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^{o}C to 60^{o}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

- Storagenergy 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/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

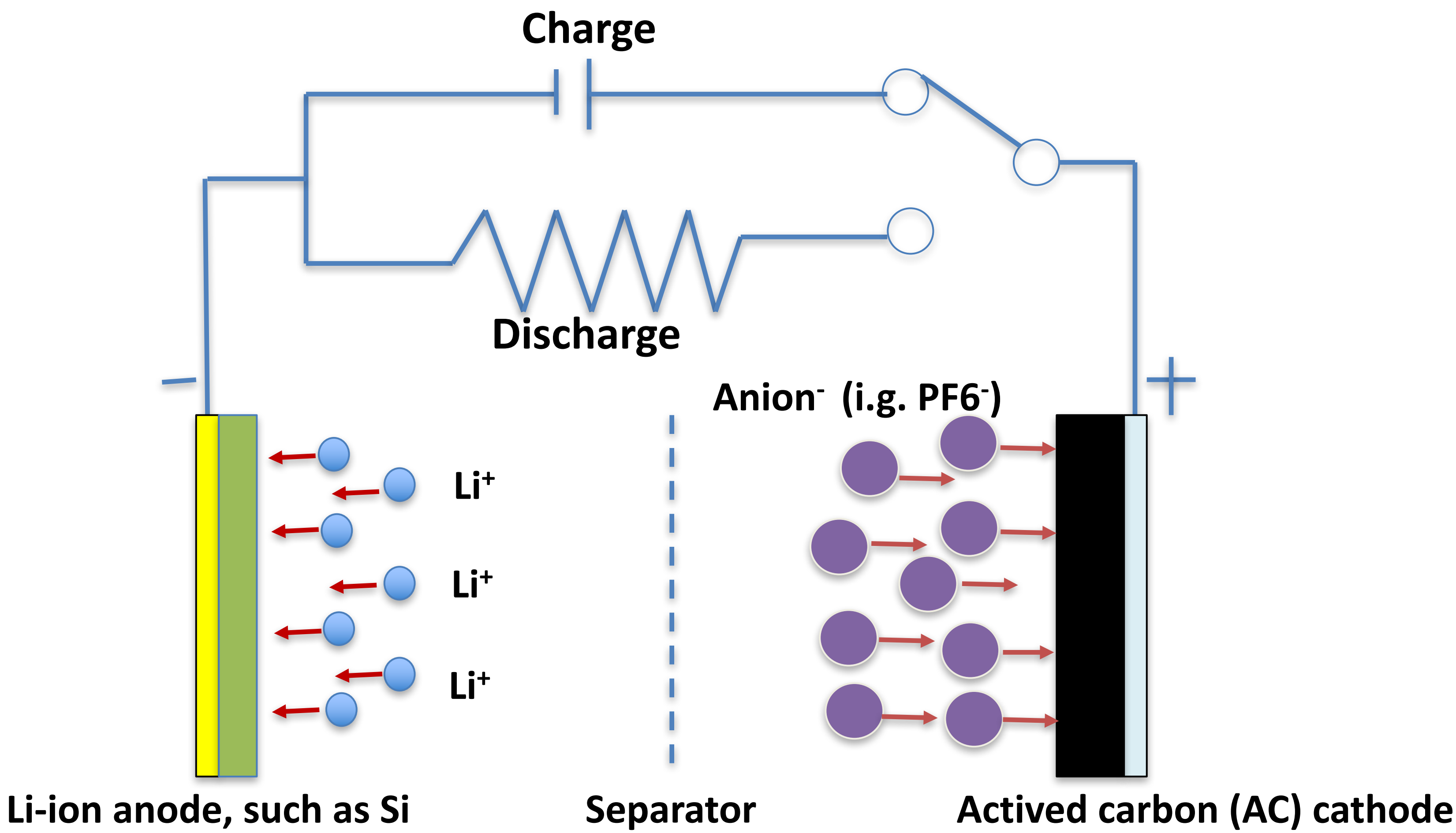
- One electrode (as cathode) from capacitor (i.e. active carbon w/high porosity and high surface area) undergoes electrostatic interaction

- 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

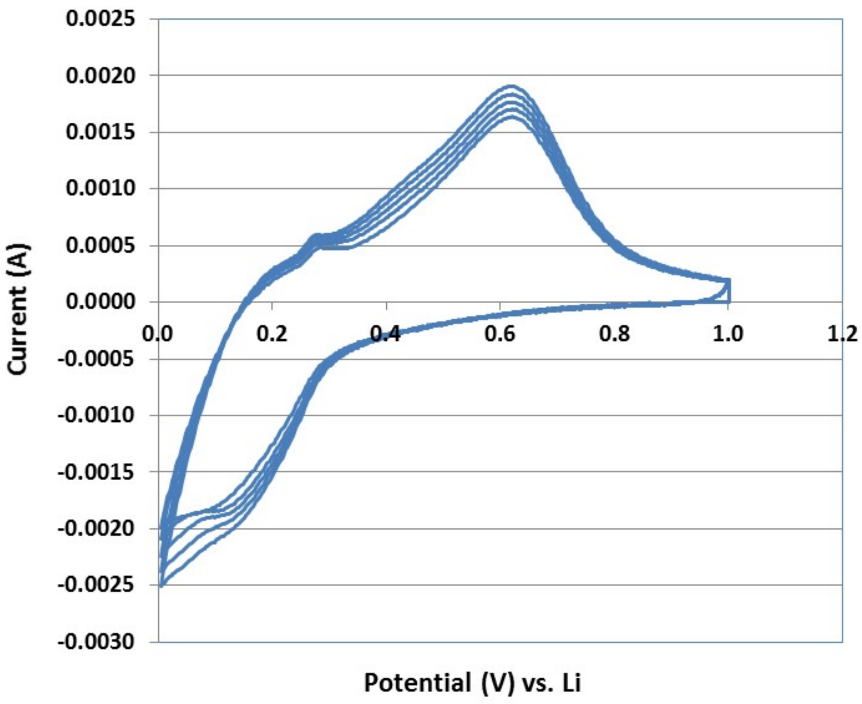
Si-Based Li-ion Capacitor



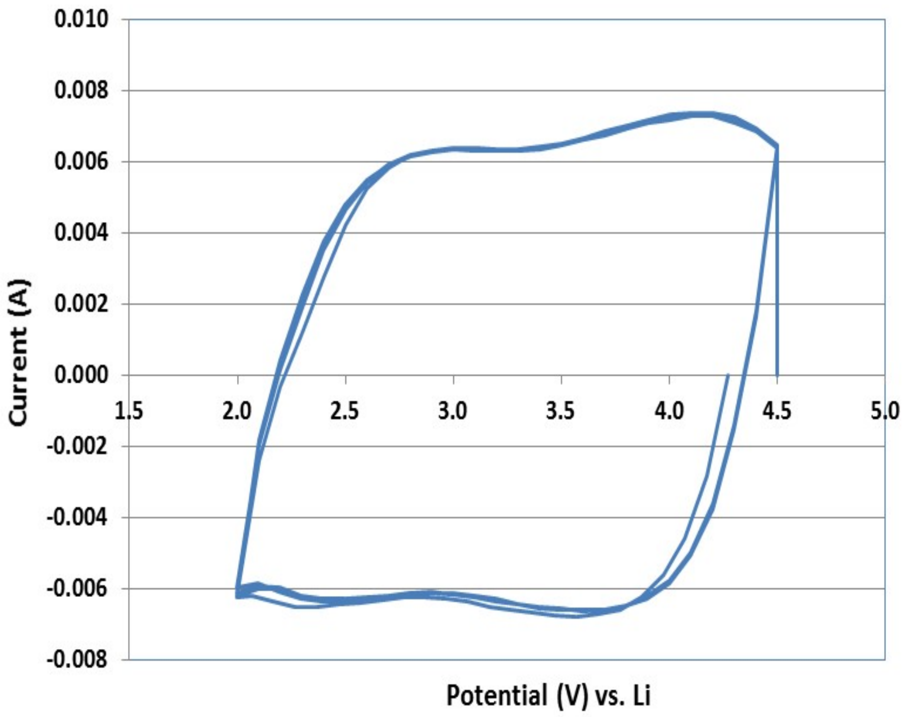
Electrolyte: 1M $LiPF_6$ in EC:DEC:DME (2:1:2) w/10% FEC

Cyclic Voltammetry of Individual Electrode in Half-Cell

Si Anode

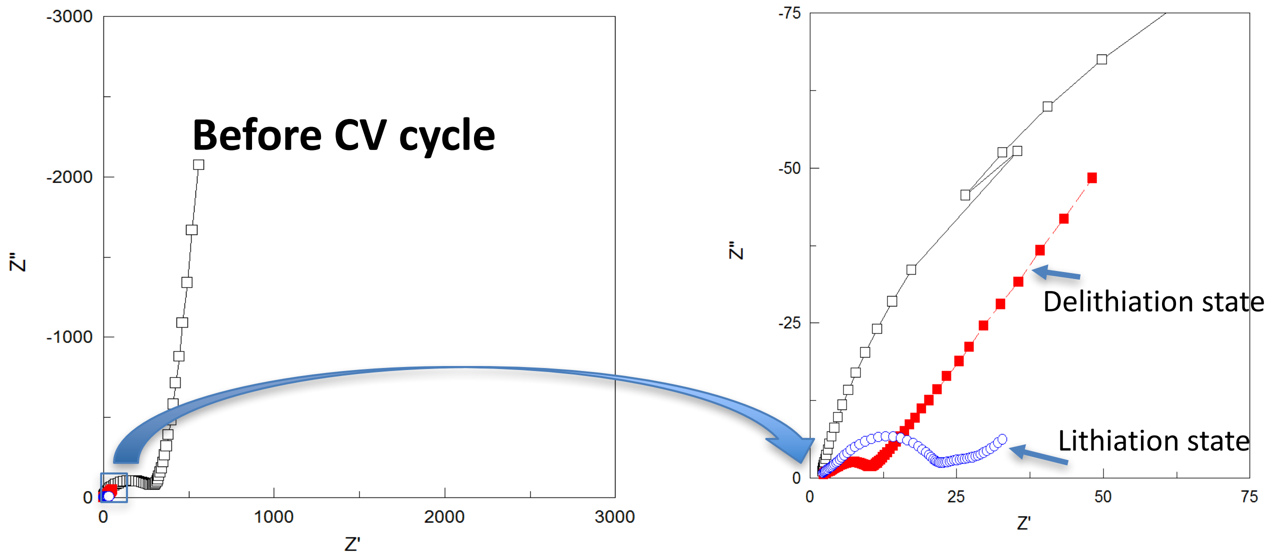


AC Cathode

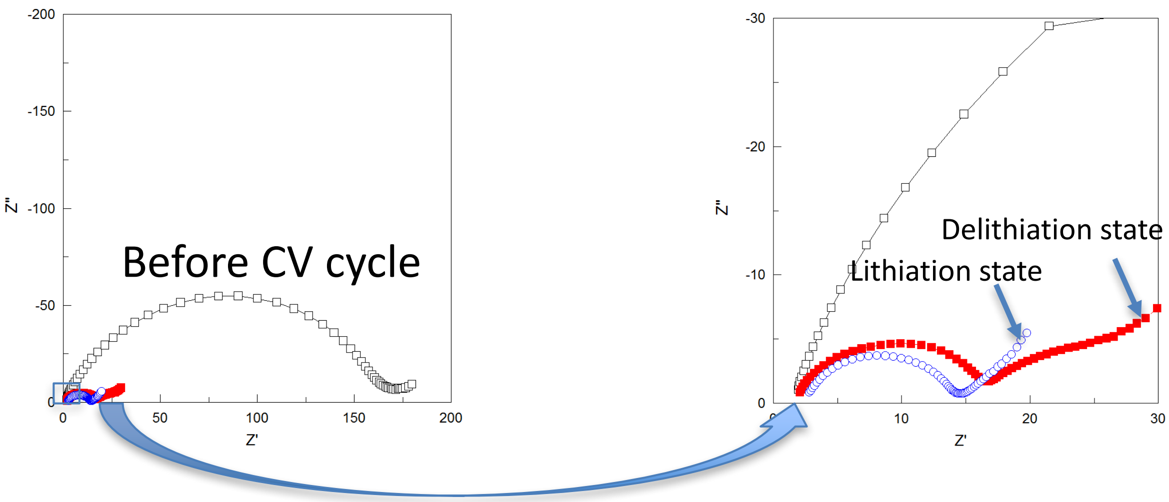


Impedance of Individual Electrode in Half-Cell

Si anode

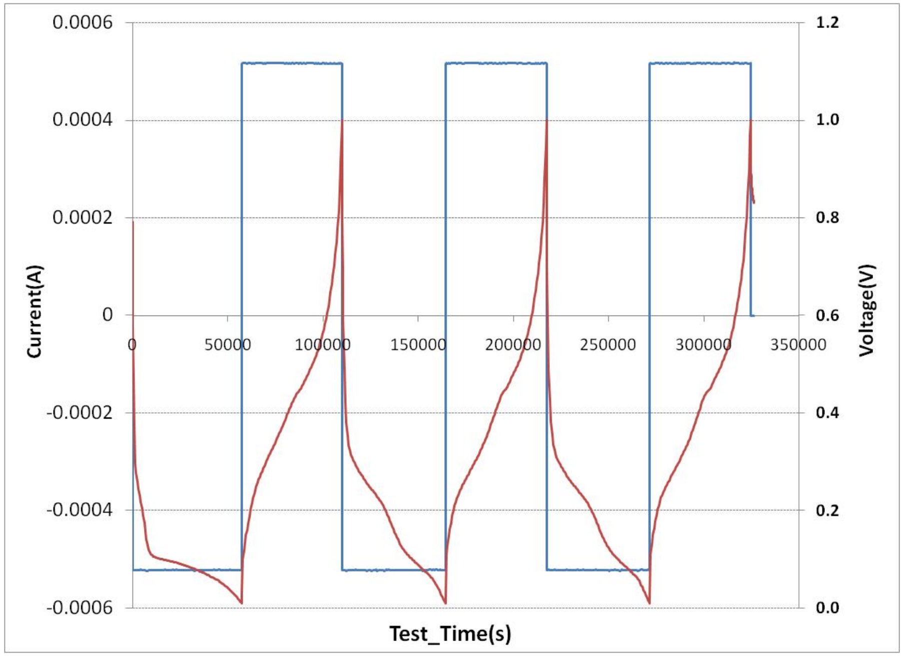


AC Cathode



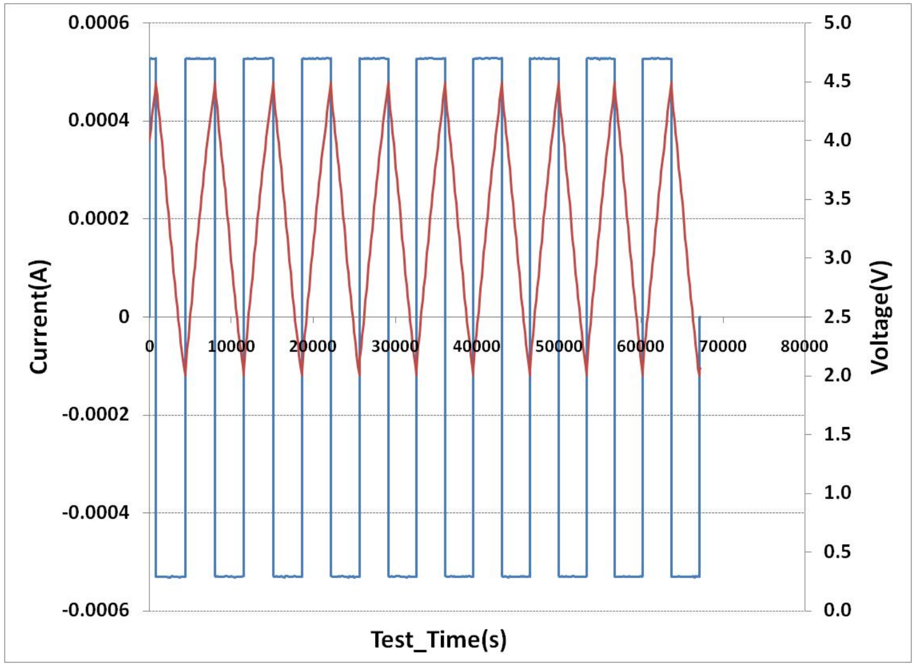
Initial Cycling of Individual Electrode in Half_Cell

Si Anode



0.01V – 1V

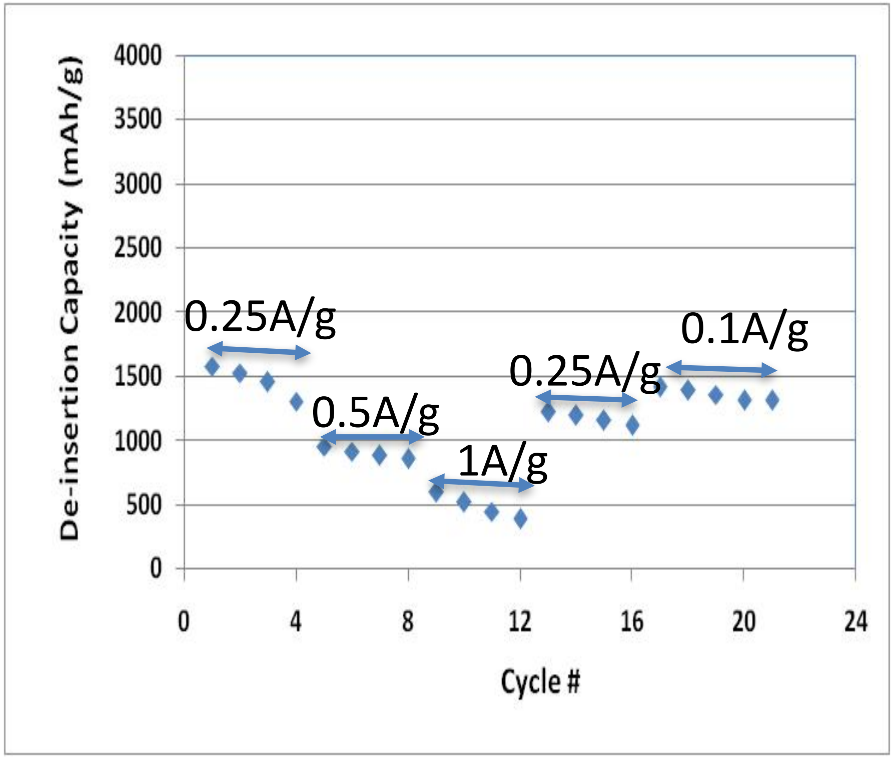
AC Cathode



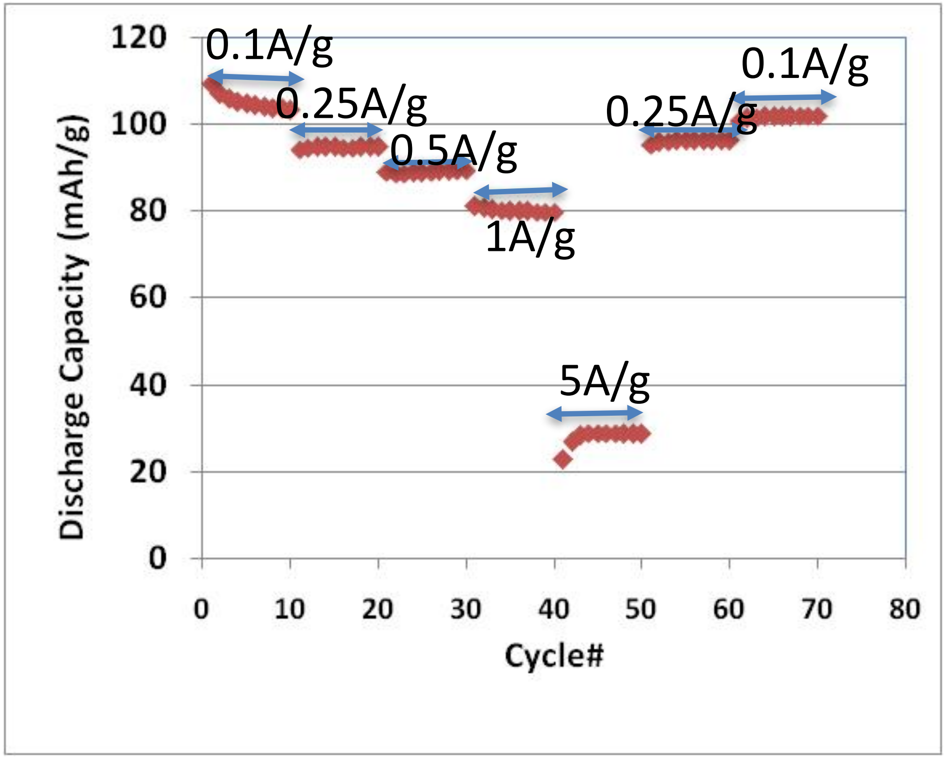
2V – 4.5V

Rate Capability Cycling of Individual Electrode in Half-Cell

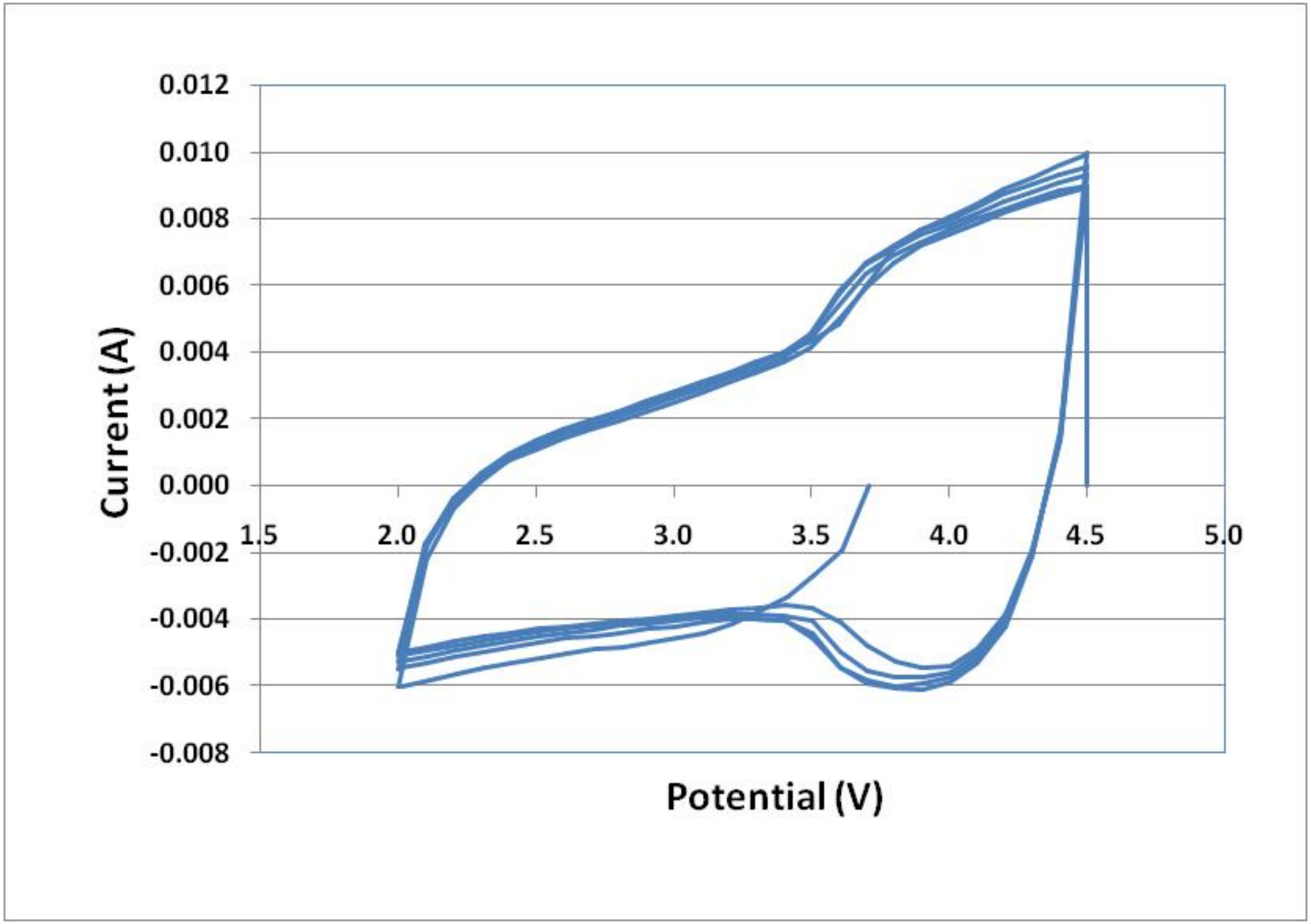
Si Anode



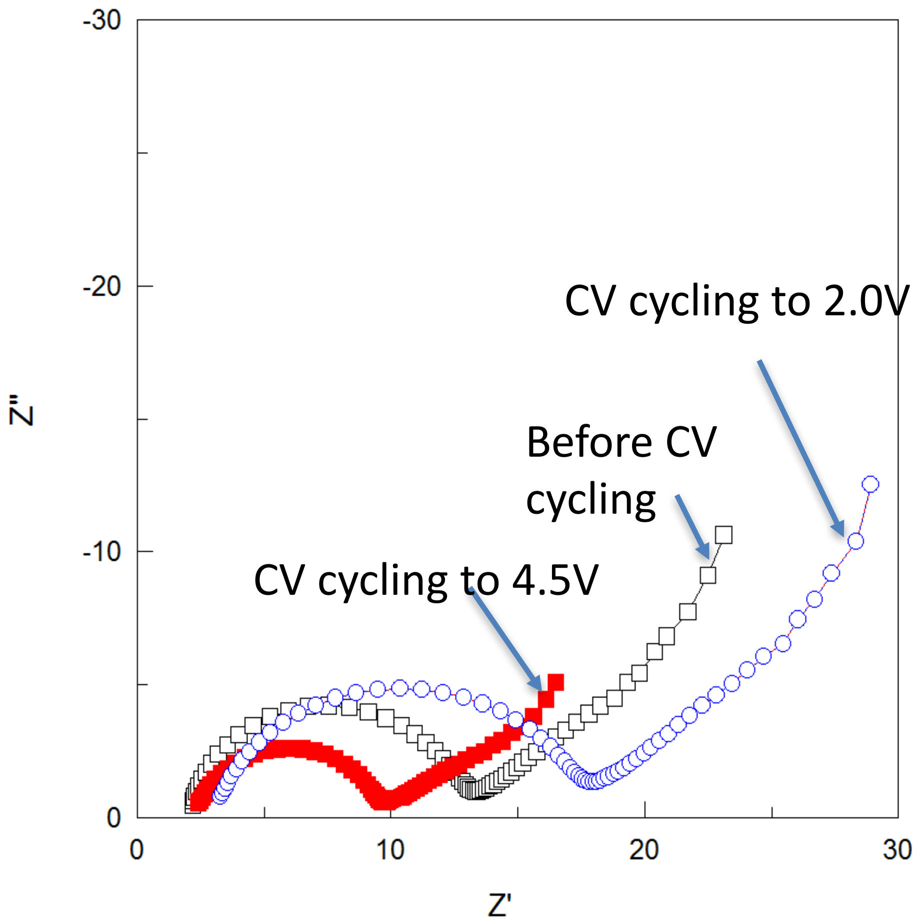
AC Cathode



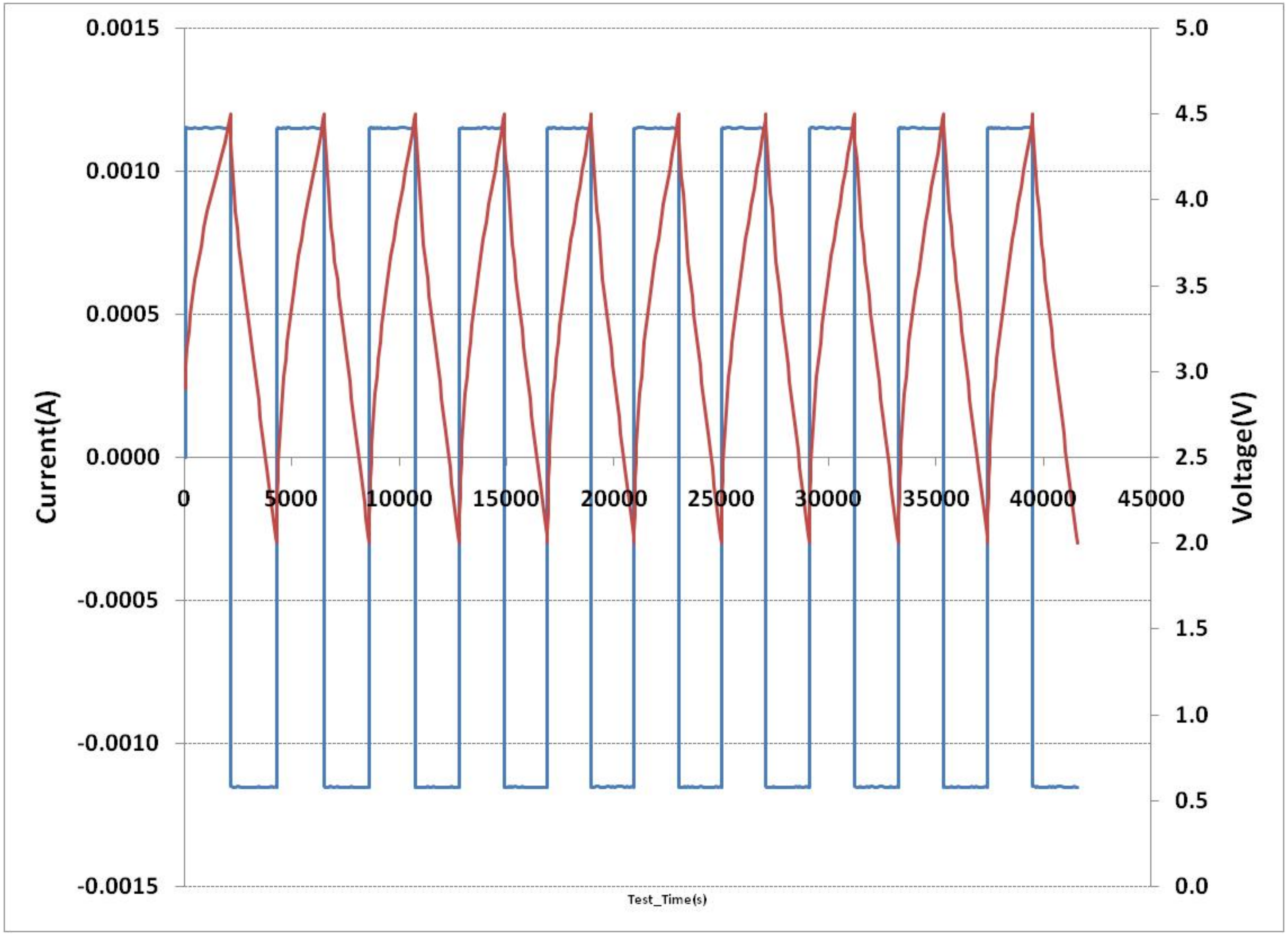
Cyclic Voltammetry of Si-AC Full Cell Capacitor



Impedance of Si-AC Full Cell Capacitor

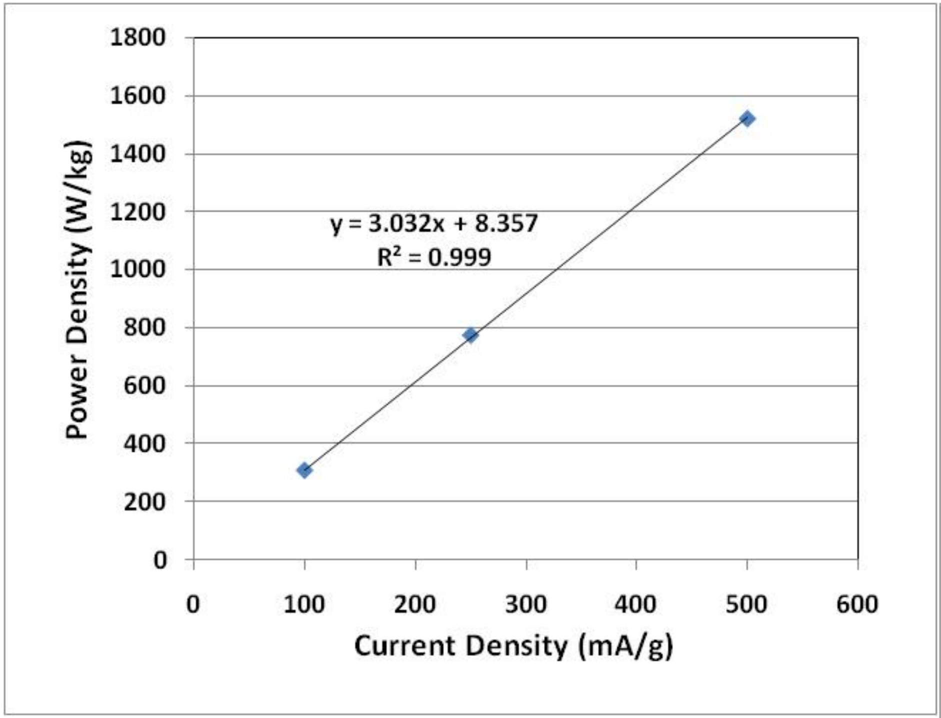


Initial Cycling of Si-AC Capacitor

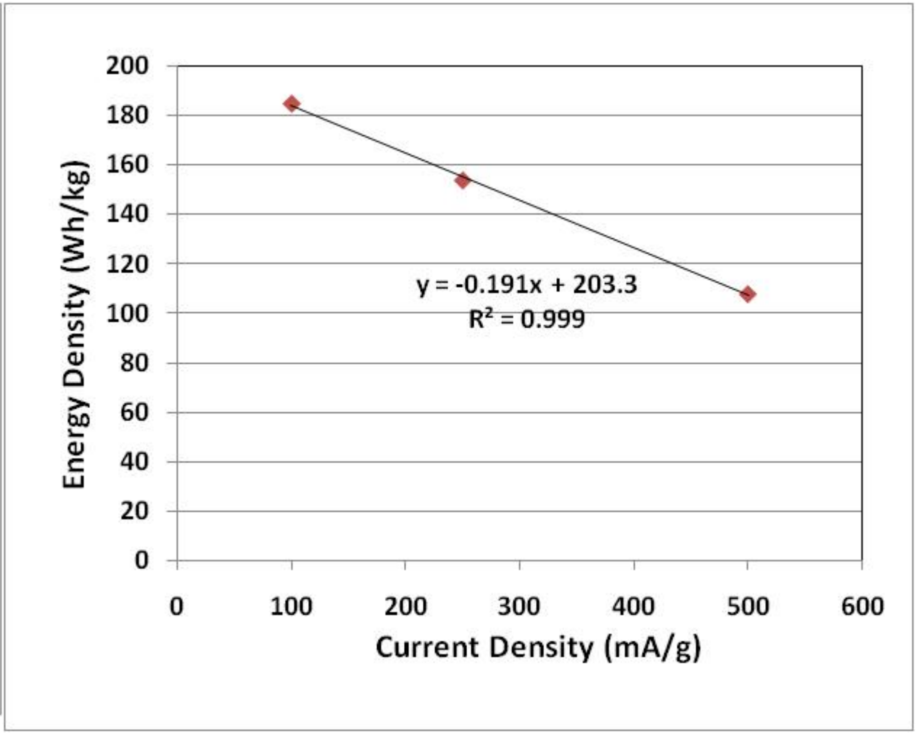


Rate Capability Cycling of Si-AC Capacitor

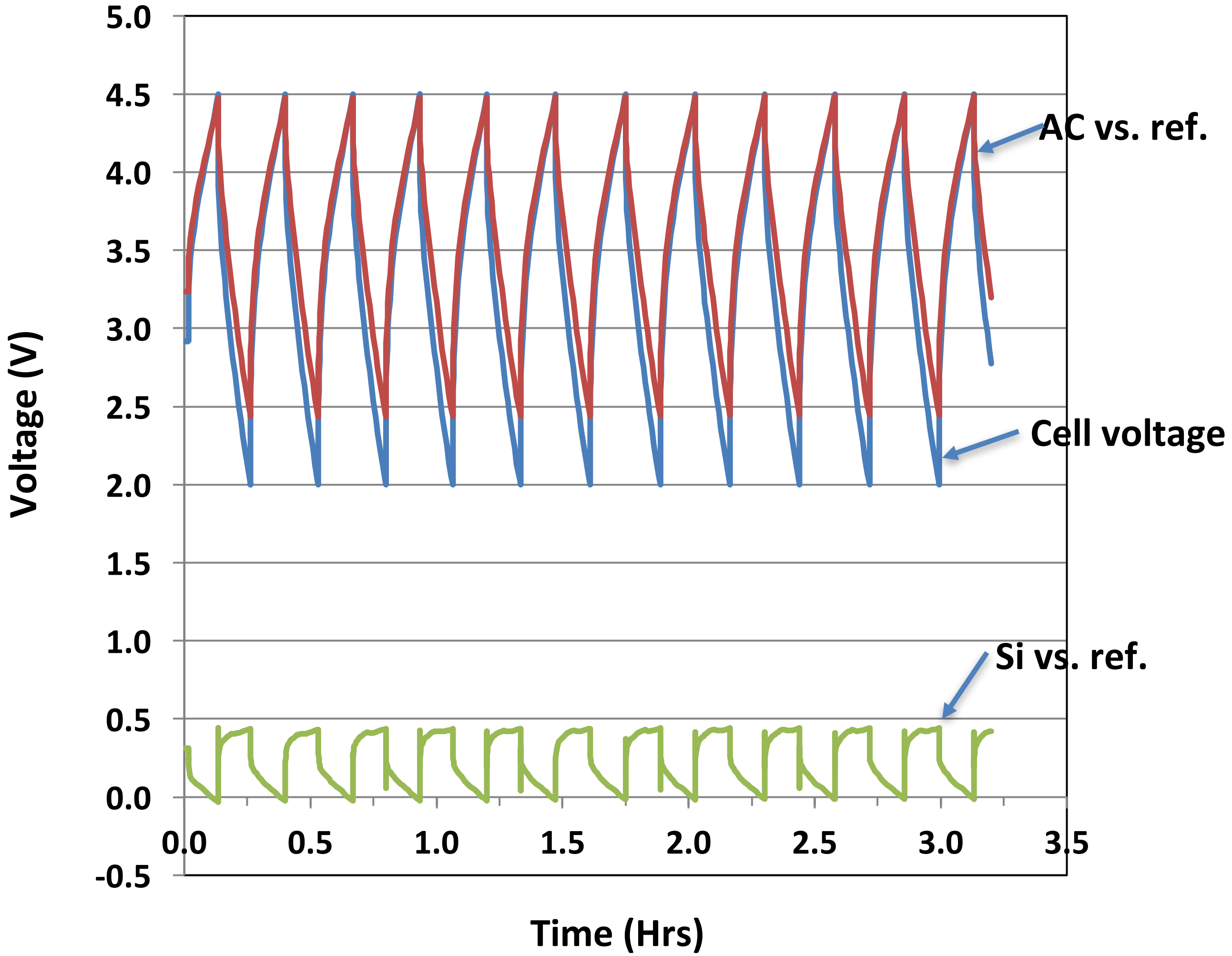
Power Density



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 applid 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!