qSafe: Power Cell of the Future

ABSTRACT

Recently, dangerous explosions in lithium-ion batteries have put many lives at risk and caused several major product recalls affecting cell phones, airplanes, hoverboards, and laptops. Researchers and technology companies worldwide have developed solutions that are often impractical and fail to address the root causes of the explosions. Our qSafe power cell uses a system of surface acoustic waves that prevent hazardous lithium buildups, which cause short circuits and explosions in lithium-ion batteries. Furthermore, advances in chemistry will allow the qSafe power cell to perform with increased efficiency through the application of quantum nano-based materials. The use of these materials also solves ethical issues created by unsafe conditions in mining cobalt, which is utilized in current lithium-ion battery technology. The qSafe power cell will be a quantum leap into safe, efficient, and ethical battery technology.

qSafe: Power Cell of the Future

PRESENT TECHNOLOGY

The most basic form of any rechargeable galvanic battery cell consists of a positively charged cathode and a negatively charged anode made of different metals (the charges are reversed in an electrolytic cell); a separator between both electrodes; and a conductive paste called the electrolyte. For an efficient battery, both the anode and cathode must have a high energy density, and one must have a higher electronegativity than the other to allow movement of electrons in a closed circuit. Presently, lithium-ion (Li-ion) batteries are the most common form of rechargeable galvanic cells, and their use is expected to increase dramatically as more homes and cars incorporate this lightweight energy storage device.

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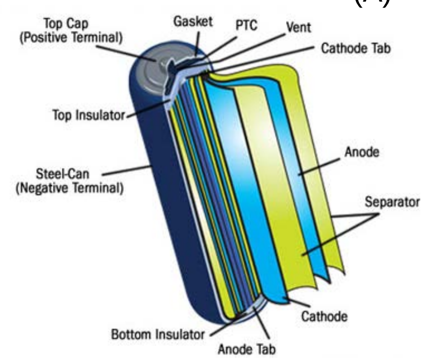
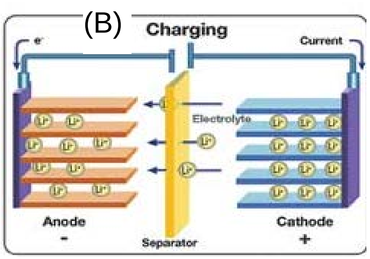


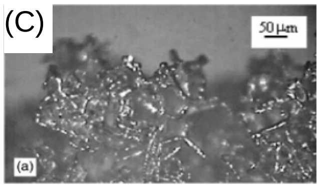
The cathode of a Li-ion battery consists of a lithium metal oxide, while the anode is made of a porous carbon substance such as graphite. When the battery is charging, the lithium atoms contained within the latticed cathode each lose one electron, which travels through the circuit to the anode powering a device. Meanwhile, the newly formed positive lithium ions move through the electrolyte and the separator to meet the electrons at the anode. This process is reversed during discharge when the electrons return to the cathode due to its electronegativity, causing the lithium ions to do the same.

(B)



Li-ion battery technology currently faces significant challenges. Imperfections on the surface of the anode can cause buildup of metallic lithium, also known as a dendrite. Over time, a dendrite grows as additional lithium ions accumulate, resulting in a decrease of lithium ions available in the charging and discharging cycle. This causes deterioration of Li-ion battery power

(C)



efficiency over extended periods. Also, a growing dendrite can pierce the battery's separator and eventually meet with the cathode, causing electrons to flood quickly to the opposite electrode, releasing large amounts of energy that result in thermal runaway within the Li-ion cell.

Currently, batteries and their chargers contain sensors to help prevent overcharging. If this system fails, there is no backup mechanism in commercial batteries to force them to shut down before they overcharge and explode. In January 2017, researchers at Stanford devised another method to prevent thermal runaway. This method includes a cylindrical-polymer shell that contains flame retardant. When a lithium battery reaches 160 degrees Celsius, the polymer shell melts, releasing the flame retardant and extinguishing the battery before it explodes.

A solution to safety risks posed by exploding devices is the use of flameproof bags by airlines. If devices catch fire while a plane is in flight, they are placed in flameproof bags. A researcher at Stanford University has discovered another safety measure that can be taken to prevent Li-ion battery explosions. Her solution involves an expanding separator consisting of a filmy nanoparticle layer of nickel and graphene. When the battery reaches a certain temperature, the separator expands and isolates the electrodes, effectively shutting the battery down in less than one minute.

Our qSafe prevents the buildup of dendrites, thereby eliminating the risk of short circuits and explosions while increasing efficiency and battery life. The qSafe also negates the use of cobalt by using iron pyrite in the cathode instead, which creates a more ethical manufacturing process; cobalt is most commonly hand-mined in the Democratic Republic of the Congo, where child labor is utilized for working in compact spaces underground.

HISTORY

ca. 250 B.C.: The "Parthian Battery" is created (rediscovered near Baghdad in 1936). Instead of energy storage, it is likely used to electroplate metals.

1800: Count Alessandro Volta invents the "voltaic pile," consisting of copper zinc discs separated by cardboard discs soaked in acid.

1836: The Daniell cell is invented, supplying a steady, longer-lasting current.

1859: Gaston Planté creates the first rechargeable lead-acid battery.

1899: A patent for a nickel-cadmium rechargeable battery with twice the energy density of the lead-acid battery is filed in Sweden by Waldemar Jungner.

1949: The alkaline-manganese battery is invented by Lewis Urry at Eveready Battery Co.

1965: The first surface acoustic wave-generating devices (SAWs) are created.

1980: At Oxford University, Professor John Goodenough creates the first Li-ion batteries using both lithium cobalt oxide and lithium manganese dioxide cathodes.

1981: Quantum dots are discovered in a glass matrix at the State Optical Institute in Russia.

1991: Sony commercializes the lithium cobalt oxide version of the Li-ion battery.

2000–present: Safety recalls include millions of laptops and smartphones due to Li-ion battery explosions. The FAA grounds all Boeing Dreamliners due to lithium-ion battery malfunctions.

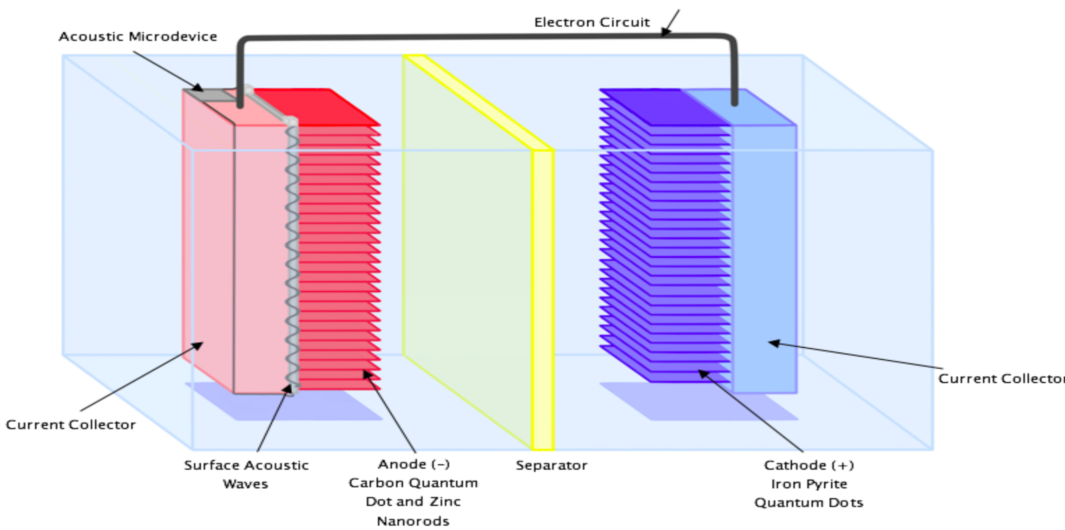
2015: Researchers at Hunan University grow zinc oxide nanorods on carbon cloth, with promising applications for anodes in Li-ion batteries.

2015: At Vanderbilt University, researchers test an anode made of iron pyrite quantum dots.

2015: Tesla unveils its Powerwall, which uses Li-ion batteries to store energy for homes and businesses.

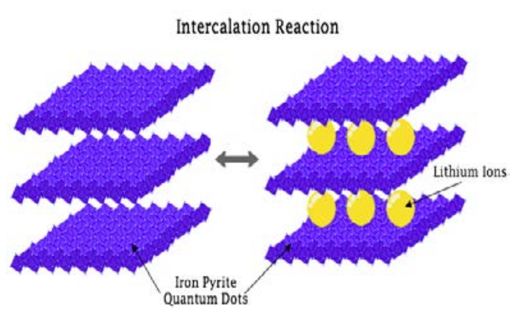
FUTURE TECHNOLOGY

The qSafe power cell is the lithium-ion (Li-ion) battery of the future, with faster charging, increased safety, and a greater number of recharge cycles as compared to current Li-ion batteries. Three improvements will create a safer and more efficient battery: a cathode consisting of iron pyrite quantum dots, an anode composed of woven carbon with zinc nanorods, and a system of surface acoustic waves (SAWs).



Cathode: Iron Pyrite Quantum Dots

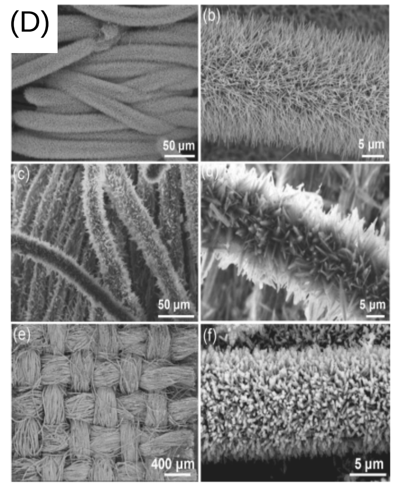
Our qSafe cathode will consist of quantum dots (QDs) made from iron pyrite (FeS_2), also known as fool's gold. These QDs create the shelf-like layers of the cathode. Energy for the qSafe power cell comes from the lithium ions that intercalate between the layers when the battery is fully charged. A polymer binder called Polyvinylidene fluoride (PVDF) is necessary to hold a single layer of iron pyrite QDs together. The iron pyrite carbon dots create higher energy efficiency due to the superior ability of QDs to store energy. In our discussions

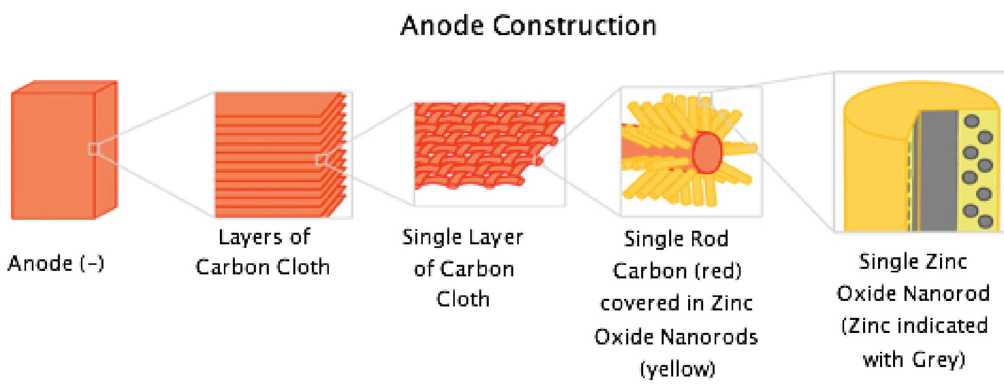


with a Vanderbilt researcher, we found that this cathode design allows the Li-ion battery to be charged in under 30 seconds.

Anode: Woven Carbon with Zinc Nanorods

During the charging process of Li-ion batteries, the ions intercalate between layers of the anode, causing it to expand. A recent product recall was the result of compacting the battery into too tight of a shell, which caused the electrodes to touch when the anode expanded, thereby shorting out the battery and causing it to vent flame. The anode of the qSafe power cell prevents this expansion by consisting of nanorods (shown in figure D) composed of a mixture of zinc oxide (ZnO) and carbon QDs grown on carbon cloth, as shown in the diagram below.





Researchers at Hunan University have demonstrated that anode expansion is suppressed due to the mechanical strength of the cloth, combined with the increased surface area of the zinc nanorods. This improvement allows the battery to charge faster and retain its charge for a longer period. The current collector is made of carbon cloth, similar to the material of the anode, which allows the electrons to travel more freely because it eliminates their need to move between different substances.

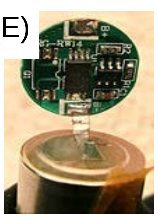
During the manufacturing process, Stabilized Lithium Metal Powder (SLMP) is diffused into the anode material. SLMP consists of powdered lithium coated in a layer of wax that prevents the lithium from encountering oxygen or moisture from the air. Research has shown that SLMP improves the energy capacity of current Li-ion batteries from 5% to 15%, which contributes to the efficiency of the qSafe power cell.

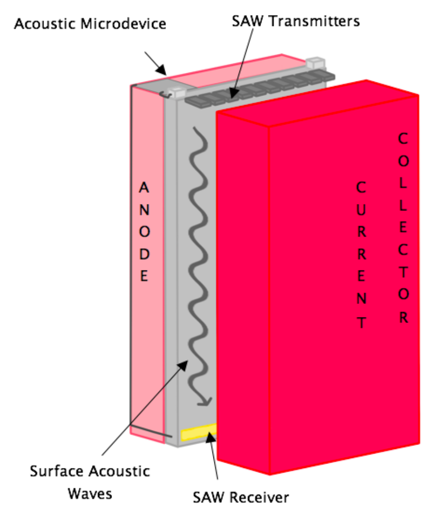
qSafe Surface Acoustic Waves (SAWs)

Our qSafe power cell solves the problem of dendrite formation on the anode through a system of SAWs, shown in the diagram below. SAWs will be generated along the surface of the anode at micron wavelengths, shaking off lithium ions before they can form dendrites.

Li-ion batteries contain a microprocessor, shown in figure E, that monitors both the temperature of the cell and the charging rate. In addition to the existing microprocessor, the qSafe circuit contains an acoustic micro device (AMD) consisting of a piezoelectric substance for the SAWs to propagate and an interdigital transducer, which converts electrical signals into acoustic waves. The AMD is attached to the back of the anode within the qSafe power cell and derives negligible energy from the battery.

(E)





The qSafe system transmits the SAWs along the back of the anode to a corresponding set of receivers. The receivers will detect any changes in the amplitude of the wave and transmit the data to the microprocessor; a drop in amplitude will indicate irregularities on the surface of the anode. If it senses a significant change, the microprocessor prompts the battery to either increase the amplitude of the SAW or notify the user. By constantly monitoring and correcting the health of the battery, qSafe will prevent thermal runaway caused by battery damage or dendrites.

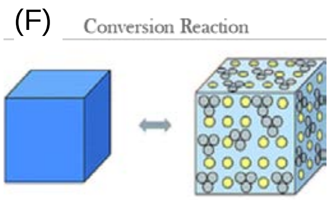
Using these technologies, the qSafe power cell offers increased energy efficiency and shorter charging times. Applications of the qSafe range from grid storage to mobile devices and clean transportation, making the qSafe the power cell of the future.

BREAKTHROUGHS

Today qSafe would be limited by its materials and manufacturing processes. To make our qSafe power cell a reality, breakthroughs are needed in the designs of the cathode, anode, and generation of surface acoustic waves.

Cathode: Our qSafe cannot yet exist because the iron pyrite cathode material limits the number of charge cycles, creating a battery that lasts for only a few uses. At high voltages, iron pyrite QDs undergo conversion reactions in which the lithium ions exchange with the material of the cathode rather than fit between the layers, allowing for extremely fast charging. However, conversion reactions are relatively unstable due to the rearrangement of atoms, and they significantly decrease the efficiency of the battery with each charge cycle. At lower voltages, the QDs undergo an intercalation reaction that is more efficient than a conversion reaction, but charging takes much longer. Our qSafe will need to make the iron pyrite QDs charge quickly at a high voltage while still undergoing an intercalation reaction.

(F)



Anode: In order to produce the qSafe battery on a commercial scale, developments are needed in the manufacturing process of the anode. The carbon cloth and zinc nanorods of the qSafe battery are at the nanoscale and currently take some time to produce. New equipment will be necessary for fast production of the necessary nanoscale materials. Ultimately, when the qSafe is put into mass production, large-scale qSafe factories will be needed, similar to the Tesla Gigafactory.

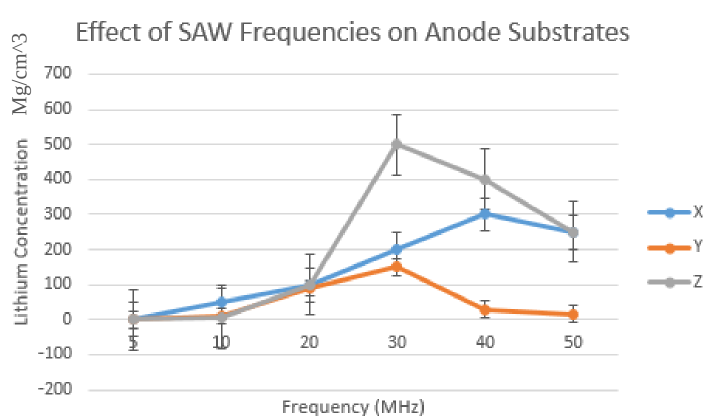
SAWs: Surface acoustic waves would have to be engineered in order to propagate the entire length of the anode at an appropriate frequency that can prevent dendrite formation. Additionally, in our discussions with a researcher at Lithium Battery Engineering LLC, we found that large vibrations in the electrolyte present serious safety issues. In qSafe, the SAWs propagating the length of the anode have a small enough amplitude (~ 100 nm) not to disturb the electrolyte; however, tests must be completed to confirm this. Technology that enables SAWs to prevent dendrites efficiently will need to be developed before our qSafe system can be perfected.

Investigation: To perfect the qSafe power cell, we will need to investigate the effect of the dispersal of lithium ions at various frequencies on different SAW substrates. The best substrate would be one that allows the SAWs to successfully shake lithium ions intercalated in the anode while still providing as little resistance as possible to the flow of electrons. As an example, we could use zinc oxide substrate, attach the interdigital transducer, and measure the concentration of lithium ions in the electrolyte. Here we show a hypothetical data table and graph using substrates X, Y, and Z.

SUBSTRATE X

Frequency (Independent Variable)	**Li-ion Concentration* (Dependent Variable)**
0-500 MHz	*Amount of lithium removed from the anode by the SAWs in mg/cm³*
50	. . .
100	. . .
200	. . .
300	. . .
400	. . .
500	. . .

**values are undetermined*



DESIGN PROCESS

Our team began working on this project in response to the growing problem of unsafe Li-ion batteries. Our goal was to engineer a safer rechargeable cell that would decrease incidence of shutdown when overheated while maintaining optimum efficiency. We discarded the following three concepts as we explored this problem.

Design 1 -- Bio-Based PCM Separator: Phase change materials (PCMs) are materials that can absorb large amounts of thermal energy. When a PCM is in its solid state, its temperature will mirror the external temperature until its melting point is reached. We saw potential to prevent the thermal runaway inside the battery by building the separator with a bio-based PCM, which would be non-toxic, fire resistant, and long lasting. However, we rejected this idea because once the separator in a Li-ion melts, it can cause the electrolyte to catch fire. We were unable to find a PCM that would remain in a solid state in temperatures over 169 degrees Celsius, which is the point when dangerous reactions begin to take place between the cathode and anode.

Design 2 -- Physical Separation of Electrodes: Our second idea was to make Li-ion batteries safer by twisting the battery in order to physically separate the two electrodes. This concept would shut down the battery completely, preventing the separator from overheating and the cathode and anode from reacting. We then decided this was not a practical solution because, to twist the battery, we would have to build another mechanism inside the device that could accomplish the action. Such a mechanism would take up extra space inside the device, detracting from features like storage and battery life. This safeguard would also mean a complete shutdown of the device, which we wanted to avoid. We rejected this concept and continued searching for a better solution that was safe and would keep the battery running.

Design 3 -- Laser Cooling System: Our third concept was to incorporate a sheet of nanolasers coating the inner shell of the battery. This technology, paired with a temperature-sensing chip, could target and cool "hot spots" within the electrolyte to prevent thermal runaway. In theory, when the lasers would fire and slow the atoms in the electrolyte, the excess light energy could be redirected from the battery to the outside of the device in the form of a glowing rim. We discarded this idea because it would drastically decrease the efficiency of the battery and increase the cost. We were also unable to devise a practical solution for powering the lasers or channeling the excess light energy out of the battery to create a glowing rim. This solution had many errors that we were unable to address, and it had to be designed in a way that would make the technology applicable only to cell phones.

Our Final Design -- The qSafe Power Cell: Our team ultimately decided on our qSafe power cell technology because it solved the problem of dendrite buildup that our discarded ideas failed to address. The qSafe power cell addresses dendrite buildup by using an acoustic micro device (AMD) to power surface acoustic waves on the anode, creating a safer battery. In addition, we replaced the materials that traditionally make up both electrodes in Li-ion batteries with materials that have higher energy densities, creating a faster charging time without compromising the efficiency of the battery.

CONSEQUENCES

The consequences of qSafe power cells are far reaching. As we transition to renewables, dependence on batteries for energy storage in homes and on the electrical grid will be common. The increased energy capacity of our qSafe power cell provides an efficient solution to meet peak demand. The few negative consequences of the qSafe include: (1) use of stabilized lithium metal powder that requires manufacturing while the battery is live, increasing the risk of shorting out the battery while in production; (2) energy used to monitor the battery's safety; and (3) the cost of quantum technology. The positive consequences of the qSafe power cell are far more significant.

- ***Safety*** Our battery is a safer energy source for all types of technological uses. Current technologies aim to create a safer lithium-ion battery by shutting down the battery entirely when it reaches an unsafe temperature. By preventing the buildup of dendrites with surface acoustic waves and suppressing anode expansion with improved materials, our technology does not allow thermal runaway to occur, eliminating the need for battery shutdown.
- ***Efficiency*** The materials we chose for qSafe have a higher energy density and, paired with surface acoustic waves, our power cell provides faster charging for increased efficiency without compromising safety or the lightweight characteristic of today's Li-ion batteries.
- ***Ethical Sourcing*** In building the cathode with iron pyrite, we have eliminated the use of cobalt as a material. The leading source of mined cobalt is the Democratic Republic of the Congo, where child miners—some as young as seven years old—are common, and working conditions for all miners are unsafe. Iron pyrite is found in many other countries and is less than half the price of cobalt. Utilizing this alternative metal in the cathode, the qSafe power cell is both a more ethical and economical battery technology.

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