Next Generation Energy Storage Technologies

Subramanya Herle PhD
Director and DMTS
Energy Storage Solutions, Office of the CTO
Subra_Herle@amat.com
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Overview

Subramanya Herle
Director of Energy Storage Technologies

2019 NCCAVS Symposium, Holiday Inn, San Jose
OUR VISION
Our innovations make possible the technology shaping the future

OUR MISSION
To lead the world with materials engineering solutions that enable customers to transform possibilities into reality
FOR THE PAST DECADE,
~$1Billion invested annually in RD&E
Our Story

**FOUNDED in 1967**

Applied Materials began in a small industrial unit in Mountain View, California
World’s #1 semiconductor and display equipment company

$17.3 billion revenue

$2.0 billion R&D spending

>12,500 patents

AMAT stock listing on NASDAQ

Headquartered in California’s Silicon Valley

~21,000 employees
93 locations
In 17 countries

Data as of fiscal year end, October 28, 2018
Businesses

Semiconductor Systems

Applied Global Services

Display and Adjacent Markets
Accelerating Innovation

Collaborate earlier and deeper with customers on inflections

Extend the technology roadmap with fast cadence in product innovation

Drive materials-enabled scaling to improve PPAC* with new materials, new structures, new devices

Solve customers’ complex technical challenges with Integrated Materials Solutions (IMS)

Enable faster learning and breakthrough technologies through the Maydan Technology and META Centers

* PPAC = Power Performance Area Cost
Applied’s Display and Flexible Technology Products

- CVD
- PVD
- Thin Film Encapsulation
- Roll-to-Roll E-Beam Evaporation PVD CVD
- E-Beam Tester
- In-Line SEM Review

More Products in the Pipeline that will Triple our Footprint in Display
Energy Storage Technologies
**Energy Storage Landscape**

**Miniature Batteries**  
(100mWh – 2Wh)  
Electric watches, calculators, implanted medical devices

**Batteries for Portable Equipment**  
(2Wh – 100Wh)  
Flashlights, toys, power tools, portable radios, and TV, mobile phones, camcorders, lap-top computers, memory refreshing, instruments, cordless devices, wireless peripherals

**Transportable Batteries**  
(Starting, Lighting & Ignition)  
(100Wh – 1,000Wh)  
Cars, trucks, buses, lawn mowers, wheel chairs, robots

**Large Vehicle Batteries**  
(1kWh – 1,000kWh)  
HEV/PHEV, Trucks, traction, locomotives

**Regenerative Braking**

**Stationary Batteries**  
(0.25MWh – 5MWh)  
Emergency power, local energy storage, remote relay stations, communication base stations, uninterruptible power supplies (UPS).

**Stationary**

**Large Energy Storage**  
(5MWh – 100MWh)  
Frequency regulation, Spinning reserve, peak shaving, load leveling

**Thin Film Batteries**

**Lithium-ion**
Energy Storage Technologies

Sukhvinder Badwal  DOI: 10.3389/fchem.2014.00079
Commercially Available Battery Technologies

Cells → Batteries

Primary

Zn-MnO₂ (dry cells)
Zn/Al-air
Zn-NiOOH

Thermal battery
AgVOₓ
Li-CFx
Li-Thionyl chloride
Li-MnO₂
Li-FeS₂

Secondary (Rechargeable)

Lead Acid
NiMH
NiCd

Flow (ZnBr, V-V⁺, NiFe, Fe/Cr, ZnFe)
Organic Flow Battery
Li-ion
NaMClₓ
NaS

Aqueous electrolyte
Non-aqueous electrolyte
Battery Energy Density and Ragone Plot

- Cell chemistry and cell design determines Ragone chart
- New cell chemistries needed to increase practical energy density of cells
Performance Limits of Battery Chemistries

Si/Li metal anode will enable > 1000 Wh/L battery
Rapidly Falling Costs of xEV Battery Packs

http://www.nature.com/doifinder/10.1038/nclimate2564
Electricity Storage: Mobility, Transportation and Grid Storage

Global installed grid-connected electricity storage capacity (MW)

- Pumped Storage Hydro (PSH) 1,40,000
- Sodium-Sulphur 304
- Lithium-ion 100
- Lead-acid 70
- Nickel-cadmium 27
- Flywheel 25
- Redox-flow 10

Source: IEA, Technology Roadmap 2014

Grid: Next big opportunity; cost sensitive & regulated market
Li-ion Recycling Could Supply Most of Needed Material …Eventually

Recovering more materials reduces energy to make new cells

Ref: Linda Gains, ARNL, International Battery Seminar and Exhibit 2018

Low cost recycling technology is essential for sustainability
Active Materials
Factors Affecting Battery Design (Li-ion)

Tradeoffs
- Energy
- Power
- Safety
- Gas
- Cost
- Life

Graphite/LiCoO₂ cell: Typical usage guidelines

Source: Sony
Comparison of Anodes

- **Graphite**
  - Lithium intercalation, Limited capacity
  - No C-C bond breaking
  - Limited volume expansion ~12%
  - ~10% 1st cycle irreversible Li loss

- **Si**
  - All Si-Si bonds are broken, high capacity
  - Many Li-Si bonds formed
  - Large 3D volume expansion (> 300 %)
  - ~30% 1st cycle irreversible Li loss

- **SiO_x anode**
  - Metallic Li-Li bond, highest capacity
  - Large 2D volume expansion

- **Li_xC_6 Graphite**
  - Substrate

- **Li_{22}Si_5**
  - Metallic Li-Li bond, highest capacity
  - Large 2D volume expansion
Next Gen Storage Technologies
2017-2025 Available Battery Technologies

Source: AVICENNE Analysis 2018, Inventus Power
## Time to Market for New LiB Materials

<table>
<thead>
<tr>
<th>Year</th>
<th>Cathode</th>
<th>Anode</th>
<th>Electrolyte</th>
<th>Separators</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>LCO</td>
<td>Graphite</td>
<td>LiPF$_6$ + Org. solvents</td>
<td>Polyelefin</td>
</tr>
<tr>
<td>2005</td>
<td>LMO</td>
<td>Soft Carbon</td>
<td>Gel-polymer electrolyte</td>
<td>Polyelefin-ceramic coating</td>
</tr>
<tr>
<td>2010</td>
<td>NMC/NCA</td>
<td>C/Alloy Composite</td>
<td>Li$_2$Ti$_3$O$_7$</td>
<td>Cellulose Non-woven</td>
</tr>
<tr>
<td>2015</td>
<td>LiNiMnMnO$_2$</td>
<td>Li Metal</td>
<td>LiPF$_6$ free electrolyte</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>5V spinel</td>
<td>Non Si Alloys</td>
<td>Gel-polymer electrolyte</td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td>LiNiPO$_4$, 5V</td>
<td>Si Alloys</td>
<td>5V electrolyte</td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>LiCoPO$_4$, 5V</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*Source: AVICENNE ENERGY 2016*
Energy Storage Solutions

System power and discharge time of energy storage technologies

- High Energy super Cap
- Li-S
- Sodium-ion
- Metal Air
- Lithium-ion
- Pb-Carbon
- Acid Pb-Acid
- NiCd batteries
- NiMH batteries
- High power Flywheels
- High power super Capacitor
- SMES
- Fuel cells
- Flow batteries
- Na-Ion
- NaNiCL
- Lift storage
- CAES
- Hydrogen generation
- Pumped Hydro

Mostly suitable for seasonal arbitrage
Mostly suitable for arbitrage and back-up
Mostly suitable for regulation and UPS

Source: AVICENNE Energy, 2016
Technical Challenges
Li Dendrite

Ref: Prof. Wittingham, 1980

120x real time, 1M, 2.61 mA/cm²

Ref: Prof. Bazant, 2016
Summary

1. Battery Manufacturing Capacity is Growing Fast
   >$ 90 Bn investment announcements by automakers till 2030 for EV
   Global capacity for energy storage is expected to reach 8.6 GW/ 21.6 GWh by 2022, enough to power to electrify roughly 6 million homes

2. Lithium-ion is Becoming the Technology of Choice for Solar-based ESS
   The prices for Lithium-based batteries are steadily declining by 8% on an annual basis (the average price of batteries has dropped 80% since 2010), making solar + storage projects more investment-friendly.

3. Asia is On Track to Become the World Leader in ESS
   Alternate energy storage technologies available including fuel cell technologies

4. Utilities are Primed to Partner With / Acquire ESS Companies
   There were four Energy Storage M&A transactions in Q2 2018.

5. Government Incentives for Energy Storage are Driving Growth
   At the federal level, the 30% Investment Tax Credit remains available for energy storage, provided it is coupled with renewable generation

6. Energy Storage-as-a-Service (ESaaS) is Becoming a Key Service Model

7. Residential ESS Growth is Outstripping Utility-scale
   Residential installations of battery storage beat commercial installations in Q1 of 2018, 15.9 MW to 11.7 MW (almost beat utility-scale installations at 16 MW)

8. Levelized Cost of Storage (LCOS) is Emerging as a Popular Revenue Metric
   Cost of storing electricity in ESS and divides by the retail price of electricity stored. LCOS has only been in existence for the last 3 years, and this new metric will continue to evolve and provide a standard metric of providing better insights to the financiers

9. Ethical Sourcing is Increasingly Critical for Battery Materials

10. Recycling of battery and materials is critical for sustainability