Materials for Lithium-Ion Batteries

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Lithium-ion batteries (LIBs) are the most commonly used ESS in modern society, mainly due to their high specific capacity, making them appropriate for small and light portable devices without limiting their performance. LIBs are also characterized by prolonged cycle life and no memory effects. These are important advantages that increased the use of LIBs, leading to a progressive replacement of previous technologies, such as nickel–cadmium and nickel–metal hydride batteries, which are less efficient, in particular for small device applications.

electrodes solid polymer electrolytes separators battery systems

1. Overview

Environmental issues related to energy consumption are mainly associated with the strong dependence on fossil fuels. To solve these issues, renewable energy sources systems have been developed as well as advanced energy storage systems. Batteries are the main storage system related to mobility, and they are applied in devices such as laptops, cell phones, and electric vehicles. Lithium-ion batteries (LIBs) are the most used battery system based on their high specific capacity, long cycle life, and no memory effects. This rapidly evolving field urges for a systematic comparative compilation of the most recent developments on battery technology in order to keep up with the growing number of materials, strategies, and battery performance data, allowing the design of future developments in the field. Thus, this review focuses on the different materials recently developed for the different battery components—anode, cathode, and separator/electrolyte—in order to further improve LIB systems. Moreover, solid polymer electrolytes (SPE) for LIBs are also highlighted. Together with the study of new advanced materials, materials modification by doping or synthesis, the combination of different materials, fillers addition, size manipulation, or the use of high ionic conductor materials are also presented as effective methods to enhance the electrochemical properties of LIBs. Finally, it is also shown that the development of advanced materials is not only focused on improving efficiency but also on the application of more environmentally friendly materials.

2. Background

The search for more efficient and sustainable energy storage devices is a growing need and a fruitful research field, based on the increasing mobility of society. Industrial production and mobility require significant quantities of energy, mostly relying on fossil fuels, as coal or petroleum, and more recently natural gas and nuclear fission [1]. Nowadays, with the growing awareness with respect to environmental issues, renewable energy sources gained significant interest as they allow to obtain green energy, with the reliance in inexhaustible sources, such as wind, water or sun [2][3]. However, the use of renewable energies is limited by their irregularity, which does not warrant a constant energy supply [4]. In this context, the integration of renewable energies with efficient energy storage systems (ESS) arises as a potential solution regarding this issue.

These ESS can vary depending on the application needs, batteries being the most used systems worldwide. Since the voltaic pile, created in 1800 [5], until the commercialization of the first lithium-ion battery (LIB) in 1991, battery technology has undergone strong developments, with significant improvements on capacity, durability, and reversibility (Figure 1).

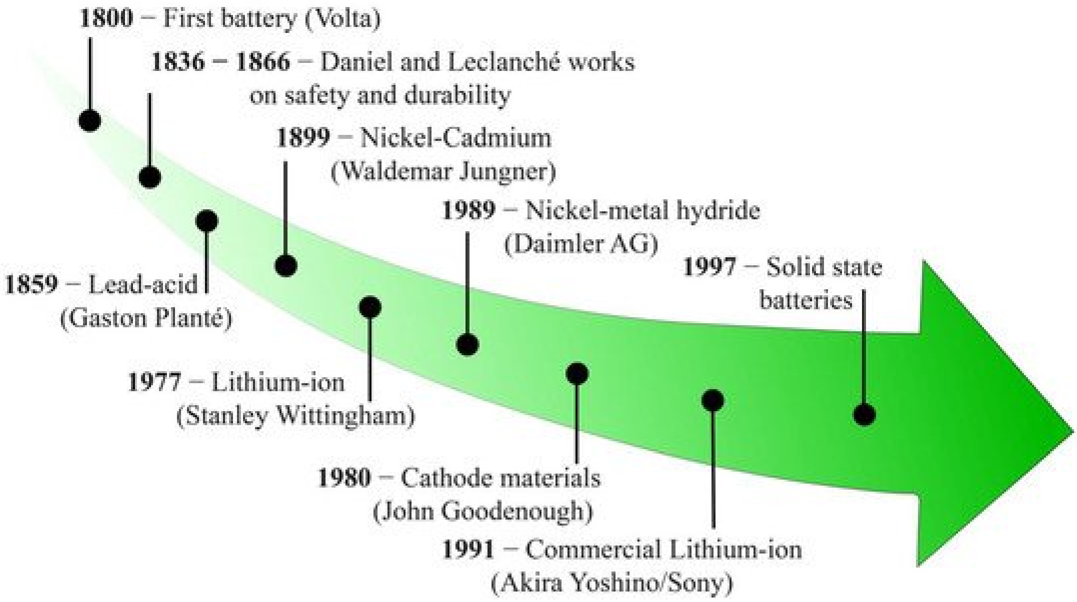

Figure 1. Advances in battery system development over the years.

LIBs are the most commonly used ESS in modern society, mainly due to their high specific capacity, making them appropriate for small and light portable devices without limiting their performance. LIBs are also characterized by prolonged cycle life and no memory effects [6]. These are important advantages that increased the use of LIBs, leading to a progressive replacement of previous technologies, such as nickel–cadmium and nickel–metal hydride batteries, which are less efficient, in particular for small device applications. In fact, the developments in the area of ESS further supported the strong evolution of the market of portable equipment with increased and improved features, capacity and smaller sizes. LIBs are present in a large variety of commonly used devices including smartphones, tablets, laptops, grid stabilization, electric vehicles, and a vast range of other electronic systems [7].

In this constant growing field, it is extremely important to keep up with the high number of works that are published every year. Thus, a frequent systematization and review of the literature is needed in order to comparatively analyze newly developed materials, integration strategies, and battery performance data to properly design further developments in the field. The main focus of the research community in the field nowadays is the search for new high-performance materials, but also to address environmental questions, by finding more sustainable and green solutions. In the present work, the LIB constitution and working principles are described, presenting the most recent solutions for each component of the battery separately. In particular, the latest developed materials and production/modification strategies are considered.

3. Conclusions

Lithium-ion batteries (LIBs) are the most used energy storage system with increasing applicability on devices ranging from small sensors to large-scale and complex electric vehicles. The recent development in the materials used in the main three LIBs components, anode, cathode, and separator/electrolyte, have been presented and compared. These materials are focused on the resolution of the most frequent LIB issues, such as the ones related to their processability, safety, and stability, as well as to increase their performance. Furthermore, the environmental impact of materials and processes are gaining increasing relevance in this area. For the anode, the most studied active materials are carbon, metal alloys, and silicon-based materials. Furthermore, conversion-type transition metals and their composite-based anode materials increased interest in recent years due to their high theoretical capabilities, low cost, and availability. Materials such as iron oxides and MOFs increase lithium storage capabilities and electrical conductivity, and they act as a buffer medium to reduce the volume change.

With respect to cathode active materials, the most used ones, including LFP, LCO, LMO, or LNMO, are being modified through doping with different elements, innovative synthesis methods have been developed, composites with different particles have been processed, particle size and morphology are being optimized, and performance is being improved by functionalization and coating. Efforts are also being made in the field of hybrid structures, using materials such as MXenes and MOFs, to improve the electrode’s performance, with a focus on improving cycling behavior. Future trends in this area also include research in cobalt-free active materials, which will allow for the reduction of the battery costs, as cobalt is a scarce and costly component of batteries. These optimizations are focused to improve the electronic and thermal properties, to stabilize the particle with the electrolyte, and to improve the mechanochemical activation. Separator materials based on PP, PE, and PVDF, among other polymers, have been studied as microporous membranes, nonwoven membranes, and electrospun membranes. In addition to the structure, surface modification, composite membranes, and polymer blends have been studied showing improved lithium dendrite growth inhibition, improving thermal and safety properties, increasing the wettability, and improving interfacial issues. Studies of new environmentally friendly materials and SPE are increasing due to the commitment with advanced sustainable and safer materials in LIBs systems. Materials such as cellulose and silk, and fillers such as natural clay are some of these examples. The elimination of the liquid electrolyte in SPE strongly decreases the safety concerns visualized in the typical separators. Furthermore, SPE studies show that additional functionalities as battery shutdown, self-healing, and/or self-sensing ability can be implemented in those systems, strongly increasing battery characteristics, particularly at the safety level. In addition, initial studies demonstrate that natural polymers are a possible route for SPE development, once they allow for high room temperature ionic conductivity, without compromising sustainability. Thus, efforts to enhance the material properties of chitosan, iota-carrageenan, pectin, and guar gum have been made in order to be applied to LIBs.

The work on LIBs should always take into consideration improvements on all components of the batteries in order to achieve the best compatibility and improve the performance of the devices. Thus, the study of the different materials for a specific battery component must take into consideration the materials that will be integrated into the other components. The selection and combination of these materials will affect the overall performance of the system, aiming to solve the current performance, safety, stability, and environmental issues.

The development of LIB technology must also be accompanied with the advance in alternative energy storage systems, which allows for a higher diversity of options, limiting the over exploration of the same type of resources. These alternatives include sodium, potassium, and manganese-based batteries, which are areas of increasing research activity.

Thus, despite the strong success and implementation of Li-ion batteries in modern technology, efforts and the levels of materials must continue to provide a new generation of higher performance, safer, and environmentally friendlier batteries.

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