



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



NASA Advanced Space Power Systems (ASPS) Program (2008-2014)

- **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



NASA Advanced Energy Storage System (AESS) Project under Game Change Program (2014-2017)

POC: Don Palac, Project Manager (GRC)

- **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



NASA SBIR/STTR Program

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

- Solid Power, Inc. *Ultra High Energy Solid-State Batteries for Next Generation Space Power*
- Nohms Technologies-*Li Metal Protection for High Energy Space Batteries*

2012

- Storaenergy Technologies – *Advanced Li/S Batteries Based on Novel Composite Cathode and Electrolyte System*



High Energy and High Power Energy Source

- **Two major types of electrochemical-based energy storage devices**
 - **Battery: Faradic/exothermic 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**

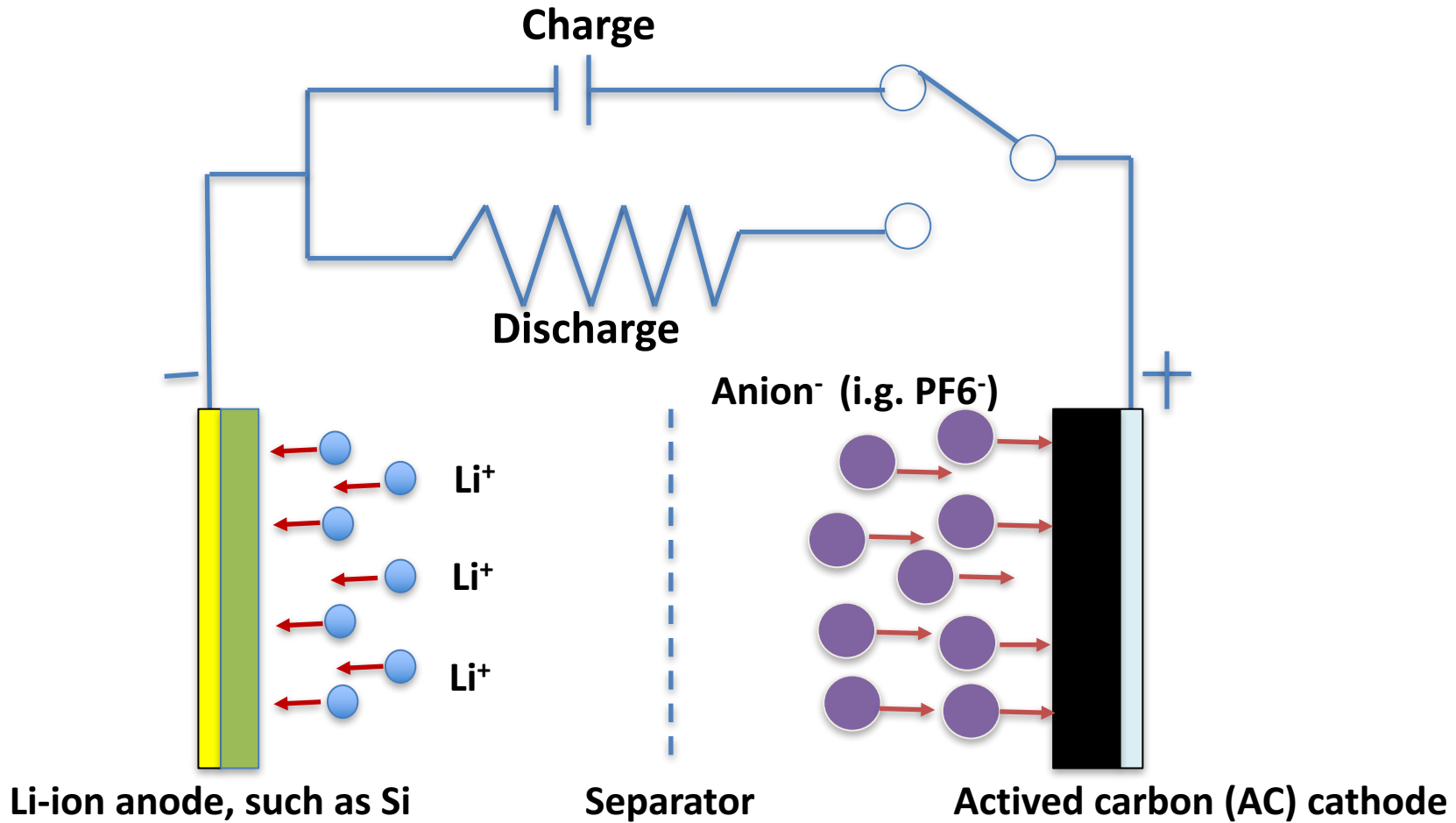
- Low electronic conductivity
- Large volume expansion (300-400%)
- Unstable SEI – fast capacity fade

- **Approaches**

- Carbon/Si composite, w/nanosized or nanostructured Si
- Enabler for SEI formation



Si-Based Li-ion Capacitor

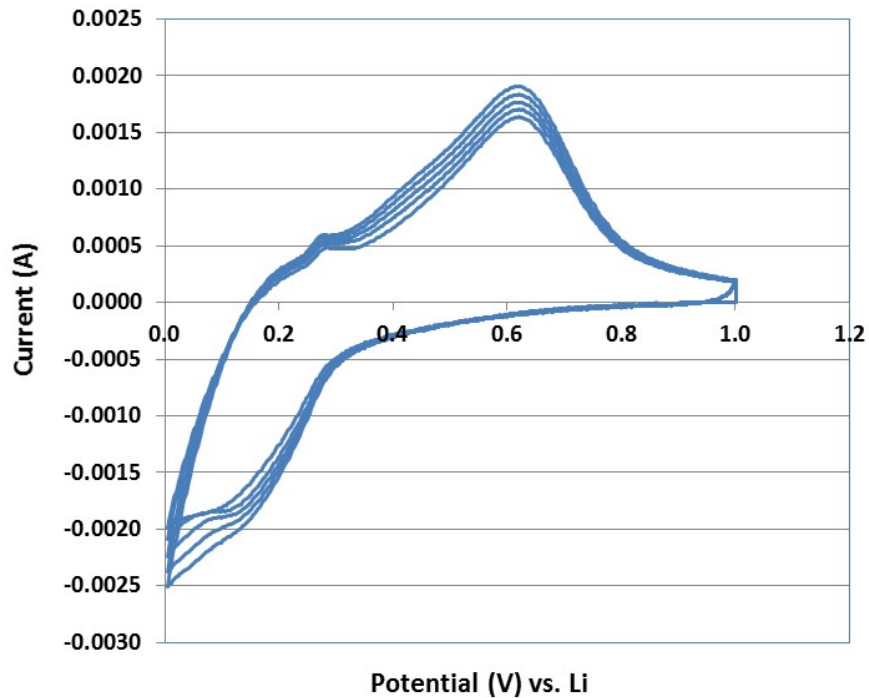


Electrolyte: 1M LiPF₆ in EC:DEC:DME (2:1:2) w/10% FEC

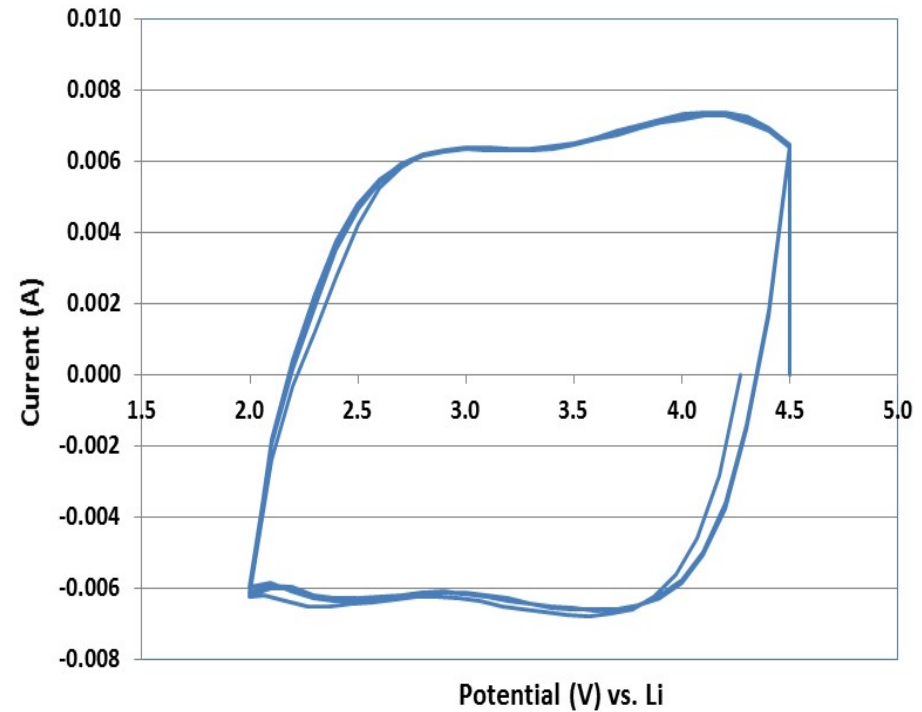


Cyclic Voltammetry of Individual Electrode in Half-Cell

Si Anode



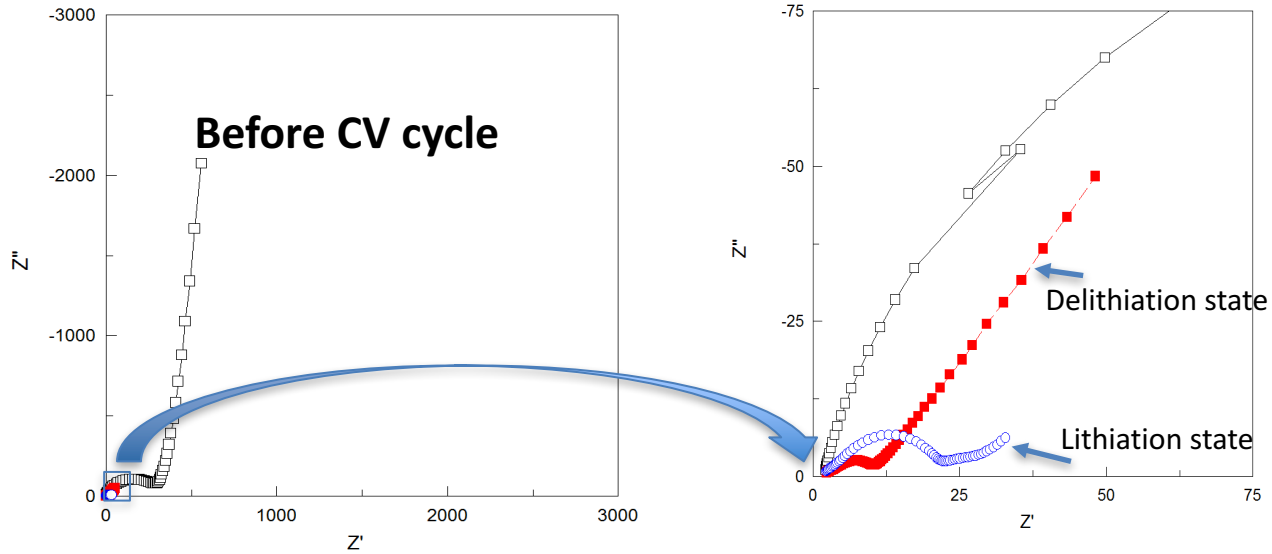
AC Cathode



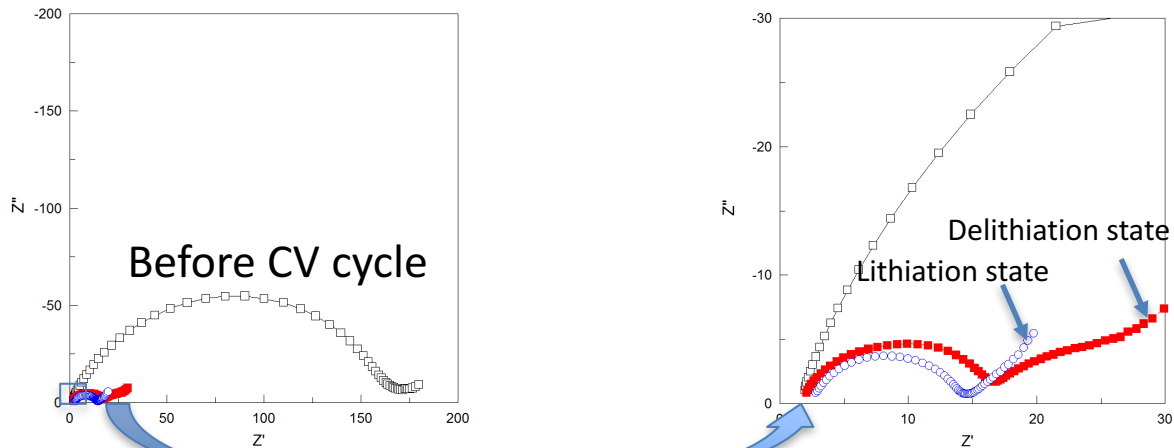


Impedance of Individual Electrode in Half-Cell

Si anode



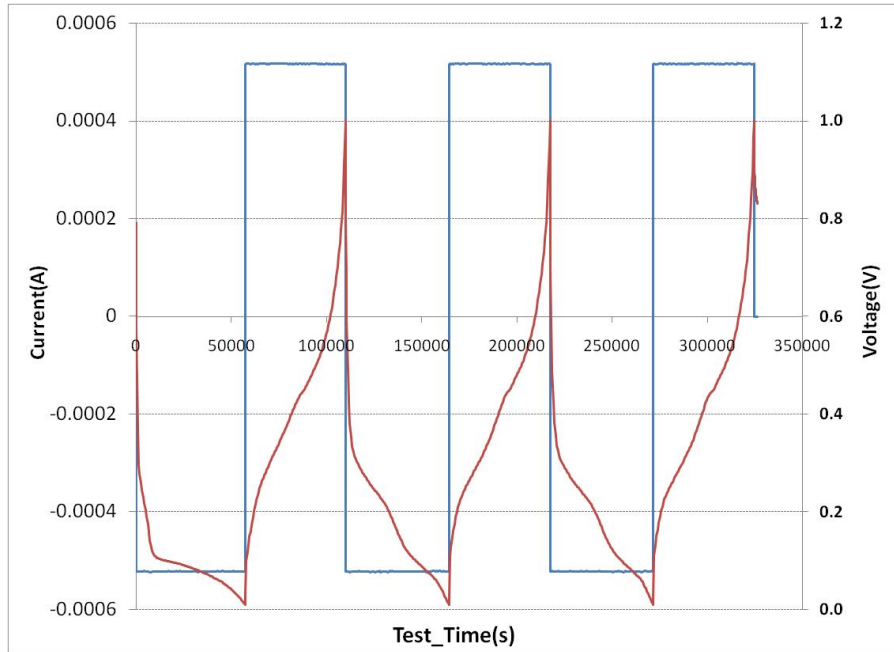
AC Cathode





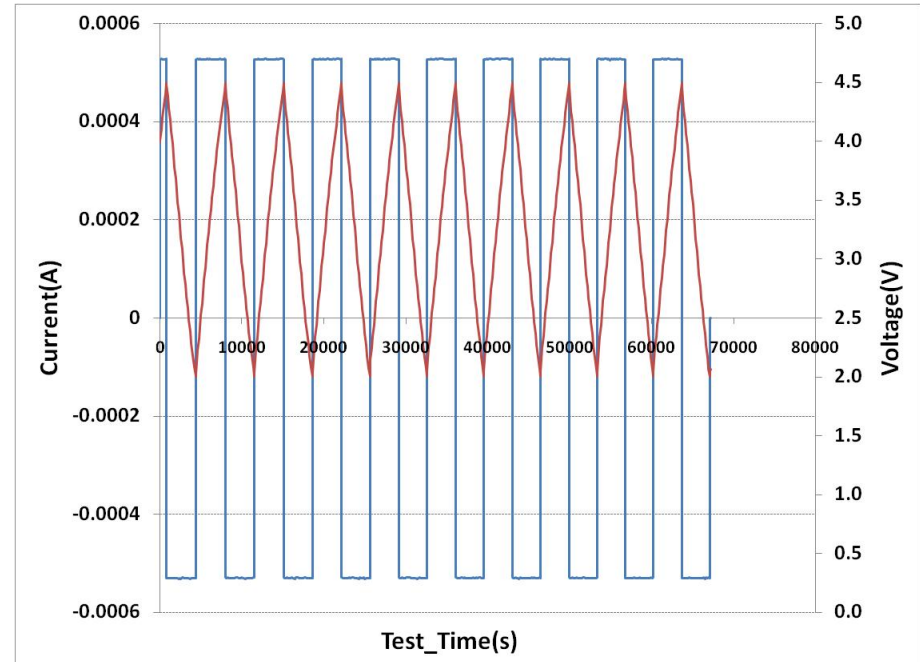
Initial Cycling of Individual Electrode in Half Cell

Si Anode



0.01V – 1V

AC Cathode

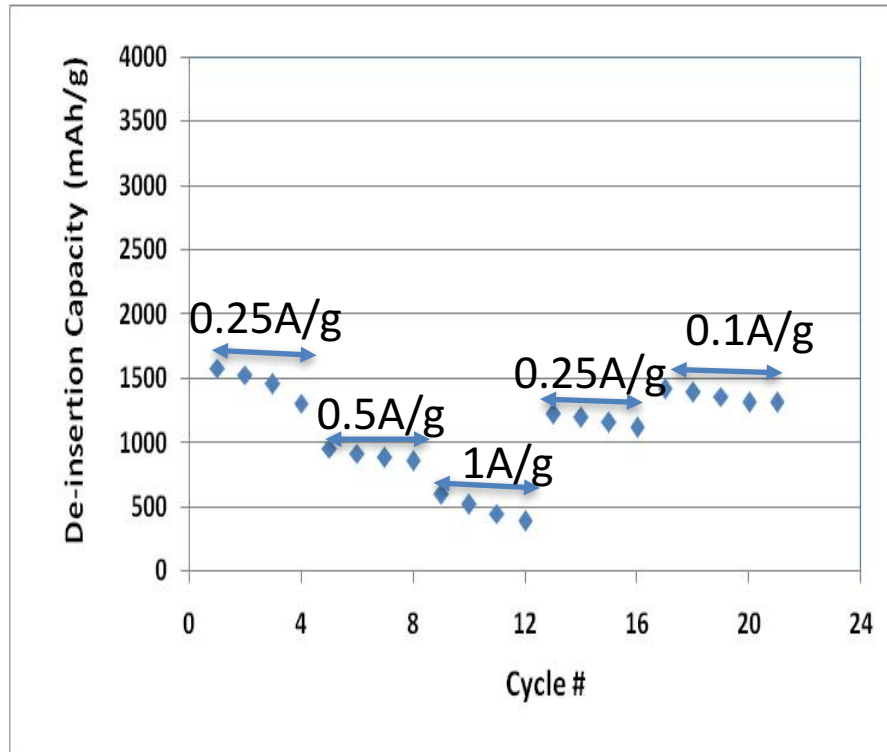


2V – 4.5V

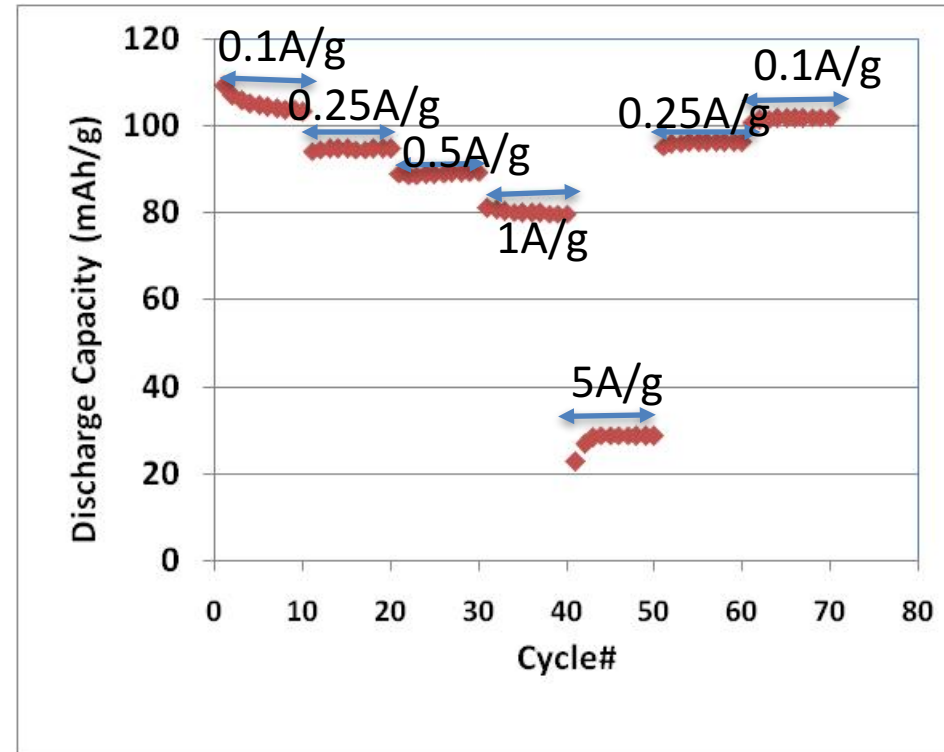


Rate Capability Cycling of Individual Electrode in Half-Cell

Si Anode

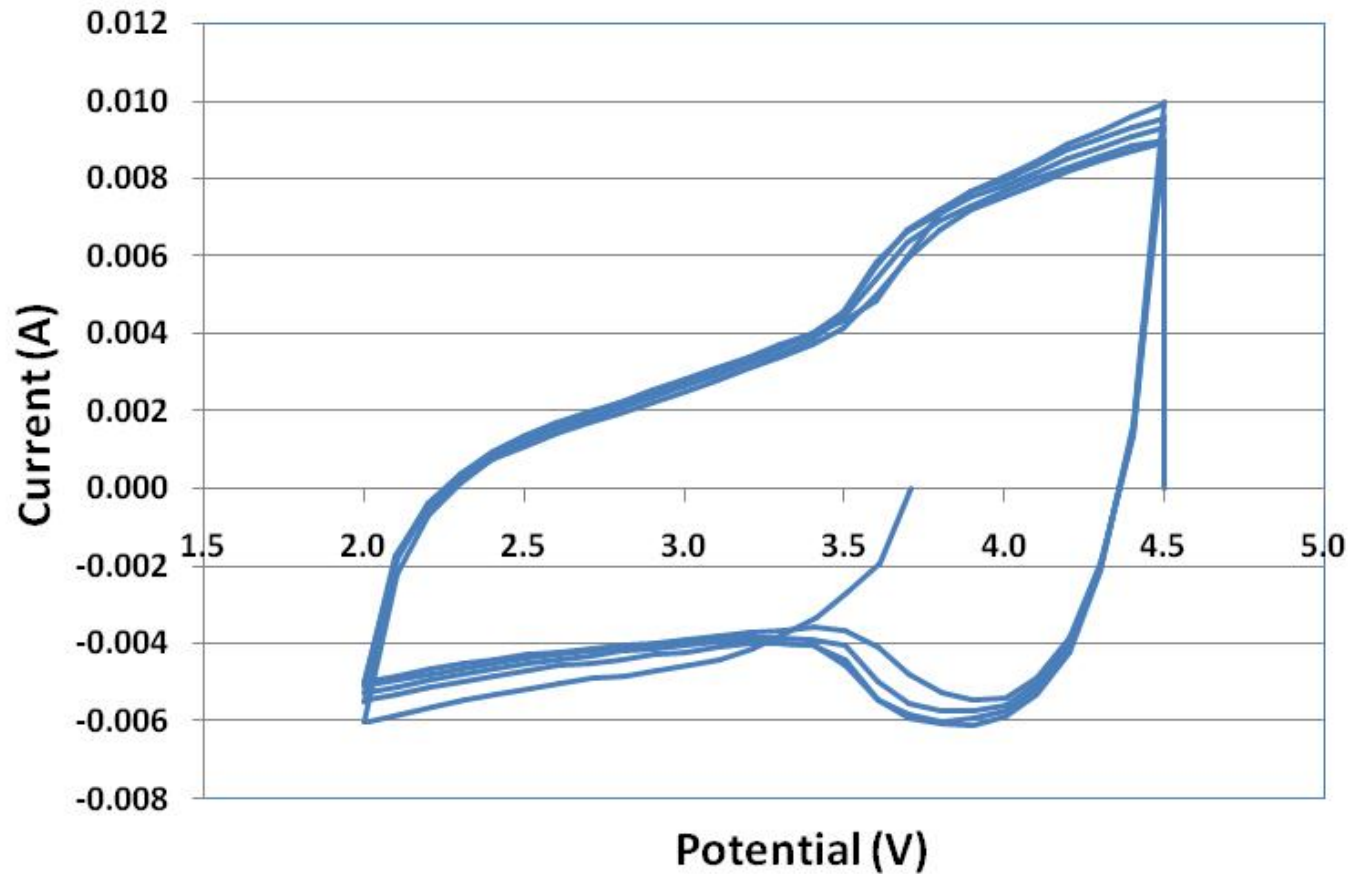


AC Cathode



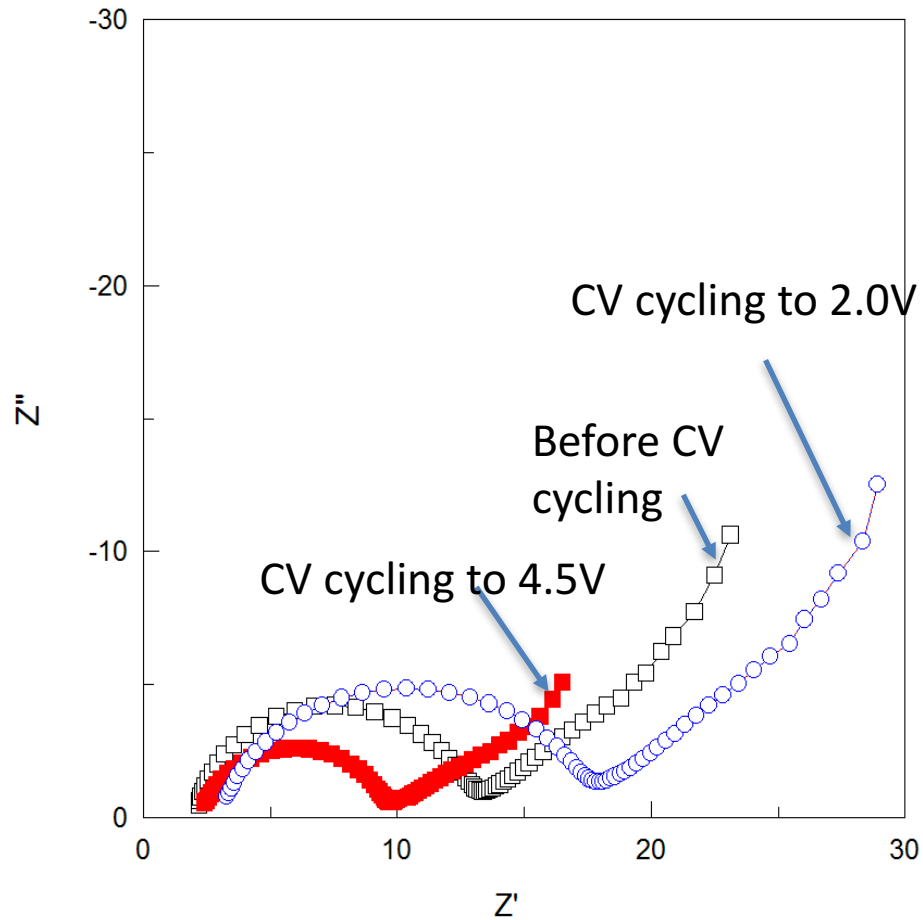


Cyclic Voltammetry of Si-AC Full Cell Capacitor



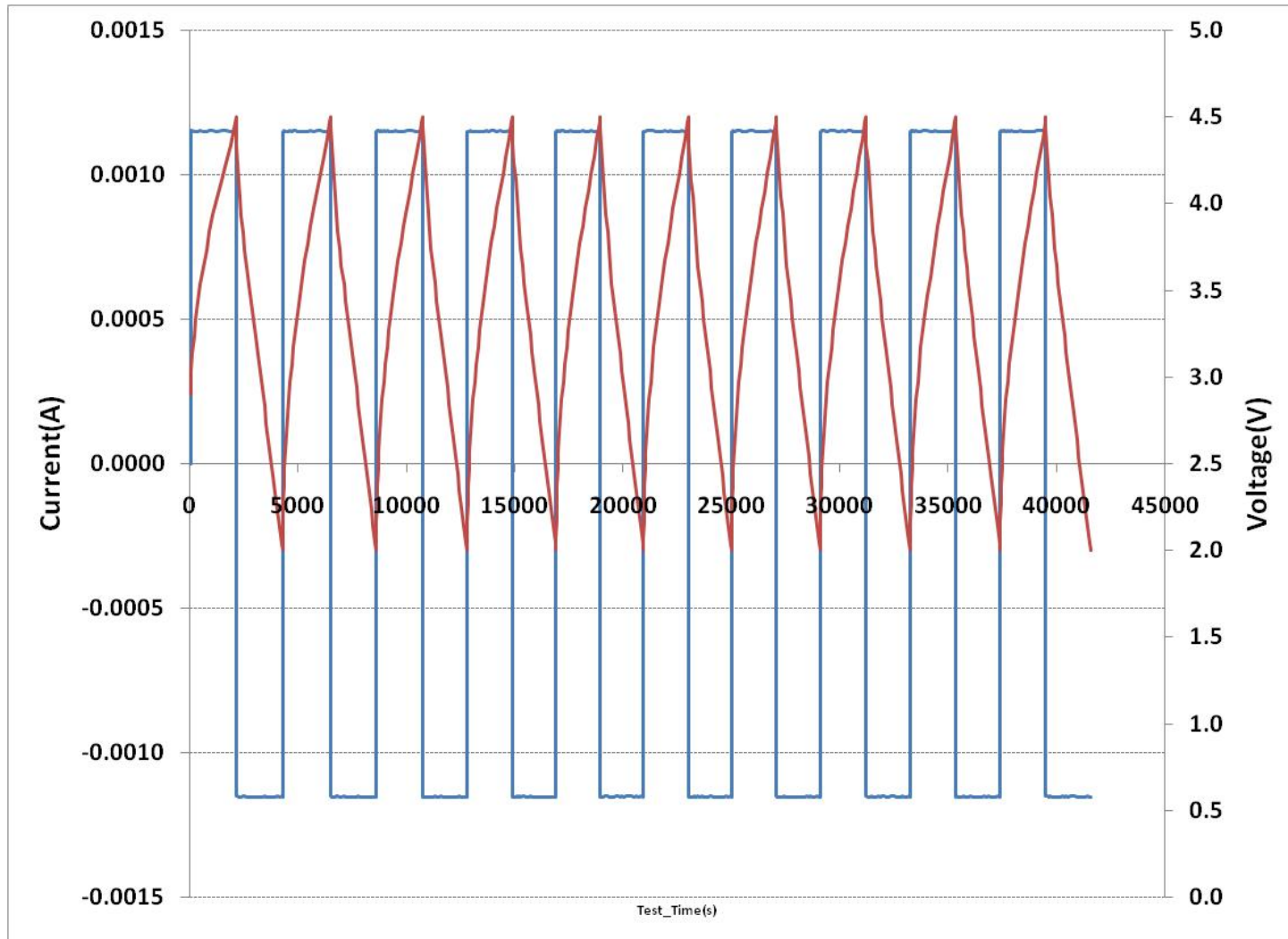


Impedance of Si-AC Full Cell Capacitor





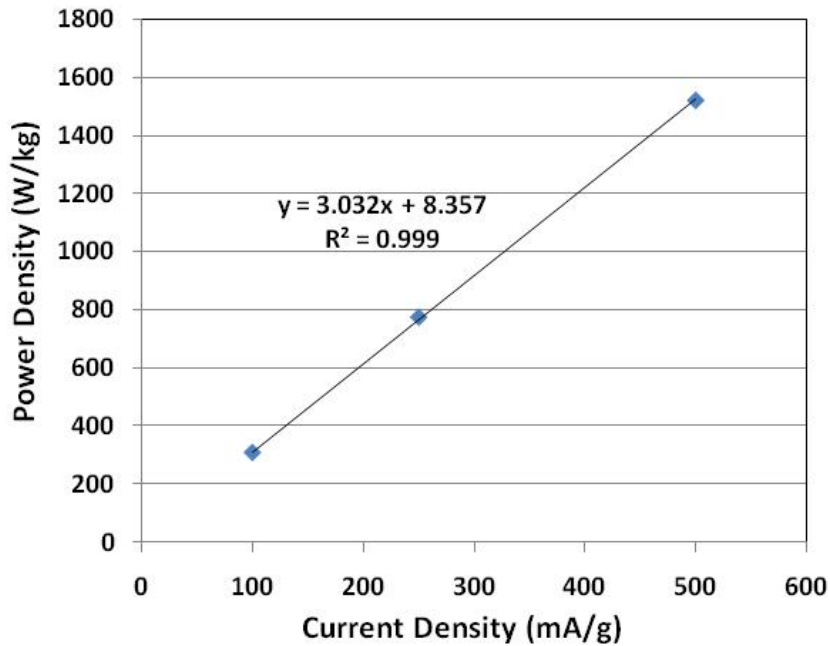
Initial Cycling of Si-AC Capacitor



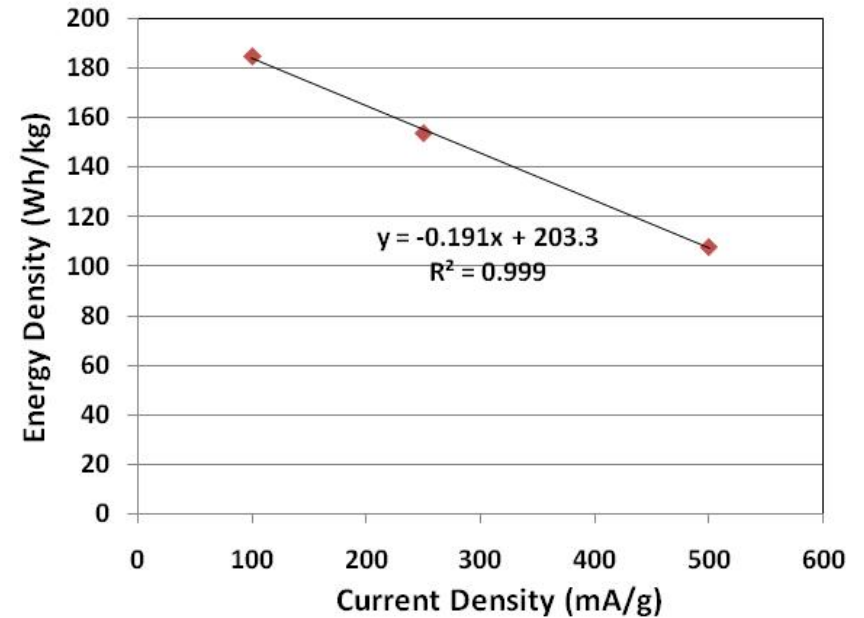


Rate Capability Cycling of Si-AC Capacitor

Power Density

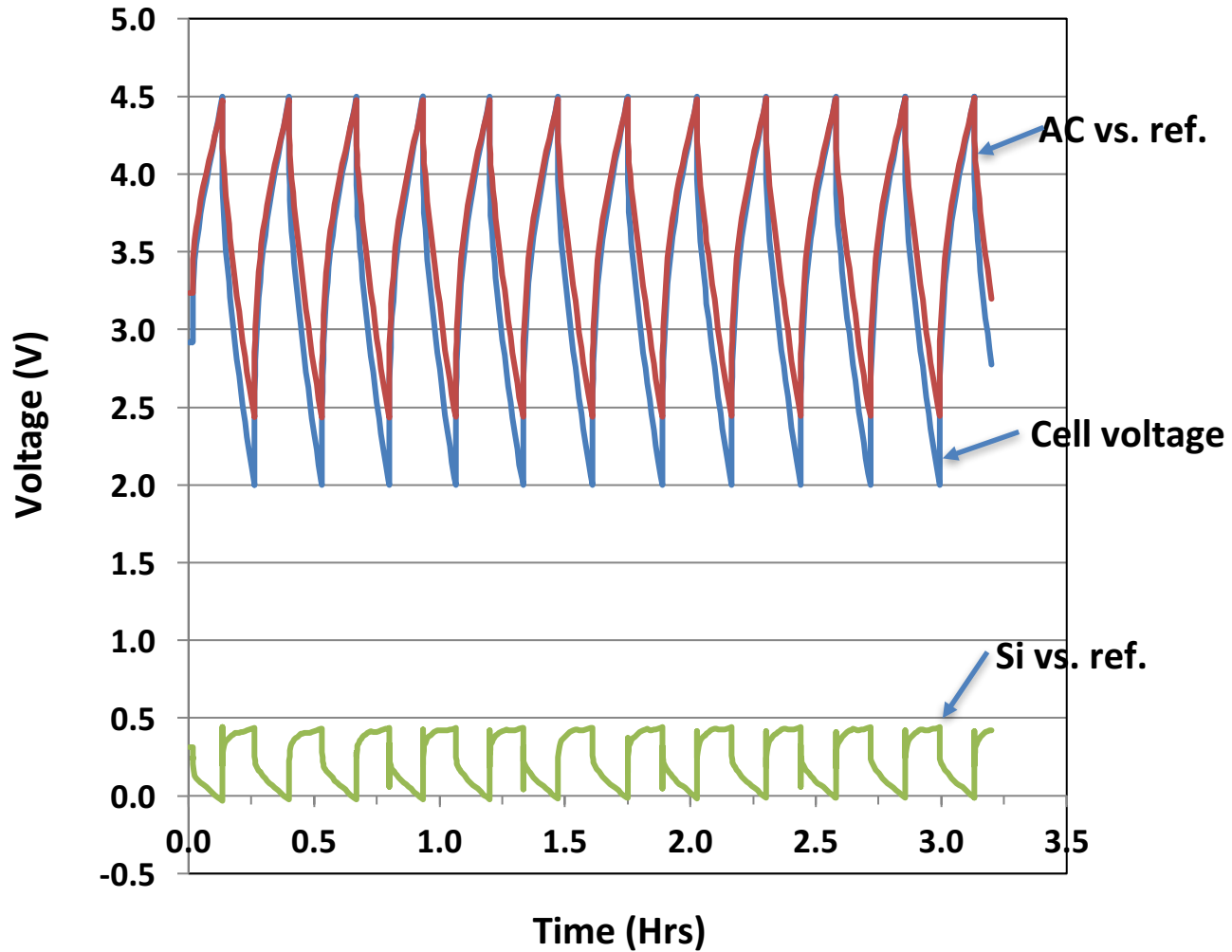


Energy Density





Voltage Profile of Individual Electrode in Si-AC Capacitor using Reference Electrode





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!