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Lithium-Ion Battery Technology Development Review: History, Current Status, and Future Prospects

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Abstract

Lithium-ion batteries (LIBs), as the core of modern energy storage technology, have profoundly reshaped human society's understanding and application of mobile energy. Since Sony Corporation first commercialized LIBs in 1991, they have expanded from consumer electronics to strategic industries such as electric vehicles (EVs), energy storage systems, and aerospace. Under the global con-sensus on carbon neutrality goals, the technological iteration and market ex-pansion of LIBs have become key drivers of the energy revolution. This article systematically reviews the technological development history of LIBs, analyzes the current industrial status, and explores future technological trends and chal-lenges.

Keywords

Lithium-ion batteries; Cathode materials; Electrolytes

1. Introduction

Since their initial commercialization in the early 1990s, lithium-ion batteries (LIBs) have emerged as the cornerstone of modern energy storage technology.[1] Their high energy density, long cycle life, and broad application scenarios have solidified their dominance in portable electronic devices, electric vehicles (EVs), and largescale energy storage systems. As global demand for clean energy and sustainable development grows, advancements in LIB technology are critical for reducing greenhouse gas emissions and replacing fossil fuels.[2, 3] With the projected exponential growth in EV sales, the demand for LIBs is expected to surge. LIBs currently dominate the portable electronics market and are the preferred choice for the automotive industry. Another significant envisioned application lies in grid energy storage, though these sectors require higher energy densities than those offered by current LIBs. Driven by emerging technologies such as energy storage systems (ESS) and electric drive vehicles (EDV)[4], the prospects for LIB applications continue to evolve. This dynamic environment poses unique challenges for traditional battery manufacturers, who must continuously adapt to changing design and performance requirements. This article reviews the historical development, current research status, and future prospects of LIB technology to provide insights for related fields.

2. Historical Development of Lithium-Ion Batteries

Among all metals applicable to battery chemistry, lithium is considered the most promising. Its widespread availability, nontoxicity, lightweight nature, and high electronegativity provide lithium-based batteries with superior energy storage potential compared to other chemistries.[5] However, lithium's high reactivity poses significant technical challenges in manufacturing safe batteries.

The development of LIBs traces back to the 1970s, when researchers began exploring lithium metal as an anode material. However, its high reactivity and safety concerns limited practical applications. In 1991, Sony Corporation commercialized the first LIB, utilizing graphite as the anode and lithium cobalt oxide (LCO)[6] as the cathode, marking the formal birth of LIB technology. Since then, LIBs have undergone multiple breakthroughs, including diversification of cathode materials, optimization of electrolytes, and structural improvements. The structure of the currently commercialized lithium-ion battery is shown in **Figure 1**.

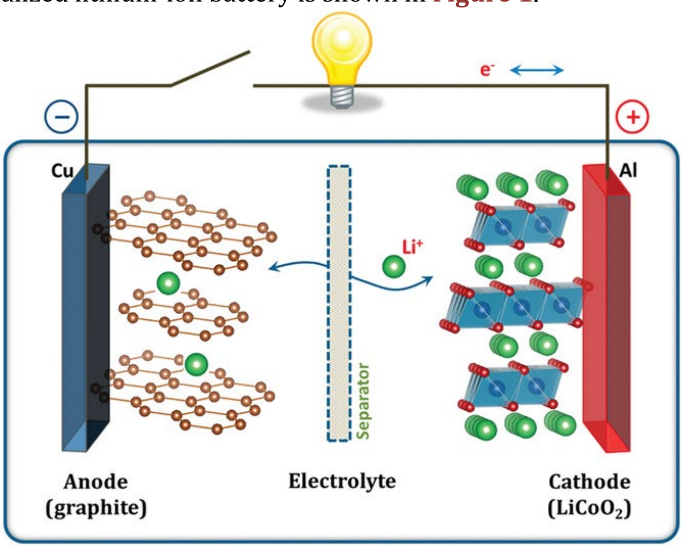

Figure 1. Basic working principle of LIB.[7]

3. Literature References

LIBs consist of three primary components: the anode, cathode, and electrolyte. During charging, Li^+ ions are extracted from the cathode, migrate through the electrolyte to the anode, and facilitate energy storage. The driving force behind this movement is electric current. During discharge, stored energy is released as Li^+ ions relocate to the cathode in aged cells. Safety remains a critical concern, as uncontrolled temperature rise can lead to thermal runaway (**Figure 2**)—a phenomenon causing damage, leakage, or even combustion[7]. Temperature monitoring is essential for enhancing operational safety. Extreme temperatures, whether high or low, impair capacity retention, discharge rates, and cycle life. Maintaining recommended operating temperatures is crucial for optimal battery functionality and durability.

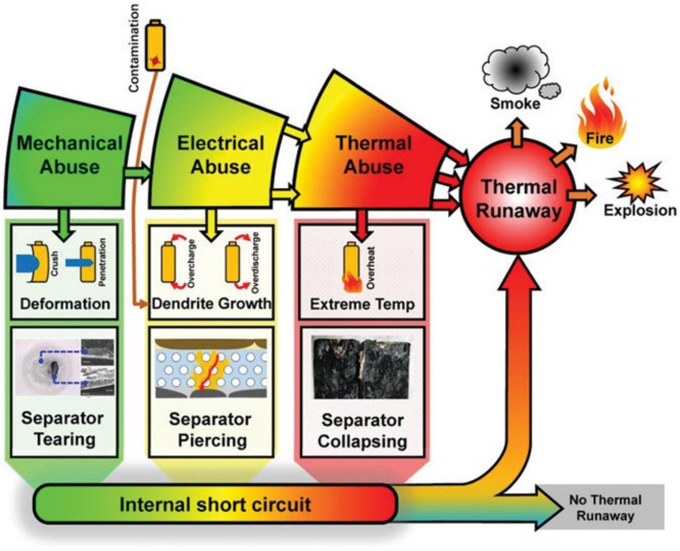

Figure 2. The inducements of battery thermal runaway. Reproduced with permission.[4]

3.1. Cathode Materials

Cathode materials are pivotal in determining LIB performance. Current commercial LIBs primarily employ the following cathode materials: lithium cobalt oxide (LCO), lithium manganese oxide (LMO)[8], lithium iron phosphate (LFP)[9], lithium nickel cobalt aluminum oxide (NCA)[10], and lithium nickel manganese cobalt oxide (NMC). Each material has distinct advantages and limitations. For instance, LCO offers high energy density but suffers from high costs and safety risks, whereas LFP is renowned for its safety and long cycle life but lower energy density. Recent advancements, such as doping, surface modification, and nanostructure design, have further enhanced these materials' performance.

3.2. Anode Materials

Graphite remains the most common anode material, but its theoretical capacity is limited (372 mAh/g). To overcome this, researchers have developed novel anode materials, including silicon-based materials, lithium titanate (LTO), and transition metal oxides. Silicon-based materials exhibit an extremely high theoretical capacity (4200 mAh/g), yet severe volume expansion during charge-discharge cycles compromises cycling stability. Nanostructure design and composite material preparation have significantly improved their cyclic performance.[7]

3.3. Electrolytes

Electrolytes, the medium for Li+ ion transport in LIBs, directly influence battery safety and cycle life.[11]Conventional liquid electrolytes, composed of lithium salts (e.g., LiPF6) and organic solvents (e.g., carbonates), face limitations due to flammability and poor thermal stability. Recently, solid-state and gel electrolytes have gained attention for their enhanced safety and mechanical robustness. The introduction of novel additives, such as flame retardants and film-forming agents, has further improved electrolyte performance.

3.4. Separators

Separators are critical components that prevent direct contact between the anode and cathode while allowing Li+ ion permeation. Commercial LIBs primarily use polyolefin-based separators, though their thermal stability and mechanical strength require improvement. Recent developments include ceramic-coated separators and polymer-based composite separators, which demonstrate superior performance under high temperatures and mechanical stress.

4. Future Prospects of Lithium-Ion Batteries

4.1. High-Energy-Density Batteries

With increasing demands from EVs and portable electronics, developing high-energy-density LIBs is a research priority. Innovations in electrode materials, such as high-nickel cathodes and silicon-carbon composite anodes, are expected to enhance energy density.[12] Additionally, advancements in solid-state battery technology may provide new pathways for achieving high-energy-density LIBs.

4.2. Enhanced Safety

Safety remains a major challenge for largescale LIB adoption. Future strategies include developing novel electrolytes (e.g., solid-state electrolytes)[13] and optimizing battery management systems (BMS)[14]. The integration of smart separators and self-healing materials could further bolster safety.

4.3. Environmental Sustainability

Growing environmental awareness is driving research into ecofriendly LIBs. The use of renewable materials (e.g., organic cathode materials) and green manufacturing processes will reduce environmental impacts. Advances in battery recycling technologies will also support sustainable LIB development.

4.4. Emerging Battery Technologies

Despite LIB advancements, energy density and cost challenges persist. Emerging technologies, such as lithium-sulfur and lithium-air batteries, hold promise for surpassing LIB performance limits. These systems offer ultrahigh theoretical energy densities but face practical hurdles, including poor cycle stability and electrolyte decomposition.[9]

Conclusion

Lithium-ion battery technology has achieved remarkable progress over the past decades, enabling widespread applications across multiple sectors. However, challenges such as safety concerns, limited cycle life, slow charging rates, and constrained reversible capacity hinder broader adoption. Future advancements in electrode material design, electrolyte optimization, and novel battery technologies will further enhance LIB performance, paving the way for their expanded use in EVs, renewable energy storage, and beyond.

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