

**High Energy and Power Density
Lithium-Ion Cells with Silicon
Nanowire Anode Technology**

2019-11-20

Ionel Stefan
CTO, Amprius Technologies
1180 Page Ave., Fremont, CA

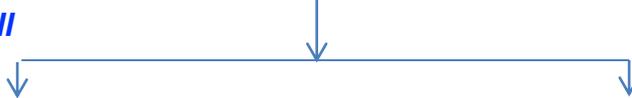
NASA Aerospace Battery Workshop
Huntsville, AL, Nov 19-21, 2019



Amprius introduction - company structure



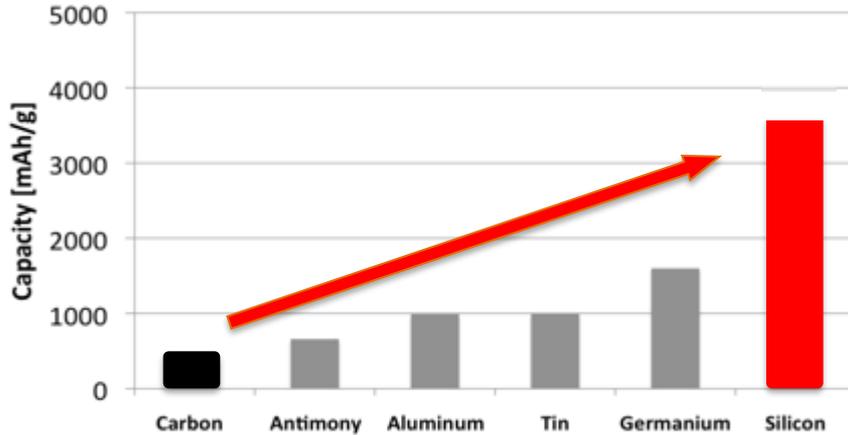
Si nanowire anode R&D and pilot-scale cell manufacturing



a JV between Amprius and Wuxi IDG



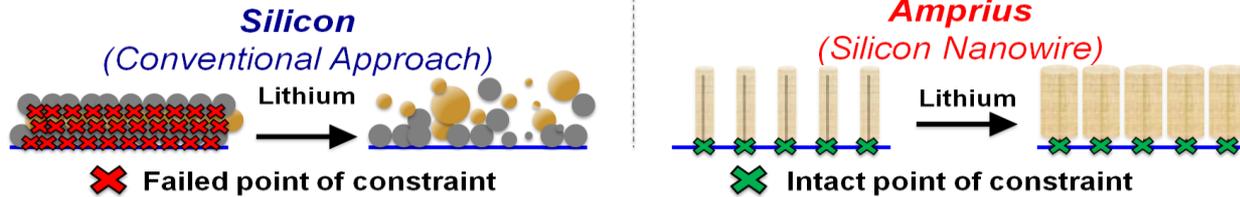
Silicon has 10X Capacity vs. Carbon



Amprius solutions enable:

- * Longer endurance / operation
- * Smaller and/or lighter devices
- * More functionalities
- * Broader applications

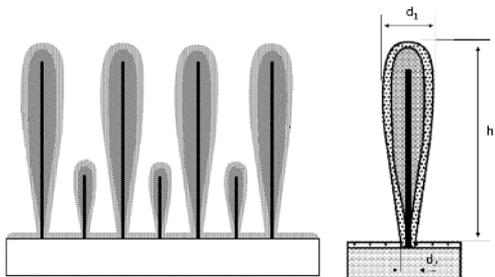
- *The design and manufacturing of silicon-containing anodes remains a major challenge in research and industry.*
- *Amprius' Silicon Nanowire technology is a proven solution.*



Fundamental Problem of Silicon-Containing Anode

- *Silicon swells 300% when charged with Lithium*
- *Silicon gets pulverized after a few charge/discharge cycles*
- ***Amprius' solution:***
 1. *nanowires tolerate volume expansion and are rooted to substrate*
 2. *nanowires have micro and macro porosity that accommodate swell*
 3. *Surface treated to improve Solid-Electrolyte-Interphase & cycle life*
 4. *Anode thickness is reduced to half of a graphite electrode thickness*

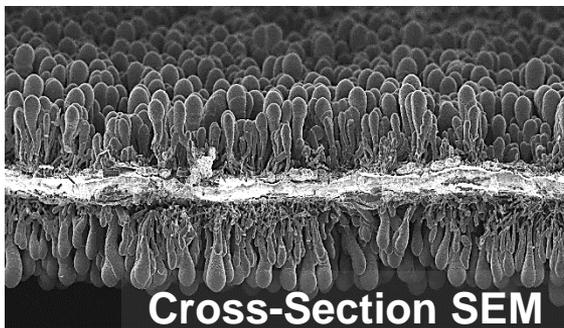
Silicon Nanowire Structure



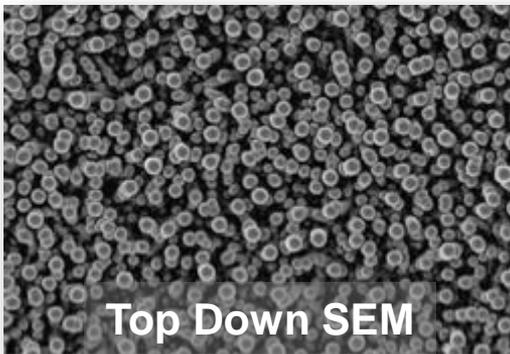
(54) STRUCTURALLY CONTROLLED DEPOSITION OF SILICON ONTO NANOWIRES
(71) Applicant: Amprius, Inc., Sunnyvale, CA (US)
(72) inventors: Weiwei Wang, Sunnyvale, CA (US); Zuoqin Liu, Sunnyvale, CA (US); Song Han, Foster City, CA (US); Jonathan Bornstein, Cupertino, CA (US); Constantin Ionel Stefan, San Jose, CA (US)
(21) Appl. No: 14710,103

Major advantages:

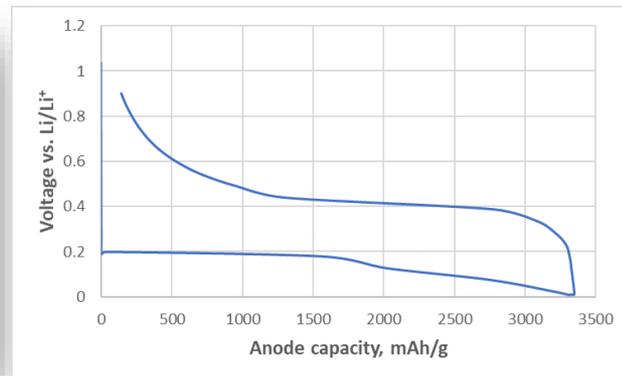
- Highest content active silicon material (100%)
- High conductivity and connectivity (rooted to substrate)
- Low tortuosity – high rate capability
- Ideal and adjustable porosity distribution
- High mass loading (2-3 mg/cm²)
- High first cycle efficiency



Cross-Section SEM



Top Down SEM



Installed “Pilot Tool” for Continuous Roll-to-Roll Anode Production



Replaces:

- Graphite powder mixing
- Slurry mixing
- Roll coating (2x)
- Drying
- Calendaring

Bare Foil In → Finished Anode Out

- Pilot Tool capable of ~300 kWh/year



Installed in Sunnyvale... Feb-2018
Qualified..... Apr-2018
Second Tool..... Q4-2019
Upscaled Tool(s)..... 2021+

Market Applications



Produce Ultra-High Capacity Silicon Nanowire Anodes for Li Ion Cells that have the Highest Energy Density Available

Amprius Technologies' Cells are Game Changers for Mission Critical Applications

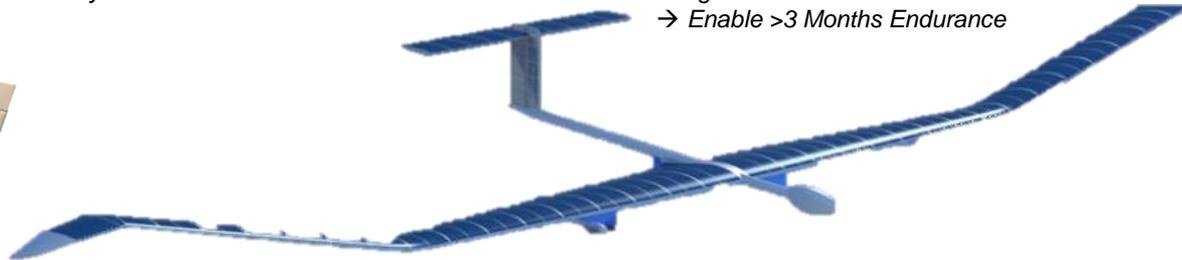
*Power Cells for Quads
→ Enable Very Long Endurance
(World Record with Major Defense Contractor)*



*Cells for Lightweight Drones
→ Enable >4 hr Missions
(>2x current endurance)*



*Cells for High Altitude Pseudo Satellites
→ Enable >3 Months Endurance*



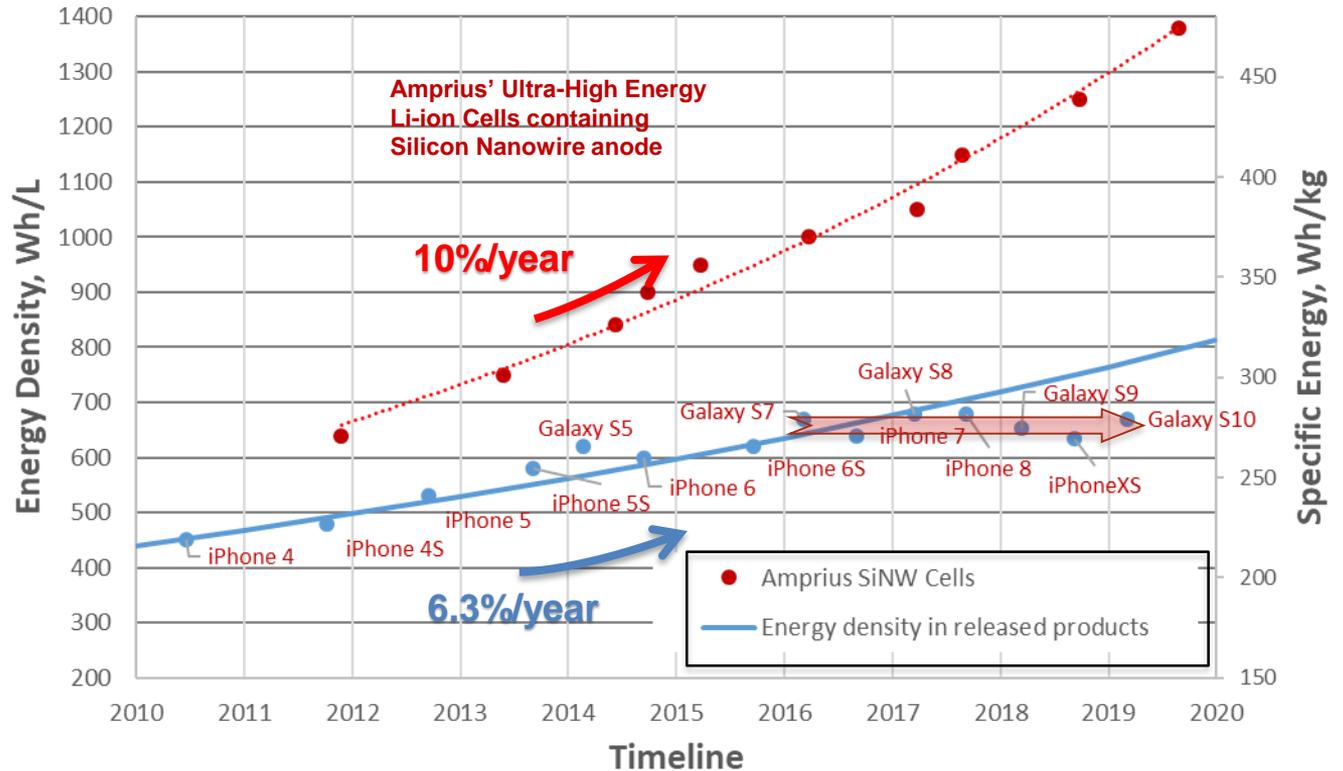
*Cells for Conformal-Wearable Pack
→ Enable 40% lower weight for Army*



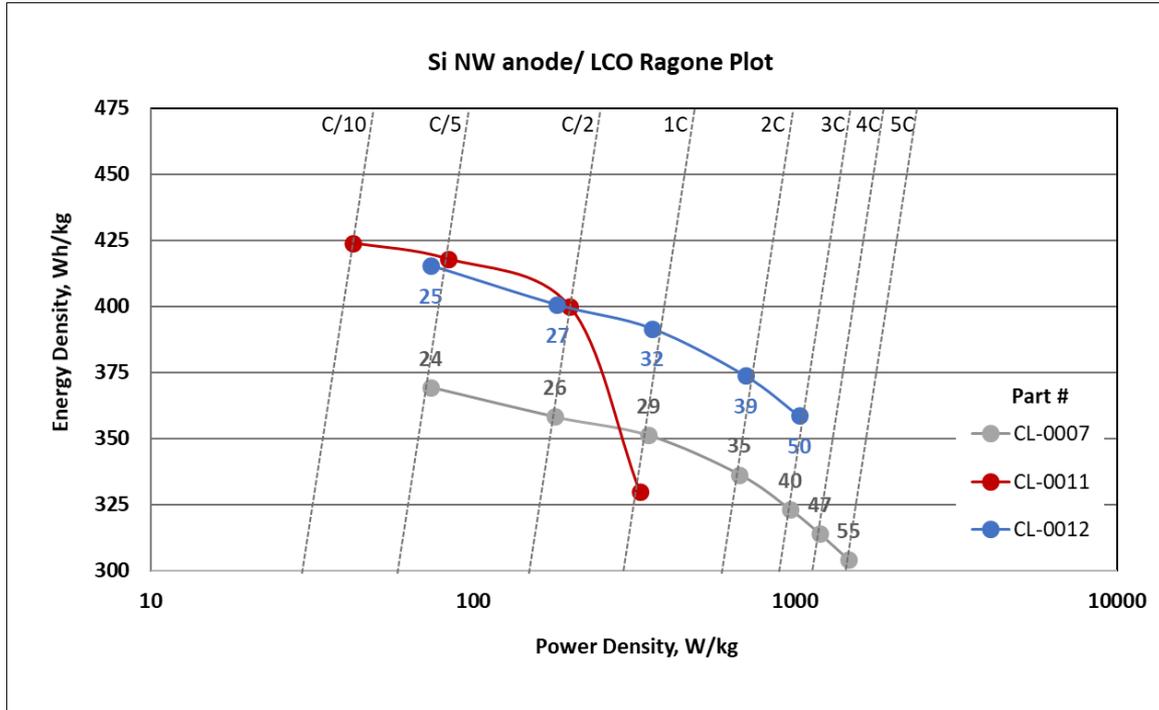
Silicon Nanowire Progress



Si nanowire anode cells leverage progress in other cell components, amplifying improvements



Amprius Technologies Products: High Energy and Power Capability



* Numbers indicate maximum cell body temperature during discharge

High energy density cells (>400Wh/kg and 1200Wh/L) can be designed for lower power applications

Power density can be increased with small penalty in energy density

High power density cells (>1000W/kg) need thinner cathodes, and can achieve 325Wh/kg in 3C discharge

High Power capability with highest energy density and specific energy

Product ID	Dimensions (T x W x H) mm	Mass g	Capacity Ah	Energy Wh	Wh/L	Wh/kg	Capacity Ah	Energy Wh	Wh/L	Wh/kg
			Charge-Discharge Rate: C/5-C/5				Charge-Discharge Rate: 1C-3C			
CL0005	4.5 x 50 x 55	33.1	3.8	13.9	1125	420				
CL0007	4.2 x 50 x 55	27.8	2.8	10.1	875	365	2.65	9.0	780	325
CL0012	4.6 x 50 x 55	31.7	3.6	13.2	1040	416	3.4	11.5	870	360
CL0018	4.5 x 50 x 105	68.1	8.1	29.3	1240	430				
CL0021	5.4 x 54 x 64	49.5	5.4	21	1125	425				

Operating temperature range: -20 °C to 55 °C

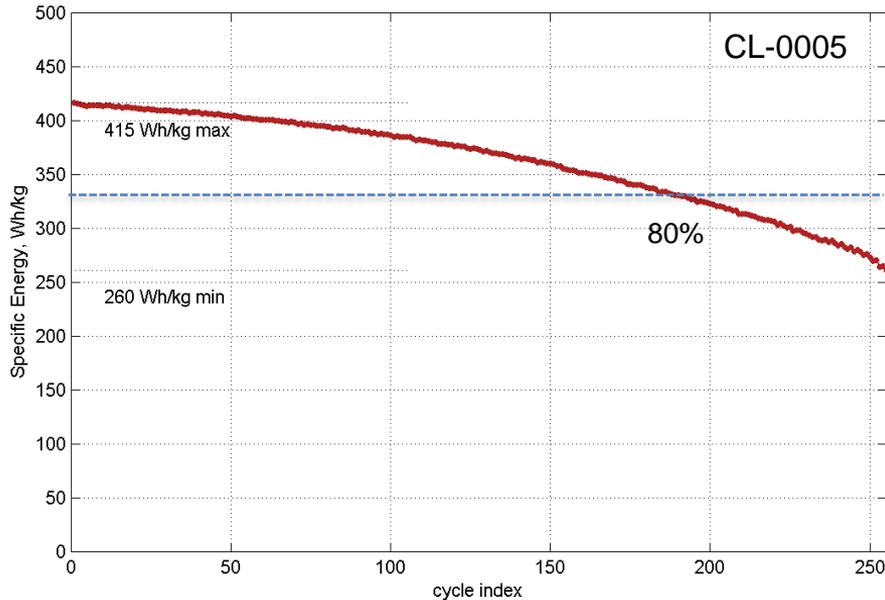
Cycle life of 150-300 cycles, depending on operating conditions

Amprius Technologies High Energy Products: Cycle Life – Lower Rate Drone Applications

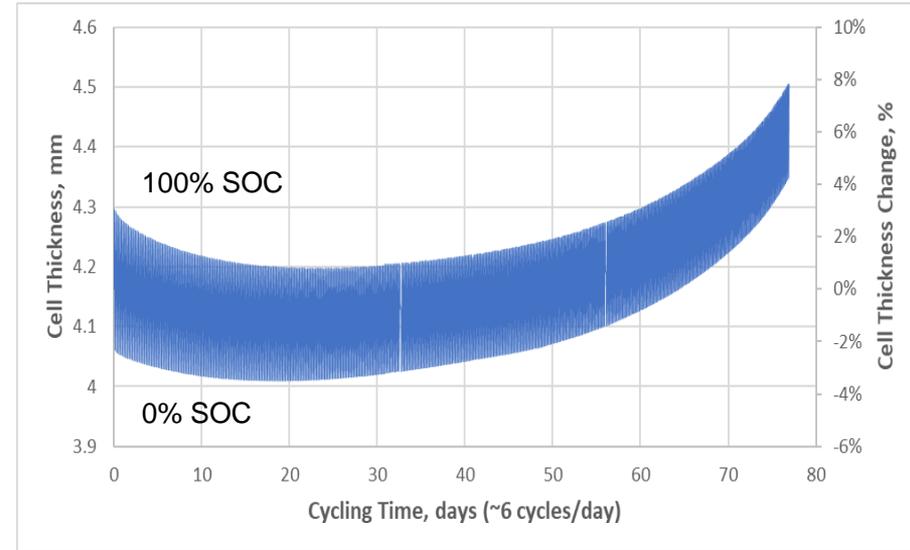


High Voltage LCO Cathode

Specific Energy



Cell Thickness

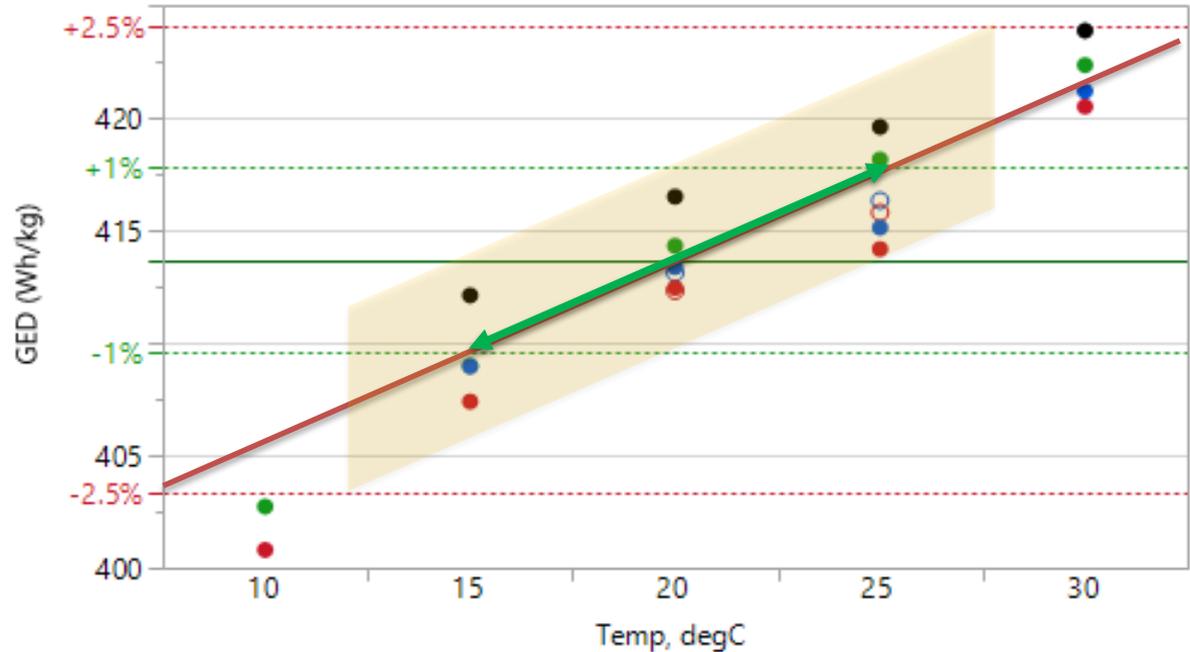


C/5 rate, for High Altitude Drone applications

Amprius Technologies High Energy Products: Pack temperature range

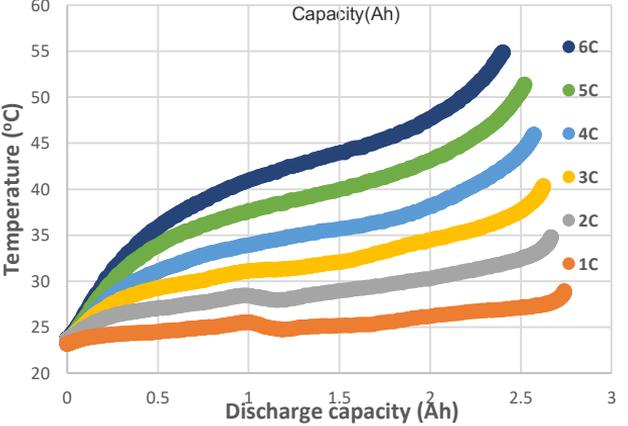
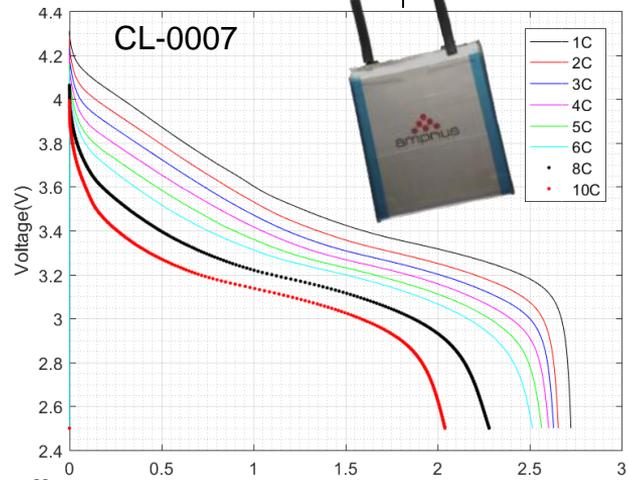
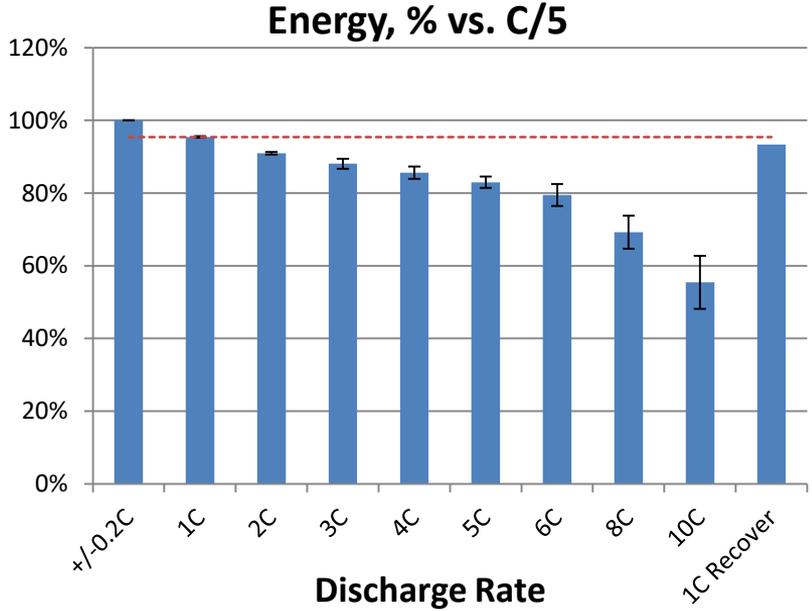


Thermal Characterization



- 5°C shifts capacity by about 1% in the 15-30°C range
- Temperature range in the pack should not exceed 5°C (20±2.5°C) to maintain initial cell matching (±1%)

Amprius Technologies High Power Products: Rate Capability



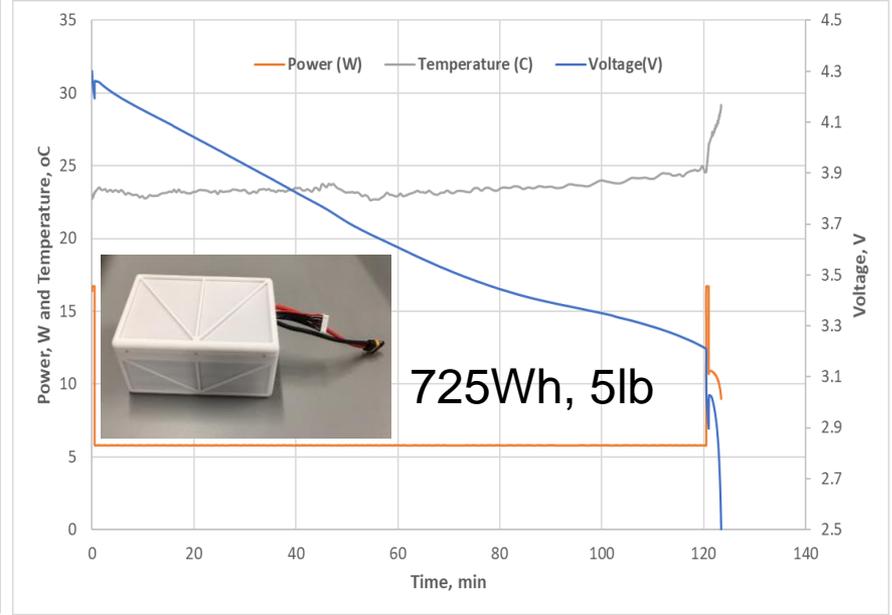
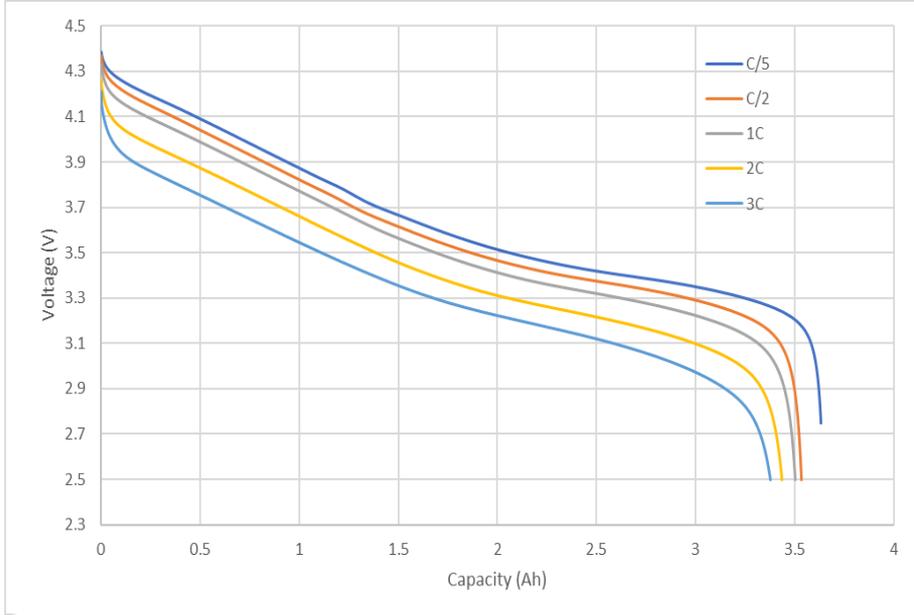
>80% relative energy to 6C rate

The temperature increase is small and within operating limits to 10C rate

Amprius Technologies Medium Power Products: Discharge Voltage profiles



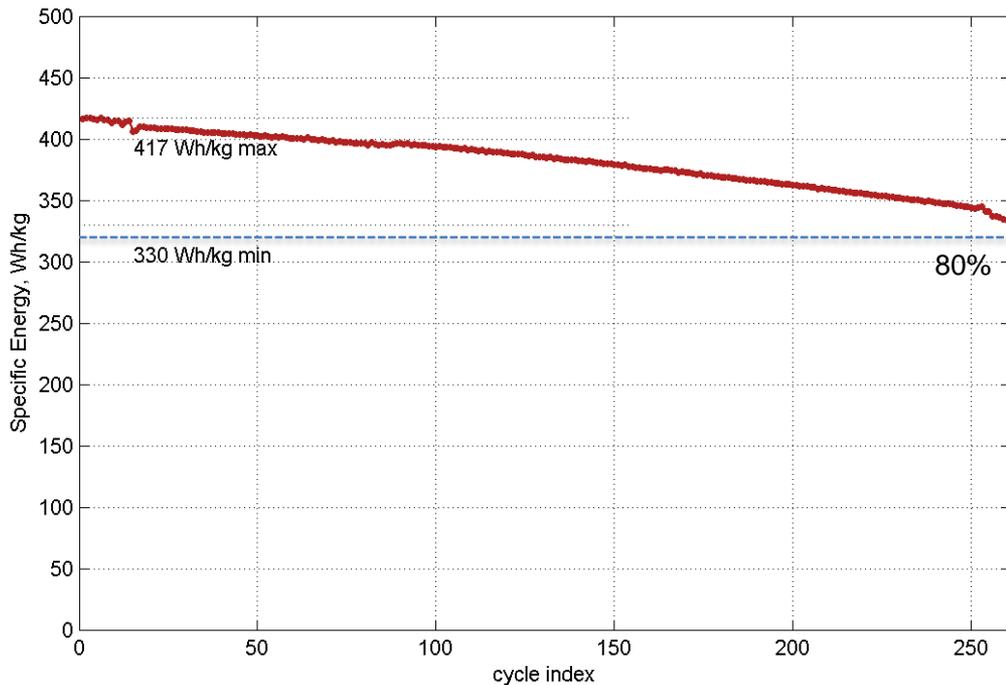
CL-0012



>400Wh/kg at C/5 and 370Wh/kg at 2C

Designed for eVTOL and multirotor drones – double endurance typically

New developments – higher cycle life



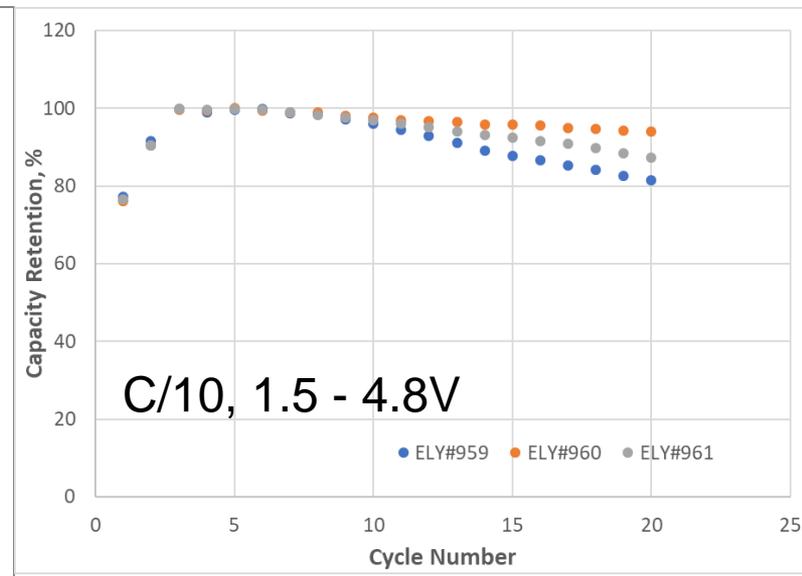
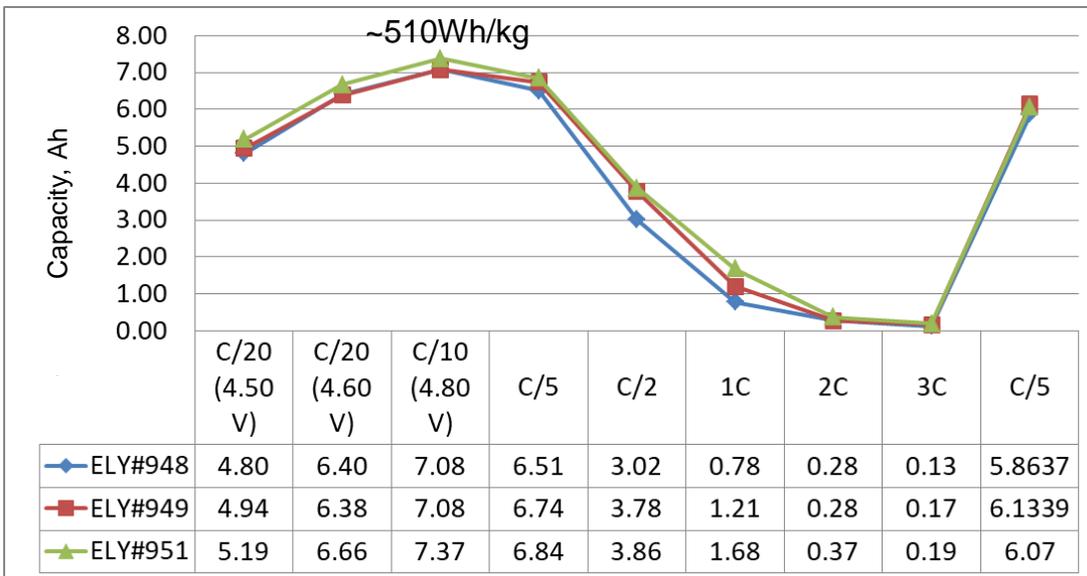
Voltage range 2.75-4.25V at C/5 rate, 23°C

~50% increase in cycle life, the direction has room for improvement

New developments – higher specific energy



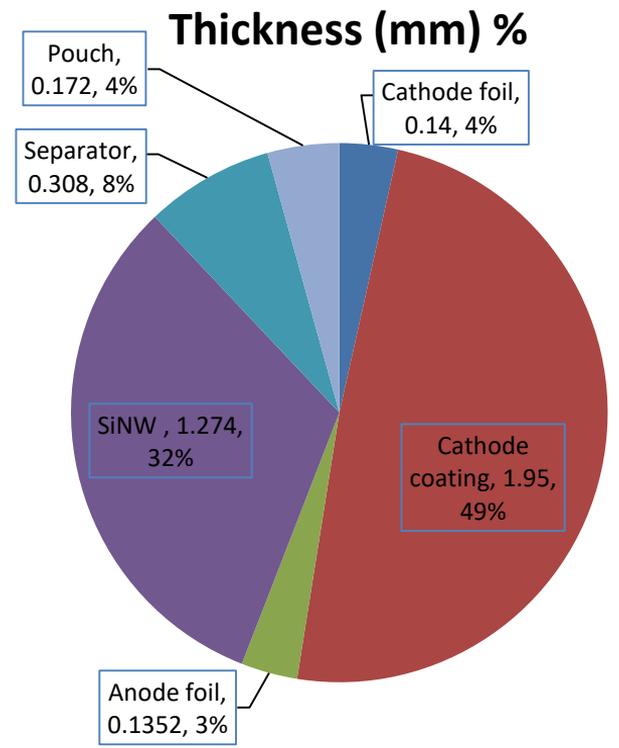
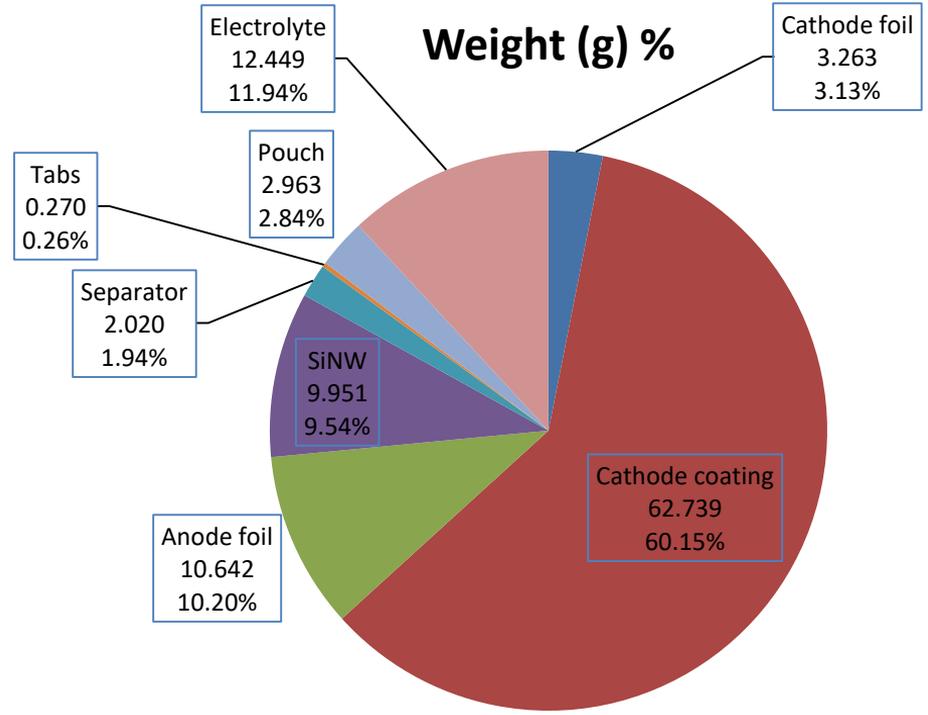
- High capacity LRMO cathode material
- ELY#951: New electrolyte composition + high voltage additive



Voltage range 1.5-4.8V at C/10 rate, 23°C

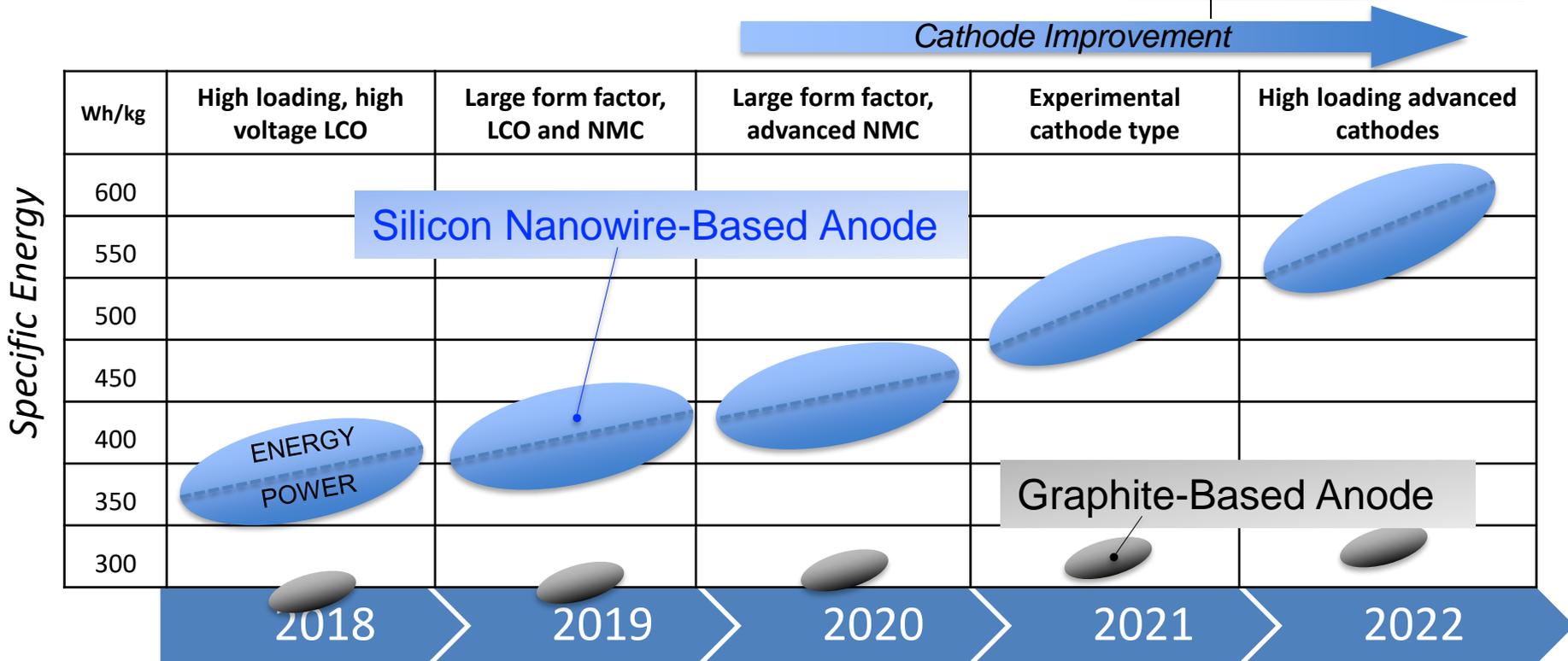
More electrolyte development for higher voltage operation needed

Roadmap: Cathode performance critical for further specific energy improvement



The cathode material dominates both in weight and volume proportion

Si Nanowire Anode Specific Energy Roadmap



Power/energy ratios are optimized in the design space (blue ellipses)

Thank You

Amprius wishes to acknowledge the funding received from US Army (Contract No. W911QY-12-C-0118), NASA (Contract No. NNC16CA10C), USABC (Project No. DE-EE0006250) and DOE (Award No. DE-EE0005474).

Ionel Stefan, (510) 512-5484, ionel@amprius.com

Jon Bornstein, (408) 406-2671, jonb@amprius.com