All Solid-State, Thin-Film Lithium Rechargeable Battery for Flexible Electronics

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Need: Ultra-Thin, Flexible Power Sources

- Wearable, Flex Electronics, IoT, ... are Limited by the Battery Size and Energy Density

http://www.idownloadblog.com/2015/04/24/apple-watch-battery/
Battery Energy Density is Increasing Over Time

..But Not for Ultra-Thin Batteries

<table>
<thead>
<tr>
<th></th>
<th>Panasonic</th>
<th>LG</th>
<th>Samsung</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCR18650GA</td>
<td>INR18650-MJ1</td>
<td>INR18650-35E</td>
<td>697 Wh/l</td>
</tr>
<tr>
<td>697 Wh/l</td>
<td>726 Wh/l</td>
<td>714 Wh/l</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Wanxiang A123</th>
<th>Li Tec</th>
<th>Samsung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pouch</td>
<td>Daimler</td>
<td>Fiat BMW</td>
<td></td>
</tr>
<tr>
<td>247 Wh/l</td>
<td>316 Wh/l</td>
<td>243 Wh/l</td>
<td></td>
</tr>
</tbody>
</table>

Ultra-Thin Batteries (<500 μm thick)

Energy Density ~50-250 Wh/l
<0.7 Wh/l-μm package thickness

*Source: http://www.emvalley.com/?From=Quora

450 μm thick, 108-196 Wh/l
Solid State Lithium Batteries (SSLB)

- Enabling Energy Density >1,000 Wh/l (>2 Wh/l-\(\mu\)m package thickness):
  - 20 \(\mu\)m Thick (or less) Self-Supporting, Flexible YSZ Substrate that Serves as Both a Substrate and Packaging Material;
  - SSLB Maximizing Energy Density with Employing Thick Cathodes, 5-15\(\mu\)m, Deposited over Large Area, up to 40 cm\(^2\);

*Project sponsored by the FlexTech Alliance (Sept 1 2016-Feb 18, 2018)

Ultra-Thin, High Energy Density SSLB Enable a Thin, Flexible Power Supply no larger than 2\"x3\"x0.01\" with capacity from 20 mAh to over 100 mAh for Flexible Electronic Devices*
SSLB on 20 μm YSZ Substrate

- Feasibility of Ultra-Thin SSLB Cells has Been Established on 20 μm YSZ Substrates
  - Area up to 40 cm², Cathodes 5-15 μm Thick
Scalable SSLB Designs

• Capacity Scales with Area and Cathode Thickness
  – Adjust to Meet Application Requirements
  – Same Materials and Processes
SSLB Design Rules

• Optimal Battery Design will Depend on Both Capacity and Duty Cycle
  – Relative Capacity Consistent (Low C-Rate)
  – Thicker Cathodes Support Higher Capacity
SSLB Design Rules

• Optimal Battery Design will Depend on Both Capacity and Duty Cycle
  – Nominaly Smaller Relative Capacity with Thicker Cathodes (2C-Rate)
  – High Current Possible with Thinner Cathodes and/or Higher Capacity
Cell Integration to Batteries

- **2-Cell Stack**
  - Parallel Connection
- **SSLB Battery**
  Capacity = Sum of Cell Capacities

![SSLB Battery Performance Graph](chart.png)

Cells Discharged at 1 mA (C/4)
Battery Discharged at 2 mA (C/4)
Cell Integration to Batteries

SSLB Battery Performance
2-Cell Stack, Rate Dependence

Discharge Voltage (V)

Capacity (mAh)

~1C
C/4

2017 FLEX
Duty Cycles for Flexible Electronics

- Devices Often Demand Low Power with Periodic High Current Spikes

*Wireless sensors for Spacesuit Health Monitoring (NASA SBIR)*
SSLB High Current Pulsing

3.5 V chosen based on a survey of power down spec from a survey of a few consumer electronic devices.
SSLB High Current Pulsing

>2,500 Pulses

4 mAh SSLB Capacity

100 millisecond High Current Pulses
C/10 Discharge in Between
SSLB High Current Pulsing

High Current Pulse Duty Cycle
50mA 400ms - 25mA 800ms Pulse with Rest

4 mAh SSLB Capacity
Novel Packaging Validated

SSLB Packaging Test
25°C, 85% RH

% Discharge Capacity Retention

Total packaged thickness ~ 100 μm

No additional packaging required!
SSLB Powering Flexible Electronics

Flexible Electronic Print (FEP) Device
Single “Cycle” Profile

Simulated Operation of Functional Electronic Print Device

SSLB Simulated Operation of FEP
52 “Cycles” (1 min rest between cycles)
SSLB UL Safety Testing (1642)

• Initial Testing: Pass Short Circuit, Crush Test

<table>
<thead>
<tr>
<th>Short Circuit Test</th>
<th>Crush Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Short Charged Cell; R &lt; 0.1 Ohm</td>
<td>• Charged Cell Placed in Mechanical Press</td>
</tr>
<tr>
<td>• Track Temperature, Voltage vs time</td>
<td>• 3000 lbs Force Applied</td>
</tr>
<tr>
<td>• No Fire or Explosion to Pass Test</td>
<td>• No Fire or Explosion to Pass Test</td>
</tr>
<tr>
<td>• Temperature &lt; 45°C</td>
<td>• No Fire or Explosion</td>
</tr>
<tr>
<td>• Time &lt; 1 sec to discharge</td>
<td></td>
</tr>
<tr>
<td>• No Fire or Explosion</td>
<td>~1 mAh SSLB</td>
</tr>
</tbody>
</table>
Accelerated Environmental Tests

- Water Vapor Transmission Rate (WVTR)
  Measurement Technique Established in OLED Industry
  - Monitor Reactive Metal Resistance Change over Time
    - Ca for OLED, Li for SSLB

\[ WVTR = -n \frac{M_{\text{reagent}}}{M_{\text{Ca}}} \delta \rho \frac{1}{b} \frac{1}{R} \frac{d}{dt} \]

WVTR for Novel Packaging

• WVTR Supports Long SSLB Life

<table>
<thead>
<tr>
<th>Condition</th>
<th>WVTR (g/m²-day)</th>
<th>% Li Loss 5 Years</th>
<th>% Li Loss 20 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C, 85% RH</td>
<td>1.3x10⁻⁵</td>
<td>&lt;1%</td>
<td>&lt;3%</td>
</tr>
</tbody>
</table>

• Li Resistance Stable >150 hours @85°C, 85%
## Thin, Flexible Power Systems (TFPS)

<table>
<thead>
<tr>
<th></th>
<th>1st TFPS (Q3 2017)</th>
<th>2nd TFPS (Q4 2017)</th>
<th>Roadmap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Thickness</td>
<td>20 µm</td>
<td>20 µm</td>
<td>12 µm</td>
</tr>
<tr>
<td>Substrate Area</td>
<td>25 cm²</td>
<td>50 cm²</td>
<td>50 cm²</td>
</tr>
<tr>
<td>Battery Thickness</td>
<td>&lt;100 µm</td>
<td>&lt;150 µm</td>
<td>250 µm</td>
</tr>
<tr>
<td>Battery Capacity*</td>
<td>20-25 mAh</td>
<td>50-120 mAh</td>
<td>360 mAh</td>
</tr>
<tr>
<td>Energy Density*</td>
<td>480 Wh/l</td>
<td>Up to 600 Wh/l</td>
<td>&gt;1,000 Wh/l</td>
</tr>
</tbody>
</table>

* Projection based on current materials and cell performance
* Projection based on anticipated improvement in materials and cell performance
Acknowledgements