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# Nano-energy system coupling model and failure characterization of lithium ion battery electrode in electric energy vehicles

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## ABSTRACT

With good energy storage characteristics, lithium-ion battery electrodes become promising nano-energy storage systems for renewable energy vehicles. However, during the charging and discharging of an electrode system, deformation and degradation may occur, causing battery and material failure that seriously affect the cycling performance and service life of a battery. This is a challenge for the application of lithium batteries in the electric vehicle field. This paper describes the nano-energy system models of different electrode structures and the failure characterization mechanisms during the process of charging and discharging. Moreover, it reviews the new development in the cycling performance evolution and experiment theory, and it analyzes the new research results of Si-C electrode failure. Additionally, this paper addresses the low utilization rate, poor cycling performance and low energy capacity problems associated with lithium batteries. Furthermore, it discusses the highlights, challenges and future direction of lithium batteries and the optimal design technologies that are providing support for the research of lithium battery technologies and development in the energy storage industry. It also reveals the energy system model, nanoscale defects of evolution rules and performance degradation mechanisms according to the failure characterization of nano-structures. Finally, it evaluates the operating mechanism, failure process and engineering application of silicon-carbon-lithium electrode systems.

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## 1. Introduction

Energy is the backbone of the world's economy. As a result, it is extremely urgent to develop electric vehicles with renewable energy to replace those with traditional ones, and technical requirements have been proposed for high-performance energy storage systems [1,2]. Metal lithium can react with many

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substances, and it is easy for lithium batteries to form dendrites that puncture the diaphragm during the charging process causing accidents due to the internal short-circuit of a battery [3]. In order to overcome lithium battery shortcomings involving safety and poor circulation, lithium compounds may be used instead of metal lithium electrodes to avoid the growth of dendrites, which improves safety [4]. With the advantages of high voltage, wide temperature range, a low self-discharging rate, light pollution, long life, high energy density and high power density [5], lithium-ion batteries have broad potential applications in electric vehicle energy storage fields, and these batteries have been identified as the main driving energy for current electric vehicles when considering specific capacity, lithium-intercalation potential, cycling performance and cost [6]. However, the cruising mileage of electric vehicles has long been a challenge. Electric vehicles require a power battery with a greater energy density, longer life, better safety and a lower price [7]. How to further improve the performance of lithium batteries is a great challenge facing the energy academia and industry, and there is plenty of room to improve the energy density of lithium batteries [8]. For example, by modifying the traditional lithium iron phosphate battery, designing new architecture and adding new doping elements [9], as shown in Fig. 1, a lithium battery with a higher energy density can be formed, which will greatly enhance the cruising mileage of electric vehicles.

The key to the development of lithium batteries is to achieve a high energy density, a high power density and a high cycling stability [10]. Electrodes are the core of a lithium battery. During the long-time cycling process, lithium dendrites may form on the cathode surface leading to safety accidents [11]. A rocking-chair type lithium battery adopts the compound with low intercalation potential on the cathode, and it adopts the compound with high intercalation potential as an anode to avoid the dendrite deposition and improve safety [12]. However, due to the low voltage and slow diffusion of lithium ions at the cathode of a battery, R&D was caught in a bottleneck [13]. At this time, materials such as carbon and silicon are being researched and developed as the electrode matrix, and new nano-silicon, carbon nanotubes and graphene, with the special one-dimensional and two-dimensional nano-storage structure, possess an excellent electrical and thermal conductivity and show enormous potential in applications [14]. In the case of lithium-ion electrodes [15], as shown in Fig. 2, little or no deformation of electrode structures can ensure good cycling performance, stable charging and discharging voltage, good electrical and thermal conductivity, can reduce the polarization effect and perform large current charging and discharging. The electrode surface structure and electrolyte form a stable membrane not reacting with the electrolyte, and thus facilitate rapid charging and discharging.

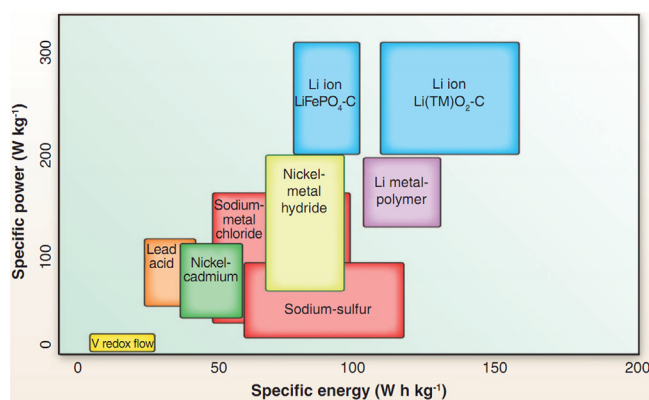


Fig. 1. Schematic diagram of energy density and power density of batteries [9].

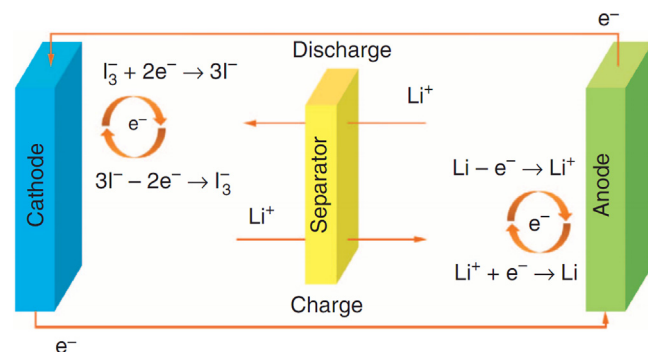


Fig. 2. Ideal energy system for lithium-ion battery electrodes in charging and discharging [15].

Essentially, lithium batteries are a kind of battery with a lithium-ions concentration gradient structure and have concentration differences of lithium-ions with anode and cathodes composed of two kinds of lithium-ion intercalated compounds [16,17]. When charging, lithium-ions release from the anode and intercalate into the cathode through the electrolyte, and thus, the cathode is in its lithium-rich state. Meanwhile, the compensation charges of electrons are supplied from the external circuit to the cathode to ensure the charge balance at the cathode [18]. In normal charging and discharging, lithium ions intercalate between the layers of the spherical gradient structures of carbon silicon materials and nano-systems. Ideally, such a dynamic process only leads to a spherical distance change [19] without destroying the crystal structure of the electrode, as shown in Fig. 3. During the charging and discharging process, the structure of the electrode is substantially constant. Thus, the electrode reaction of a lithium battery is an ideal reversible reaction.

## 2. Coupling defect and modification of energy storage electrode

Although the short cruising mileage of electric vehicles can be solved by increasing the battery energy density, the slow charging rate becomes a restriction for practical applications [20]. Normally, it takes 4–8 h to fully charge the lithium battery of an electric vehicle. For rapid charging, 1–2 h are enough, but the cycling performance and service life of a battery will be greatly affected [21]. Experiments show that if a battery is rapidly charged frequently, then the battery life will reduce by 1/3 of its original capacity, the cycling performance will decline significantly and the probability of safety accidents will be greatly increased [22]. For example,  $\text{LiCoO}_2$  has a layered crystal structure with stable discharging, good cycling performance and is being widely used currently. The amount of the reversible release of lithium ion from  $\text{LiCoO}_2$  is 0.5 units at most. If it is greater than 0.5,  $\text{Li}_{1-x}\text{CoO}_2$  is unstable [23]. As shown in Fig. 4a, the capacity then degrades and is accompanied by a loss of cobalt causing the electrode structure to become unstable. Part of the cobalt ions migrate into the electrolyte, and therefore, the actual capacity of  $\text{LiCoO}_2$  is less than 50% of the theoretical one.

At the nano-energy level, the faster the charging rate, the faster the nano-electrode deformation rate [24]. If the energy of deformation and stress migration cannot be released in time, plastic deformation and stress gradient may occur causing easy dislocation defects of the material [25]. As shown in Fig. 4b, the critical value of the electrode becomes smaller, which is prone to damage. Conversely, if the charging rate is small, the damage critical value is relatively large, and the electrode is more stable. For example, in 2014, one type of electric vehicles took a lithium cobalt oxides

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