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REVIEW

Electrode surface engineering by atomic layer deposition: A promising pathway toward better energy storage

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Summary Research on electrochemical energy storage devices including Li ion batteries (LIBs), Na ion batteries (NIBs) and supercapacitors (SCs) has accelerated in recent years, in part because developments in nanomaterials are making it possible to achieve high capacities and energy and power densities. These developments can extend battery life in portable devices, and open new markets such as electric vehicles and large-scale grid energy storage. It is well known that surface reactions largely determine the performance and stability of electrochemical energy storage devices. Despite showing impressive capacities and high energy and power densities, many of the new nanostructured electrode materials suffer from limited lifetime due to severe electrode interaction with electrolytes or due to large volume changes. Hence control of the surface of the electrode material is essential for both increasing capacity and improving cyclic stability of the energy storage devices.

Atomic layer deposition (ALD) which has become a pervasive synthesis method in the microelectronics industry, has recently emerged as a promising process for electrochemical energy storage. ALD boasts excellent conformality, atomic scale thickness control, and uniformity over large areas. Since ALD is based on self-limiting surface reactions, complex shapes and nanostructures can be coated with excellent uniformity, and most processes can be done below 200 °C. In this article, we review recent studies on the use of ALD coatings to improve the performance of electrochemical energy storage devices, with particular emphasis on the studies that have provided mechanistic insight into the role of ALD in improving device performance.

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Introduction

The increasing demand for portable electronics, electric vehicles, and large-scale grid storage requires efficient and environment friendly energy storage technologies with high energy and power densities and excellent life time [1—4]. Electrochemical energy storage devices offer numerous advantages such as high efficiency, low cost, excellent reversibility, extended cyclic performance and environment friendly operation. The most commonly used electrochemical energy storage devices are Li ion batteries (LIBs), first commercialized by Sony in 1991, provide excellent life span and performance [5,6]. In addition, high energy density Li-sulfur batteries (LSBs) and Li-oxygen batteries (LOBs) have reaped research focus due to their high theoretical capacity and cost effectiveness [7—10]. Furthermore, Na ion batteries (NIBs) have garnered increasing research attention because of abundant sodium (Na) resources, lower materials cost, and identical ion transfer chemistries with LIBs [11,12]. Despite their lower energy density as compared to LIBs, NIBs are considered viable candidates for large-scale energy storage systems. On the other hand, though batteries can deliver high energy density, their power density is low. Hence, for applications requiring high power, electrochemical capacitors, including electrical double-layer capacitors (EDLCs) and pseudocapacitors, are preferred [13—17].

Since the performance of energy storage devices largely depends on the choice of electrode materials, it is desirable to design and develop new materials with favorable electrochemical properties [18]. Recently, nanostructured materials have shown promise in energy storage applications due to various attractive properties. For instance, in LIBs, nanostructured anode and cathode materials provide short diffusion paths, large surface area, and can accommodate volumetric changes during charge/discharge process [19]. The synthesis of nanostructured materials has been carried out by different chemical and physical methods such as hydrothermal growth, electrodeposition, chemical vapor deposition and sol—gel. In addition, some of these techniques are used for making composites such as the hydrothermal process has been reported for preparing composites of graphene with different oxides and/or sulfides, providing improved performance in supercapacitors and batteries. Since electrochemical energy storage strongly depends on surface reactions at the electrolyte/electrode interface, an alternate approach to enhance electrode material performance is to passivate the electrode surface with appropriate layers. These surface passivation layers can be deposited by numerous methods such as sol—gel method [20] or chemical vapor deposition technique [21]; however, these techniques lack precise control over layer thickness, surface coverage, uniformity of coating, and they often require high temperature.

In recent years, atomic layer deposition (ALD) has emerged as powerful technique to deposit conformal coatings of different materials with excellent thickness control and conformality by using sequential surface chemical reactions. The prime application for ALD has been microelectronics, however as the technology has matured significantly, it is being considered for a variety of applications such as solar cells and catalysts. The implementation of ALD in electrochemical energy storage devices is rather recent topic, but it is already showing promising results. In LIBs, for example, ALD has been used to fabricate electrochemically active electrode materials, to prepare composites of different electrode materials, to deposit solid state electrolyte, and to modify electrode/electrolyte interface.

In energy storage devices, ALD offers advantages such as conformal coatings of complex structures, uniformity over large surface area, excellent control over thickness of deposited layer, and making composite nanostructures. The unique coating mechanism of ALD facilitates the electrode surface engineering according to customized requirements. For instance, the deposition of thin layer on electrode/electrolyte interface ensures the ionic diffusion and compensates volumetric changes during charge/discharge process. In addition, complex 2D and 3D nanostructures can be fabricated with ease. These features make ALD a promising solution to the problems of next generation energy storage devices. One potential drawback of ALD could be the cost of the system operation and precursor materials. However, these costs should drop as ALD becomes more pervasive. Another potential drawback could be in conventional electrode making process, where binder and conductive carbon are added to the active cathode or anode material. The multicomponent nature of such electrodes affect the uniformity of the ALD coating process. Another potential compromise is that the ALD process is inherently slow, so thick coatings such as solid-state electrolytes will require significantly more time than other deposition processes. Hence, in this article, we briefly review the ALD technique and its recent application in Li ion batteries, Li sulfur batteries, Li oxygen batteries, Na ion batteries and supercapacitors. We have categorized the ALD's application based on the function of the deposited ALD layer. Further, our review focuses on studies that have provided mechanistic insight into the role of ALD coatings, and provides overview of the future directions and prospects of this emerging topic in energy storage.

Atomic layer deposition — Overview

Atomic layer deposition (ALD) is a vapor-phase deposition technique, first proposed by Suntola and Antson in 1970 [22]. Initially, the application of ALD was limited to the semiconductor industry for synthesis of Group III-V and II-VI compounds [23,24]. However, in recent years, ALD has shown promise in various emerging fields such as solar cells and energy storage devices.

Although alternative methods such as chemical vapor deposition (CVD), physical vapor deposition (PVD) and electrodeposition can be used to deposit coatings for electrochemical devices fabrication, they are not as versatile as ALD. For instance, electrodeposition requires very conducting surfaces to deposit coatings, while ALD can coat conducting and non-conducting surfaces. Furthermore, unlike CVD and PVD, ALD is a surface controlled process where film growth is controlled by self-terminating gas-solid