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Design principles and energy system scale analysis technologies of new lithium-ion and aluminum-ion batteries for sustainable energy electric vehicles

Yong Li[a,c,*], Jie Yang[b], Jian Song[c]

[a] Key Laboratory of Dynamics and Control of Flight Vehicle, Ministry of Education, School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, PR China
[b] E & M School, Beihang University, Beijing 100191, PR China
[c] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China

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ABSTRACT

Battery power is one of the most important sources of energy for vehicles that do not produce harmful gases, electric vehicles. These electric vehicles are also capable of taking advantage of the electric grid to recharge at night. Scientists worldwide are searching for practical battery designs and electrodes with high cycling stability for electric vehicles by combining nanotechnology with surface coating technologies. Multiple tests have been performed upon lithium-ion batteries; however, new research is focusing on aluminum-ion batteries. The production and application of this form of battery technology is expected to improve greatly in the future. This Review summarizes the recent highlights in the energy industry as well as our laboratory work regarding lithium-ion and aluminum-ion batteries. The focus of this work is on battery structure models and nanoscale analysis technologies. Furthermore, this Review outlines the challenges that exist in producing cheaper and more accessible batteries by examining the energy storage and transmission principles of these new batteries. The structure and size effects of nanoparticles allows, as well as probes on the thermodynamic mechanism for mediating lessened battery performance due to heat expansion of the nanostructure. Finally, this Review looks at batteries and electrodes of electric vehicles as objects, commenting on the design ideas and feasibility of new battery technologies.

1. Introduction

With oil resources becoming more difficult to access, reversing the current oil-based energy economy and diversifying the number of viable alternative energy sources has become the future trend of the automotive industry. Governments around the world have also recognized this trend and have begun funding the development of new technologies and supporting industries for alternative energy. Major automobile companies, related businesses, and research institutions have increased their R & D investments, introducing new advanced technologies [1–3]. The world's automobile industry is expected to quickly accelerate away from its dependence on oil in order to make a switch to sustainable energy sources. The proliferation of incentives, such as subsidies for electric vehicles and other policies favorable to electric vehicles has made it a very hot market. However, electric vehicles suffer from long charging times and poor ranges. Presently, the cruising mileage of commercial electric vehicles is approximately 200 km, after which a 6–8 h full charge or 1 h fast charge is required [4–6]. Sluggish charging and high cost are two things that are hampering lithium ion battery technology in electric vehicles. This acts a technical bottleneck for advancement of the technology.

Batteries are composed of various elements [1,3,5,7,8]: lithium, iron, and aluminum. Save for lithium, all other elements used in batteries are found in abundance on Earth, as shown in Fig. 1. Currently, there are three types of anodes for these batteries: lithium iron phosphate, lithium manganese oxide, and ternary batteries possessing long cruising mileage with a capacity of 275 mAh/g. The Si ratio is larger than that of Fe in reserves which results in a cheaper price. The Fe and Si in ternary batteries have similar electronic structure and properties and little difference in the size of ions. In order to obtain a more stable high solid solution material, Fe is added along with Si, which can further improve the stability and safety of the

* Corresponding author at: Key Laboratory of Dynamics and Control of Flight Vehicle, Ministry of Education, School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, PR China.
E-mail address: yongli@bit.edu.cn (Y. Li).

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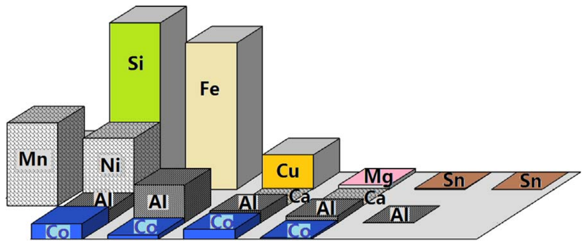

Fig. 1. Distribution of elements in lithium battery.

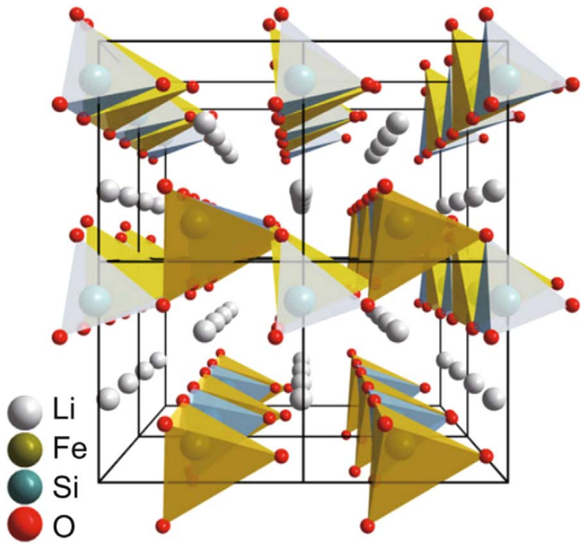

Fig. 2. Design model of ternary lithium battery.

material while maintaining the nano-structure, as shown in Fig. 2. It reduces the surface Fe content for the ternary battery, which reduces the sensitivity to moisture and improves cycling performance. Solving the issue of moisture sensitivity is the key to the application of the ternary battery, which can be realized by reducing the surface alkaline level through surface coating or additives. New vehicles powered by these ternary batteries are constantly being introduced worldwide [8,9]. The development of graphene lithium batteries is largely fueled by the development of lithium battery technology. This development then promotes rapid development of electric vehicles. This results in a mutual progression of technology in which a development in one area benefits the other. Graphene batteries have great potential for application, with its advantages including flame retardant ability, safety, low resistance, fast electron mobility, large surface area and good electrical properties. Graphene is considered the ideal electrode for lithium-ion batteries, as shown in Fig. 3. The new Tesla battery will adopt graphene as well.

2. High-performance lithium-ion battery for sustainable energy electric vehicles

Commercial lithium-ion batteries use graphite as a cathode, while lithium iron phosphate, lithium manganese oxide, and ternary batteries are used as anodes in battery [10–13]. By substantially increasing the lithium salt concentration, a large number of free solvent molecules are associated with a lithium salt which effectively dissolves the polysulfide ions in the electrolyte. It also effectively avoids the shuttling effect of multiple ions in the process of charging and prevents the battery from overcharging. This enhances the coulombic efficiency to 85% and improves cycling stability [14–16]. Additionally, it prevents dendrite growth inside the lithium due to uneven deposition [17,18]. High concentration and viscosity of lithium ion is not only ideal for the uniform exchange of electrode material [19], but also helps to reduce the spatial charge layer produced on the electrode surface. This reduces the driving force from the electric field due to uneven deposition of lithium. High systemic viscosity increases the resistance to lithium dendrite growth so that cycling stability is greatly improved.

Since lithium-ion batteries have become commercially available, they have been approaching the theoretical limit of the specific capacity of the carbon cathode, 370 mAh/g. There is little room for improvement in this regard. Due to this, finding alternative cathode materials with high specific capacity in order to replace carbon is an important trend [20–23]. Silicon and lithium can form alloys like $Li_{12}Si_7$, $Li_{13}Si_4$, Li_7S_{i3}, $Li_{15}Si_4$, and $Li_{22}Si_5$, of which $Li_{22}Si_5$ has a high capacity of 4200 mAh/g. It is a very promising material for cathodes due to the rich reserves and low cost of silicon. However, in the charging and discharging process, the intercalation reaction of silicon will be accompanied by large volume changes, which can cause mechanical damage. This also leads to the separation of the electrode and collector, as well as the materials of the electrode. Loss of this electrical contact leads to rapid capacity and cycling performance degradation [24–27]. So the key to the study of silicon based electrodes is how to best improve cycling performance while retaining high battery capacity. In the intercalation process, changes in the crystal structure generate large stretch stress, resulting in volume change and mechanical damage [28–31], as well as the delamination of coating. In order to understand the changes in volume and crystal structure during the intercalation process, synchrotron radiation and electron microscopy can be used for characterization and analysis.

The structure and morphology of the lithium alloy significantly affect the stability of its spatial configuration, and thus affect the transport of electrons during charging and discharging. After a large number of lithium ions are intercalated, the metastable amorphous Li-Si alloy is eventually formed. When Li escapes, the ordered structure of silicon is gradually restored, and the crystalline regions are gradually expanded. However, the starting crystalline structure cannot be fully recovered. Small amorphous areas can still exist inside the particles [32–35]. Take nano-silicon for instance, when Li is intercalated in the crystalline Si, the crystalline Si becomes amorphous Si. Isolated Si atoms and small Si-Si clusters are formed during ionization. Crystalline

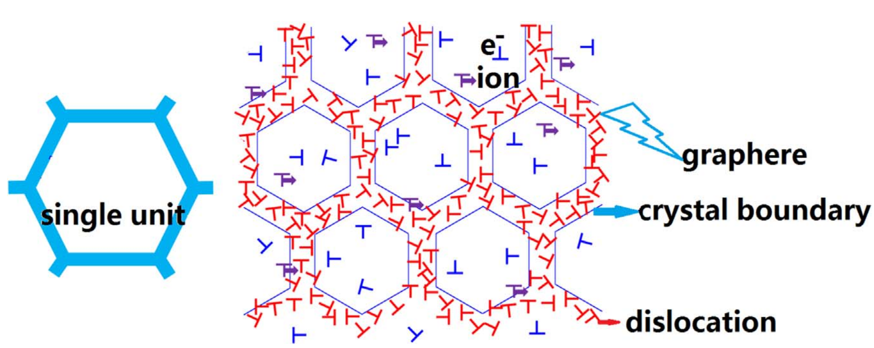

Fig. 3. Nano energy model of graphene battery.