High Power, High Energy, High Safety Cell Technologies

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Abstract

Amprius is continually improving its pure silicon anode with nanowire structure that has enabled lithium-ion batteries with energy density and specific energy performance exceeding current state of the art graphite cells by 50-100%, depending on cell size and form factor. The rooted nanowire structure has very good mechanical stability, electrical conductivity, and connectivity, and allows material expansion within the structure, extending the cycle life to hundreds of cycles. Amprius cells have shown that silicon anode-based batteries can reach 1,300 Wh/L and 500 Wh/Kg while maintaining a cycle life compatible with aerospace, military, and other high-end applications. Moreover, the open nanowire structure enables cells to function at high rates of charge and discharge without overheating, achieving 1000 W/kg power density in cells with over 400 Wh/kg specific energy density. Recent cell design optimizations have substantially improved resilience to thermal runaway conditions, such as internal short circuit and nail penetration.

Keywords

silicon anode; lithium-ion; batteries; energy density; specific energy; power; aerospace; wearable batteries; drones.

Introduction

Amprius is a Li-ion cell manufacturer with silicon anode and related technologies that enables an increase in energy density of over 50% compared to cells containing graphite anodes. Amprius' main technology, a highly engineered silicon structure made of 100% silicon, enables Li-ion cells with specific energies reaching 500 Wh/kg and energy densities of over 1300 Wh/L. The technology thus provides a significant step forward in lithium-ion battery development, roughly equivalent to the entire improvement over the last two decades with graphite anodes.

Amprius' silicon nanowire anode is unique in the industry because it is the only anode that is made of pure silicon (i.e., no binders, conductive carbons, or other inactive materials) and physically rooted in (i.e., grown from) the current collector foil, which confers unprecedented mechanical stability to the anode structure. The growth-rooted low tortuosity structure is optimal for high power (fast charge/discharge) performance due to very good electrical connectivity between the active anode material and the foil and an open, short pore structure. This combination of properties led to the development of cells that are not only energy dense (Wh/kg and Wh/L) but also power dense (W/kg and W/L), capable of fast charge (minutes instead of hours) and high-power delivery.

Amprius cells are used in unmanned drone applications, such as high-altitude pseudo satellites, unmanned and manned flying drones and vehicles. Amprius cells have also been integrated for a demonstration in conformal wearable batteries (CWB). The CWB battery, developed in collaboration with Inventus Power with C5ISR funding, has demonstrated a doubling of energy stored in the same volume and mass as the graphite cell model, achieving a specific energy above 300 Wh/kg and capacities of more than 300 Wh. To meet the MIL-PRF-32383/4X specifications, the CWB cell safety was improved in order to survive mechanical abuse, which includes crushing, impact (bowling ball test), and nail penetration, by developing additional safety cell components, such as non-flammable and flame-retardant gel polymer electrolytes for silicon anode cells.

The silicon nanowire technology, currently in low volume manufacturing of about 400 kWh annually, will scale to MWh capacity in 2023, and to hundreds of MWh by 2025. This capacity will be enough to support many aerospace and defense applications as well as to demonstrate competitive manufacturing costs at scale, further enabling investment for GWh capacities for electric mobility (electric vehicles and electric flight), replacing graphite-based cells with energy dense storage solutions in most applications, with game changing impact on energy storage weight and endurance. The technology relies entirely on a domestic supply chain, with silane, the silicon precursor available in large quantities, made in the USA.

Technical Description

Structure and Properties: The silicon nanowire structure, shown in Figure 1, includes a metallically conductive nanowire core, metallurgically connected to the current collector. This robust connection is essential in creating and maintaining a stable electrical connection and mechanical structure at the electrode level. Each silicon wire is directly connected and does not need to rely on particle-to-particle contacts for conductivity. Since this connection is very robust compared to connections between particles created by electrode calendaring and binders, the silicon material remains in electrical contact, i.e., electrochemically active, over the entire cycle life of the cell. The fast loss of electrical connectivity and changes in mechanical structure that plague the majority of other silicon technologies are virtually non-existent in the rooted silicon nanowire anodes. Moreover, this significant stability is achieved in a structure that is virtually 100% silicon, without any binder or conductive additive to dilute its active material content.

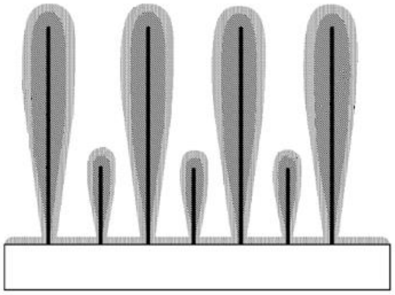

Figure 1. Amprius' growth rooted silicon nanowire structure

The silicon nanowire has a tapered shape, with a much lower thickness toward the root, where it connects to the current collector. This shape is essential in reducing the mechanical stress at the interface during lithiation/ delithiation cycles. When silicon films or particles are coated on foils as thin as those used currently in lithium ion cells, e.g. 6-12 µm in thickness, upon lithiation the foils are stretched and that leads to wrinkles, ripples and foil ripping. In the case of silicon nanowire electrodes, the minimum contact surface between the root of the silicon wire and foil eliminates mechanical stress in the foil during cell cycling.

A second feature of Amprius' silicon nanowire material is its nanostructure. The internal porosity and amorphous structure accommodate and dissipate some of the mechanical stress induced in the material during lithiation/delithiation processes. Since these processes start from the silicon/electrolyte interface, they occur mostly radially, and the stress and material expansion are of the same geometry. The silicon nanowire structure can accommodate a large amount of lithium without significant radial expansion. Even at full lithiation, the axial expansion, which is responsible for the cell expansion, is less than 25%, resulting in less than 10% cell thickness increase. This allows electrode loadings (mAh/cm^2) that are significantly higher (approaching 100% increase) than conventional graphite electrodes.

Because the nanowires, which work as electron conduction paths, are attached to the current collector, the structure does not rely on particle-to-particle contact for electronic conductivity and is able to achieve high conductivity, energy and power. This structure difference is shown in Figure 2, where the difference in the ionic and electronic conductive paths are indicated by arrows. Both paths are short and straight in the nanowire anode case, making the structure ideal for high power applications. Combined, these properties result in superior results to particle type graphite, silicon, or lithium metal anodes, exceeding them both in energy density and power capability, including fast charge capability and low temperature operation.

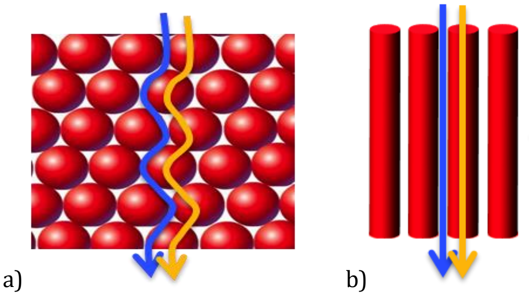

Figure 2. Electronic and ionic conductivity paths in silicon nanowire anode (b) are shorter and straight compared to the tortuous paths in graphite anodes (a

The nanowire material structure also enables a relatively high 94% first coulombic efficiency in half cells and 90% coulombic efficiency in full cells with LCO cathode. These values are competitive with graphite materials and reduce or eliminate the need for prelithiation steps that compensate for the first cycle loss in the cell fabrication. A typical first cycle at a 0.05C rate of a silicon nanowire electrode is shown in Figure 3.

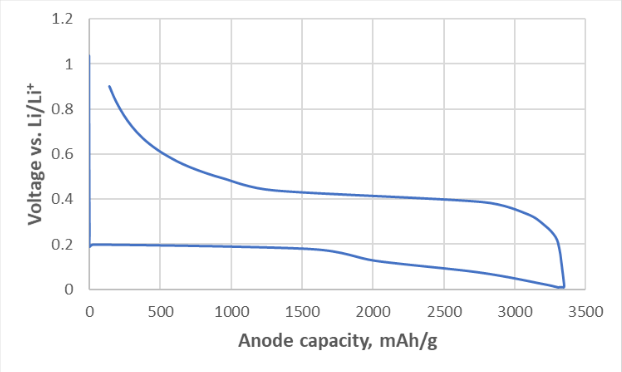

Figure 3. Silicon nanowire voltage profile in half cell, lithiated to 10mV vs. Li/Li+ electrode and delithiated to 0.9V at a 0.05C rate

Energy and Power Density: As described in the previous section, the silicon nanowire anode has intrinsically high-power capability. The Ragone plot in Figure 4 shows the energy and power application range of three silicon nanowire cell types that were developed by matching silicon nanowire anode with different cathode structures. With high loading cathodes, the specific energy reaches over 450 Wh/kg, but has a relatively narrow power range. This platform is used in applications that need operation times of many hours, such as day/night cycles or long mission applications. A porosity optimized high loading structure resulted in cells with a specific energy of over 400 Wh/kg and specific power of 1000 W/kg. This power-and-energy platform is used in long endurance drones and eVTOL applications where target endurance exceeds one hour.

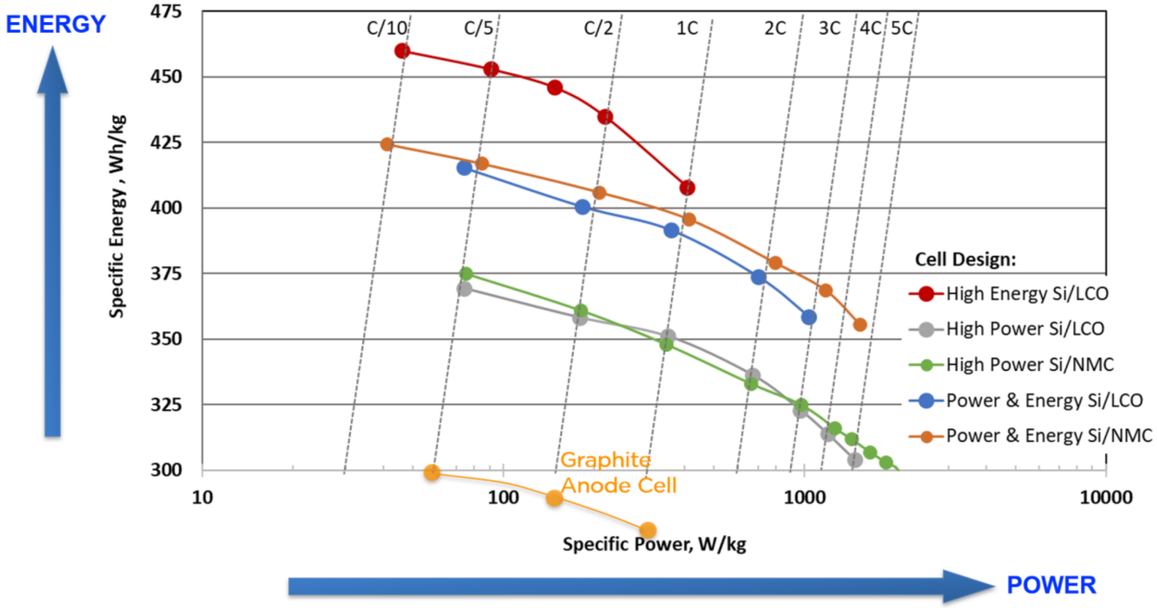

Figure 4. Amprius has developed three power-energy platforms by matching silicon nanowire anode with Lithium Cobalt Oxide (LCO) and Nickel Manganese Cobalt (NMC) cathodes with different loadings.

When matched with a high-power, thin cathode, the cells still have over 350 Wh/kg specific energy and can support 3000 W/kg of continuous power load. This power platform is used for applications that require very high specific power, such as load carrying power drones, and typically doubles the running times compared to graphite cells. In most high-power applications, the limits are usually the cell body temperature and the thermal management of the battery.

Cycle Life: The silicon nanowire anodes can cycle for hundreds of cycles in full cells due to limited swell at the material and cell level, and stable material and electrode structure. The stability of the material and partial utilization of the theoretical capacity of silicon also limits lithium consumption for SEI repair and, thus, extends the cycle life to numbers approaching those of graphite cells. In real applications, when cells are not fully discharged, cycle life exceeds 1000 cycles (Figure 5).

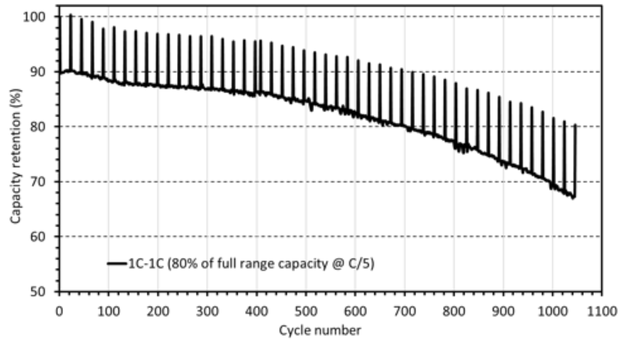

Figure 5. 1C/-1C cycling with 80% depth of discharge and +0.2C/-0.2C capacity check every 20 cycles.

Extreme Fast Charge: As shown in Figure 2, the silicon nanowire anode has a low diffusion distance (thin electrode), low tortuosity structure (straight pores), and short electric path to current collector (all silicon is "metallurgically" connected to the foil). These properties have led to cells products that have demonstrated 5-minute charge (Extreme Fast Charge, XFC) capability in cells with 360 Wh/kg specific energy (see Figure 6). Thus, additional capabilities that are only possible with silicon anode are available for deployment.

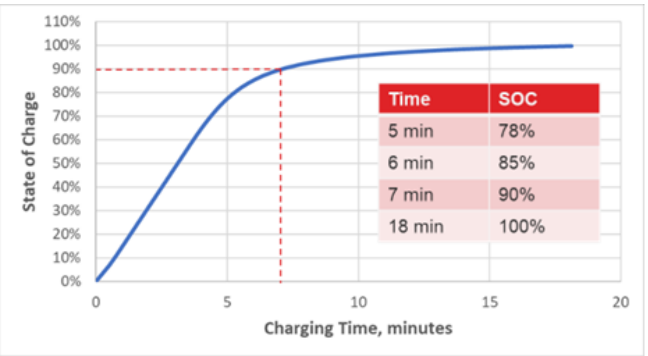

Figure 6. 1C/-1C cycling with 80% depth of discharge and +0.2C/-0.2C capacity check every 20 cycles.

Low Temperature: Silicon also has intrinsically better capability at low temperatures, due to its slightly higher operating voltage than graphite. For example, Amprius cells operate down to -30°C without low temperature optimized electrolytes and can operate even at -50°C with low freezing point electrolyte formulations. Similarly, the high temperature limit can be tailored by electrolyte formulation to meet targets. Cell data shown in Figure 7 indicates that about 80% of the energy available at 20°C is available at -20°C, for cells with specific energy over 400 Wh/kg. This capacity retention is about double compared to graphite cells at low temperatures.

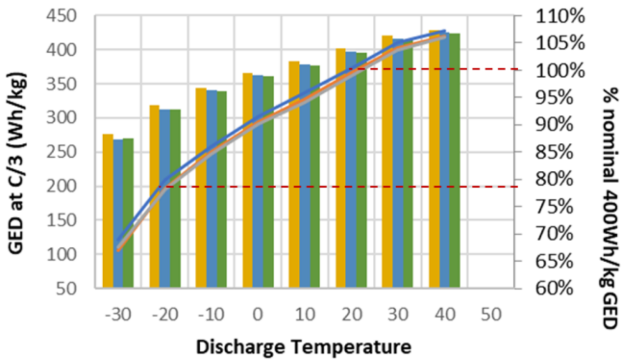

Figure 7. Amprius' 400 Wh/kg silicon cells perform very well at low temperatures, retaining 80% of room temperature performance at -20°C. The figure shows the retained specific energy of three cells between -30°C and 50°C).

Safety: Silicon nanowire cells developed in the last few years were successfully tested in multiple abuse and safety evaluation conditions, including electrical, mechanical, and thermal factors. For example, 5.4Ah pouch cells with silicon nanowire anode and LCO cathode were certified to pass the tests required for air cargo shipping, according to UN 38.3 specifications. Amprius has developed a gel polymer electrolyte formulation that insulates penetrating objects, such as nails, preventing thermal runaway. Separately, silicon nanowire cells passed other abuse and safety tests, including hot box at 130°C and overcharge by 150% charge capacity. These results suggest that there is little argument to support the assumption that silicon materials are inherently less safe than graphite anodes.

Products: Amprius has developed cells in multiple sizes, from 200mAh capacity for wearable applications to 45Ah for electric vehicles. Cells of 5.4Ah capacity were built into battery packs for drone applications by primary defense contractors, setting records of endurance in multi-rotor flight. In smaller form factors, Amprius is currently performing on a contract with Army's RCCTO office to develop a battery for the nano-UAS drones and has demonstrated an increase in flight endurance of over 60%. Pouch cells can be customized in different form factors with relative ease, and Amprius has experience in prototyping and developing such cells. Moreover, the silicon chemistry platform can be used as developed or with small optimization changes in multiple cell form factors. The cell pictures shown in Figure 8 illustrate the variety of designs in different cell form factors and stages of production.

Manufacturing: The complete set of manufacturing processes was integrated by 2016 into a continuous roll-to-roll pilot scale anode fabrication line. Two pilot lines and associated cell production are operated currently in Fremont, California, with expansion to a ten times larger capacity available in 2023. A 500MWh manufacturing scale project also started in 2023 and is the next step toward the commercialization of the silicon nanowire technology for larger markets. Customers in aerospace and defense will be able to use Amprius' high-performance lithium-ion cells to the full requirements of these markets at prices competitive to graphite cells.

Figure 8. Multiple designs were developed with Amprius' silicon anode chemistry.

Summary and Conclusions

Silicon is recognized as one of the most promising materials for next generation lithium-ion battery anode to replace the conventional carbon-based anode due to its high theoretical capacity, similar discharge potential and reliable operation safety. However, in most silicon material structures and compositions, the critical drawback of huge volume expansion upon lithiation causes series of adverse consequences, leading to very poor cyclic stability.

The rooted silicon nanowire structure developed by Amprius has largely mitigated the drawbacks that afflict other silicon materials and has led to the development of lithium-ion pouch cells with energy and power performance significantly above those of commercial state of the art graphite anode cells, in most cases by 50-100% improvement. Moreover, the cycle life of these cells is closing in on graphite cell performance, already meeting the requirements of a variety of markets. Some of the silicon nanowire cell products have already been qualified for applications, including safety and abuse tolerance validation. In general, the development of the first silicon nanowire products has shown that the safety and abuse tolerance of silicon nanowire cells can be as good or better than that of similar graphite cells. It is expected that, in parallel with an increase in manufacturing capability and capacity, the application scope of silicon nanowire cells will expand from premium and mission critical markets to consumer and commercial application in the next few years.

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