

# Original Article: Development of Solid State Electrolytes for Next Generation Lithium-Ion Batteries

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## ABSTRACT

Lithium-ion batteries have changed the landscape of energy storage and ushered in a new era of clean, efficient and sustainable energy solutions. From powering our smartphones and laptops to fueling the transportation and renewable energy sectors, lithium-ion batteries are essential to modern life. The main goal of the innovative technology is to solve one of the old challenges of the battery industry: The erosion of liquid electrolytes. As research and innovation continue to push the boundaries of battery technology, the future holds exciting opportunities for even more efficient, safer and environmentally friendly energy storage solutions. By harnessing the potential of lithium-ion batteries, we can pave the way to a greener and more electrified future for generations to come. Additionally, this solution can improve battery safety by reducing the risk of thermal runaway – a common concern in older lithium-ion batteries. This development is in line with phenomena such as the global determination for sustainable energy solutions as well as the increasing demand for high-performance batteries.

## Introduction

Battery is one of the most important technologies today, which is used in various devices, and its use as a source of energy supply is expanding rapidly [1-3]. The battery plays a significant role in the development and expansion of electric cars and shows the need to improve the technologies used in making batteries with more energy and safety. Lithium

ion solid state batteries are one of the promising options in the next generation of electric car batteries and are considered a suitable replacement for lithium ion batteries. Solid non-flammable electrolytes replaced flammable liquid electrolytes. Therefore, solid state batteries such as lithium metal, lithium air, and lithium sulfur with high energy density and high safety are still obstacles in the commercialization of these types of batteries.

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## Proposed methods to solve the challenges of solid state batteries on three different levels

In these types of batteries, due to the presence of solid electrolyte, there is an interaction between the electrode and the battery electrolyte, which has the following consequences [4].

1. Production of mechanical stresses in the interacted area;
2. Negative effect on properties such as battery capacity density in successive charge and discharge cycles.

Therefore, it is important to design and choose the right materials and structure of the electrolyte in the solid state battery. Mechanical tests in various materials - these tests are very important in solid state batteries.

## Introduction of lithium ion batteries

In the search for cleaner and more efficient energy storage solutions, lithium-ion batteries have emerged as a game changer. From revolutionizing consumer electronics to enabling the widespread adoption of electric vehicles and renewable energy systems, lithium-ion batteries have changed the way we power the world. Li-ion batteries are used in many applications, including portable electronic devices, electric vehicles, solar and wind power generation systems, and medical devices due to features such as light weight, small volume, fast charging time, and long life. Also, lithium-ion batteries are very popular in applications that require high stability and low maintenance due to their long life and no need for continuous maintenance [5].

## The birth of lithium-ion batteries

Historical Background: Lithium-ion batteries were first introduced in the 1970s by pioneers such as John B. Goodenough, Stanley Whittingham and Akira Yoshino, who pioneered revolutionary technology.

- ✓ **Basics:** Lithium-ion batteries work based on the movement of lithium ions between positive and negative electrodes during charge and discharge cycles, facilitated by an electrolyte solution.
- ✓ **Chemistry evolution:** Over the years, researchers have refined the chemistry of lithium-ion batteries and experimented with different electrode materials such as graphite, lithium cobalt oxide, lithium iron phosphate, and lithium manganese oxide to improve performance, energy density, and safety [6].

## Key components and working principles

- ✓ **Anode:** The anode of a lithium-ion battery is usually composed of graphite or other carbon-based materials that can agitate the lithium ions during charging.
- ✓ **Cathode:** The cathode is usually made of metal oxides such as lithium cobalt oxide, lithium iron phosphate, or lithium nickel cobalt manganese oxide, which reversibly absorb and release lithium ions during charging and discharging.
- ✓ **Electrolyte:** The electrolyte acts as an ion transfer medium between the anode and the cathode, usually consisting of a lithium salt dissolved in a solvent such as ethylene carbonate or propylene carbonate.
- ✓ **Isolator:** Isolator prevents short circuit by physically separating anode and cathode while allowing lithium ions to pass through [7].
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### CHARGING

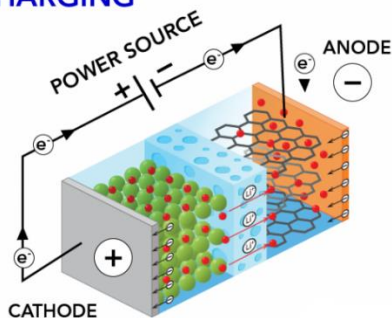


Figure 1. Lithium battery

### Applications of lithium ion batteries

- ✓ **Consumer electronics:** Li-ion batteries have revolutionized portable electronics such as smartphones, laptops, tablets, and wearables,

providing lightweight, high-energy-density power sources with long cycle lives.

- ✓ **Electric Vehicles (EV):** The automotive industry has adopted lithium-ion batteries as the preferred energy storage solution for electric and hybrid vehicles, offering better range, performance and durability compared to traditional lead-acid batteries.
- ✓ **Renewable energy storage:** Li-ion batteries play an important role in storing energy from renewable sources such as solar and wind, providing grid stabilization, peak shaving and backup power in residential, commercial and urban-scale applications [11].
- ✓ **Portable Power Banks:** Lithium-ion battery packs are widely used in portable power banks and backup systems, providing convenient and reliable power solutions for outdoor activities, emergencies, and remote locations.
- ✓ **Solid-state batteries:** Researchers are investigating solid-state lithium-ion batteries as a next-generation technology with potential advantages such as higher energy density, improved safety, and a wider operating temperature range compared to traditional liquid electrolyte batteries.
- ✓ **Silicon Anodes:** Silicon-based anode materials are being developed to increase the energy density and performance of Li-ion batteries because silicon can store significantly more lithium ions than graphite.
- ✓ **Recycling and sustainability:** Efforts are underway to develop efficient recycling processes for Li-ion batteries to recover valuable materials such as lithium, cobalt, nickel, and copper while

minimizing environmental impact and resource depletion [12].

### Challenges and future prospects

- ✓ **Safety concerns:** Despite significant progress, safety remains a major concern for Li-ion batteries, as issues such as thermal runaway, dendrite formation, and electrolyte decomposition can lead to fires and explosions.
- ✓ **Cost reduction:** Continuous research and innovation are needed to reduce the cost of lithium-ion batteries through economies of scale, improved manufacturing processes, and material optimization.
- ✓ **Energy density and performance:** Future advances in battery technology aim to further increase energy density, cycle life and power output while reducing charging time and extending battery life [13].

### Problem design and solution

In the lithium ion battery, due to the presence of the electrolyte liquid, the tensions in the structure have not had much effect on the performance of the battery. But in solid-state batteries, dynamic stresses occur in the structure during the manufacturing process and battery operation time. As a result, it causes changes in the volume of the battery and the formation of interphase materials. To solve this problem and also to achieve an energy density comparable to lithium-ion batteries, the separating part in the battery must be made of dense films with a thickness of microns and compatible with the cell. Oxide materials have electrochemical stability and high resistance to failure. Similarly, making dense films from these materials requires special temperature, pressure and production conditions. But sulfide crystalline materials have lower

fracture strength and their surface melting temperature is also lower (sintering temperature). As a result, they are easily compacted and mechanically more compatible than oxides. Film production with sulphide materials has the following consequences:

1. Improving the electrode and electrolyte contact surface;
2. Increasing ionic conductivity, especially in composite cathodes in batteries.

### Challenges and important issues in the design of solid state batteries

#### Electrolyte Additives for Silicon Anode Based LIBs

Adding a small amount of additives to the electrolyte has been considered as a suitable, economical and effective solution to prevent the large volume of silicon from changing and losing the initial capacity. Loss of initial capacity occurs due to the continuous decomposition of the electrolyte in batteries with high capacity electrodes and reactive electrodes (such as lithium metal, silicon, sodium, etc.) [14]. Reducible and oxidizable electrolyte additives modify the solid inter electrolyte (SEI) and cathode-electrolyte (CEI) phases, respectively, by changing and adjusting their composition and properties. Regarding the comparison between anode electrodes based on graphite and silicon, their uniqueness affects SEI layer chemistry and its main characteristics more than the similarities of these two electrodes [15].

#### The differences are

- ✓ Pure silicon always contains oxidatively active passivating species such as  $\text{SiO}_2$  and  $\text{OH}^-$ , which can be irreversibly reduced and/or undergo other harmful chemical reactions with the binder and other battery cell components.
- ✓ Silicon anode dealloying chemistry is affected by the irreversible morphological

transformation of crystalline to amorphous phases.

- ✓ The large volume change of silicon causes continuous rounds of SEI formation, and this accounts, at least in part, for the much faster capacity loss of silicon-based anode electrodes [16].
- ✓ These facts show that due care should be taken in the design of functional electrolyte additives for alloying in general and silicon-based anode materials in particular. Therefore, additives that work well with graphite anodes may not meet the requirements for silicon anode-based electrode materials. Due to the lack of a clear guideline on the amount of an electrolyte additive that should be considered additive and/or co-operator (solvent, salt), an arbitrary threshold of 10% by weight will be used throughout the text.
- ✓ Various properties should be considered while selecting the desired electrolyte additives for silicon anode based LIBs. These features include:
  - ✓ **Low cost:** Additives should have low material, synthesis and processing costs.
  - ✓ **Sustainability and Green Chemistry:** Synthesis, preparation and storage processes should be environmentally friendly, easily scalable and have low negative impact.
  - ✓ **Target oriented:** They should fulfill the intended functional role with minimal negative effects, for example, on the bulk properties of the electrolyte.
  - ✓ **Synergistic effect:** If possible, additives should have multipurpose roles using positive synergistic effects.
  - ✓ **“Small Dose → Big Effect” Viewpoint:** The name “Additives” suggests that they should have a significant effect when added in small amounts [17].

- ✓ Lead to very high conductivity and large equivalent volume (i.e. large surface coverage) of SEI-forming species.
- ✓ Additives reported so far for use with silicon-based anodes are categorized based on their nature and chemistry as presented below.

#### Important parameters of solid state battery

To design an efficient, effective and suitable solid electrolyte, the following important parameters must show acceptable performance, such as: Conductivity, fracture strength and coefficient elastic.

#### Important parameters in solid state batteries - comparison of these parameters in different materials and technologies

Lithium-ion batteries used in electric vehicles are always facing challenges to keep the performance of the battery in the car optimal and the health of the battery. These challenges are also discussed in solid state batteries. In addition, nucleation, diffusion of lithium filaments, and arrangement of vacancies in solid-state batteries will have obvious effects on battery performance so that they cause a short circuit inside the battery cell and cause a sudden drop in impedance. Knowing these challenges and controlling them in the future can increase the efficiency and effectiveness of solid state batteries. The speed of growth and development of solid-state batteries, especially in the electric vehicle industry, makes these types of batteries more widespread. By solving these challenges, reaching an energy density of 900 to 1000 kWh/kg and operating at a lower temperature, it can be used in cars in the future is very close to reality [18].

Solid state batteries (SSBs) have been highly sought after by automotive manufacturers due to their unique properties. These batteries are not only smaller and lighter than current lithium-ion batteries, but also safer. The solid

state battery is a next-generation battery that uses solid electrolyte and significantly increases driving range.

The use of solid electrolytes in these batteries helps to increase the energy density in them and allows electric cars to travel a long distance with a single charge. Samsung SDI has introduced a series of new solid-state batteries that, in addition to increasing driving range, reduce charging time and eliminate the risk of battery fires. These batteries can reach 80% charge from 10% or 20% in a short period of time (for example, 9 minutes). This charging method is commonly used in the electric battery industry, as the charging rate slows down significantly after 80% to avoid damaging the battery and preserve its lifespan. Samsung has achieved fast charging technology by optimizing the transport path of lithium ions in the battery and reducing the internal resistance of the battery. The company plans to bring this technology to mass production by 2026.

### **Doubling the energy density**

Samsung's solid-state oxide batteries have a much higher energy density (500Wh/kg) than current chemical batteries, which have an energy density of around 270Wh/kg. This means a significant increase in energy storage capacity. Current chemical batteries allow electric vehicles to travel more than 300 miles on a single charge. Samsung uses advanced technologies such as special solid electrolytes and anode-less technology (which helps remove the anode from the battery structure). Removing the anode leads to an increase in the capacity of the cathode, which allows batteries to store more energy. Samsung SDI CEO Yoon Ho Choi believes that the company is on the way to mass production of solid-state batteries and next-generation products [19].

### **Samsung battery roadmap**

At the Battery Day 2024 exhibition organized by SNE Research in Seoul, South Korea, Samsung announced that a pilot production line for electric vehicle solid-state batteries is now fully operational. The production line is located at Samsung SDI's R&D center in Suwon and is currently producing prototypes for testing. Samsung's ultimate goal is mass production of these batteries by 2027. Samsung SDI's battery roadmap shows that the company is preparing to mass-produce solid-state battery products. The energy density of Samsung's new solid-state batteries is supposed to be 40% higher than the company's current P5 prismatic lithium batteries. However, due to high production costs, these advanced batteries are expected to be used initially only in high-end electric cars [20].

### **Using cell-to-pack technology in prismatic batteries**

The cell-to-pack (CTP) technology that Samsung uses for prismatic batteries is an innovative approach that increases efficiency and reduces the weight of batteries. By changing the location of the battery terminal from the top to the sides, this technology increases energy efficiency and improves the battery cooling process. In addition, these changes reduce the number of battery parts (more than 35%) and reduce its weight (20%). As a result, the energy density of these batteries increases and production costs decrease. These optimizations will have a great impact on reducing production costs and increasing productivity in the electric vehicle industry. Samsung SDI plans to produce batteries that last more than 20 years by 2029 [21]. According to the company's plan, this longer life is possible thanks to the increased durability of the materials used in making the batteries. Solid-state batteries are also greatly improved in terms of safety, as the risk of fire is reduced due to the absence of a liquid

electrolyte. In addition, Samsung has used a new technology to prevent the spread of heat, which prevents the spread of fire in the event of a fire. This technology reduces the risk of overheating or explosion by releasing hot gases through vents built into the battery cells and significantly increases the safety of batteries.

### Weighted energy density

Weighted energy density is a measure that shows how much energy a battery can store relative to its weight. Samsung has launched a series of different batteries for different applications. NCA batteries with high nickel content are used in premium segments due to their higher energy density. NMX medium nickel batteries offer a good combination of performance and price, and LFP batteries, which are cheaper and more durable, are used for budget applications. In this way, Samsung can cover both premium and affordable electric car markets. However, the Korean company has yet to announce target values for weighted energy density. Weight energy density, which is also sometimes called specific energy, is the amount of energy available per unit mass of a substance. This measure is usually expressed in watt-hours/kg (Wh/kg) or mega joules/kg (MJ/kg).

The higher energy density leads to two important results: Either it provides a longer range for electric vehicles, or it makes it possible to produce smaller and cheaper batteries with the same range. In addition to focusing on solid-state batteries, Samsung is also trying to develop other types of batteries, including lithium-ion phosphate (LFP) and cobalt-free batteries, which are suitable for economy cars due to their lower costs. Samsung is trying to reduce battery production costs by developing a dry electrode production method. Samsung plans to reduce the price of batteries first, and by 2026, mass-produce

batteries that can be quickly charged in 9 minutes [22].

Apart from long life, safety and high energy density, one of the most important benefits of solid state batteries is the possibility of designing them in different shapes and sizes. (from a few millimeters to a few centimeters) According to Samsung, the technology of making multilayer ceramic capacitors is used to make these types of batteries. This feature makes these types of batteries candidates for use in small wearables. Samsung seems to have the upper hand in this part of the battery market, because more than 40 patent applications related to all-solid oxide-based batteries have been registered under this company's name.

Battery innovation is one of the hot topics in the smartphone market. In confirmation of this proposition, it is not bad to refer to this year's Mobile World Congress, where the development of long-life batteries and fast charging capability was in the spotlight. Manufacturing companies are working on materials such as lithium-sulfur and graphene to increase battery life. Solid state batteries contain less carbon and are less dangerous for the environment. Also, these batteries can work in a wider temperature range. Of course, along with these positive points, it is not bad to point out that the production of solid-state batteries (compared to lithium-ion batteries) requires more money [23].

### Discussion

Recently, researchers have developed a new chloride-based solid electrolyte for solid state (lithium) batteries. This solid electrolyte in solid state batteries includes high ionic conductivity and greater safety at a lower cost. This discovery is considered an important step in the development of the battery industry and its commercialization capability. Recently, scientists have developed a new chloride-based

solid electrolyte for solid-state (lithium) batteries. This discovery, which promises high ionic conductivity and greater safety at a lower cost, is an important step in battery manufacturing and production technology, as well as its commercialization. Scientists led by Professor Kang Kisuk from the Nanoparticle Research Center at the Institute of Basic Sciences (IBS) have announced a major breakthrough in the next generation of solid-state batteries. They have discovered a new chloride-based solid electrolyte with exceptional ionic conductivity, which is expected to lead to more efficient batteries.

### The need for solid electrolytes

A pressing concern with current commercial batteries is their reliance on liquid electrolytes, leading to flammability and explosion hazards. Therefore, the development of non-combustible solid electrolytes is of great importance for the advancement of solid state (lithium) battery technology. Due to the change and movement of the world towards sustainable transportation, today we see the importance and use of electric vehicles in the world. In this regard, research on the main components of secondary (rechargeable) batteries, especially solid state batteries, has become an important topic in the world. The arrangement of metal ions (yttrium in this case) inside each layer affects the ion conductivity. To ensure the unimpeded movement of lithium ions, the number of metal ions occupying the sites in each layer should be less than 0.444. In addition, to create a wide enough path for lithium ions in each layer, the occupancy of metal ions should be more than 0.167. Therefore, achieving the occupancy of metal ions between 0.167 and 0.444 per layer leads to a conductive layer with high ionic conductivity. High ionicity, strong chemical and electrochemical stability, as well as mechanical (mechanical) flexibility are very important

issues. In previous research, scientists have successfully achieved solid electrolytes based on sulfide and oxide with high ionic conductivity, but none of these materials fully include all these requirements and characteristics to achieve solid-state batteries and use them in daily use [24].

### Advances in chloride-based solid electrolytes

In the past, scientists have discovered chloride-based solid electrolytes known for their superior ionic conductivity, mechanical flexibility, and high-voltage stability. These properties have led some to believe that chloride-based batteries are a viable alternative to solid-state batteries. However, these hopes were quickly dashed as chloride batteries were recognized as unusable secondary components due to their heavy reliance on expensive rare earth metals, including the elements yttrium, scandium, and lanthanide. To address these concerns, the IBS research team investigated the distribution of metal ions in chloride electrolytes. As a result, they found that the variety of arrangement of metal ions in the structure is the main reason for the low ionic conductivity in trigonalized chloride electrolytes. They first tested this theory on lithium yttrium chloride, a common lithium metal chloride compound [25].

They observed that when metal ions were placed near the path of lithium ions, electrostatic forces caused blockages in their movement, and conversely, if the occupation of metal ions was too low, the path of lithium ions became very narrow and hindered their movement. Based on this insight, the research team introduced strategies to design electrolytes to mitigate these opposing factors, ultimately leading to the successful development of a solid electrolyte with high ionic conductivity.

This group successfully put this strategy into practice by creating a zirconium-based metal chloride (lithium) solid-state battery that is far more efficient and cheaper than types that use rare earth metals. In fact, this discovery is the first case that shows the importance of the arrangement of metal ions on the ionic conductivity of a material. A group of engineers announced the development of a series of solid electrolytes with atmospheric stability. The team of Prof. Lee Jong-won from the Department of Energy Science and Engineering at DGIST together with the team of Prof. Moon Jung-hyuk from Changang University announced the development of solid electrolytes with advanced atmospheric stability. Lithium-ion batteries are widely used as energy storage systems for electronic products and Electric vehicles are used. However, these batteries are vulnerable to ignition because they are mainly produced with flammable organic liquid electrolytes, safety issues have been continuously raised recently. On the other hand, oxide-based solid electrolytes have the advantage of having high thermal stability and physically preventing the growth of lithium dendrites. Among them, garnet-type electrolyte  $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$  (LLZO) is considered as a next-generation electrolyte due to its excellent lithium ion conductivity. Despite these advantages, LLZO electrolyte has a problem; When exposed to the atmosphere, lithium carbonate forms on its surface due to the reaction with moisture and carbon dioxide. This compound then grows along the grain boundaries and penetrates into the solid electrolyte, thereby disrupting the transport of lithium ions, which leads to a decrease in the lithium ion conductivity of the LLZO solid electrolyte [26].

The research team improved the atmospheric stability of the LLZO electrolyte through gallium and tantalum hetero-elemental doping, that is, by adding gallium and tantalum to pure

LLZO electrolytes. In particular, it was confirmed that  $\text{LiGaO}_2$ , a third material formed through the addition of gallium, suppresses surface adsorption of moisture and carbon dioxide and enhances particle growth during heat treatment. Therefore, it prevents the growth of lithium carbonate through the grain boundary and preserves the ionic conductivity properties of LLZO electrolytes. In conclusion, it has been experimentally verified that the lithium ion conductivity in the LLZO electrolyte is maintained even when exposed to air for a long time, and the performance remains stable even after repeated lithium adsorption and desorption [27].

### **Next-generation batteries can be organic and cobalt-free for long-term energy supply**

In the shift to "Greener" energy sources, the demand for rechargeable lithium-ion batteries is increasing. However, their cathodes usually contain cobalt – a metal whose extraction has high environmental and social costs. Now, researchers in ACS Central Science report evaluating an Earth-abundant carbon-based cathode material that could replace cobalt and other rare and toxic metals without compromising lithium-ion battery performance. Today, lithium-ion batteries power everything from cell phones to laptops to electric cars. One of the limiting factors for realizing a global shift towards energy produced by renewable sources – especially for the transition from gasoline vehicles to electric vehicles – is the scarcity and difficulty of extracting metals such as cobalt, nickel and magnesium, which are used in the production of rechargeable battery cathodes. Charges are used. Previous researchers have made cathodes from more abundant and less expensive carbon-containing materials, including organosulfur and carbonyl compounds, but these prototypes could not

match the energy output and stability of traditional lithium-ion batteries [28].

Therefore, Mircea Dincă and his colleagues wanted to see if other carbon-based cathode materials could be more successful. They may have found a suitable alternative in beta-tetraaminobenzoquinone (TAQ). TAQ molecules form solid-state layered structures that can potentially compete with the performance of traditional cobalt-based cathodes. Building on their previous work showing the effectiveness of TAQ as a super capacitor material, Dincă's team tested the compound in a cathode for lithium-ion batteries. To improve the cycling stability and increase the adhesion of TAQ to the cathode stainless steel current collector, materials containing cellulose and rubber were added to the TAQ cathode. In the researchers' proof-of-concept demonstration, the new composite cathode cycled safely more than 2,000 times, delivered a higher energy density than most cobalt-based cathodes, and was charged in less than 6 minutes. TAQ-based cathodes need more testing before they can appear on the market, but researchers are optimistic they could enable the high-energy, long-lasting, fast-charging batteries needed to help accelerate the global transition to a cobalt- and nickel-free renewable energy future.

### **Cobalt-free batteries could power the cars of the future**

Chemists have developed an organic-based battery cathode that could reduce the electric vehicle industry's reliance on rare metals. Many electric vehicles are powered by batteries that contain cobalt – a metal with high financial, environmental and social costs. MIT researchers have now developed a battery material that could provide a more sustainable way to power electric vehicles. The new lithium-ion battery has an organic-based

cathode instead of cobalt or nickel (another metal often used in lithium-ion batteries). In a new study, researchers have shown that the material, which can be produced at a much lower cost than cobalt-based batteries, can conduct electricity at the same rate as cobalt batteries. According to the researchers, the new battery also has comparable storage capacity and can be charged faster than cobalt batteries. Mircea Dincă, W.M says: "I think this substance can have a big impact because it works really well. Keck Professor of Energy at MIT. "It is already competitive with current technologies, and can save a lot of the cost, pain and environmental issues associated with extracting the metals that currently go into batteries. Dincă is the senior author of the study, which was published today in the journal ACS Central Science. Tianyang Chen PhD '23 and Harish Banda, former MIT postdoc, are lead authors of the paper. Other authors include Jiande Wang, an MIT postdoc; Julius Oppenheim, MIT graduate student; And Alessandro Franceschi, a researcher at the University of Bologna [29].

### **Cobalt substitutes**

Most electric vehicles are powered by lithium-ion batteries, a type of battery that charges when lithium ions flow from a positively charged electrode called the cathode to a negatively charged electrode called the anode. In most lithium-ion batteries, the cathode contains cobalt, a metal that provides stability and high energy density. However, cobalt has significant disadvantages. A rare metal, its price can fluctuate wildly, and many of the world's cobalt reserves are located in politically unstable countries. Cobalt mining creates dangerous working conditions and produces toxic waste that contaminates the land, air and water around the mines [30]. Cobalt batteries can store a lot of energy, and have all the features that people care about in

terms of performance, but they have the problem that they are not widely available and the cost fluctuates. "They're certainly going to be more expensive than many EVs on the consumer market," says Dink. Due to the many disadvantages of cobalt, much research has been done to develop alternative battery materials. One of these materials is lithium-iron-phosphate (LFP), which some car manufacturers have started using in electric vehicles. Although still useful in practice, the LFP has only about half the energy density of cobalt and nickel batteries. Another attractive option is organic materials, but so far most of these materials have not been able to match the conductivity, storage capacity and lifetime of cobalt-based batteries. Because of their low conductivity, such materials usually need to be mixed with binders such as polymers that help them maintain a conductive network. These, which constitute at least 50% of the total material, reduce the storage capacity of the battery. About six years ago, Dincă Lab began working on a project funded by Lamborghini to develop an organic battery that could be used to power electric vehicles. While working on porous materials that were partly organic and partly inorganic, Dink and his students realized that an entirely organic material they had made appeared to be a strong conductor.

It is composed of many layers of TAQ (bis-tetraaminobenzoquinone), a small organic molecule consisting of three fused hexagonal rings. These layers can extend outward in any direction and form a graphite-like structure. Inside the molecules are chemical groups called Quinone's, which are electron reservoirs, and amines, which help materials form strong hydrogen bonds. These hydrogen bonds make materials very stable and also very insoluble [31].

This insolubility is important because it prevents the material from dissolving in the battery electrolyte, as some of the battery's

organic materials do, thereby extending its life. Dincă says: "One of the main ways that organics degrade is that they simply dissolve in the battery electrolyte and go to the other side of the battery, essentially creating a short circuit. If you make the material completely insoluble, this process will not take place. So we can go to over 2,000 charge cycles with minimal degradation."

### Strong performance

Tests of this material showed that its conductivity and storage capacity are comparable to traditional batteries containing cobalt. Also, batteries with TAQ cathodes charge and discharge faster than existing batteries, which can increase the charging speed of electric vehicles. To stabilize the organic material and increase its ability to stick to the battery's current collector, which is made of copper or aluminum, the researchers added fillers such as cellulose and rubber. These fillers make up less than a tenth of the total cathode composite. Therefore, they do not significantly reduce the storage capacity of the battery. These fillers also increase the life of the battery cathode by preventing it from cracking when lithium ions flow into the cathode while the battery is being charged [32].

The raw materials required to make this type of cathode are a Quinone precursor and an amine precursor, which are currently commercially available and produced in large quantities as commodity chemicals. The researchers estimate that the material cost of assembling these organic batteries could be about one-third to one-half the cost of cobalt batteries. Lamborghini has issued a patent for this technology. Dincă Lab plans to continue developing alternative battery materials and is investigating the possible replacement of lithium with sodium or magnesium, which are cheaper and more abundant than lithium [33].

## Challenges of solid state battery development

In an article entitled Nanoscale interface characterization to sustainable energy storage using all-solid-state batteries, which was published in the prestigious journal Nature Nanotechnology, UCSD University researchers have stated four issues that should be at the top of the solid-state battery development program:

- ✓ Achieving stable chemical interfaces between electrolyte and electrodes;
- ✓ Effective tools for indicators;
- ✓ Sustainable production processes;
- ✓ Recyclable design.

Shirley Meng, professor of nano engineering at UCSD University, expresses the importance of developing a road map for the development of these batteries as follows: "It is very important that if we intend to achieve favorable results in this field; We have to go back and think about how to solve these challenges at the same time because they are all connected and we have to find solutions that solve all of these challenges at the same time." [34].

Recyclable solids are very important. The reusability and eco nomicization of the technology should be considered in future developments to produce all-solid-state batteries capable of providing energy densities of 500Wh/kg. An issue that was less seen in the development of lithium-ion batteries [35].

## A new way to use solid state batteries with twice the capacity was invented

One potential way to achieve the next generation of batteries for smartphones, laptops and electric cars is to use solid-state electrolytes instead of the liquid electrolytes found in today's lithium batteries. A group of researchers in America has produced a test sample of these solid state batteries. These batteries can remove the obstacles in the way of producing the next generation of batteries,

and with the help of a self-repairing material, they can provide the possibility of using stable and high-capacity batteries.

In existing lithium-ion batteries, liquid electrolyte transports lithium ions back and forth between pairs of electrodes during charging and discharging. If we can make the electrolyte out of solids, the batteries will be safer and we can store much more energy in them. Experimental versions of these cells have shown that with this technology, the capacity of existing lithium-ion batteries can be doubled. The problem of using solid materials is the formation of tentacle-like forms called "Dendrites" that appear on the surface of one of the electrodes along with battery cycles. These tiny needles can short circuit the battery and cause damage or even fire. Therefore, achieving a solution in the design of solid state batteries that does not have this problem is considered a great achievement [36].

Now researchers from MIT University, Texas A&M University, Brown University and Carnegie Mellon University have presented a promising solution. They have developed a semi-solid electrode made of a sodium-potassium alloy similar to the material dentists use to fill teeth. This material is such that it does not get small cracks and does not form dendrites in contact with solid electrolyte. As the battery is charged and discharged, the operating temperature of the material is kept exactly in a semi-solid state so that it can handle high currents - about 20 times higher than solid lithium - without forming dendrites. This solution solves another problem with solid-state batteries, which prevented the batteries from being able to recharge at realistic rates without dendrite formation. In another design, the researchers inserted a thin strip of liquid sodium-potassium alloy into the battery, creating a sandwich of solid electrode and solid electrolyte. This method prevented dendrites from forming and opened up another

fascinating avenue for discovery and innovation [37].

Based on the promising results of their experiments, the researchers are now looking for ways to apply this technology to other solid-state battery architectures. "We think we can implement this approach for all solid-state lithium-ion batteries," says Venkatasubramanian Viswanathan, a professor of mechanical engineering at Carnegie Mellon University. We believe that this technology can be immediately used in the production of a wide range of hand-held devices to electric cars and airplanes."

### Conclusion

The development of solid electrolytes in batteries can significantly improve the lifespan and safety of these batteries. This innovative technology answers the long-standing challenges of the battery industry; In particular, by replacing liquid electrolytes with solid electrolytes, scientists intend to not only extend the useful life of batteries, but also dramatically improve their safety and efficiency. This is especially important for applications where safety and durability are critical, including electric vehicles and energy storage systems. Sulfide-based solid electrolyte has unique properties that can have a significant impact on battery performance. One of these features is its high energy density, which allows batteries to store more energy in a smaller volume. Also, the ability to charge and discharge quickly is another positive aspect of this technology, which allows users to charge and use batteries in a shorter time. In addition, excellent performance at low temperatures makes this electrolyte suitable for a variety of applications, including in cold weather conditions.

One of the most important advantages of this new technology is reducing the risk of thermal ignition, which greatly increases the safety of

batteries. This is especially critical in traditional lithium-ion batteries, which have many safety concerns. With these advancements, Huawei's solid-state batteries can help accelerate the adoption of electric vehicles and renewable energy sources, thereby responding positively to the global trend toward sustainable energy solutions. Although common lithium-ion batteries are widely used in daily life, their low energy density leads to lower usage time of these batteries, and short circuit and even fire can occur due to the presence of liquid electrolyte. The energy density in Li-ion batteries can be improved by substituting lithium metal for the graphite anode, since the theoretical capacity of lithium metal for charging can reach about 10 times that of graphite. But during charging and discharging, often dendrites are formed and if they enter the separator membrane, they can cause a short circuit and increase the concern about battery safety. The scientists focused on solid ceramic electrolytes because they have great potential to improve safety and energy density compared to the workable electrolytes commonly found in lithium-ion batteries because most solid electrolytes are ceramic and non-flammable, which can address battery safety concerns. And with the help of boron nitride layer, battery performance is improved.

Lithium metal is essential to increase the energy density and it is important to use it as an anode along with a solid electrolyte. To adapt these unstable electrolytes in real applications, we need to develop stable mechanical and chemical interfaces to protect these solid electrolytes against the lithium anode. Not only is it necessary that this interface is very electrically insulating, but it must also be an ionic conductor in order to transfer lithium ions. In addition, this junction must be extremely thin to avoid reducing the energy density of the batteries. To address

these challenges, the team collaborated with researchers at Brookhaven National Laboratory and the City University of New York. They used a 5 to 10 nm thick nano layer of boron nitride as a protective layer to break the electrical contact between the lithium metal and the ion conducting material (solid electrolyte with a small amount of polymer or liquid electrolyte to penetrate the electrode-electrolyte interface). They addressed the reason for choosing boron nitride as a protective layer was its chemical and mechanical stability with lithium metal and its high insulation value. They designed a boron nitride layer with intrinsic defects through which lithium ions can move, making boron nitride an excellent separator. In addition, boron nitride can be easily produced through chemical vapor deposition on a large scale (decimeter scale) and atomic scale (nanometer scale). In the initial researches, 200 nm thick polymer protective layers were used, but in this research, the protective layer was made of boron nitride and is only 5-10 nm thick, without reducing the energy density of the batteries, which was considered a record among such thin layers. It is a complete material that prevents lithium from invading the solid electrolyte.

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