Multi-Functional Cathode Additives for Li-S Battery Technology

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Brookhaven National Laboratory
2016 Annual Merit Review
June 9, 2016

Project ID # ES281

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline
• Project start Oct. 2014
• Project end Sept. 2017
• 50% complete

Barriers
• Performance: Low Wh/kg (or L) & W/kg (or L)
• Cycle life: Poor cycle life
• Cost: High $/kWh

Budget
• Total project funding
  - FY 2015 $500K
  - FY 2016 $500K

Partners
• Brookhaven National Laboratory (BNL) (lead)
• Stony Brook University
Project Objectives

- Develop high energy Li-S batteries for HEV/PEV/EV applications and reduces the cost associated with batteries.
- Achieve long cycle life of Li-S battery by increasing the sulfur cathode conductivity with transition metal sulfides as multifunctional cathode additives (MFCA).
- Optimize the chemical and physical properties of selected MFCA for high sulfur utilization and long Li-S cell cycle life.

Project Relevance

- Our project objectives are aimed at addressing three barriers associated with today’s benchmark Li-ion batteries: high cost, lower energy density and short cycle life.
  - Li-S battery technology potentially may double the energy density and lower the battery cost.
  - Success development of MFCA will help to achieve long cycle life for Li-S battery.
## Milestones for FY 2015 and 2016

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestones</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>December, 2014</td>
<td><strong>Benchmark MFCA coin cells:</strong> Achieve &gt; 50% of theoretical capacity of MFCA upon activation</td>
<td>Completed</td>
</tr>
<tr>
<td>March, 2015</td>
<td><strong>Benchmark S coin cells:</strong> Achieve 1st cycle utilization of cathode comparable to literature report (&gt; 50% of theoretical capacity of Li$_2$S and S) upon activation</td>
<td>Completed</td>
</tr>
<tr>
<td><strong>June, 2015</strong></td>
<td><strong>Go/No-Go</strong></td>
<td>Completed</td>
</tr>
<tr>
<td><em>Go/No-Go</em></td>
<td><strong>Concept demonstration:</strong> Achieve Li$_2$S or S efficiency &gt; 60% theoretical in the presence of MFCA for hybrid cathode</td>
<td>Completed</td>
</tr>
<tr>
<td>September, 2015</td>
<td><strong>Synthesis of the selected MFCA (FeS$_2$ and TiS$_2$)</strong></td>
<td>Completed</td>
</tr>
<tr>
<td>December, 2015</td>
<td><strong>Lab prepared TiS$_2$ and FeS$_2$ testing in hybrid cathode:</strong> Achieve equal or better cathode utilization vs. the control with commercial TiS$_2$ and FeS$_2$</td>
<td>Completed</td>
</tr>
<tr>
<td>March, 2016</td>
<td><strong>Go/No-Go</strong></td>
<td>Completed</td>
</tr>
<tr>
<td><em>Go/No-Go</em></td>
<td><strong>Obtain MFCA material with different PS and shape and testing in hybrid cathode:</strong> Achieve equal or better cathode utilization vs. the control with commercial MFCA.</td>
<td>Completed</td>
</tr>
<tr>
<td>June, 2016</td>
<td><strong>Binder selection:</strong> Achieve good electrode mechanical integrity with no delamination from Al foil and no loose particles.</td>
<td>On-schedule</td>
</tr>
<tr>
<td>September, 2016</td>
<td><strong>Cathode formulation optimization for maximized capacity density:</strong> Achieve &gt;500 mAh/g (S + Additive).</td>
<td>On-schedule</td>
</tr>
</tbody>
</table>
Approach/Strategy

Phase I – Material characterization and optimization

<table>
<thead>
<tr>
<th>FY 2015</th>
<th>FY 2016</th>
<th>FY 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
</tbody>
</table>

Q3 2015 – Successfully demonstrated sulfur-MFCA interaction

Q2 2016 – Improved cell cycling performance achieved for S:TiS$_2$ hybrid cathode

*Go/No-Go*

Benchmark Sulfur & MFCA Cells Establishment

Construct Sample Cells and Characterization

Hybrid Cathode Interaction demonstration Go/No-Go

Material, Process, Cell Design Optimization

Sulfur – MFCA Interaction Mechanism Understanding

Best MFCA Selection for Optimization Go/No-Go

Metal Sulfide Electronic Conductivity

Brookhaven Science Associates

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Accomplishments and Progress
Benchmark MFCA cell performance and activation

CuS cell cycling: 1.0V – 3.0V

FeS$_2$ cell cycling: 1.1V – 2.5V

TiS$_2$ cell cycling: 1.5V – 3.0V

A. Marschilok, K. Takeuchi, E. Takeuchi, Q. Zhang, C. Cama
Accomplishments and Progress
Benchmark Li$_2$S cell performance

- Li$_2$S cell activation requires electrolyte additives.
- 50% sulfur utilization in the presence of LiNO$_3$ and LiI at C/40.
- Fast capacity fade upon cycling at C/20.
Accomplishments and Progress
Benchmark sulfur cell performance – loading effect

- The initial sulfur utilization is sulfur loading dependent.
- Up to 53% theoretical capacity delivered in the initial discharge (882 mAh g⁻¹ S) for Li-S cells at C/5 rate.
- Activation required for high sulfur loading cells (2+ mg/cm²).

Helen Liu, Ke Sun, Hong Gan, “The effects of carbon type and cathode loading on Li-S battery performance”, Poster at 2015 American Institute of Chemical Engineers (AIChE) Annual Meeting, Nov. 8-13, 2015.
Accomplishments and Progress

Concept demonstration – Sulfur/CuS interaction

- Sulfur reacts with Cu$_2$S at RT to form nano-structured flake CuS crystals.
- With excess Cu$_2$S:S ratio > 1.0, 100% of sulfur utilization can be achieved (3.0V to 1.8V at C/10 rate).
- Low sulfur utilization observed when Cu$_2$S:S ratio < 1.0.
Accomplishments and Progress
Sulfur cell discharge rate and sulfur-MFCA interaction

<table>
<thead>
<tr>
<th>MFCA</th>
<th>Sulfur%</th>
<th>MFCA%</th>
<th>Carbon%</th>
<th>PVDF%</th>
<th>S Utilization (1C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>45</td>
<td>0</td>
<td>45</td>
<td>10</td>
<td>24%</td>
</tr>
<tr>
<td>CuS</td>
<td>45</td>
<td>15</td>
<td>30</td>
<td>10</td>
<td>54%</td>
</tr>
<tr>
<td>FeS2</td>
<td>50</td>
<td>17</td>
<td>25</td>
<td>8</td>
<td>39%</td>
</tr>
<tr>
<td>TiS2</td>
<td>50</td>
<td>17</td>
<td>25</td>
<td>8</td>
<td>36%</td>
</tr>
<tr>
<td>CoS2</td>
<td>50</td>
<td>17</td>
<td>25</td>
<td>8</td>
<td>24%</td>
</tr>
</tbody>
</table>

- Transition metal sulfide (CuS, TiS₂, FeS₂, CoS₂) in S:MFCA hybrid cathodes promote initial sulfur cell discharge power capability at 1C rate.
Accomplishments and Progress
CuS additive effect on sulfur cathode - background

- CuS has high theoretical capacity – 560 mAh/g

\[
\begin{align*}
2\text{CuS} + 2\text{Li} & \rightarrow \text{Cu}_2\text{S} + \text{Li}_2\text{S} & 3.0\text{V to } 1.8\text{V} & (1) \\
\text{Cu}_2\text{S} + 2\text{Li} & \rightarrow 2\text{Cu} + \text{Li}_2\text{S} & 1.8\text{V to } 1.0\text{V} & (2)
\end{align*}
\]

- CuS is electronically as conductive as carbon black.
- The presence of CuS promote sulfur electrode utilization under high rate discharge.

- Reaction 2 is not reversible.
- 1.8V discharge limit for reversible cycles.

Accomplishments and Progress

CuS additive effect on sulfur cathode - electrochemical

- All hybrid electrode delivered less capacity than the sulfur control.
- Shuttling effect severity proportional to CuS content.
- All hybrid electrode cells showed fast capacity fade within the initial 5 cycles – why?

Accomplishments and Progress
CuS additive effect on sulfur cathode – Cu dissolution

- Recovered anode – different discoloration and morphology.
- EDS - more Cu and S on hybrid cell anode surface.
- TEM/ED - Li$_2$S, Cu$_2$S, and Cu$_8$S$_5$ on hybrid cell anode surface.
- XRF - decreased Cu fluorescence signals from hybrid cathode after cell cycling (pristine vs. cycled hybrid cathode).

Accomplishments and Progress

CuS additive effect on sulfur cathode – Cu dissolution

- Is CuS soluble in electrolyte?
- Do polysulfides catalyze the solubility of CuS?

Copper Concentration Measurement by ICP-OES

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Sample*</th>
<th>Cu Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electrolyte for calibration</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>Electrolyte + CuS</td>
<td>6.9</td>
</tr>
<tr>
<td>3</td>
<td>Li₂S₄ + Electrolyte + CuS</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>Li₂S₈ + Electrolyte + CuS</td>
<td>0.0</td>
</tr>
</tbody>
</table>

*Electrolyte: 1.0 M LiTFSI / DOL:DME = 1:1 v/v + 1 wt% LiNO₃

Polysulfide concentration = 70 mM

- CuS is only slightly soluble in pure electrolyte.
- CuS is insoluble in electrolyte in the presence of polysulfides.
Accomplishments and Progress

CuS additive effect on sulfur cathode – Cu dissolution

- 2.6V to 2.15V cycling
  - Clean anode surface
- 2.6V to 1.8V cycling
  - Dark anode surface
- Polysulfide (Li$_2$S$_8$ and Li$_2$S$_4$) is not the cause of CuS dissolution.

Accomplishments and Progress
CuS additive effect on sulfur cathode – Cu dissolution

Can CuS dissolution caused by the insoluble Li₂S₂ or Li₂S?

- The low ordered soluble polysulfide species (S₃ – either ions or radical) generated at voltages below 2.15V is the cause of CuS dissolution.

Accomplishments and Progress
CuS additive effect on sulfur cathode – conclusion

- The presence CuS in hybrid cathode promotes sulfur cell discharge under high rate.
- CuS additive is detrimental to the sulfur cell cycling stability due to CuS dissolution.
  - High ordered polysulfide (Li$_2$S$_n$, $n = 4$ to $8$) does not cause CuS dissolution.
  - Electrolyte soluble low ordered polysulfide (Li$_2$S$_n$, $n = 3$ or less) is responsible for CuS dissolution.
  - Deposition of conductive Cu$_2$S species on the anode surface catalyze the polysulfide reduction, enhancing shuttling effect and inducing more Li$_2$S deposition on anode surface.

Accomplishments and Progress
FeS₂ additive effect on sulfur cathode - background

- FeS₂ is conductive (semi-conductor) and used as cathode in thermal lithium batteries - theoretical capacity – 890 mA/h/g

\[
\text{FeS}_2 + 2\text{Li} \rightarrow \text{Li}_2\text{FeS}_2
\]

\[
\text{Li}_2\text{FeS}_2 + 2\text{Li} \rightarrow \text{Fe} + 2\text{Li}_2\text{S}
\]

- Phase transition during 1\textsuperscript{st} discharge
  - 1\textsuperscript{st} discharge needs to go down to ~1.0V to activate FeS₂
Accomplishments and Progress
FeS$_2$ additive effect on sulfur cathode – without activation

- Cell with FeS$_2$ exhibited higher voltage relative to control cell.
- Without FeS$_2$ activation, hybrid electrode cell showed no obvious effect on cycling.

<table>
<thead>
<tr>
<th>Study</th>
<th>Hybrid Formulation</th>
<th>Electrolyte</th>
<th>Cycling Voltage Range</th>
<th>Discharge Rate</th>
<th>Charge Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S:FeS$_2$:C:PVDF</td>
<td>Yes</td>
<td>2.6V - 1.8V</td>
<td>1C</td>
<td>C/5 - C/20</td>
</tr>
<tr>
<td>2</td>
<td>60:20:30:10</td>
<td>Yes</td>
<td>2.6V - 1.8V</td>
<td>1C</td>
<td>C/5 - C/20</td>
</tr>
</tbody>
</table>
Accomplishments and Progress
FeS$_2$ additive effect on sulfur cathode – LiNO$_3$ and activation

- FeS$_2$ activation at voltage below 1.5V during 1$^{st}$ discharge.
- With LiNO$_3$ leads to significant cell impedance growth resulting in polarized cell voltages.
- Without LiNO$_3$, cells can not be charged due to severe shuttling effect – Why?

<table>
<thead>
<tr>
<th>Study</th>
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<th>Electrolyte</th>
<th>Cycling Voltage</th>
<th>Discharge Rate</th>
<th>Charge Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S:FeS$_2$:C:PVDF</td>
<td>LiNO$_3$</td>
<td>Range</td>
<td>0.2C</td>
<td>C/5 - C/20</td>
</tr>
<tr>
<td>2</td>
<td>60:20:30:10</td>
<td>No</td>
<td>2.6V - 1.0V</td>
<td>0.2C</td>
<td>C/5 - C/20</td>
</tr>
</tbody>
</table>
Accomplishments and Progress

**FeS\(_2\)** additive effect on sulfur cathode – Fe dissolution

- FeS\(_2\) dissolution observed for the hybrid cathode cell with iron identified on anode surface.
- Severe Fe dissolution happens only for FeS\(_2\) activated (1.0V) hybrid cathode cells
- XPS identified FeS and FeO on the anode surface - correlated to severe shuttling effect.

**Anode EDS**

**XPS – S:FeS\(_2\) Cell Anode SEI (1.0V)**

- Sulfur control
- S:FeS\(_2\) activated
- No FeS\(_2\) activation

- S:FeS\(_2\) w/o LiNO\(_3\) 1.0V discharge
- S:FeS\(_2\) w/o LiNO\(_3\) 1.8V discharge
- Sulfur w/o LiNO\(_3\) 1.0V discharge
- S:FeS\(_2\) w/o LiNO\(_3\) 1.8V discharge
- FeS\(_2\) activated S:FeS\(_2\) w/o LiNO\(_3\) 1.0V discharge
- No FeS\(_2\) activation S:FeS\(_2\) w/o LiNO\(_3\) 1.8V discharge
Accomplishments and Progress

**FeS₂ additive effect on sulfur cathode – Fe dissolution**

A. Marschilok, K. Takeuchi, E. Takeuchi, D. Bock, J. Huang

Does polysulfide catalyze the dissolution of FeS₂? – No!

**Iron Concentration Measurement by ICP-OES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Corrected Fe Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeS₂ in 1:1 DME:DOL</td>
<td>2.6</td>
</tr>
<tr>
<td>FeS₂ + 0.07 M Li₂S₈ in 1:1 DME:DOL</td>
<td>1.8</td>
</tr>
<tr>
<td>1:1 DME:DOL only</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Is FeS₂ activation sufficient for iron dissolution? – No!

- Polysulfide does not catalyze FeS₂ dissolution.
- FeS₂ activation only is not sufficient for iron dissolution.
- The charging of FeS₂ activated hybrid cathode leads to Fe dissolution.
- Deposition of FeS on anode surface leading to severe shuttling effect, preventing cells to be fully charged.

Manuscript in preparation
Accomplishments and Progress

FeS$_2$ additive effect on sulfur cathode – conclusion

- Activation of FeS$_2$ requires cell to be discharged to 1.0V.
- The presence of FeS$_2$ additive leads to higher sulfur cell discharge voltages.
- Without activation, FeS$_2$ has no obvious impact on sulfur cell cycling performance.
- The presence of LiNO$_3$ allows the FeS$_2$ to be activated and the cell can be cycled, but with the compromised cell impedance growth.
- Elimination of LiNO$_3$ from the electrolyte also allows the FeS$_2$ to be activated, but resulting in uncontrollable shuttling effect during charging.
- Significant iron dissolution occurs during charging step of the FeS$_2$ activated S:FeS$_2$ hybrid cathode cell.
- FeS and FeO deposition on anode SEI layer catalyzes the polysulfide shuttling effect during cell charging.
Accomplishments and Progress

**TiS\textsubscript{2} additive effect on sulfur cathode - background**

- TiS\textsubscript{2} has layered crystal structure and capable of reversible lithium intercalation - theoretical capacity 239 mAh/g.

\[
\text{TiS}_2 + \text{Li} \rightleftharpoons \text{LiTiS}_2
\]

- TiS\textsubscript{2} can be activated at voltage above 1.5V.
- TiS\textsubscript{2} is electronically more conductive than carbon black.
- TiS\textsubscript{2} cells have high rate capability even without carbon conductive additive.
Accomplishments and Progress

**TiS\(_2\) additive effect on sulfur cathode**

<table>
<thead>
<tr>
<th>Cell #</th>
<th>Electrode</th>
<th>S:TiS(_2):C:PVDF</th>
<th>Total Loading (mg/cm(^2))</th>
<th>S Loading Capacity (mAh/cm(^2))</th>
<th>TiS(_2) Loading Capacity (mAh/cm(^2))</th>
<th>Total Loading Capacity (mAh/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S:TiS(_2)</td>
<td>60:20:30:10</td>
<td>1.71</td>
<td>1.43</td>
<td>0.07</td>
<td>1.50</td>
</tr>
<tr>
<td>2</td>
<td>S:TiS(_2)</td>
<td>60:20:30:10</td>
<td>2.69</td>
<td>2.25</td>
<td>0.11</td>
<td>2.36</td>
</tr>
<tr>
<td>3</td>
<td>Sulfur</td>
<td>60:00:30:10</td>
<td>2.58</td>
<td>2.59</td>
<td>0.00</td>
<td>2.59</td>
</tr>
<tr>
<td>4</td>
<td>Sulfur</td>
<td>60:00:30:10</td>
<td>2.54</td>
<td>2.55</td>
<td>0.00</td>
<td>2.55</td>
</tr>
</tbody>
</table>

2032 Coin cells; 1.0M LiTFSI/DOL:DME = 1:1 v/v + 1wt% LiNO\(_3\); C/10 rate charge/discharge

- TiS\(_2\) activated with more sloped voltage profile near the end of discharge.
- Similar initial sulfur utilization observed (based on S only).
- S:TiS\(_2\) hybrid electrode cells exhibited lower capacity fade rate.
Accomplishments and Progress

TiS$_2$ additive effect on sulfur cathode – BET & particle size

Amy Marschilok, Kenneth Takeuchi, Esther Takeuchi, Qing Zhang, Jeff Jou

- 12 minutes ball milling sample selected for hybrid cathode study
Accomplishments and Progress

TiS$_2$ additive effect on sulfur cathode – particle size effect

TiS$_2$ distribution in coated cathode

- EDS – Ti Mapping – Raw TiS$_2$
- EDS – Ti Mapping – Milled TiS$_2$

- Capacity fade: 0.039% per cycle (1C, cycles 1 to 500)

- Discharge capacity (mAh g$^{-1}$)

- Cycle Number

- Cathode Formulation
  - S:TiS$_2$:C:PVDF
  - Control S Cathode: 60:00:50:10
  - S:TiS$_2$ Hybrid Cathode: 60:20:30:10

- Brookhaven National Laboratory
Accomplishments and Progress
**TiS₂ additive effect on sulfur cathode - mechanism**

Why TiS₂ help sulfur cell performance?

- **TiS₂ additive benefit**
  - No TiS₂ dissolution
    - Smooth and clean anode surface.
    - EDS detect no Ti on anode surface.
  - Polysulfide adsorption by TiS₂
    - Decreased polysulfide solution coloration vs. control.

---

**Sulfur**

No Ti detected

**S:TiS₂**

Counts

Energy (keV)

- Li₂S₈ 5 mM in DOL:DME = 1:1

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**Anode from sulfur cell**

**Anode from S:TiS₂ cell**

- 5 cycles (1.8V to 2.6V; C/5)
- 5 cycles (1.8V to 2.8V; C/5)

---

**Why TiS₂ help sulfur cell performance?**

- **No color change**
- Lighter color

---

**+FeS₂**

No color change

6 days

---

**Control**

6 days

---

**+TiS₂**

Lighter color
Accomplishments and Progress

TiS$_2$ additive effect on sulfur cathode - conclusion

- TiS$_2$ can be reversibly cycled at up to 10C rate with good capacity retention.
- TiS$_2$ additive promotes sulfur electrode high rate discharge with improved cycling life.
- Adsorption of polysulfide by TiS$_2$ contributes to the better cell electrochemical behavior.
- Smaller TiS$_2$ particle size and uniform TiS$_2$ distribution are beneficial for S:TiS$_2$ hybrid cell cycle life.
- Sulfur cells with TiS$_2$ additive achieved 500 cycles at 1C discharge rate with $< 0.04\%$ capacity fade per cycle.
Responses to Previous Year Reviewers’ Comments

- This project is a new start and was not reviewed last year.
Partners / Collaborations

- **Brookhaven National Laboratory (BNL)**
  - Dr. Hong Gan (PI) – Project coordination
  - Dr. Ke Sun – Project execution

- **Stony Brook University**
  - Prof. Esther Takeuchi (Co-PI), Prof. Amy Marschilok, Prof. Kenneth Takeuchi – Transition metal sulfide cathode testing, transition metal sulfide synthesis and sample preparation for particle size study, ICP dissolution studies

- **Center of Functional Nanomaterials (CFN), BNL**
  - Dr. Dong Su – TEM/ED, SEM morphology and structural characterization
  - Dr. Xiao Tong – XPS analysis on anode SEI from S:FeS$_2$ cycled cells

- **National Synchrotron Light Source II, (NSLS II) BNL**
  - Dr. Yu-chen Karen Chen-Wiegart – XRF on CuS dissolution studies

- **Columbia University**
  - Prof. Simon Billinge – PDF structural characterization on S:FeS interaction
Remaining Challenges and Barriers

- It is challenging to resolve Li-S cell performance issues at just cathode level. Strong interactions between cathode, anode and electrolyte at the system level need to be addressed.
- Decreased sulfur utilization with high sulfur cathode mass loading (>2 mg/cm²) impedes the achievement of low cost, high energy density Li-S batteries.
- Low energy density at the electrode and cell levels due to the low active sulfur % in electrode formulation and low sulfur utilization.
- Dissolution of metal sulfides (CuS and FeS₂) in the conventional electrolyte system limits our choice of MFCA to TiS₂.
- Polysulfide dissolution is still a major challenge for Li-S cell to achieve high energy efficiency and long cycle life.
- Fast capacity fade during the initial cycles needs to be mitigated.
- Anode passivation by LiNO₃ limit the discharge voltage cut off to 1.8V.
Proposed Future Work

- Understand the mechanism that governs the beneficial interaction between sulfur/TiS$_2$ and continue modify TiS$_2$ properties for optimized sulfur cell performance.
- Optimize the S:TiS$_2$ electrode mechanical and electrochemical properties by selecting the appropriate electrode binders and conductive carbons, as well as the electrode preparation process.
- Optimize sulfur cathode formulation and achieve high areal sulfur mass loading of > 2 mg/cm$^2$ for high cathode energy density.
- Develop method for cell activation with high sulfur loading.
- Evaluate electrode and cell design factors, such as interlayer cathode structure, to promote sulfur utilization and maximize cell cycle life.
- Reduce polysulfide dissolution by developing new electrolyte systems and revisit some promising MFCA additives.
- Anode surface protection to minimize or prevent side reactions between polysulfide and lithium metal anode.
Summary

- MFCA improves sulfur cathode discharge power capability.
- MFCA activation is highly dependent on metal types (CuS, FeS$_2$, TiS$_2$) with unique characteristics for each candidate.
- Dissolution of CuS and FeS$_2$ is the leading cause for poor cycling performance in cells with hybrid sulfur cathode.
- TiS$_2$ additive improves sulfur cell high rate cycle life and contributes to the delivered cell capacity.
- Smaller TiS$_2$ particle size and uniform TiS$_2$ particle distribution within the S:TiS$_2$ hybrid cathode are beneficial for improved sulfur cell cycle life.
- Hybrid S:TiS$_2$ cathode exhibits no Ti dissolution with strong adsorption interaction between TiS$_2$ and polysulfide.