A Review of Solid-State Battery for Advancement in Energy Storage

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ABSTRACT

This paper provides a comprehensive review of Solid-State Batteries (SSBs), a transformative energy storage technology poised to surpass conventional lithium-ion batteries. SSBs utilize solid electrolytes in place of flammable liquid or gel-based electrolytes, leading to improvements in safety, energy density, lifecycle, and thermal stability. The study explores the key components of SSBs, including advanced solid electrolytes such as garnet-type LLZO, and evaluates various synthesis methods like sol-gel, spark plasma sintering, and electrospinning. While SSBs show immense potential, challenges remain, particularly in ionic conductivity at room temperature and interface stability with lithium metal anodes. The research highlights recent advancements and future prospects of SSBs in revolutionizing applications in electric vehicles, portable electronics, and renewable energy systems.

Keywords: Solid state batteries (SSB), Lithium -ion battery (LIB), lithium lanthanum zirconium oxide (LLZO), Lithium Iron Phosphate (LIP), Nickel Manganese Cobalt (NMC) and Lithium Manganese Oxide (LMO), Lithium Lanthanum Titanium Oxide (LLTO), Na Super Ionic Conductor (NASICON), Li Super Ionic Conductor (LISICON) and Room temperature (RM).

BACKGROUND OF STUDY

The global demand for safe, high-performance, and long-lasting energy storage systems has intensified with the rapid advancement of electric vehicles (EVs), portable electronics, and renewable energy technologies. Conventional lithium-ion batteries (LIBs) are constrained by safety concerns primarily due to the use of flammable liquid electrolytes and limited energy density. Solid-state batteries (SSBs) offer a transformative solution by replacing the volatile liquid electrolyte with a solid-state counterpart, significantly improving safety, thermal stability, and lifespan. Furthermore, SSBs enable the use of lithium metal anodes, which can theoretically triple the energy density compared to current LIBs, making them ideal for next-generation EVs and grid-scale storage systems (Janek and Zeier, 2016). A major limitation in energy technology is the challenge of large-scale energy storage, highlighting the urgent need to transition from the current reliance on fossil fuel-generated power (Janak *et al.*, 2025). Their solid architecture also minimizes leakage and degradation, enhancing performance under extreme conditions. As a result, SSBs are positioned at the forefront of energy innovation, with the potential to overcome the inherent limitations of LIBs and meet the growing need for robust, scalable, and sustainable power solutions.

Electric battery

An electric battery is a source of electric power consisting of one or more electrochemical cells with external connections (Crompton, 2000). A battery is a device that stores chemical energy, and converts it to electricity

Main Components of battery:

- Anode (negative electrode)
- Cathode (positive electrode)

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• Electrolyte (medium for ion transport)

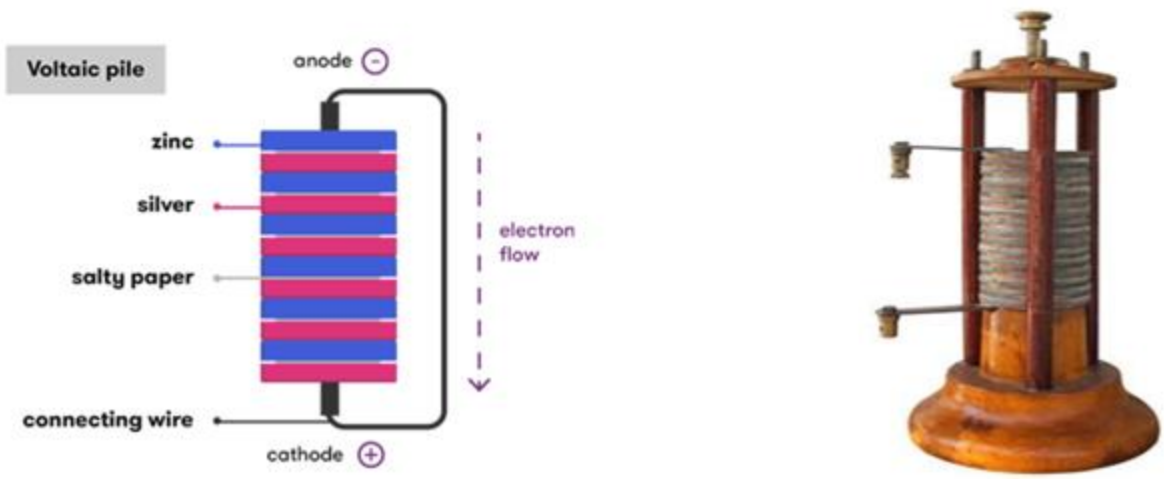

Figure 1: 1n 1800, The first electrochemical battery by Italian Physicist, Alessandro Volta: stack of zinc and silver plates, separated by soaked saltwater paper/cloths to give voltage (Bellis, 2008)

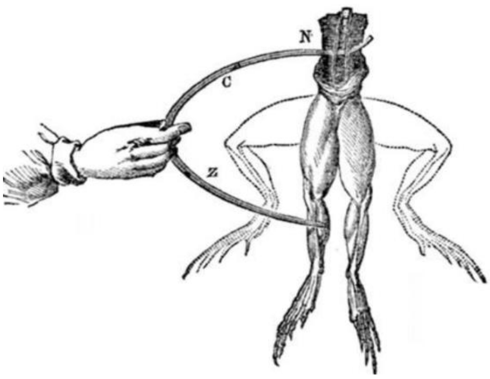

Figure 2: In 1780 Luigi Galvani: Hanging legs of fog on iron/brass- animal electricity (*Lim et al.,* 2020).

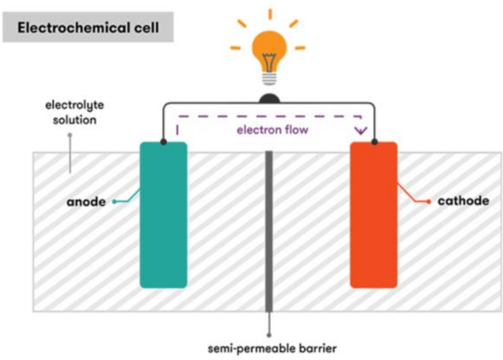

Figure 3: Electrochemical cell (Lim *et al.*, 2020)

Solid State Batteries

Solid-State Batteries (SSB) uses solid electrolytes instead of liquid or gel-based found in traditional lithium-ion batteries (LIBs) (Janek and Zeier, 2016).

These batteries offer the potential to revolutionize industries ranging from electric vehicles to renewable energy systems. By replacing the liquid electrolyte found in LIBs with solid materials (Lim *et al.*, 2020).

SSBs Uniqueness:

- Enhance safety
- Ultra- fast charging (about 6 times)
- High energy density
- Extend the overall lifespan of energy storage systems.
- Better thermal and chemical stability
- Emerging as a next-generation power storage solution.

The main difference between SSBs and LIBs is the state of their electrolytes. Traditional LIBs have a liquid or gel electrolyte, whereas SSBs employ solid electrolytes. The positive and negative electrodes act as either anode and cathode depending on whether the device is charging or discharging (Lim *et al.*, 2020).

According to Lim *et al.*, 2020 stated Solid electrolytes explored in SSB are:

- Ceramics
- Polymers
- Resins
- Glass composites

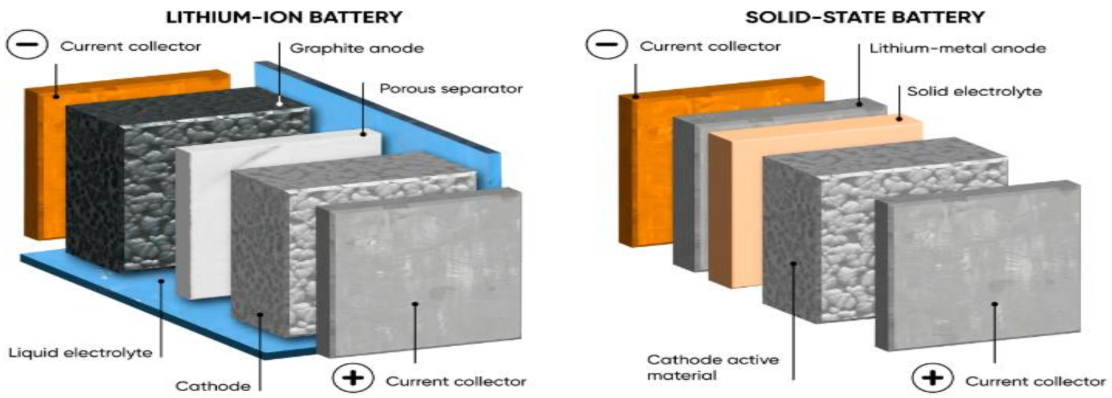

Figure 4: The structure of a traditional lithium-ion battery and a solid-state battery (Lim *et al al.*, 2020)

Table 1: Solid state Battery (SSB) VS Lithium-Ion Battery (Randau, 2020)

Feature	Lithium-Ion Battery	Solid-State Battery
Electrolyte	Liquid or gel	Solid (ceramic, polymer, etc.)
Energy Density	Moderate	High
Safety	Risk of fire/explosion	Much safer
Lifecycle	Shorter	Longer
Operating Temp. Range	Narrow	Wider

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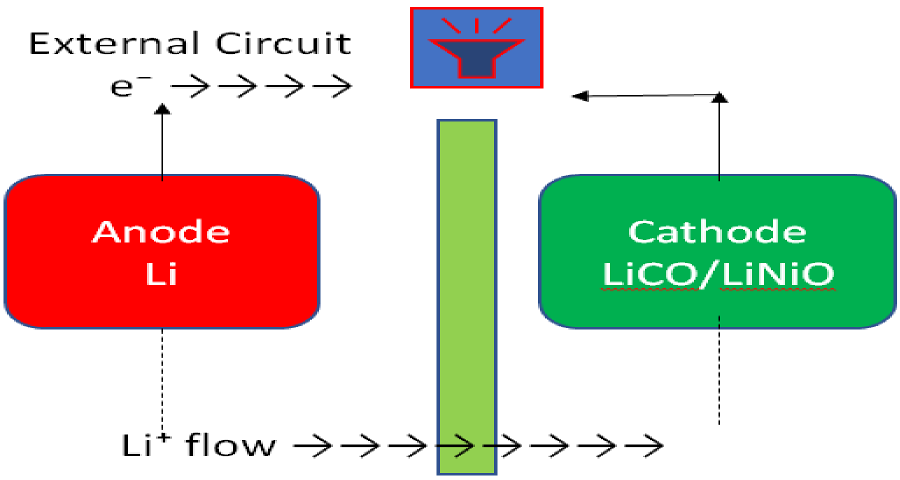
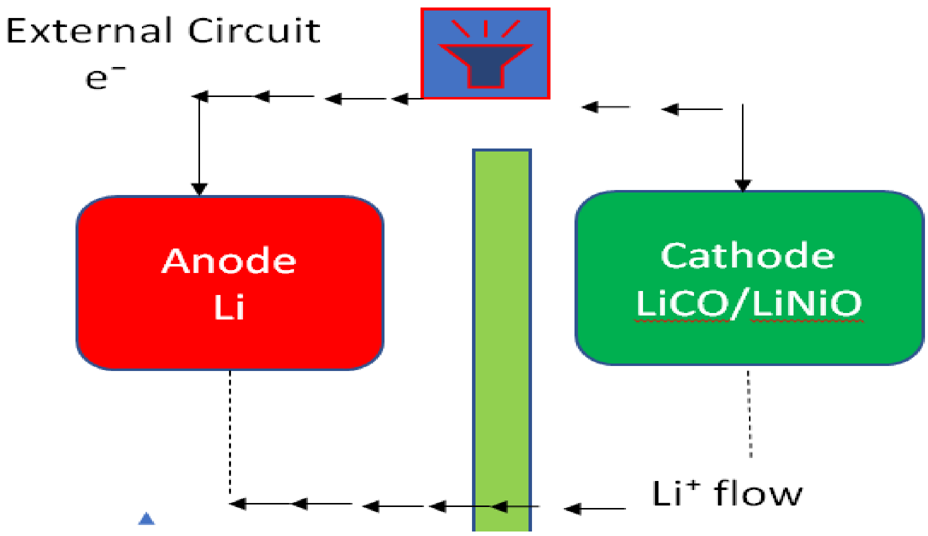
Commercial Availability	Mature	Emerging(under development)
Anode	Graphite	Lithium metal
Cathode	Metal oxide compounds (LFP, NMC, LMO)	Nickel manganese cobalt oxide (NMC) and cobalt oxide (LCO)

Working Principles of Solid-State Batteries

1. Discharge: Lithium ions (Li^+) travel from the anode to the cathode through the solid electrolyte, while electrons flow through the external circuit, powering a device. Both recombine at the cathode.



2. Charging: An external power source drives lithium ion from the cathode back to the anode via the solid electrolyte, with electrons returning through the external circuit.



Solid state Batteries Electrodes

A. Anode:

- Metallic lithium: This is used in solid-state lithium-ion batteries and solid-state lithium-sulfur batteries to have high-energy-density.
- Carbon materials: SSB utilities carbon nanotubes have a high specific surface area and excellent electrochemical performance.

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- Silicon materials: silicon materials can react with solid electrolytes to form lithium ions, thereby enabling the charging and discharging of the battery and can react with solid electrolytes to form lithium ions, thereby enabling the charging and discharging of the battery (Neware, 2024).

B. Cathode

- Lithium cobalt oxide ($LiCoO_2$): A commonly used cathode material in lithium-ion batteries, it can provide high energy density and long cycle life, but there are safety concerns.
- Lithium iron phosphate ($LiFePO_4$): Compared to lithium cobalt oxide, lithium iron phosphate has better safety and longer lifespan, but lower energy density.
- Lithium nickel oxide ($LiNiO_2$): High energy density and long cycle life, but the material is expensive and has safety issues.
- Lithium aluminum oxide ($LiAlO_2$): High energy density, but the cycle life is slightly lower than that of lithium nickel oxide.
- Various material combinations in solid-state electrolytes: For example, lithium manganate ($LiMn_2O_4$) and lithium titanium ($Li_4Ti_5O_{12}$), which can provide higher safety and longer lifespan, but have relatively lower energy density (Neware, 2024).

C. Solid-state battery separator

- Separator materials in solid-state batteries prevent electronic conduction by isolating the positive and negative electrodes.
- They are mainly composed of polymers and nanoscale powders. Research also indicates that a double-layer coating could serve as an alternative to traditional separators. (Neware, 2024).

D. Solid State Electrolytes

1. Polymer Solid-State Electrolytes:

- Flexible and lightweight
- Low potential and poor conductivity at room temperature
- Composed of high molecular weight polymers and lithium salts (e.g., $LiClO_4$, $LiPF_6$)
- Common polymers: ether-based, nitrile-based, siloxane-based, carbonate-based, and PVDF
- Most widely used: PEO (Polyethylene oxide)

2. Oxide Solid-State Electrolytes:

- High stability and wide electrochemical window
- Mechanically strong but brittle
- Includes garnet: $Li_7La_3Zr_2O_{12}$ (LLZO), perovskite (LLTO), NASICON, and LISICON types

3. Halide Electrolytes:

- High conductivity and pressure resistance

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- Sensitive to humidity and temperature
- General formula: Li_a-M-X_β (where X = Cl, Br, F; M = high-valence metal)
- Formed by modifying lithium halides with transition metal cations to enhance Li^+ transport (Neware, 2024).

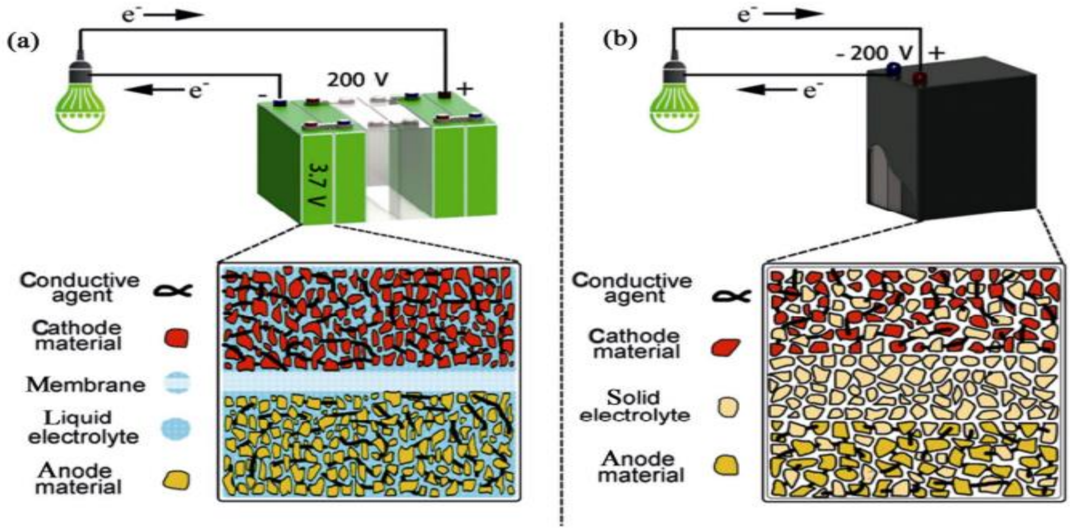

Figure 5: (a)Traditional Li-ion battery (LiB) using a liquid electrolyte and (b) solid-state lithium-ion battery (ASSLB) using a solid electrolyte (Gonzalez Puente *et al.*, 2021)

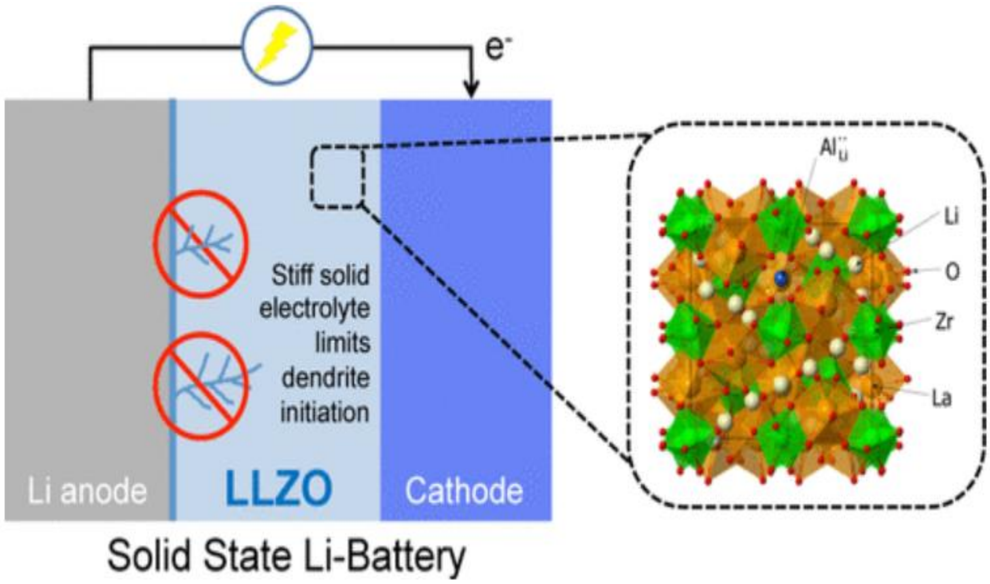

Figure 6: Solid State Lithium Battery (Seungho *et al.*, 2015)

Main Parameter of a solid-state Batteries

The transition from liquid to solid electrolytes introduces its own set of challenges. Some of these challenges include:

Reduced conductivity of solid electrolytes at room temperature.

Reduced conductivity of solid electrolytes at room temperature:

Solid-state batteries exhibit lower ionic conductivity compared to traditional liquid electrolyte batteries due to the inherent nature of solid electrolytes. Ions are not as free to move around in solids, or even polymers, as they are in liquids because ions must move through lattices and grain boundaries. Conductivities of Li^+ solid electrolytes tend to be 2-4 orders of magnitude lower than liquid electrolytes (Lou, 2021).

$$\sigma = \sigma_0 \exp\left(-\frac{E_a}{K_b T}\right)$$

Where:

- σ_σ is the DC ionic conductivity ($S \cdot m^{-1}$)
- σ_0 is the pre-exponential factor ($S \cdot m^{-1}$)
- E_a is the activation energy (J)
- K_b the Boltzmann constant (8.61×10^{-5} $eV \cdot K^{-1}$)
- T is the absolute temperature (K)

At higher temperatures, ions have more thermal energy, which helps them overcome the activation energy barriers and move more freely through the solid electrolyte lattice. As a result, the ionic conductivity of solid electrolytes increases with higher temperatures.

Wide-Bandgap Semiconductor Devices

The exploration of materials like GaN, SiC, and diamond highlights their critical role in revolutionizing power electronics for extreme environments. These materials, characterized by high breakdown voltages, wide bandgaps, and exceptional thermal conductivity, not only advance device reliability and efficiency but also complement the operational demands of next-generation solid-state batteries (SSBs). SSBs, with their promise of enhanced safety, energy density, and thermal stability, benefit immensely from the integration of WBG-based control electronics. Specifically, the superior heat resistance and high-frequency performance of GaN and SiC enable more compact and efficient battery management systems (BMS), reducing parasitic losses and improving energy utilization. Additionally, WBG materials' capability to operate at elevated voltages directly aligns with the high-voltage nature of advanced SSB architectures, particularly in electric vehicle and aerospace systems where weight, reliability, and safety are paramount. Thus, Kolawole’s research offers a foundational framework for synergistically coupling WBG semiconductors with solid-state battery technologies to realize highly efficient, compact, and thermally resilient energy systems of the future (Michael, 2025).

According to Gonzalez Puente et al., 2021, Crystalline materials offer the highest Li-ion conductivities in Solid Electrolytes.

The main inorganic SEs being explored are

- NASICON-type
- perovskite-type
- LISICON type
- Garnet-type; Ceramic electrolytes
- Sulfide-type materials.

The most Promising Solid Electrolytes is Garnet-type: $Li_7La_3Zr_2O_{12}$ (LLZO) ceramic electrolytes stand out as the most promising SEs.

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LLZO uniqueness according to the first-principals calculation and experimental results. LLZO is also simple environmental caring (Zhu et al., 2015)

- High ionic conductivity at RT 10^{-4} - 10^{-3} $S.cm^{-1}$
- Wide electrochemical window range (0–5 V)
- Good stability against Li metal anode

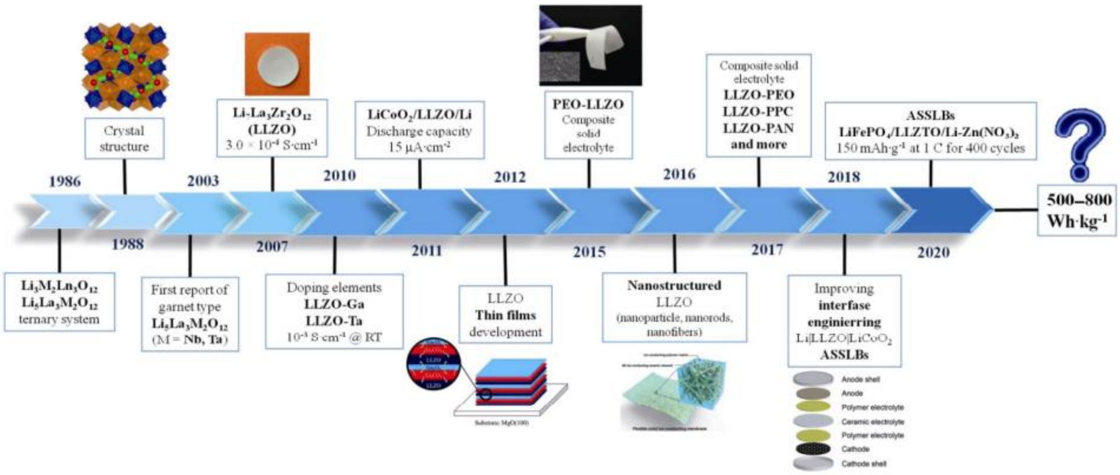
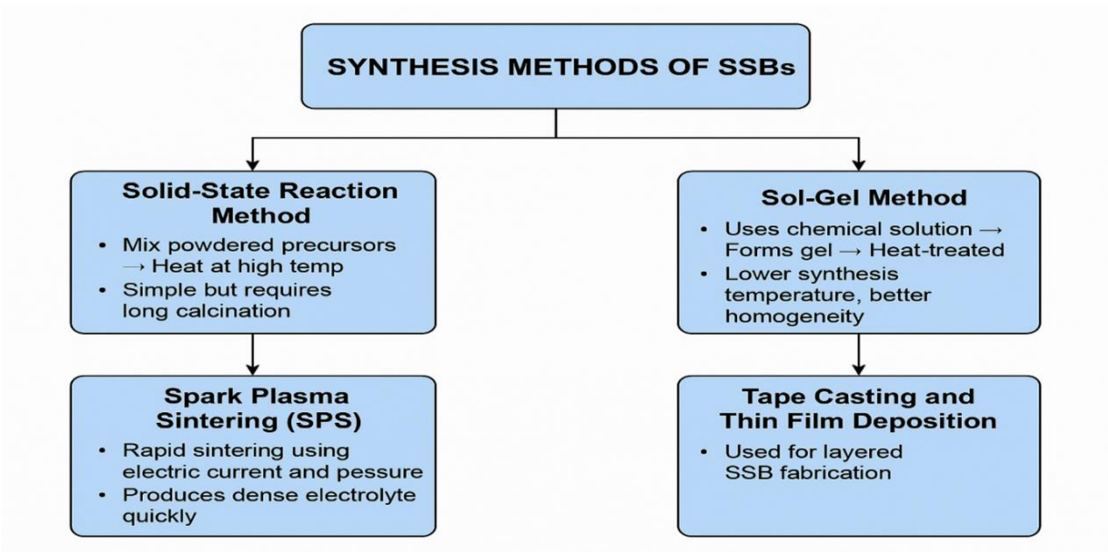


Figure 7: Chronology of the development of garnet-type solid electrolytes (Thangadurai *et al.*, 2003, Hyooma & Hayashi 1988, Ramakumar *et al.*, 2017, Murugan *et al.,2007*, Thangadurai *et al.*, 2014, Kotobuki *et al.,2010*, Dirican et al., 2019, Zhou *et al.*, 2019, Zhong *et al.*, 2020, Zhu *et al.*, 2020, Xia *et al.*, 2019 and Gonzalez Puente *et al.*, 2021).

Synthesis Methods of solid-state batteries



Source: Liu, Z., et al. 2013)

Synthesis Methods of Lithium Lanthanum Zirconium Oxide (LLZO)

Conventional Solid-State Reaction

Process: This is simple and scalable but suffers from lithium volatilization and requires repeated grinding.

- Mix solid precursor powders (e.g., Li_2CO_3, La_2O_3, ZrO_2).

- Ball mill for uniform mixing.
- Pre-calcine at intermediate temperatures.
- Final sintering at high temperatures (~1000–1200 °C) for long durations.

Sol-Gel Method

Process: This yields fine powders with better homogeneity and lower synthesis temperatures.

- Dissolve metal precursors in solvents to form a solution.
- Add a chelating agent (e.g., citric acid or EDTA).
- Gel formation by evaporation and aging.
- Drying and calcination at moderate temperatures (~700–900 °C).

Hot-Press Sintering

Process: This produces dense pellets with high conductivity; not easily scalable.

- Place LLZO precursor powder in a die.
- Apply high pressure (20–100 MPa) and heat simultaneously (~1000–1200 °C).
- Maintain for several hours.

Field-Assisted Sintering (e.g., Flash or Spark Plasma Sintering)

Process: This is rapid and energy-efficient, but needs costly equipment.

- Apply pulsed electric current through graphite die containing the powder.
- Use moderate temperature (~800–1000 °C) under pressure.
- Achieve densification in minutes.

Electrospinning

Process: This is the best for nanostructures but not suitable for bulk material.

- Prepare a polymer-metal precursor solution.
- Electro spin fibers using high voltage to create Nano-fibers.
- Calcine to remove polymer and form ceramic LLZO.

Thin Film Deposition

- Process: This is ideal for micro batteries but low conductivity and high cost.
- Use techniques like PLD (Pulsed Laser Deposition), sputtering, or sol–gel spin coating.
- Deposit thin LLZO layers on substrates.
- Post-annealing to crystallize.

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Spark Plasma Sintering (SPS)

Process: This method helps to achieve high density quickly with minimal lithium loss

- Load synthesized LLZO powder into a graphite die.
- Apply pulsed DC current and uniaxial pressure (~50 MPa).
- Rapid heating and sintering (~800–1000 °C for <10 min).

Table 2: Major summary of **LLZO** ($Li_7La_3Zr_2O_{12}$) synthesis (Gonzalez Puente et al., 2021)

Synthesis Method	Advantages	Disadvantages	Ionic Conductivity ($S \cdot cm^{-1}$)	Reference
Solid-State Reaction	High density, industrial scalability, flexible, low cost	High sintering temp, long processing time, lithium loss	2.11×10^{-4}	[Hu *et al.*, 2016]
Sol–Gel	Lower sintering temperature, improved homogeneity	Low sample density, phase instability	3.0×10^{-4}	[El-Shinawi et al., 2017]
Hot-Press Sintering	High density and ionic conductivity	No industrial scalability, slow heating/cooling	9.9×10^{-4}, 4.0×10^{-4}	[Rangasamy et al., 2012]
Field-Assisted Sintering	High heating rate, enhanced densification, short sintering time	Requires expensive equipment	0.33×10^{-3}, 5.7×10^{-4}	[Botros et al., 2016 and Zhang et al., 2014]
Electrospinning	Nano structuring, cubic phase stability at RT, advanced morphology	Bulk LLZO cannot be synthesized at scale	—	[Fu et al., 2017]
Thin Film Deposition	Scalable for micro-devices, practical for flexible electronics	Low ionic conductivity, requires nanopowders	1.67×10^{-6}	[Chen et al., 2014]
Spark Plasma Sintering	Rapid densification, industrial scalability, low sintering time	Requires pre-synthesized LLZO powder	1.35×10^{-3}	[Baek et al., 2014 and Kali & Mukhopadhyay 2014]

CONCLUSION

Solid-State Batteries offer superior safety, energy density, and longevity. Research has shown various material that exhibit high ionic conductivity (up to 10^{-3} S/cm), but they are unstable against Li metal anodes. According to Gonzalez Puente *et al.*, 2021, Garnet-type of ceramics solid electrolytes are focus of intensive research and interesting due to their high ionic conductivity, wide electrochemical window, and chemical stability against Li ions. These are one of the most promising solid electrolyte materials to be used in the future SSLBs. However, after years of development, the ionic conductivity of LLZO at RT is still lower than liquid electrolytes.

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