Silicon-Based Lithium-Ion Capacitor for High Energy and High Power Application

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Outline

• Introduction/NASA Energy Requirements
• Challenges and Opportunities
• Approaches
• Result Summary
• Next Steps and Future Directions
Energy Storage: Important for NASA Missions

– Battery and capacitor: versatile, reliable, safe and portable energy sources

– Electrical energy storage options for NASA space mission, such as
  • power source during spacecraft eclipses
  • peaking power for high power needs

– an essential component of the power system of virtually all NASA missions
Desired Properties of Energy Source for NASA Missions

- Safe
- High in specific energy
- Light in weight
- Compact in volume
- Long in shelf life
- Durable in wide temperature range and at harsh environment
- Reliable in meeting mission requirements
State-of-Art (SOA) Li-Ion Battery (LIB)

• Typical LIB Specs:
  – Specific energy: 180-200 Wh/kg
  – Specific power: 300 W/kg
  – Cycles: 1000s
  – Temp range: -20°C to 60°C

• Limitations:
  – Maximum of energy density <250 Wh/kg
  – Electrolyte flammable and fire hazards
NASA Demands Very High Energy Density

**Electric Aviation**

- 500 – 750 Wh/kg
- Green aviation – Less noise, lower emissions, high efficiency
- Hybrid / All-electric aircraft – Limited by mass of energy storage system
- Commercial aviation – Safe, reliable, lightweight on-board electric auxiliary power unit

**Extravehicular Activities (Spacesuit power)**

- >400 Wh/kg
- Required to enable untethered EVA missions lasting 8 hours within strict mass and volume limitations.
- Astronaut life support
- Safety and reliability are critical
- 100 cycles

**Landers and Rovers, Robotic missions, In-space habitats**

- >500 Wh/kg
- Batteries are expected to provide sufficient power for life support and communications systems, and tools including video and lighting
- >100 cycles

NASA future mission requirements far exceed the capabilities of SOA Li-ion chemistries

➢ requires advances in safe, very high energy batteries development
• Advanced safe, high energy/ultra-high energy Li-ion batteries

• Advanced electrode materials
  • Advanced anode active materials (i.e. Si anode, w/Georgia Tech, Physical Science, inc.)
  • Advanced cathode active materials (i.e. high capacity NMC, w/University of Texas at Austin)

• Advanced electrolyte to improve safety
  • Non-flammable additives to reduce the flammability (w/ NASA/JPL)

• Industrial manufacturers
  • Saft America, Yardney etc
**Phase I**: 8 month, 4 awards were given:
- 1 award (Category I) on Si Anode based Li-ion battery (Amprius)
- 3 awards (Category II) on Li/S battery development (JPL/CIT, IUPIU, University of Maryland (UMD))

**Phase II**: 12 month, 2 award were given:
- **Amprius**: Silicon Anode Based Cells for High Specific Energy Systems (COR: Brianne Demattia)
  - Commercial standard cathode paired with Amprius’ silicon anode
  - Phase I: Deliverables with >300 Wh/kg after 225 cycles (pouch cell)
  - Phase II: Scale-up cells (2X size in phase I) with >300 Wh/kg over 200 cycles
    - Additional temperature & safety evaluations at cell & battery levels
    - Battery pack brassboard delivering > 250 Wh/kg
- **University of Maryland**: Garnet Electrolyte-Based Safe Lithium-Sulfur Energy Storage (COR: James Wu)
  - All solid state battery with unique and scalable trilayer (porous-dense-porous) solid state electrolyte (SSE) structure.
  - Phase I: demonstrated the feasibility in lab cells (coin cell)
  - Phase II: optimize the parameters and scale up to 5cm x 6cm sizes with targeted energy density ~500 Wh/kg
POC: Lisa Kohout, Battery Subtopic Manager (GRC)

- NASA SBIR topics are aligned with one of four Mission Directorates
  - Solicitations focus on specific technology gaps
- Subtopics in FY17 solicitation with focus on electrochemical technologies led by NASA Glenn Research Center

Funding
- Phase I: $125K (6 months) for SBIR, or 12 month for SBIR/STTR
- Phase II: $750K (24 month)

Current/previous SBIR Phase II award:

**2017:** Cornerstone Research Group, *Advanced Lithium Sulfur Battery*

**2014**
- Nohms Technologies - *Li Metal Protection for High Energy Space Batteries*

**2012**
- Storagenergy Technologies – *Advanced Li/S Batteries Based on Novel Composite Cathode and Electrolyte System*
Two major types of electrochemical-based energy storage devices

- **Battery:** Faradic/exothermal redox reaction (many different varieties)
  - High energy density
  - Electrode degradation
  - Limited cycle life

- **Capacitor:** Electrostatic/capacitive interaction
  - High power density
  - Electrode structural integration
  - Long cycle life
How to Improve Both Power Density and Energy Density of Battery

• New materials with high specific capacity

• Novel architectures: 3D design of electrode
  • Thinner electrode (fast ionic transport)
  • High electronic conductivity (fast $e^-$ transport)
  • High electrode/electrolyte interfacial area (fast charge transfer across the interface)
How to Improve Both Energy Density and Power Density of Capacitor

- One approach is to hybrid the capacitor electrode with one battery electrode i.e. asymmetric supercapacitor

- One electrode (as cathode) from capacitor (i.e. active carbon w/high porosity and high surface area) undergoes electrostatic interaction

- The other electrode (as anode) from battery (i.e. silicon with high specific capacity) undergoes electrochemical redox reaction
Si: a Promising Li-Ion Anode Material

**Attractive Features**
- High theoretical specific capacity (4200 mAh/g)
- Low potential 0.4V vs. Li/Li⁺
- Nontoxicity
- Abundance element on Earth crust

**Challenges**
- Low electronic conductivity
- Large volume expansion (3005-400%)
- Unstable SEI – fast capacity fade

**Approaches**
- Carbon/Si composite, w/nanosized or nanostructured Si
- Enabler for SEI formation
Si-Based Li-ion Capacitor

Li-ion anode, such as Si

Separator

Actived carbon (AC) cathode

Electrolyte: 1M LiPF6 in EC:DEC:DME (2:1:2) w/10% FEC
Cyclic Voltammetry of Individual Electrode in Half-Cell

Si Anode

AC Cathode
Impedance of Individual Electrode in Half-Cell

Si anode

AC Cathode
Initial Cycling of Individual Electrode in Half_Cell

Si Anode

AC Cathode

0.01V – 1V

2V – 4.5V
Rate Capability Cycling of Individual Electrode in Half-Cell

Si Anode

AC Cathode

De-insertion Capacity (mAh/g)

Discharge Capacity (mAh/g)

Cycle #

Cycle #
Cyclic Voltammetry of Si-AC Full Cell Capacitor
Impedance of Si-AC Full Cell Capacitor

Before CV cycling

CV cycling to 2.0V

CV cycling to 4.5V

CV cycling
Initial Cycling of Si-AC Capacitor
Rate Capability Cycling of Si-AC Capacitor

Power Density

\[ y = 3.032x + 8.357 \]
\[ R^2 = 0.999 \]

Energy Density

\[ y = -0.191x + 203.3 \]
\[ R^2 = 0.999 \]
Voltage Profile of Individual Electrode in Si-AC Capacitor using Reference Electrode

Voltage (V)

Time (Hrs)

AC vs. ref.

Cell voltage

Si vs. ref.
Results Summary

- Si-based Li-ion capacitor has been developed and demonstrated
- The results show it is feasible to improve both power density and energy density in this configuration
  - The applied current density impacts the power and energy density: low current favors energy density while high current favors power density
  - Active carbon has a better rate capability than Si

Next Steps/Future Directions

- Si electrode needs to be further improved
- Further optimization of Si/AC ratio and evaluation of its impact on energy density and power density
Acknowledgement

• Convergent Aeronautics Solution Project – Multifunctional Structure with High Energy Lightweight Loadbearing Storage

• Former Advanced Space Power System Project
Thank you!