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Recent advances of electrode materials for low-cost sodium-ion batteries towards practical application for grid energy storage

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ABSTRACT

Energy storage plays an important role in the development of portable electronic devices, electric vehicles and large-scale electrical energy storage applications for renewable energy, such as solar and wind power. Lithium-ion batteries (LIBs) have dominated most of the first two applications due to the highest energy density and long cycle life. Room-temperature sodium-ion batteries (SIBs) have re-attracted great attention recently, especially for large-scale electrical energy storage applications. This is on one hand due to the abundant and widely distributed sodium resources and on the other hand due to the predicted lower cost from using Na, as well as Al current collectors for both cathode and anode. One of the important advantages as well as challenges in SIBs is to use low-cost materials as active electrodes to compete with LIBs in terms of cost/kWh. In this review, both cathode and anode materials for SIBs are reviewed, with focus on the latest development of electrode materials from 2013. Advantages, disadvantages and future directions on the existing electrode materials will be discussed based on the literature and our experience. Although a large number of electrode materials have been reported in the literature, SIBs are still facing grand challenges, which can be overcome by continuing the research efforts to search for new electrode materials with better performance, lower cost, higher safety and more stable interface with electrolyte. Once the right electrode materials are discovered throughout a fundamental understanding of the intimate relationships between its structure and performance, we believe that SIBs with low cost and long life will have promising prospects in low-speed electric vehicles (e.g., bicycle, quadricycle, etc.) and large-scale energy storage in the future.

1. Introduction

With the rapid exhaustion of fossil fuel resources and the increase of environmental pollution, the use of renewable and cleaner energy sources, such as solar radiation, wind and waves, is becoming urgent. However, the variability of renewable resources in time, duration and location limits their developments and a wide range of applications. Therefore, a large-scale energy storage system (ESS) is needed to store the on-peak electricity and release it during the off-peak periods in a stable and reliable manner. Among various energy storage technologies, secondary batteries present the most appropriate pattern for energy storage at large scale, in terms of energy density and conversion efficiency [1–4]. However, there are still some challenges for the application of existing secondary batteries in EES when taking performance, cost and safety issues into consideration. Abundant, low-cost, nontoxic, stable and low-strain electrode materials of rechargeable batteries need to be developed to meet the energy storage requirements for long cycle life, low cost and high safety [5–8].

There are different rechargeable battery technologies commercially available for energy storage. For instance, high-temperature sodium–sulfur (Na–S) batteries have been applied in energy storage on a small scale, but the safety issue brought by high temperature conditions at which they operate impedes their further development [9]. Benefiting from the highest energy density and long cycle life, lithium-ion batteries (LIBs) have been successfully developed as power sources for portable electronics [1]. However, the large-scale applications of LIBs in portable electronics and electric vehicles (EV) market will drive the increase of price of Li resources due to its low abundance in the Earth's crust and its non-uniform geographic distribution (Fig. 1) [10–12]. This will make the application of LIBs in stationary energy storage uneconomical in the near future. Therefore, the development of low-cost, highly-safe and cycling stable rechargeable batteries based on

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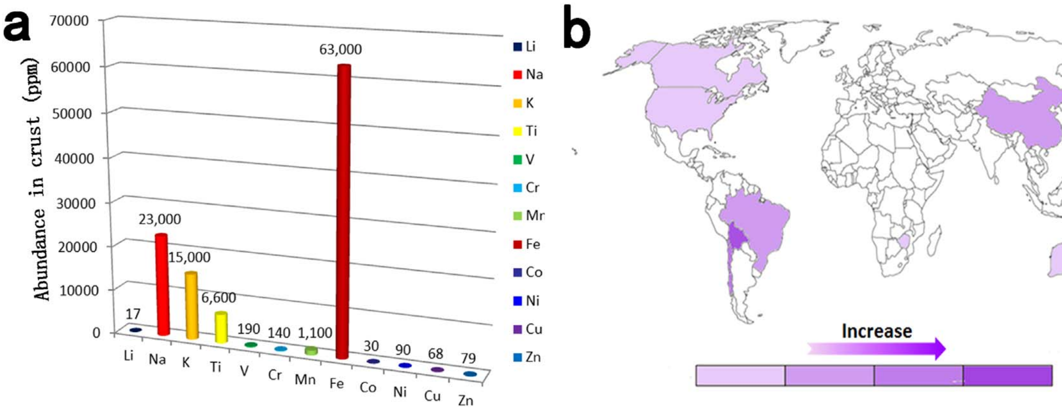

Fig. 1. (a) Element abundance in Earth's crust [10]; (b) The world distribution of lithium resource.

abundant resources is becoming urgent and highly desired.

Considering the similar physical and chemical properties with Li, along with the huge abundance and low cost of Na, sodium-ion batteries (SIBs) have recently been considered as an ideal energy storage technology (Fig. 2). Actually, SIBs started to be investigated in the early 1980s [13], but the research related to SIBs decreased significantly after the successful commercialization of LIBs in 1991. Recently, with the rise of energy storage market, the room-temperature SIBs arouse the research interest once again due to the abundance and low cost of Na in Earth. Compared with LIBs, SIBs shall have a lower energy density due to the relatively heavier and larger Na atom [14–20]. However, the energy density is not the most critical issue in the field of large-scale ESS. In addition, there are numerous unexplored opportunities in SIBs because of the different intercalation chemistry between Na and Li. Early results seem to indicate that materials with the same structure which function well as Li-intercalation compounds may not work well with Na [21]. Thus, the research on electrode materials for SIBs still attracts a large number of scientific researchers in order to promote their practical application in EES [22–24].

The major challenge for SIBs lies in finding suitable electrode materials with excellent sodium storage performance, in particular considering that their electrochemical properties determine their specific capacity and operation voltage. In general, materials with the same crystal structure that allows Li intercalation are sometimes suitable for Na intercalation due to the similar physical and chemical properties, as a result, various SIBs electrode materials have been mimicked from LIBs electrode materials previously [25]. In turn, the research on electrode materials for SIBs also has certain reference significance for the invention of new electrode materials for LIBs. However, this strategy will not always be feasible as obvious differences in intercalation behaviour existed between Na and Li equivalent. Recently some new Na compounds which are different from Li electrode materials have been discovered [35,44,134–136]. In this review, we focus on the development of currently available cathode and anode materials for SIBs, focusing on the latest research progress since 2013 onwards. For the cathode materials, we emphatically introduce the transition-metal layered oxides, polyanion compounds and other cathode compounds while for the anode materials, we mainly discuss carbonaceous materials and oxides. Our perspectives on future developments for SIB´s electrodes are provided at the end of the review .

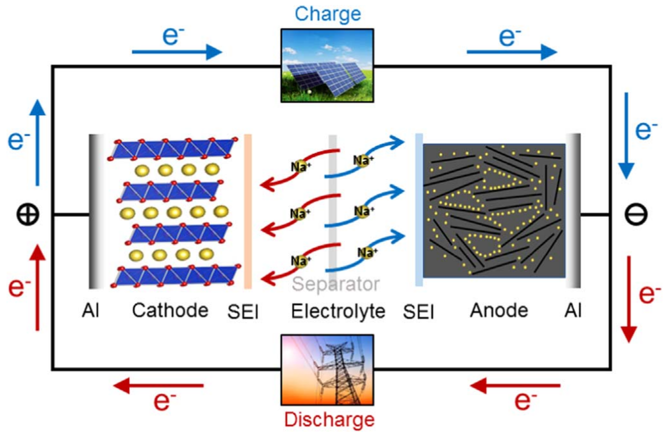

Fig. 2. The working principle of rechargeable sodium-ion batteries.

2. Cathode materials

2.1. Transition-metal oxides

2.1.1. Layered oxides

Layered oxides are the most extensively studied cathode materials for SIBs, particularly in recent years. Layered oxides with a general formula Na_xMO_2 are composed of sheets of edge-shared MO_6 octahedra, wherein Na^+ ions are located between MO_6 sheets forming a sandwich structure. Typical layered oxides can be categorized into two main groups: O3 type or P2 type depending on the surrounding Na^+ environment and the number of unique oxide layer stacking, which was first specified by Delmas et al. [26]. “O” or “P” represents octahedral or trigonal prismatic coordination environment of Na^+ ions, and the number indicates the repeated stacking unit with different oxide layers. Schematic illustration of crystal structures of O3 and P2 phases is shown in Fig. 3. The phase structure determined by Na amount and the kinetics has important implications in the electrochemical behaviours.

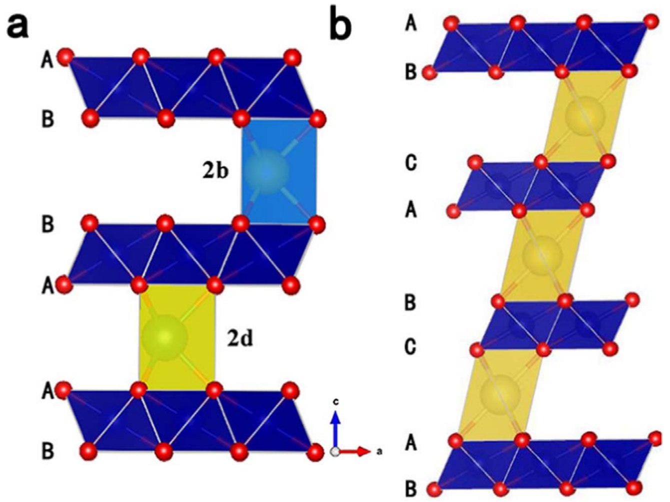

Fig. 3. Structure framework of: (a) P2-type layered oxides and (b) O3-type layered oxides.

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