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Research Progress of Separator Materials in Lithium-ion Batteries

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Abstract:

Solar energy, recognized as a clean and sustainable resource, stands as a pivotal technology within the renewable energy landscape. As the core of photovoltaic technology, solar cells directly convert light into electricity via the photovoltaic effect, operating without greenhouse gas emissions and thereby playing a significant role in energy security and environmental protection. This paper systematically reviews the research progress in solar cell technologies through a comprehensive literature study, with a focus on the working principles, technical characteristics, and application status of crystalline silicon, thin-film, and emerging perovskite solar cells. The study finds that crystalline silicon cells dominate the current market due to their high conversion efficiency (22-24%) and reliability, despite their energy-intensive production process and temperature sensitivity. In contrast, thin-film cells offer advantages in terms of material usage and manufacturing energy consumption; however, their efficiency faces developmental bottlenecks, and their market presence remains limited. Perovskite solar cells demonstrate remarkable efficiency potential, with recorded rates exceeding 29%, yet their commercialization is hindered by challenges in material stability and the risk of lead leakage. Furthermore, this paper discusses the critical roles of energy storage technologies, smart management systems, and material optimization in advancing the future development of solar energy.

Keywords: Lithium-ion batteries; battery separators; development prospects.

1. Introduction

The global energy crisis and growing environmental concerns are accelerating the shift toward sustainable, low-carbon energy systems. Electrification is at the center of this transition. Advanced energy storage technologies form its backbone. Among them, lithium-ion batteries (LIBs) remain the leading choice [1]. They offer high energy density, long cycle life, and stable power performance. These strengths have en-

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abled wide use, from smartphones to electric vehicles and grid-scale storage.

However, demand is rising for even higher energy density. At the same time, operating conditions are becoming more diverse. This raises urgent concerns about both safety and long-term reliability. One component of the battery governs these issues most directly: the separator.

A well-designed separator does more than allow ionic transport. It must provide high ionic conductivity and strong electrolyte wettability [2]. It also needs mechanical strength and resistance to thermal shrinkage. Commercial separators, usually made of polyethylene (PE) or polypropylene (PP), benefit from low cost and mature processing. Yet they have serious drawbacks. They soften at elevated temperatures and can burn easily. These weaknesses limit their use in next-generation, high-energy LIBs.

Researchers have proposed several solutions. Some apply inorganic coatings such as Al_2O_3 or SiO_2. Others develop polymer–inorganic composites, electrospun nanofiber membranes, or bio-based films like cellulose derivatives. These designs improve thermal stability, ionic conductivity, and electrolyte affinity –. They also help suppress lithium dendrite growth. But new problems appear. The cost of production is high. Manufacturing can be complex. Scalability remains uncertain.

This review focuses on PE, PP, composite, and ceramic-coated membranes. It compares their advantages and limitations. It also highlights where the most progress has been made, as well as which trade-offs remain unresolved. Special attention is given to functionalized and sustainable materials –. These materials aim to balance safety, performance, and environmental responsibility [3].

Looking ahead, three themes appear critical. Separator design must be smarter. Materials must be more sustainable. Production methods must be scalable. These priorities will determine whether laboratory success can become industrial reality. The central question is clear: how can future separators deliver both safer operation and higher energy density for lithium-ion batteries?

This review article systematically examines the morphology of silicon anodes for lithium-ion batteries. It summarizes the characteristics and electrochemical performance of various silicon morphologies and investigates their influence on energy storage properties. Furthermore, the review offers perspectives on future development directions, aiming to guide the design of high-energy-density and long-life lithium-ion batteries.

2. Classification and Advantages/Disadvantages of Battery Separator Materials

2.1 Polyethylene (PE)

Polyethylene (PE) separators are among the most widely used materials in commercial lithium-ion batteries. Their main advantages lie in low cost, mature processing technology, good mechanical strength, and chemical stability. High-density polyethylene (HDPE) is particularly known for excellent tensile strength and resistance to chemical corrosion [4]. However, PE separators suffer from relatively poor thermal stability and limited electrolyte wettability, which can cause severe shrinkage or even failure at elevated temperatures. To overcome these shortcomings, researchers have applied surface coatings with inorganic fillers (e.g., Al_2O_3, SiO_2) or grafted functional groups to enhance electrolyte affinity and ionic conductivity. Optimization of thermal treatment and film processing can also improve the cycling stability and reliability of PE-based separators.

PE separators are mainly used in consumer electronics and electric vehicle batteries, where balancing cost, safety, and performance is critical. Although PE remains attractive due to its processing advantages, further improvements in heat resistance and electrolyte wettability are required for next-generation high-energy LIBs [5].

2.2 Polyproptlene (PP)

Polypropylene (PP) separators are another mainstream material in commercial LIBs, featuring strong chemical resistance, high mechanical integrity, and corrosion resistance. Compared to PE, PP exhibits slightly better high-temperature stability and, with optimized porous structures, offers improved electrolyte wettability [6]. Nevertheless, PP separators are also prone to thermal shrinkage at temperatures above 130°C, creating safety concerns.

Recent studies have incorporated hydrophilic additives, bilayer structures, or elastic particles into PP membranes to enhance wettability and shrinkage resistance. For instance, bilayer PP membranes with uniformly distributed micropores combine strength with favourable electrochemical properties. Polyimide (PI) has also emerged as a promising alternative material with superior heat resistance and electrolyte affinity. Composite membranes such as PI/PP and PI/PET have demonstrated excellent thermal stability and tensile strength up to 145 MPa, highlighting their potential for advanced batteries [7].

2.3 Composite Separators

Composite separators integrate polyolefin membranes with additional functional materials to achieve a balance between mechanical strength, thermal stability, and electrochemical performance. Common approaches include polymer–inorganic hybrids, electrospun nanofiber composites, and bio-based composites [8]. Inorganic fillers such as Al_2O_3 and SiO_2 improve thermal resistance and help suppress lithium dendrite formation. Electrospun nanofiber networks, with high surface area and interconnected porosity, provide superior electrolyte uptake and ionic conductivity.

Recently, bio-based separators derived from cellulose and its derivatives have attracted growing attention. These sustainable membranes are not only renewable and environmentally friendly but also demonstrate good ionic conductivity and mechanical robustness [9]. For example, dual-network bacterial cellulose membranes deliver high wet strength and unique dual-ion transport mechanisms, ensuring uniform lithium deposition and longer cycling stability.

2.4 Alumina-coated Separators

Alumina (Al_2O_3) coated separators represent an effective modification strategy to enhance the thermal and electrochemical performance of polyolefin membranes. The Al_2O_3 layer reduces shrinkage at elevated temperatures, improves electrolyte wettability, and contributes to enhanced ionic conductivity. Electrospun Al_2O_3/polymer hybrid coatings on PP membranes, for instance, have demonstrated improved efficiency at high charge/discharge rates and significantly reduced shrinkage [10].

In addition, alumina coatings suppress lithium dendrite growth, thus improving battery safety and cycling life. However, their relatively high production cost and complex fabrication remain major barriers to large-scale application.

3. Outlook for Separator Materials

As lithium-ion batteries continue to expand into electric vehicles and grid-scale storage, the requirements for separator materials are becoming more stringent. Future progress can be anticipated in several key directions.

3.1 Technological Innovation

The first direction is technological innovation. Novel composites, functional coatings, and nanostructured designs are regarded as essential to achieving safer and more efficient separators. Incorporating functional fillers, building multilayer structures, and developing bio-inspired materials are promising approaches to enhance thermal stability, ionic conductivity, and safety simultaneously. Moreover, artificial intelligence and machine learning methods are increasingly being applied to material discovery, accelerating the search for high-performance separators applied to material discovery, accelerating the search for high-performance separators.

3.2 Cost Reduction

The second direction is cost reduction. Although high-performance separators deliver substantial benefits in safety and energy density, their production often involves high cost and complex fabrication steps. Future studies should optimize raw material choices and simplify processes to enable large-scale manufacturing. The adoption of renewable, bio-based materials not only supports sustainability goals but may also help lower costs.

3.3 Development Trends

Finally, development trends indicate that smart separators, eco-friendly materials, and scalable manufacturing techniques will define the future. Smart separators with self-healing, thermoresponsive, or electrochemical feedback functions will improve safety under extreme operating conditions. Green, biodegradable materials will help reduce the environmental footprint. Meanwhile, process automation and simplification are expected to bridge the gap between laboratory-scale innovations and industrial-scale production.

4. Conclusion

This study systematically reviewed recent progress in separator materials for lithium-ion batteries, with particular attention to polyethylene (PE), polypropylene (PP), composite, and alumina-coated membranes. The research findings indicate that while conventional polyolefin-based separators remain dominant due to their low cost and established processing methods, they face intrinsic limitations in thermal stability and electrolyte wettability. By contrast, composite and ceramic-coated separators exhibit superior heat resistance, ionic conductivity, and interfacial compatibility, demonstrating significant potential for next-generation high-energy-density batteries. Therefore, it can be concluded that material innovation—especially through functionalized composites and bio-based alternatives—will be essential to balance safety, performance, and sustainability.

This work contributes to the field by integrating and evaluating the latest developments from 2022 to 2025, bridging the gap between traditional and emerging separator technologies. It highlights how design strategies such as inorganic coatings, electrospinning, and polymer–inorganic hybridization can effectively address the safety and efficiency challenges faced by modern lithium-ion systems. Furthermore, the analysis underscores the importance of scalable manufacturing techniques and cost-effective material selection for industrial application.

The findings of this study provide a valuable reference for researchers and engineers seeking to optimize separator functionality in next-generation batteries. They also point to several promising directions for future research: the exploration of biodegradable and recyclable materials, the integration of smart sensing or self-healing properties, and the use of artificial intelligence in material design. By clarifying existing challenges and opportunities, this review not only fills a gap in the recent literature on separator technologies but also offers theoretical and practical guidance for advancing safer and more sustainable electrochemical energy storage.

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