cell 1

Specific Capacity

Voltage and Current Vs. Test Time

Voltage (V) and Current (mA)

Volts Vs Li
Formation of Lithium Ion Diffusion Pathways

- Pre-Formation
- Establishment of Diffusion Pathways into Carbon Matrix
- Full Intercalation of Li⁺ Ions into Carbon Matrix and Si
- Establishment of Diffusion Pathways Through Carbon Matrix to Si
- Intercalation of Li⁺ Ions into Carbon Matrix and Surface Si

Volts Vs Li

Li⁺ Ions

Carbon

Silicon

Pre-Formation

Full Intercalation of Li⁺ Ions into Carbon Matrix and Si

Establishment of Diffusion Pathways Through Carbon Matrix to Si

Intercalation of Li⁺ Ions into Carbon Matrix and Surface Si

Establishment of Diffusion Pathways into Carbon Matrix

Pre-Formation
Initial Results

• **Microbeads**
  – 425 mAh/g
  – Short of threshold value of 600 mAh/g and goal of 1000 mAh/g

• **Nanofoam**
  – Initial results showed 400 mAh/g at the electrode level
  – “Stand Alone” anode 100% active material
  – Determined to have a higher potential to meet or exceed goals
  – Decided to focus on development of the carbon nanofoam anodes

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### Theoretical Specific Capacities at the Active Material and Electrode Levels

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<td>1000</td>
<td>312</td>
</tr>
</tbody>
</table>
New Experiments

• Improve the performance of the Si-carbon nanofoams by addition of conductive additives or binders
  – Addition of graphite to resorcinol formaldehyde gel
  – Coat with polyaniline doped with LiPF$_6$

• New formation procedure
New Formation Procedure

- Very slow initial formation to 10 mV
- Replace taper charge with very low constant current to 10 mV
Silicon-Carbon Nanofoams

Specific Capacity
- Si+graphite
- Si
- Si+PAN
- Si+graphite+PAN

Silicon Contribution to Specific Capacity
- Si+graphite
- Si
- Si+PAN
- Si+graphite+PAN

Coulombic Efficiency
- Si+graphite
- Si
- Si+PAN
- Si+graphite+PAN
Carbon-Silicon Nanofoam Electrodes

Carbon-Silicon-Graphite Nanofoam

Volts Vs. Li

Voltage Vs. Li

dq/dv

dq/dv

Cycle 1
Cycle 2

cycle 1
cycle 2
cycle 3
cycle 12
The nanofoam containing graphite has a lower impedance than the nanofoam which does not contain graphite.

Samples coated with polyaniline/LiPF$_6$ show drastically lower impedances than those without the coating.

The presence of graphite in combination with the polyaniline coating resulted in a higher impedance than that of a coated sample not containing graphite.
Conclusions

- A “Stand Alone” anode has been synthesized with specific capacities that meet and/or exceed the ETDP threshold value of 600 mAh/g and would likely compare favorably, with regard to specific capacity, at the electrode level to conventional coated anode materials.
- “Stand Alone” carbon-silicon nanofoam anodes have the greater potential to address NASA goals.
- “Stand Alone” carbon-silicon nanofoam anodes have the potential to significantly increase the specific energies (Wh/kg) for lithium-ion cells.
- Addition of graphite to the silicon containing carbon nanofoam dramatically increases capacity.
- Use of the conductive binder polyaniline doped with LiPF$_6$ dramatically increases capacity.
- Very slow formation cycle is required to fully lithiate silicon.
Future Work

• Investigate the use of various conductive additives
  – Graphites
  – Carbon Nanotubes
  – Carbon Nanofibers
• Investigate different binders or coatings
• Investigate different gel formulations
• Remove oxygen from matrix
Acknowledgements

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  – Tom Miller (NASA GRC)
  – Dave Yendriga (Sierra Lobo)
  – Marjorie Moats (SGT)
  – Michelle Manzo (Electrochemistry Branch Chief NASA GRC)
Supplementary Slides
Updated Results for Carbon-Silicon Nanofoam Electrodes
Updated Results for Carbon-Silicon Nanofoam Electrodes Continued

Silicon Contribution to Specific Capacity

- Si+Graphite-1
- Si-29%
- Si+PAN
- Si+Graphite+PAN
- Si+Graphite-2
- Si-34%
- Si+Nanotubes

Specific Capacity (mAh/g)

Cycle Number

0 5 10 15 20 25

200 700 1200 1700 2200 2700
Contribution of Non-silicon Components to the Specific Capacities Carbon-Silicon Nanofoam Electrodes

Carbon Contribution to Specific Capacity

Conductive Additive Contribution to Specific Capacity
Synthetic Conditions

• **Carbon-Silicon Microspheres**
  - Resorcinol-Formaldehyde containing 50 nm silicon is dispersed in a solution of cyclohexane and Span 80 surfactant
  - Sonicated
  - Stirred for two days at room temperature
  - Recovered and rinsed
  - Freeze dried in t-butanol
  - Pyrolyzed at 1000° C in argon

• **Carbon-Silicon Nanofoam**
  - Carbon fiber paper impregnated with resorcinol-formaldehyde gel containing 50 nm silicon particles
  - Sealed in plastic bags and placed between glass plates
  - Cured at room temperature for 2 days
  - Freeze dried in t-butanol
  - Pyrolyzed at 1000° C in argon

## Key Performance Parameters for Battery Technology Development

<table>
<thead>
<tr>
<th>Customer Need</th>
<th>Performance Parameter</th>
<th>State-of-the-Art</th>
<th>Current Value</th>
<th>Threshold Value</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Safe, reliable operation</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>No fire or flame</td>
<td>Instrumentation/control-</td>
<td>Preliminary results indicate a small reduction in performance using safer</td>
<td>Tolerant to electrical and thermal abuse such as over-temperature, over-charge,</td>
<td>Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and short circuits with no fire or thermal runaway***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lers used to prevent unsafe</td>
<td>electrolytes and cathode coatings</td>
<td>reversal, and short circuits with no fire or thermal runaway***</td>
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<tr>
<td></td>
<td></td>
<td>conditions. There is no non-</td>
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<td></td>
<td></td>
<td>flammable electrolyte in SOA</td>
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<tr>
<td><strong>Specific energy</strong></td>
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<tr>
<td>Lander:</td>
<td>Battery-level specific</td>
<td>90 Wh/kg at C/10 &amp; 30°C 83</td>
<td>160 at C/10 &amp; 30°C (HE) 170 at C/10 &amp; 30°C (UHE) 80 Wh/kg at C/10 &amp; 0°C (predicted)</td>
<td>135 Wh/kg at C/10 &amp; 0°C &quot;High-Energy&quot;** 150 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;**</td>
<td>150 Wh/kg at C/10 &amp; 0°C &quot;High-Energy&quot; 220 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
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<td>energy [Wh/kg]</td>
<td>Wh/kg at C/10 &amp; 0°C (MER rovers)</td>
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<tr>
<td>Rover:</td>
<td>Cell-level specific</td>
<td>130 Wh/kg at C/10 &amp; 30°C 118</td>
<td>199 at C/10 &amp; 23°C (HE) 213 at C/10 &amp; 23°C (UHE) 100 Wh/kg at C/10 &amp; 0°C (predicted)</td>
<td>165 Wh/kg at C/10 &amp; 0°C &quot;High-Energy&quot; 180 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
<td>180 Wh/kg at C/10 &amp; 0°C &quot;High-Energy&quot; 260 Wh/kg at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
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<tr>
<td></td>
<td>energy [Wh/kg]</td>
<td>Wh/kg at C/10 &amp; 0°C</td>
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<tr>
<td>EVA:</td>
<td>Cathode-level specific</td>
<td>180 mAh/g</td>
<td>252 mAh/g at C/10 &amp; 25°C 190 mAh/g at C/10 &amp; 0°C</td>
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<td>280 mAh/g at C/10 &amp; 0°C</td>
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<td>capacity [mAh/g]</td>
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<tr>
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<td>Anode-level specific</td>
<td>280 mAh/g (MCMB)</td>
<td>330 @ C/10 &amp; 0°C (HE) 1200 mAh/g @ C/10 &amp; 0°C for 10 cycles (UHE)</td>
<td>600 mAh/g at C/10 &amp; 0°C &quot;Ultra-High Energy&quot;</td>
<td>1000 mAh/g at C/10 0°C &quot;Ultra-High Energy&quot;</td>
</tr>
<tr>
<td></td>
<td>capacity [mAh/g]</td>
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<tr>
<td><strong>Energy density</strong></td>
<td>Battery-level energy</td>
<td>250 Wh/l</td>
<td>n/a</td>
<td>270 Wh/l &quot;High-Energy&quot; 360 Wh/l &quot;Ultra-High&quot;</td>
<td>320 Wh/l &quot;High-Energy&quot; 420 Wh/l &quot;Ultra-High&quot;</td>
</tr>
<tr>
<td>Lander:</td>
<td>density</td>
<td></td>
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<tr>
<td></td>
<td>Cell-level energy</td>
<td>320 Wh/l</td>
<td>n/a</td>
<td>385 Wh/l &quot;High-Energy&quot; 460 Wh/l &quot;Ultra-High&quot;</td>
<td>390 Wh/l &quot;High-Energy&quot; 530 Wh/l &quot;Ultra-High&quot;</td>
</tr>
<tr>
<td></td>
<td>density</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Operating environment</strong></td>
<td>Operating Temperature</td>
<td>-20°C to +40°C</td>
<td>0°C to +30°C</td>
<td>0°C to 30°C</td>
<td>0°C to 30°C</td>
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<td>0°C to 30°C</td>
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