HIGH ENERGY ANODE MATERIAL DEVELOPMENT FOR LI-ION BATTERIES

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SiNode Systems, Inc.

DOE Annual Merit Review

June 7, 2016

ES240

Overview

Timeline

- Project start date: August 2014
- Project end date: July 2016
- Percent complete: 83%

Barriers

- Barriers addressed
  - Performance (energy, power)
  - Life (cycle and calendar)
  - Cost ($/kWh)

Budget

- Total project funding: $1M
- Funding received in FY15: $500k
- Funding for FY16: $417k

Partners

- Interactions/collaborations
  - Northwestern University: characterization
- Project lead
  - SiNode Systems

Relevance – Project objectives

- **Goal/Objective:**
  - Develop a high capacity Si-C based anode that can exceed DOE performance targets when paired with commercial cathode materials
  - Further optimize its manufacturability to meet commercially viable production protocols.

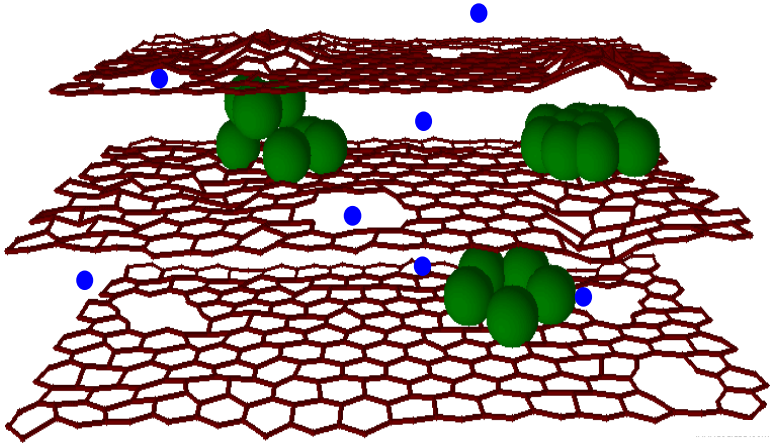
- **End performance targets:**
  - 200 Wh/kg cell energy, 1000 cycles
  - 750~1500 mAh/g anode, 1000 cycles

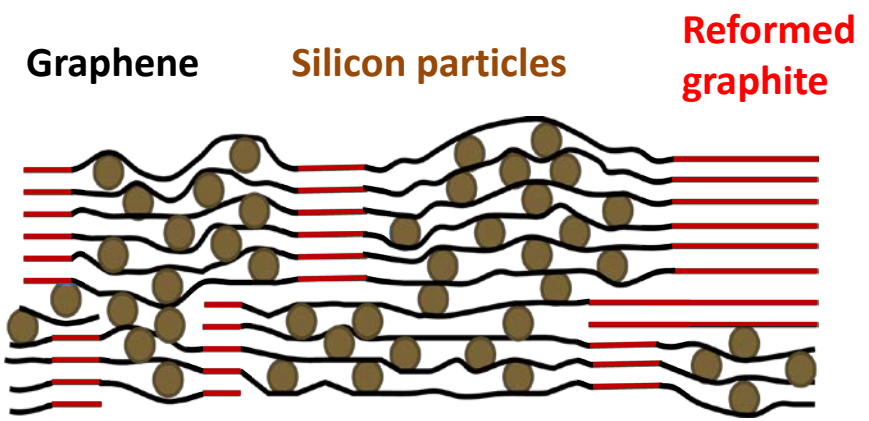
- **Year 2 Deliverables**
  - Cycling performance of a 1 Ah SiNode anode with high-energy cathode
  - Comprehensive report on current failure modes
  - Revised cost estimate on unit of SiNode material ($/kWh)
  - Roadmap to reduce costs to DOE target

Milestones (Phase II Year 2)

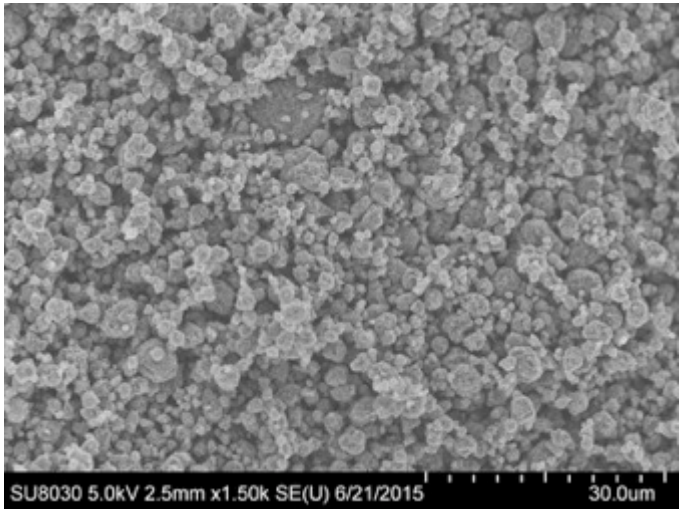
Date	Milestone	Status
November 2015	Complete transition to spray-dry processing technology	Complete
	Complete graphene structure modification results	Complete
	Increase solids content and loading	Complete
February 2016	Complete graphene oxide reduction effects analysis	Complete
	Identify improved electrolyte to increase energy and cycle life	Complete
	Design and build single-layer prototype cells	Complete
May 2016	Conduct pilot scale-up trials for powderization	On Schedule
	Complete analysis of scalable GO reduction methods	On Schedule
	Design and build updated prototype cells	On Schedule
August 2016	Complete pilot line design for industrial manufacturability	On Schedule
	Complete YR2 design and final cell build deliverable	On Schedule
	Finalize DOE Phase II testing report (w/ cost projections)	On Schedule

Approach: 3-D graphenic architecture





- ✓ Silicon particles wrapped in flexible, conductive graphene shell
- ✓ Engineered void space accommodates silicon expansion during lithiation
- ✓ Customizable micron sized particles
- ✓ Drop-in replacement for existing anode materials



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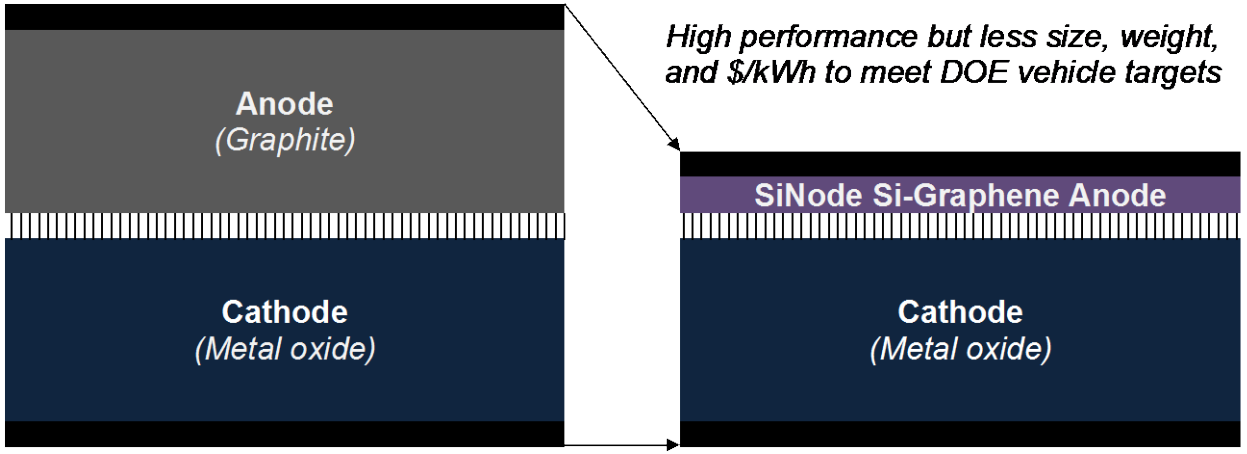
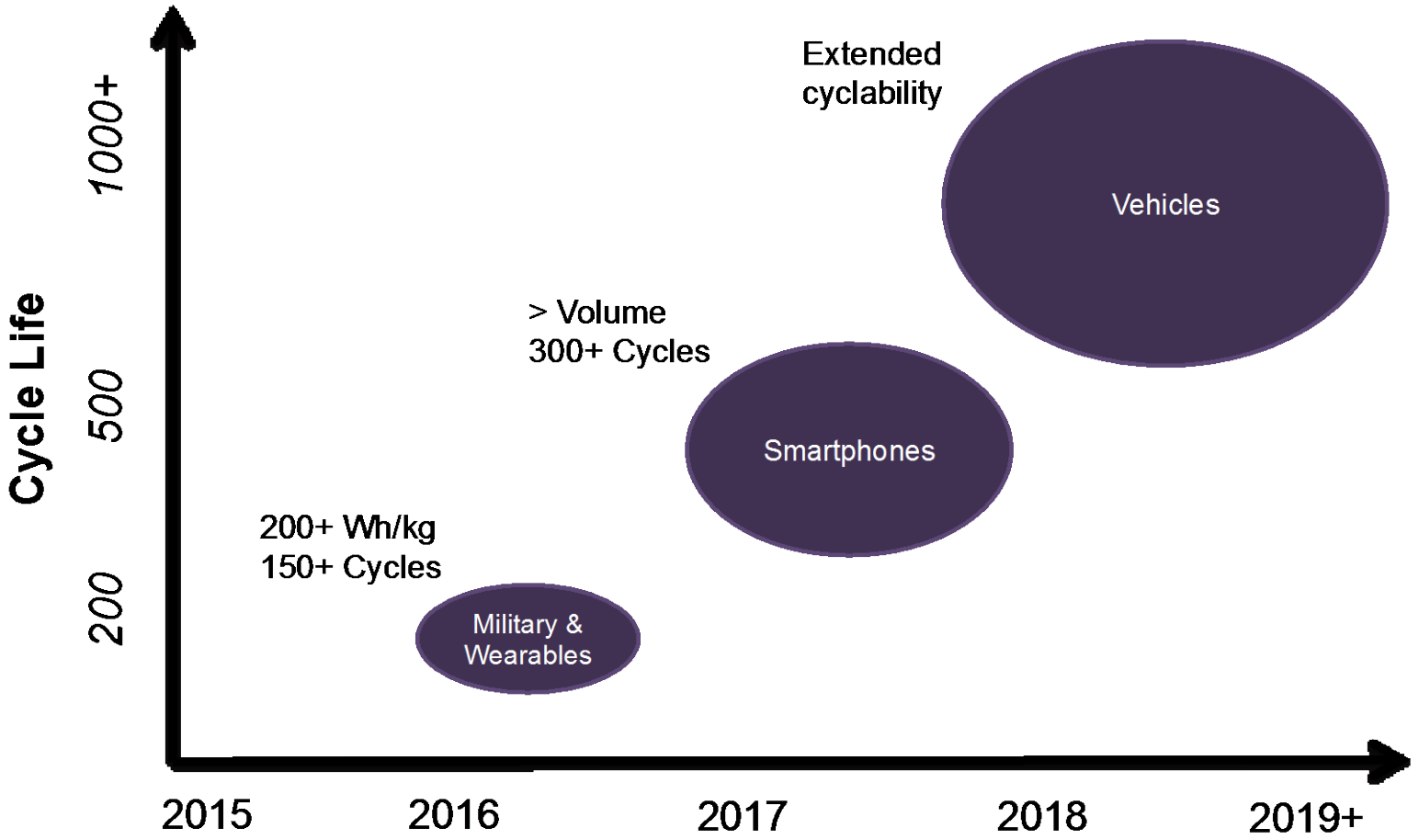
Approach: Value proposition



	Current Li-Ion Battery	SiNode Powered Battery
Cell Capacity	2 Ah	2 Ah
Anode Capacity	350 mAh/g	>2000 mAh/g
Anode Mass	6 g	1 g
Anode & Cathode Mass	17 g	12 g
Cost	$400-$500 / kWh	<$150 / kWh (Projected)

Approach: Staged market penetration



Production: Lab Prototypes → Pilot Scale → Large Scale

Funding: SBIR, Angels → SBIR, VC → Corporate Partner, PE

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Technical Accomplishments: Overview

- ✓ Rational selection of silicon materials and design has extended cycle life by >100%
- ✓ Formulation developments have further improved electrochemical characteristics (CE, specific capacity, surface area)
- ✓ Production process has been scaled by 1000X without performance degradation
- ✓ Sourcing inexpensive raw materials from multiple vendors has decreased costs by 10X and paved path to achieve USABC 2025 cost targets
- ✓ Preliminary thermal safety analysis demonstrates that silicon-graphene anode material is more thermally stable than conventional Si-C material
- ✓ Prototype failure analysis has driven development of improved anode processing

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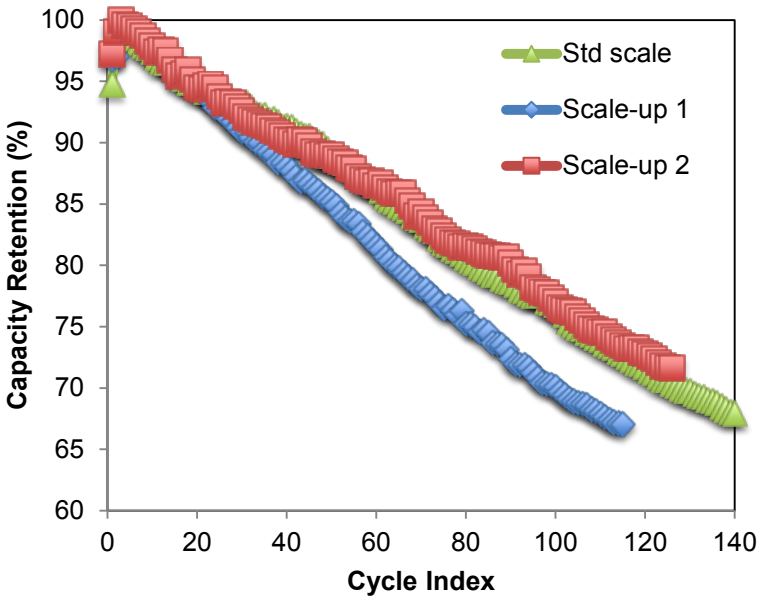
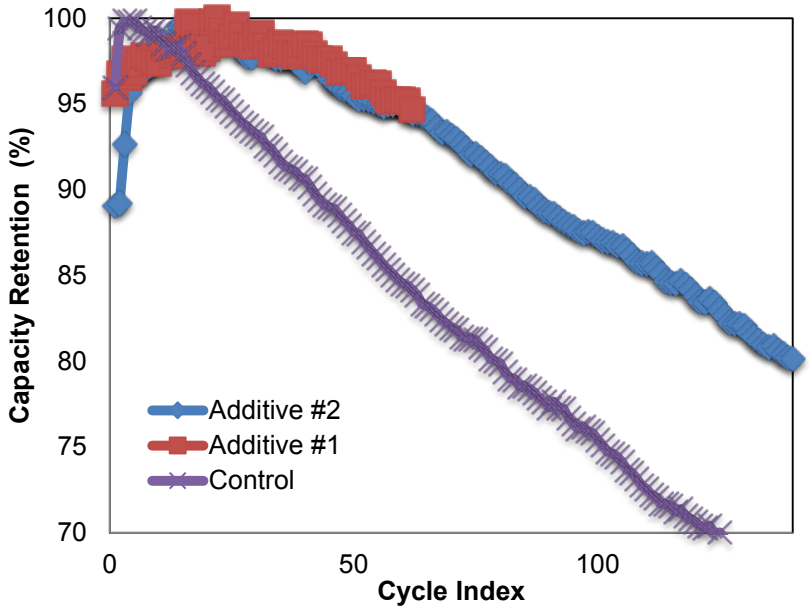
Technical Progress: Process improvements

Si-graphene system is responsive to process improvements and additives to improve manufacturability and electrochemical performance

- 1,000X scale-up was achieved without performance degradation
- Additives have been integrated into process to improve CE and cycle life

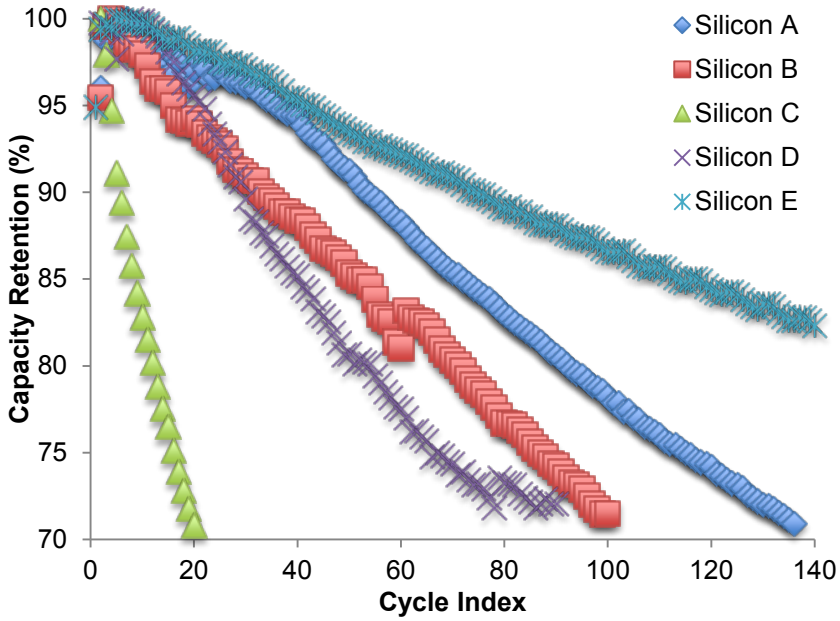


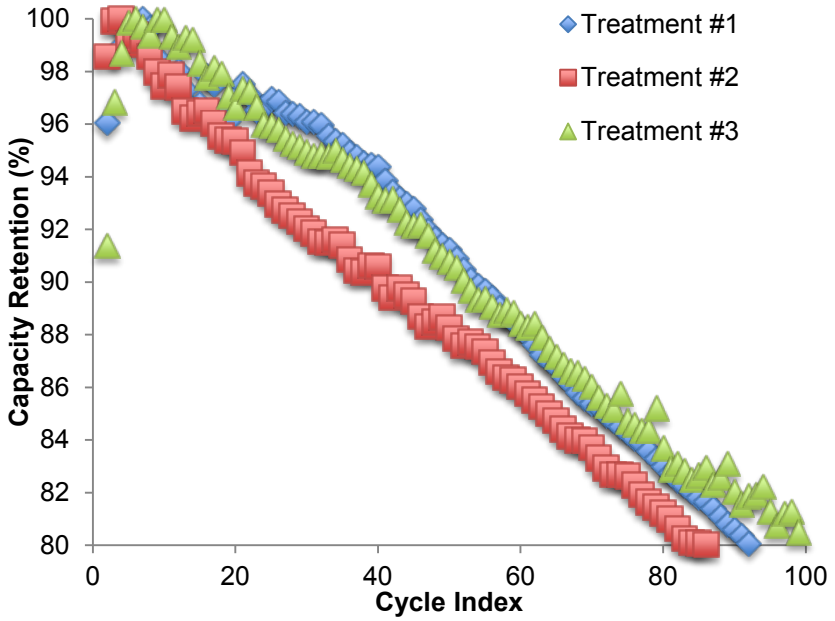


Ongoing studies include accelerated testing, failure mode analysis, and process optimization.

Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

Technical Progress: Advanced active material development



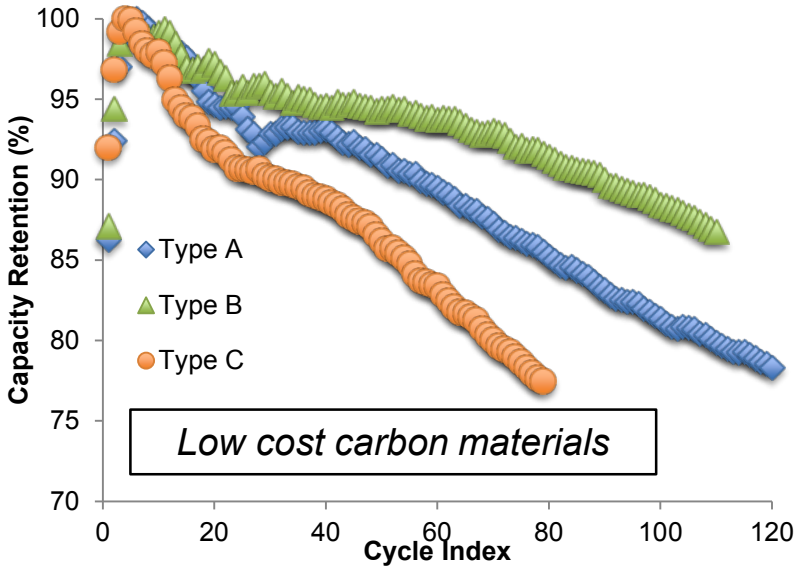


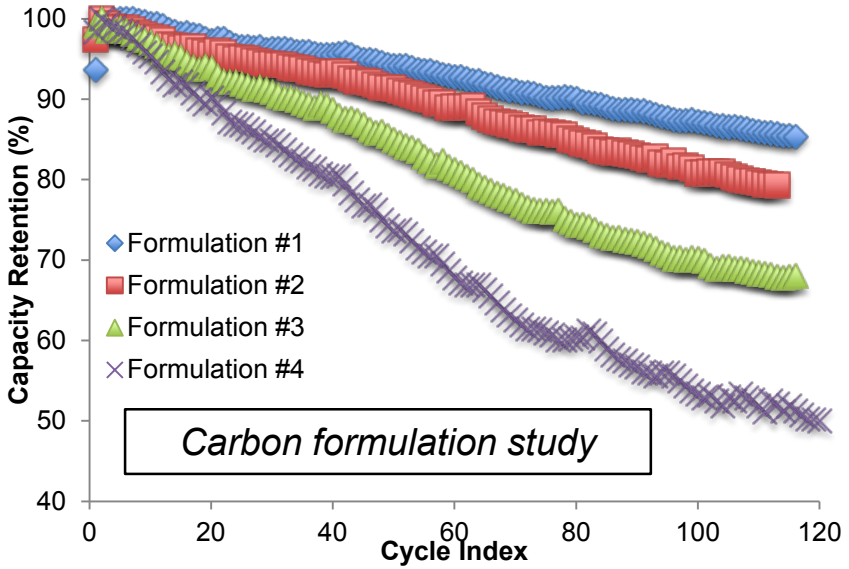
- Scalable surface treatments improved cycle life and specific capacity values
- Tuning silicon structural properties (size, morphology, crystallinity, etc) was used to optimize capacity, cycle life, and ICL values in Si-G composite materials

Advanced processing of active material particles and surface treatments were effective at increasing cycle life by >100% while still achieving high specific capacity

Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

Technical Progress: Materials sourcing for cost reduction



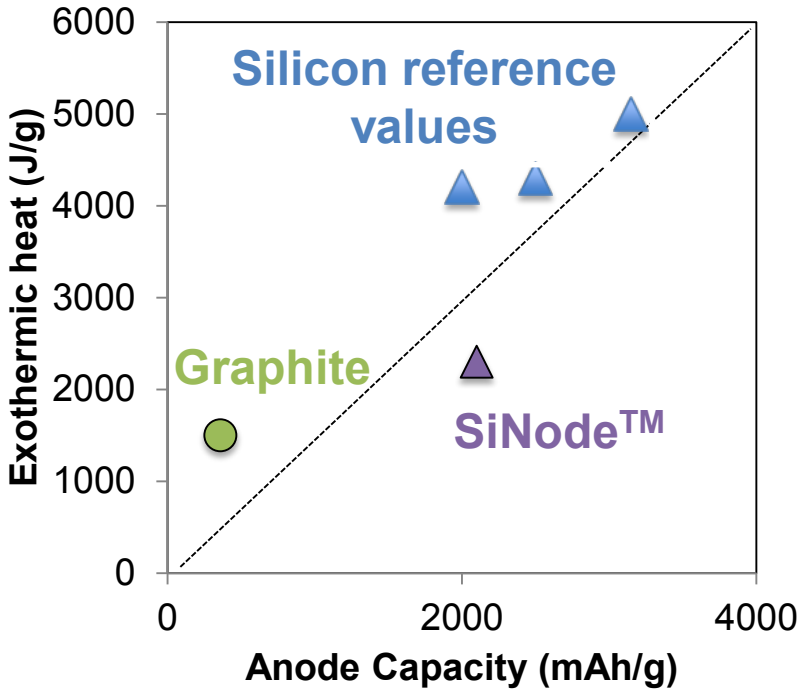


- 10+ alternative carbon/graphene sources were examined from various suppliers
- Multiple high-volume alternative carbon sources with good electrochemical stability were identified
- Alternative materials have opportunity to decrease costs by 10X
- Roadmap to reduce costs to USABC 2025 target ($125/kWh) has been identified

Integrating commercial suppliers and sourcing from multiple vendors have further significantly decreased costs and increased scale

Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

Technical Progress: Safety testing



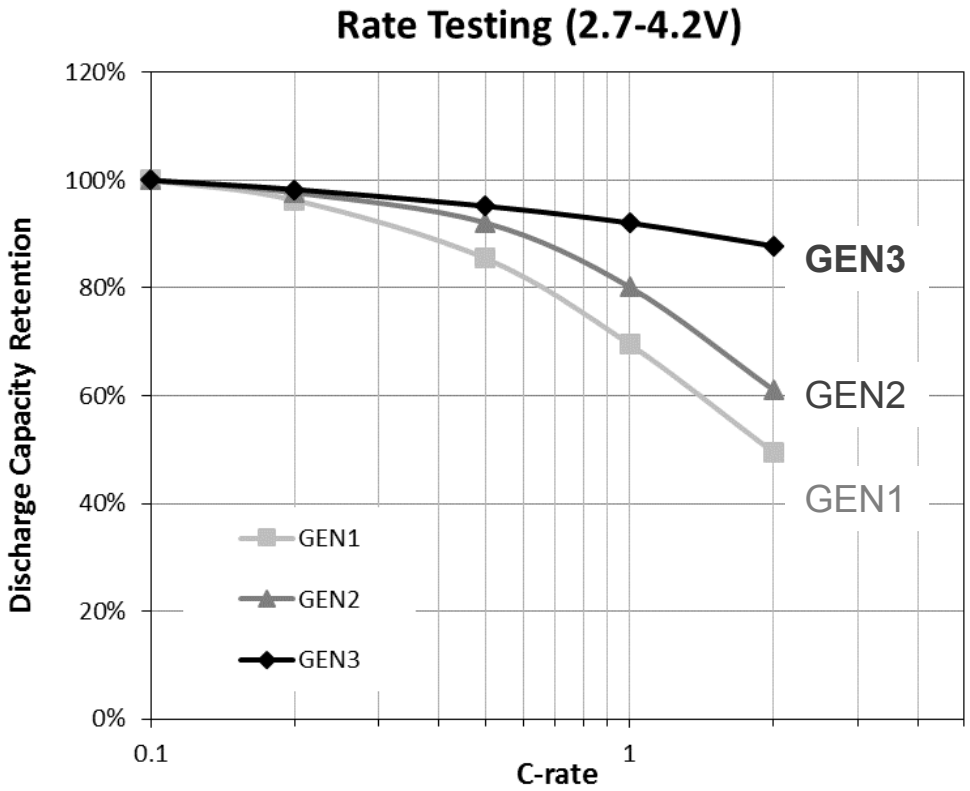
- Differential scanning calorimetry (DSC) was performed on fully-lithiated Si-graphene materials at 3rd party facility
- SiNode's Si-graphene material are more thermally stable than other Si-C composites

Silicon-graphene anode material offers combination of high capacity and high thermal stability

Technical Progress: Prototype high rate performance

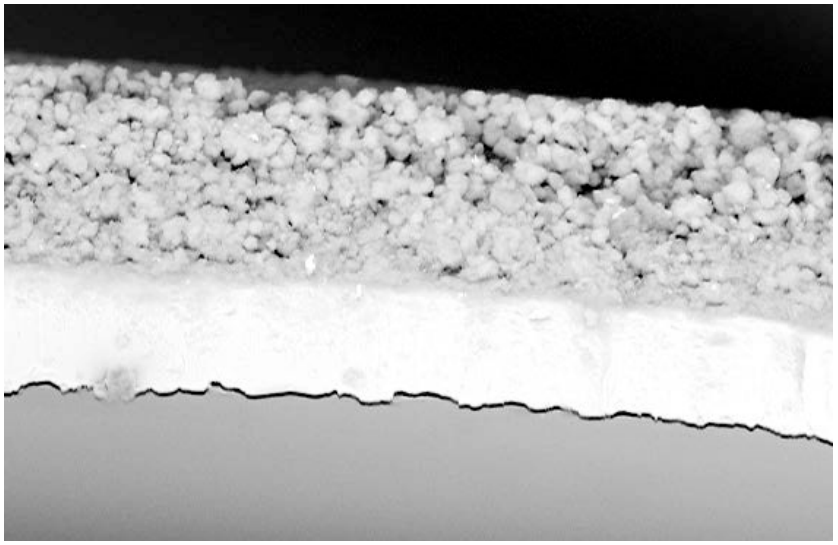
- High rate performance has improved between prototyping generations

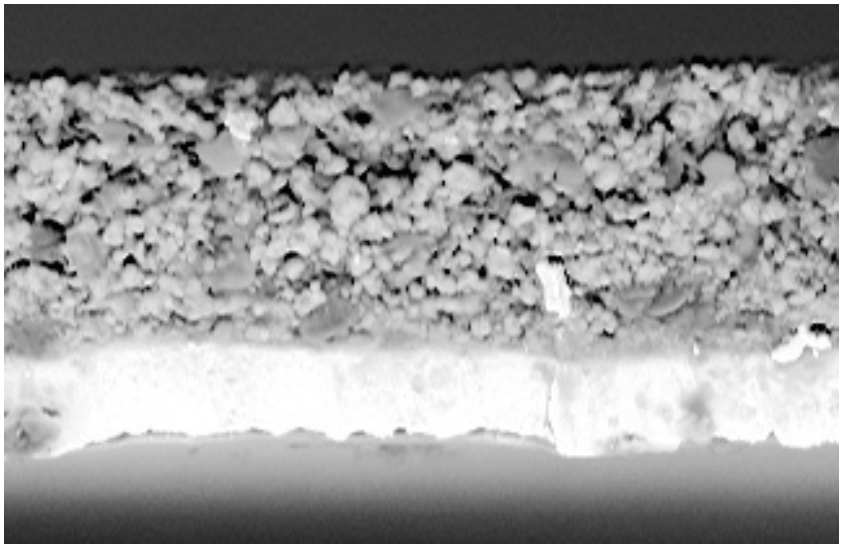
Silicon-graphene anode rate response is comparable to graphite (with similar electrochemical loading)



NCA cathode, ~20 mAh pouch cell, data collected at Navitas Systems

Technical Progress: Electrode formulation





- Aqueous slurry prepared using poly acrylic acid-based binder
- Cross-sectional SEM demonstrates uniform coatings were achieved
- High consistency across samples and replicates
- Electrodes exhibit good adhesion properties with no cracking

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Responses to Reviewer Comments

- ***Recommend using binding agent to keep electrode attached to current collector to achieve cycle life goal***
  - Conventional binders have been integrated in order to achieve cycle life goal.

- ***More focus on methods to improve cycle life should be included; and …scale-up work is also very important and not covered in much detail***
  - Additional focus on materials development has been undertaken to address cycle life improvements.
  - 1000X scale-up has been accomplished and results are included in presentation.

Collaborators

Partner	Purpose
NORTHWESTERN UNIVERSITY	▪ Sample characterization ▪ Analytical work ▪ Materials treatments
MERCK	▪ Materials supply ▪ Assess manufacturing costs ▪ Sample characterization

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Remaining challenges & barriers

Performance characteristics & cycle/calendar life

- Prototypes with longer cycle life (>500 cycles) and high energy required for commercialization
- Current materials do not yet exceed DOE/USABC 2020 goals for commercialization

Cost

- Supply chain, active material formulation, and scale-up manufacturing required to achieve long-term cost targets

Safety testing

- Comprehensive safety testing on prototype cells required to determine characteristics

Proposed future work

FY15

- **The project is scheduled to end in July 2016**

- **Anode development**
  - Finalize anode formulation, sourcing, and processing
  - Conduct pilot scale-up trials for powderization
  - Complete analysis of scalable GO reduction methods

- **Prototype cells**
  - Develop optimized cell design and electrode loading
  - Complete YR2 design and final cell build deliverable
  - Finalize DOE Phase II testing report with cost projections

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Summary

- ✓ SiNode is developing a Si-C anode that can exceed DOE performance targets when paired with conventional cathode materials
- ✓ Unique structure provides improved Si environment for extended cycling
- ✓ Materials sourcing, treatment, and processing steps have been examined in order to improve electrode cyclability
- ✓ Surface coatings and processing provides greatest opportunity for improvements
- ✓ Inexpensive raw materials can be easily integrated into existing processing
- ✓ Future work focuses on extending prototype cyclability, materials formulation & scale-up, and safety testing

THANK YOU