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Feasibility of building a 3D battery by using triblock copolymer

Yijie Wang

University College London, Department of Chemistry, London, WC1E 6BT

zccayw3@ucl.ac.uk

Abstract. Three-dimensional battery designs have emerged as a novel technique to powering micro electromechanical systems and other autonomous devices. These sources of power have the ability to achieve high power density and high energy density while occupying a compact area, despite the fact that there are still less fully functional three-dimensional batteries to date. This article examines the proposed architectures for three-dimensional batteries and the fabrication process of components made for these devices, as well as remaining technical obstacles. Also, defining guidelines for design for three-dimensional architectures and modelling sheds light on the achievable energy density and current uniformity of these architectures. Considerable advances in electrodes and electrolytes fabrication progress for three-dimensional batteries suggest that considerable battery technologies will be demonstrated successfully in the future.

Keywords: 3D batteries, battery architecture, 3D electrode, solid electrolyte, lithium batteries

1. Introduction

In the global attempt to move away from carbon-based fuels, electrochemical energy storage using batteries and electrochemical capacitors is crucial. It is commonly known that electrochemical power sources must be improved in order to satisfy expectations in the future, even though current electrochemical technologies are suitable for energy storage applications like powering portable devices [1]. Three-dimensional (3D) battery architectures to powering microelectromechanical assemblies as well as small autonomous devices have emerged as an innovative path. Despite the fact that there are now just a few completely functional 3D batteries, these power sources can deliver high energy density and power density in a small footprint.

Certain operational features of 3D batteries that are not possible with traditional 2D geometries are what make them attractive. One of the most significant benefits is the potential to increase areal capacity (mAh cm-2) within a specific footprint area by increasing the height of the 3D electrode and so adding more active material [2]. Without affecting the ion transport distances between electrodes, this design feature can be used. As a result, it is possible to increase areal capacity beyond the limit of the conventional 2D electrodes used in thin-film batteries without reducing power density. Certain geometries can effectively decouple the areal energy density (mWh cm-2) from the power density (mA cm-2) by independently altering the aspect ratio and distance between electrodes.

Building 3D electrode designs and modelling both voltage and current in nonplanar geometries have made significant advances in addition to improving the development of 3D batteries, as will be covered in the following section. The foundation for the technology's forseeable future is provided by 3D integration of the functional components (anode, electrolyte, and cathode), which is informed by modelling.

2. Current engineering challenge and alternative approach

Many conventional 2D battery geometries share a common characteristic: they are flat. A Li-ion cell consists of stacked layers, similar to a polarized sandwich. Each end contains a current collector, commonly aluminum foil on the positive end and copper foil on the negative end. Next in line are the electrodes, which consist of the negative anode and positive cathode. In the center is a separator soaked in an electrolyte solution. In order to achieve high capacities, conventional battery designs alongside 2D dimensions require expansive footprint areas. Thin-film lithium-ion batteries, for instance, have restricted areal capacities around 0.5 mAhcm−2. Increasing the thickness of the electrodes to store more energy is not a practical strategy because the mechanical integrity of the film degrades with thickness (due to the expansion and contraction of the active materials during cycling), and thicker films also limit the power density of the device [2]. As a result, energy density and power density are frequently compromised in 2D battery designs.

Height, the third dimension in a 3D battery architecture, can enhance the total amount of electrode material packed within a given footprint area, improving the areal capability; these batteries are anticipated to achieve close to 10 mAhcm-2 [3]. Instead of stacking flat sheets on top of one another, 3D batteries connect like Lego bricks. This may be accomplished in a few ways, but the simplest is the so-called interdigitated structure. A solid electrolyte surrounds an array of electrode rods that alternate between cathode and anode and are surrounded by an electrode array.

Energy and power density are two of the most significant qualities of any battery, where energy density indicates the amount of energy that can be stored, and power density explains how rapidly the battery can charge and discharge. Introducing the dimension of height enables one to increase the amount of electrode material without sacrificing the effective space between electrodes, hence making it feasible to simultaneously attain a high energy and power density. By combining the electrodes and electrolytes in three dimensions, 3D batteries may distribute electrochemical reactions more uniformly. Solid polymer electrolytes are expected to eradicate safety concerns (e.g., flammability, leakage and explosion dangers) of liquid electrolytes, in addition to their superior processing performance. For instance, lithium-sulfur batteries struggle because the organic electrolyte's intermediate polysulfides dissolve, causing severe virus reactions on the surfaces of the lithium metal and poor lithium cycle performance [4]. Lithium-oxygen batteries have a difficulty with chemically unstable liquid electrolytes on the oxygen electrode, which restricts battery cycling [5].

3. Fundamental principles that used to solve the challenge

In batteries, energy is preserved through the ion-mediated chemical redox reactions that take place as the ions move back and forth between them during charge and discharges; and the amount of energy stored is inversely correlated with the mass and volume of the active anode and cathode materials. The rate at which this energy is accessible, which is limited in the vast majority of electric energy storage devices by the diffusion and reactions of ions within solid electrode materials, determines the amount of battery power that can be produced. In nanostructured battery layouts, the close proximity of the two electrodes is helpful for fast ion diffusion, and at the same time, a high material input allows for a high energy density [6]. Ionic diffusion has become orders of magnitude faster in liquids than in solids, and the majority of lithium-ion batteries use a porous membrane infused with liquid electrolyte to transfer ions between composite electrodes. As mentioned above, the improvement of one has frequently had a negative impact on the other for 2D batteries.

Over the past two decades, a common method to boost the power capacities of batteries with faster charge and discharge has been to decrease the active aspect diameters of the materials and improve their porosity [7]. This reduces solid state diffusion distances. While the device's power output is significantly increased, the amount of active material per volume and surface area is decreased, which lowers the device's overall energy density. Thin-film batteries get overcome this problem by using micrometer-thin arrays of anode-electrolyte-cathode layers and solid electrolytes. Greater power densities at the expense of material and energy storage capacity result from shorter ion diffusion distances and smaller sheets. By including a third dimension, it is possible to keep all components close together for quick ion transport while also maximizing the amount of charge-storing material per footprint area. With short ion-diffusion distances and three-dimensional connections for electron transport, continuous networks of cathode, electrolyte, and anode folded in three dimensions would enhance structural integrity. Energy and power densities in these three-dimensional structures are separated at the device scale in accordance with the materials' respective storage and separation length-scales [8].

There are significant challenges in producing 3D batteries that are functional. Reactions at the electrode-electrolyte interface may have a considerable impact on cell performance as a whole because of the large surface area of 3D battery electrodes. Therefore, comparable events may result in changes in Li-ion transport through the electrolyte or possibly a breakdown in the dielectric characteristics because the solid electrolyte interphase is crucial for protecting the electrode/electrolyte interfaces from electrochemical deterioration. Additionally, short circuits and cell failure could be brought on by pinholes in the electrolyte. The separation of cathode and anode networks, which is necessary throughout the entire nanostructure to prevent short circuits that might render the entire device unworkable, is one of the protocols that must be addressed as a result [9]. While the electrolyte must offer ionic conductivity while preventing electronic contact between the interpenetrating cathode and anode, both electrode phases must be both electronically conductive and redox active. Finding a solvent that is compatible with the solid-state electrolyte and a suitable binder that depends on the solvent, ensuring that the solution remains homogeneous throughout the manufacturing process, and making sure that the cathode density of packing is high so that there are no voids in the 3D cell structure are all important considerations.

4. Advantages and limitations Engineering solution

4.1. *Structure category*

By incorporating block copolymer, the aforementioned issue might be fixed. A variety of self-assembling tri-block copolymers exhibit the three-dimensional network shape of 3D batteries. Triblock Copolymers are copolymers whose fundamental unit is composed of three block chains. The three polymers may be distinct, or they may be repeats. Consequently, based on their polymer structure, triblock copolymers can be classified as symmetric copolymers or asymmetric copolymers. Two different types of polymers—A, a hydrophobic polymer, and B, a hydrophilic polymer—are necessary for the synthesis of symmetric triblock copolymers like ABA and BAB. Three different polymer types are combined to form asymmetric triblock copolymers, or ABC triblock copolymers. Depending on the application, either can be made of hydrophilic or hydrophobic polymers [10]. In this article, we'll talk about an asymmetric ABC triblock copolymer with a lateral surface split that creates a third continuous matrix volume with shell and core separated by tens of nanometers. This concept features the anode, electrolyte, and cathode individually and provides a workable route to 3D batteries.

4.2. *Fabrication process*

Among these, block copolymers consisting of more than two domains with diverse chemical characteristics are regarded as an efficient method for introducing more ionic properties into a material while preserving the polymer's desirable mechanical properties. Take an example, the hydrophobic A block functions as a nonconducting domain, whereas the hydrophilic C block functions as a conducting domain. The crosslinking process utilises a middle B block. Thus, block copolymers with distinct characteristics may be easily fabricated by substituting functional monomers.

According to the previous listing, the 3D cell structure must be absent of voids (in the range of tens of microns) and the cathode packing density must be high. However, vacant areas and insufficient packing density may lead to a mismatch in capacity and a decline in cell performance as the resistance to electron and ion transport increases. Chemically speaking, voids can be reduced by adding additives to the electrolyte in order to achieve void-free filling because of the special structures of triblock copolymers. Metal filling would profit from enhanced inhibitory capability, like ethylene oxide (EO) - propylene oxide (PO) - ethylene oxide (EO) [11]. However, the dynamic via filling technique was next examined along with 0.002 g/L EPE at 0.3 ASD, while the "V shape" filling was obtained. It was found that a high concentration of EPE would generate micelles in the electrolyte, creating a lower capacity to inhibit. The impact of ultrasonic agitation on the efficiency of EPE filling was then investigated. Under identical plating conditions, ultrasonic agitation may boost the TSV filling ratio and has even been successful in achieving bottom-up filling [12]. This might be the result of ultrasonic cavitation, which boosts mass transfer and causes continual desorption of the additive for the electrodes.

4.3. Technical improvement

Furthermore, it is possible to achieve the high cathode packing density. Type A-B-A Triblock copolymer is an effective solid-state electrolyte membrane-sealing material that can be used to seal the cathode and stop active components from leaking. Triblock copolymer-based membranes can also offer a variety of useful physical and chemical characteristics, such as strong ionic conductivity close to room temperature, good chemical stability against lithium metal, and good chemical stability against moisture and air [13,14].

Besides, mixing lithium salts with solvating polymers is the most typical way to provide mobile lithium ions to a polymer electrolyte system. The choice of the salt/polymer combinations is often made based on a variety of variables, including the degree of dissociation, the degree of polymer salt complexation, and the thermal and electrochemical stabilities of the salt/polymer mixture. More salts (mobile ions) can enter the framework when there is significant complexation between the lithium salt and the polymer, but more free ions can enter the framework when there is significant dissociation. The interaction of two lithium salts with anionic polymers with a dissociation degree was examined by Bannister et al. They found that lithium salts produced from stronger acids had greater conductivities in polymer electrolytes. By restricting the quantity of mobile cations, a strong ion-pairing interaction between cations and weak acids may, on the other hand, lower conductivity. The creation of nanostructured fillers is necessary to boost the conductivity of polymer composite electrolytes because of the increased surface area of the amorphous region and the increased interaction between polymers and nanostructured fillers [15].

5. Conclusion

The drive to develop 3D batteries is presumably stronger now than it was ten years ago. A 3D battery architecture can increase power and energy density within a specific footprint area by adding a third dimension. In order to overcome the functional challenges of 3D batteries, triblock polymer could be used to partition a real surface into a third continuous matrix volume with shell and core separated by tens of nanometers. The Internet of Things has made it painfully evident that 2D batteries have not kept up with the shrinking of electrical parts. For point-of-load and on-chip applications, miniature mobile power sources have not yet been created, and in many situations, the power sources for sensors and communications are still much larger than the target device itself. These reasons have kept the promise of achieving high energy and high power in a compact (1 cm2) footprint area as a development and research goal. The study field of 3D batteries is still in its development. Many 3D battery architectures and supporting design principles have been discovered to ensure that high power densities and energy may be attained within a compact footprint area. There have been many different methods for making electrodes and related syntheses, and in many cases, the superior electrochemical performance of the materials they produce indicates a promising future. The challenges that still need to be resolved are pore volume in general and electrode inclusion inside the battery assembly. Yet, there is a significant demand for batteries with a little environmental impact, and 3D designs cost a lot but have good energy and power densities. Whether any of the approaches are adaptable and advantageous for more vehicle and grid storage usage is an intriguing subject.

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