Composite Nanofibers as Advanced Materials for Li-ion, Li-O₂ and Li-S Batteries

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Abstract The quest to increase the energy density and improve the cycle life performance of lithium ion batteries (LIBs) and beyond has led to the development of various suitable and alternative materials for energy storage and conversion. The morphology and electrode architecture in advanced battery materials have been re-designed into nanofibers and composite nanofibers. Nanofiber-based separators and electrodes have been demonstrated to improve the energy density and cycling performance of LIBs. The improvement in the structure and morphology of nanofibers in Lithium ion batteries such as LiSi and LiSn, have once again ignited the interest in these Li:M alloys anode as an alternative anode and cathode materials. The major challenges that confront this new frontier has been the seemingly lack of scalable method among the various techniques and design nanofibers with good structure and morphology that could prevent dendrite penetrations. However, there seem to be a solution in sight with the advent of mass production techniques of nanofibers by electrospinning and centrifugal spinning (i.e. Forcespinning®) that have recently been developed. In this paper, the use of nanofibers and composite nanofibers as electrode and separator materials for lithium ion, Li-O₂ and Li sulfur batteries is reviewed. The discussion focuses on the performance characteristics of these nanostructured electrode and separator materials and methods used to improve their performances.

Keywords: Lithium ion batteries, Nanofibers, Electrode, Separator, Li Sulfur batteries, Li air batteries

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1. Introduction

The use of nanostructured materials for energy storage devices has been the trend in recent years. Nanostructured fibers made from metals, metal oxides, polymers, ceramics, and composites have been developed for use in various energy storage devices such as high-performance rechargeable lithium (Li) batteries (e.g. Li-ion, Li-sulfur, and Li-air batteries), sodium (Na) , magnesium (Mg), aluminum (Al) and zinc (Zn) batteries and supercapacitors[1-18]. The popularity of these nanofibers stem from the many attributes such as; controllable fiber diameter, high surface area-to-volume ratio, low density, and high pore volume [6, 19-21]. These properties make the nanofiber structure more advantageous when used in LIBs as they deliver a superior electrochemical properties; stable cycle performance, enhanced capacity, superior low temperature performance [21-24], compared to their powder, crystal, nanowire, thin film, etc. counterparts[25-29]. The sterling properties/performance of nanofibers have seen their wide applications in lithium ion batteries (as electrode and separators materials), supercapacitors, and chemical sensors [30-33]. There are several methods employed to produce these nanofibers, with the most common include; electrostatic charge (electrospinning),external heated air jets (melt-blowing), bicomponent fiber spinning, phase separation, template synthesis, self-assembly, chemical vapor deposition, wet chemical synthesis, Nozzle-Free centrifugal or rotary jet-spinning, and the emerging Forcespinning method [34-43].

Non-woven fibrous mats that have high surface area are typically in the range of a few micron to about 200 nm in diameter. Many efforts have been made to further reduce the fiber diameter into

the nano scale [44]. This has been demonstrated through methods such as electrospinning, centrifugal spinning, and Forcespinning® (Fig.1a) that can produce fibrous mats of thickness of 10-20µm with fiber diameters that are typically less than 5µm [36, 38, 45-48]. These fiber processing methods have been successful in giving the nanofibers their high labyrinth-like pores structure. The simplicity, high efficiency, low cost, high reproducibility, comparatively environmentally benign, and the ability to scale up for mass production of these methods have significantly increased their applicability [35, 46, 49]. There is considerable work on the use of structured composite nanofibers with high surface and interfacial areas to improve the performance of electrodes and separators in lithium ion batteries [1, 2, 4, 6, 10, 25, 50-53]. While there are several topics discussed in this article on the application of structured nanofibers, the main thrust of this review is to discuss the use of nanofibrous structure materials as electrodes and separators and their electrochemical performance in the lithium ion batteries.

2. Nanofibers (NFs) Production Techniques

Non-woven fibrous mats are typically thick (i.e. 100–200µm), however, in effort to reduce this thickness, recent fiber manufacturing technology such as electrospinning(Fig.1b), centrifugal jet spinning, and Forcespinning® have emerged as promising methods to produce fibers with thickness of 10-20 µm and diameters that are typically less than 5µm [54-60]. These fiber processing methods have been successful in giving the non-woven nanofiber mat their high labyrinth-like pores structure [57]. Presently the most commonly used methods for making these nanofibers employ either an electrostatic charge (electrospinning) [57, 61-63] or external heated air jets (melt-blowing) bicomponent fiber spinning, phase separation, template synthesis, and

self-assembly [64-69]. These methods are often complex and for the past decade they have been used only to make nanofibers from limited types of polymers, often lab-scale in nature.

Electrospinning is also by far the method of choice for producing nanofibers (NFs), however it faces several drawbacks such as high electric fields requirement, solutions with better dielectric properties, and many other safety related issues. Many polymeric materials can be electrospun into fibers; however, electrospinning may not be suitable for mass production of certain materials and faces several restrictions regarding safety, especially for melt electrospinning where a high current is applied to the melt to form the fibers followed by stretching, structuring and cooling [48, 70-76]. However, the large scale production challenge of electrospinning is set to see an end in sight, with Jiangxi Advanced Nanofiber Technology Co., Ltd mass producing polyimide nanofiber separators for advanced lithium-ion in a scale of 3000 m²/day [patent is available at: <http://www.faqs.org/patents/app/20130164629>]. Forcespinning (FS) has been used to prepare fibers from a wide range of materials due to the fact that FS can produce fibers from melt and solutions without the need of applying an electric field during processing. Furthermore, the FS method has proven to be suitable for mass production of nanofibers for biomedical, energy storage, defense and aerospace-related-applications [39, 55, 77-80]. In the FS method (Fig.1a), the electric field used in the electrospinning process is replaced by centrifugal forces to overcome the polymer/material surface tension and therefore stretching the fibers [38, 39, 77, 81-84].

The production of NFs by a FS lab scale system is higher than 60 grams/hr which is much higher than the yield obtained by electrospinning (approximately i.e. 0.1 grams/hour) [46, 85]. Several NFs systems and polymer composites have been recently produced by the FS system [38, 77, 82-84, 86]. In these NFs systems, the fibers were produced with average fiber diameters in the nano

to submicron range. In this category, there is another method known as the centrifugal spinning, which has some similarities with the Forcespinning method. The in-house built centrifugal spinning system has been used quite extensively to produce nanofiber for biomedical, energy storage, and other electronics applications [43, 80]. The in-house built centrifugal system was specifically designed to produce fibers at the lab scale in a similar manner to the FS and centrifugal systems [43, 46, 60, 85, 87]. However, the in-house built centrifugal spinning system is limited for the production of micro and nano fibers at high rotational speed and it has no capability at this time for melt spinning. [88-91]. It is worthwhile to note here that the centrifugal spinning method was originally developed by Hooper back in 1924 to produce artificial silk threads from viscose or equivalent substances by applying centrifugal forces to a viscous material [87]. Hence, this method has been used in fiber production since it was introduced first time by Hooper in the beginning of the 19th century.

The Forcespinning technique on the other hand, has several features such as a fiber management system that allow tunable fiber deposition to ensure accurate cross directional coating uniformity, and also adaptable to substrate web widths. In addition, the FS system has the capability for dual materials feed thus allowing the continuous materials feed system especially for melt and solution processing with no material dielectric requirements[46]. The system (i.e. FS) has an almost 100% yield and solvent-free processing for melt spinning with melt temperatures up to 350°C. This thus eliminates the direct operating expense and environmental burdens.

3. Carbon Nanofiber (CNFs) anodes

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4 Recently, there has been an extensive research activities focusing on the development of
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6 nanostructured anode materials in the view of enhancing the capacity, energy density and
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8 specific power of rechargeable lithium-ion batteries [92-97]. In nanofiber processing such as
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10 electrospinning and Forcespinning, a polymer precursor is usually used to produce nanofibers
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12 that will be transformed into carbon nanofibers after different thermal treatments (carbonization).
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14 The produced carbon nanofiber mats can be very often brittle. This can be avoided by carrying
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16 out a stabilization process in air (i.e. oxidative stabilization) on the polymer nanofiber precursor
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18 prior to carbonization. The yield of carbon nanofibers depends on several factors including the
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20 polymer-type used during nanofiber spinning. In general, the behavior of polymeric materials is
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22 time, temperature and pressure dependent [98-100], therefore, the nanofiber morphology and
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24 structure are significantly dependent on the polymer concentration and the chemical structure of
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26 the polymer used to prepare the nanofiber precursor.
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34 Carbon nano fibers (CNFs) have been widely used as anode material to replace commercial
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36 graphite particles for LIBs [23, 101-104]. Graphitized stacked-cup carbon nanofiber, highly
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38 porous CNFs, and ultra-long thin align carbon fibers have been produced by electrospinning as
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40 alternate anode materials [25, 28, 105-108]. Carbon nanofibers can be prepared by carbonization
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42 of different types of precursor polymer nanofibers, such as polyacrylonitrile (PAN), polyimide
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44 (PI), and pitch [52, 77, 109]. The carbonization temperature can be adjusted to control the carbon
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46 crystalline structure and, hence, the electrochemical properties of carbon nanofibers.
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52 The CNFs produced from these precursors have smaller diameters and larger surface area to
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54 volume ratio [23, 101, 103]. A typical morphology and structure of the CNFs produced though
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56 the Forcespinning technique is shown in Figure 3. A large amount of defects in CNFs such as
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58 lattice and surface defects along the fiber length are expected to promote fast Li intercalation/de-
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intercalation. These physical properties of the CNFs promote fast ion transport, high accessibility of electrolyte, and shortens the Li^+ /electron diffusion path that is often attributed to the large surface area of nanofibers and their large pore volume [23, 102]. There is often a correlation between these physical properties of CNFs with the electrochemical performance of CNFs-based electrode in lithium ion batteries.

Several studies report a specific reversible capacity between $400\text{-}600\text{ mAhg}^{-1}$ and excellent cycling performance after 50 cycles for CNFs anodes [31, 101-103]. Comparatively, the electrochemical performance of CNFs anodes is much better than that for commercial graphite anode with a theoretical capacity of 372mAhg^{-1} . However, the loose structure of these nanofibers result in a low tap density, thus most of CNFs materials do not show much advantage compared to graphite anode (~ 10 micron in particle size) when based on the volumetric energy density of the electrode. In fact, the graphite is so far the best anode material to use in commercial LIBs due to its long cycle life, low cost and good capacity retention, even after hundreds of charge/discharge cycles, though its charge/discharge capacity is lower than ceramic composite nanofibers. There is no other anode materials that can compete with graphite at this time, although extensive research has been carried out to improve the performance and cycle stability of Si/C or Sn/C composite anodes. Theoretically, Si or Sn based anodes give a high capacity and might replace graphite anode in commercial LIBs in 50 years or so. This needs more work and effort to be done to improve the cycle stability and capacity retention of Si/C composite NF anodes. The apparent good electrochemical performance of CNFs anode has often been the driving force for the huge interest among researchers. However, often the carbon nanofiber mats produced using some of these common techniques are not flexible after the carbonization process. It is therefore a common practice to grind the brittle CNFs with conductive carbon black

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4 to increase conductivity and adding binding agents to produce a slurry for the electrode making
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6 process [5, 71, 110-112]. The grinding of the rather uniform nanofiber compromises the fibrous
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8 nature of the nanofiber and its intended purpose. Another challenge of CNFs is the low fiber
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10 yield (i.e. 0.1 grams/hr for electrospinning) produced by most of the techniques, thus limiting the
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12 scaling up production of these CNFs [71, 112-119]. There is however an end in sight for the low
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14 fiber yield challenge with the recent introduction of Forcespinning into the nanofiber production
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16 techniques mix. The Forcespinning has the capability of producing fiber yield greater than 60
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18 grams/hr, less expensive process, and environmentally safer [38, 46, 77] compared to
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20 electrospinning.
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26 The successes of CNFs and their associated electrochemical performance have boosted the
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28 research in the area of lithium alloys-based electrodes for lithium ion batteries. Several research
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30 activities have been reported on composite electrodes comprising various metals and metal
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32 oxides and CNFs as electrode and separators for LIBs [107, 109, 120-126]. It is still early for
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34 these composite nanofibers to be used as electrodes in commercial lithium ion batteries. The
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36 loose structure of composite nanofibers itself, is an undesired property for lithium ion batteries
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38 due the low tap density. The ensuing discussion will focus on the use of CNFs as separators and
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40 electrodes for lithium ion batteries. Generally, the capacity and energy density of lithium ion
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42 batteries depend largely on the cathode material capacity. However, noticeable improvement of
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44 the overall capacity and energy density of the cell is often observed when using an alternate
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46 anode material having a capacity of the order of $1000 \text{ mA}g^{-1}$ which is much higher than that of
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48 carbonaceous electrode ($372 \text{ mA}Hg^{-1}$) material.
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56 The driving force for such a replacement of a carbonaceous material lie in the fact that the
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58 potential of the anode vs Li/Li^+ should be close to 0V and not necessarily an intercalation type of
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electrochemical reaction as pertaining in the graphite anode. Alloying Li^+ with several viable metals and metal oxides such as Si, SiO_2 , Ge, Fe, Fe_2O_3 , Ag, Pb, Sn, SnO_2 etc. are potential candidates for use as anodes in LIBs [96, 113, 127, 128]. The Li_xM (where $\text{M} = \text{Sn, Si, Fe}_2\text{O}_3$, etc.) alloys show a much higher Li:M ratio at the end of the charge cycle therefore allowing a greater Li^+ accommodation. Therefore these lithium alloys have higher capacity and energy density than commercial graphite anode. However, the major challenge for these Li:M alloys is that they are known to degrade rapidly from their high theoretical specific capacity of 998-3600 mAhg^{-1} due to several factors including high volume change during the alloying/de-alloying process which can lead to pulverization and poor cyclability [129-131]. Nanofiber metal/metal oxides composite anodes have been an emerging trend where several research have employed metal/carbon composite nanofibers in a bid to either curb or minimize the high volumetric change of these Li: M alloys [5, 132, 133]. The fibrous structure of the nanofiber electrode provides ample room to accommodate the volume changes during the alloying/de-alloying process. We discuss below recent progress and development reported on the use of metal/CNFs as anodes for LIBs.

4. Lithium alloy-CNFs anode materials

Lithium alloys and carbonaceous materials are two classes of anode materials for lithium-ion batteries. Both materials have shortcomings (e.g., low charge capacity for carbon and low cycle life for lithium alloy) that limit the performance of lithium-ion batteries. Metal and metal oxide/carbon nanostructured composite such as Sn/CNFs , Si/CNFs , SiO_2/CNFs , SnO_2/CNFs , TiO_2/CNFs and Ferriferous oxide/CNFs have been widely used as anodes for LIBs [1, 25, 134-137]. Some of these anodes are discussed in the following section.

4.1 Tin/Carbon composite nanofibers

Tin (Sn)-based derivatives such as tin oxides, tin sulfides, and stannates have become attractive anode materials for LIBs [5, 138-140]. The popularity of these Sn-based lithium alloys stem from their properties such as; the inhibition of solvent co-intercalation and significant improvement in performance over the commercial graphite anode in LIBs [112, 115, 141-143]. In addition, Sn/carbon composite nanofibers have been studied for use as anodes in LIBs because they are easy to process and they exhibit lower potential hysteresis compared to other transition metal oxides [144]. Sn/CNFs composite are capable of hosting a higher amount of lithium ions in tin crystal structure, i.e. about four (4) atoms (i.e. Li_xSn , $0 < X \leq 4.4$) compared to carbonaceous anode (i.e. Li_xC_6 , $0 < X \leq 1$) thereby giving Sn/C composite a higher lithium storage capacity.

Sn/carbon composite nanofibers show excellent reversible capacity and cyclic performance, even at a higher current rate of 200 mAg^{-1} to 1 Ag^{-1} [5, 138, 139]. This performance has been found to depend largely on the carbonization temperature which tend to have a direct impact on the fiber morphology, structure and the pore distribution [5, 139], as shown in Figure 3. There are varying reports on the influence of Sn particles size on the overall composite Sn/CNFs electrode performance. While some of these anodes show a higher reversible capacity with a Sn particle size in the nano range ($>5\text{nm}$) [102, 137], other studies reported no significant difference in the particle size influence on electrochemical performance [145-147]. A smaller particle size largely will generally offer a higher surface area and aspect ratio, which offer the electrode more reactive sites for electrochemical reaction, however nano-size particles are equally prone to agglomeration which could affect their uniform dispersion in the polymer matrix.

4.1.1 Sn/C composite nanofibers

Ternary composites of Sn/CNFs incorporating or containing other metals and their oxides have been designed to further improve the conductivity, the cyclic and rate performance of LIBs. SnO₂/ZnO heterogeneous nanofiber [104, 148], Nitrogen doped CNFs with quantum dots Sn [123], Co-Sn alloy carbon nanofibers[149], and Fe₃O₄/SnO₂ coaxial nanofibers [150] have been investigated. The N-doped Sn/CNF's for instance, provides fast and versatile electrolyte transport and acts as efficient electron transport pathways and stable mechanical support for keeping the structural integrity of the electrodes during cycling and preventing pulverization of the composite electrode [123], while the Cobalt in the Sn/CNFs minimizes the volume expansion and enhances the electrical conductivity of the electrode [149, 151]. The electrochemical performance of Sn and its composite derivatives (Figure 4) shows a very remarkable cyclic performance when they are used as Sn/CNFs composite electrode. These composites still show a remarkable capacity retention at high current densities (Fig. 5). The CNFs/ Sn based composite electrode can inevitably reduce the volume change (i.e. > 260%) that result from alloying/de-alloying processes that sometimes lead to particle isolation and disconnectivity between the electrical conductive particles during cycling (i.e. charge/discharge process). Although Sn/CNFs-based composites are considered good alternative anodes for LIBs, their inconsistent cycle performance and their structural instability is hindering their practical applications in rechargeable batteries. Additionally, Tin by itself is expensive compared to carbon which is in abundance and can be derived from either petroleum based products or as a derivative of many polymers.

4.2. Si/Carbon composite nanofibers

Silicon is considered as a good candidate to use as anode material in lithium-ion batteries due to its high specific capacity and low discharge potentials. A fully lithiated Si- Li (i.e. $\text{Li}_{21}\text{Si}_5$) alloy has a large theoretical $\sim 4100 \text{ mAhg}^{-1}$ which is 10 time greater than that of the graphite. However, the many associated problems of the LiSi-based cells such as; large irreversible capacity at room temperature [2, 6, 7, 152-154] and poor cyclability[3, 155] that is often attributed to low electronic conductivity and the large volume change ($>300\%$) during lithium insertion/de-insertion process. This volume change impacts negatively on the Si crystal structure, inducing stresses in Si lattice and thus leading to cracks formation and pulverization of the Si particles. Various approaches have been developed to minimize the drawbacks of LiSi anodes , these include better morphological design [156], synthesis of single-phase LiSi by highly energetic ball-milling [29] using impregnating Silicon nanoparticle assemblies in templated carbon-bridged oriented graphene[157], Coating copper on a nano columnar silicon anodes [158], and creating nanosheets of silicon-based electrode by topochemical reaction synthesis [159]. These approaches and techniques help mitigate the drastic reduction of the LiSi anode capacity, but are not sufficient to maintain a good capacity retention and cycle life [160, 161].

4.2.1 Si/C composite nanofiber anode

Si/CNFs binary composite electrodes [6, 162, 163] from nanostructured metal/ oxide namely: Ge, SnO_2 , MnO_x , iron oxides, and TiO_2 [22, 164, 165] have been developed to improve the electrochemical performances of LiSi electrode. In the Si/metal binary alloys composites [26, 27, 165-170], the metal/metal oxides act as the unlithiated part of the composite alloy thereby forming a framework that prevents the pulverization of the Si particles[6], improve stability and

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4 electrochemical performance of the LiSi electrode. Some of these binary Si/metal/CNFs have
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6 been widely reported to delivered a discharge capacity of 1000 mA h g⁻¹ over 200 cycles [3, 167,
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8 171-181](Fig.4). The carbon nanofiber in the matrix acts as a buffer for the volume change and
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10 improves the electronic conductivity of the electrode. [6, 7, 182-186]. The Si/CNFs
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12 nanostructures can suppress volume changes since the pores act as the structure buffer for the
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14 large volume changes during cycling, and hence help maintain the high specific capacity and
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16 cycle performance of the electrode above 1500mAhg⁻¹ over several cycles [3, 7, 22, 163, 167].
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18 Although nanostructured Si/CNFs anodes and their composites have improved electrochemical
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20 performance, several problems need to be solved including; dispersion of Si nanoparticles in the
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22 carbon matrix, high production cost usually associated with the price of silicon as the based
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24 material. More work needs to be done to address these issues.
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35 **4.3 Ferriferous oxide /Carbon nanofibers anode**

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38 Ferriferous oxides (Fe₃O₄)/CNFs are the other class of promising alternative materials that have
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40 been widely investigated as anodes [9, 25, 33, 150, 187-192]. Ferriferous oxides typically have
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42 higher theoretical specific capacity of about 924 mAh/g, relatively inexpensive and environment
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44 friendly (non-toxic) [193-195]. However, similar to Si, Ti, and Sn, the bare Fe₂O₃ and Fe₃O₄
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46 have low conductivity and prone to structural pulverization and loss of electrical connection due
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48 to large volume changes during lithiation/delithiation, resulting in the poor rapid capacity
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50 retention during long-term cycling [9, 21, 33, 188, 193]. To overcome these drawbacks of Fe₃O₄
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52 anodes, carbon nanofibers have been employed as matrix to prepare Fe₃O₄/CNFs composites.
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54 These Fe₃O₄/CNFs composites have improved electrochemical properties (Figure 4 and Figure
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56 5.) due to the excellent electrical conductivity of the carbon nanofibers [33, 189, 192, 196]. The
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structure of the $\text{Fe}_3\text{O}_4/\text{CNFs}$, which are either honey-comb like carbon core and Fe shell or hollow [150, 197, 198], 3D nano- Fe_3O_4 , [191], or hollow $\alpha\text{-LiFeO}_2$ [196], as shown in Figure 6.

These ferriferrous structure gives the composite electrode improved low temperature performance largely on the account of the fast electron kinetics [33, 189] and the stability of the porous CNF and its buffering effect [191, 196, 198]. Other metals like Mg, Ni, and Zn [9, 21, 190, 197] have been used as binary alloy with Ferriferrous oxides along with CNFs ostensible to improve the electrochemical performance of the composite electrode. Typically the specific capacity for these binary composites are in the range of 500 mAhg^{-1} to 700 mAhg^{-1} , which is not essentially better than those reported for $\text{Fe}_3\text{O}_4/\text{CNFs}$ composite anodes (Fig.7), that have capacities 500 mAhg^{-1} - 1225 mAhg^{-1} even [25, 150, 188, 193, 194] at higher current densities (i.e. 1 A/g) [188, 191, 192, 196, 198], as shown in Figure 5. These metals in the binary alloy of the ferriferrous also acts as a buffer layer that accommodates the large volume changes and reduced polarization [21, 190, 197] and ostensibly enhancing the kinetics and mass transfer at the electrode interface. The major challenge with the use of these ferriferrous oxide electrode is how to simultaneously design and fabricate composites of Fe_2O_3 combined with CNFs. An improved fabrication technique is highly desirable since these class of alternative anode electrode are highly desired, especially for low temperature performance.

5. Lithium metal oxide-CNFs cathode materials

Electrospinning has been extensively used to produce nanofiber composite cathodes from different precursors such as spinel structured materials; LiMn_2O_4 , LiMPO_4 [199-201], LiFePO_4 and Vanadium oxide layered compounds [202-204]. Although LiMn_2O_4 is inexpensive and safer than LiCoO_2 , it has a lower capacity as compared to other cathode materials that form $\alpha\text{-NaFeO}_2$

structure [205-208]. This high capacity is mostly attributed to phase changes that occur during cycling [209-213]. Vanadium based cathode on the other hand, have high capacities but relatively low voltages (i.e. $\leq 3\text{V}$) compared to cathode compounds such as LiCoO_2 and LiMn_2O_4 [202, 204, 214]. The fibrous composite electrode of $\text{V}_2\text{O}_5/\text{CNFs}$ and $\text{LiMnO}_4/\text{CNFs}$ usually form a one dimensional (1D) nanostructure (Fig. 8). The characteristics of these 1D structured materials is their large surface areas that provides an effective diffusion pathways for both Li ions and electrons. The fast electron transfer rate and the large number of electroactive sites provided by these 1D nanofiber structured cathodes ostensibly improved the electrochemical performance [199, 200, 202, 214]. Typically, these nanofibrous cathode materials show an impressive specific capacity in the range of $240\text{-}300\text{ mAhg}^{-1}$ which are much better than those typically used in commercial LIB (Fig.7). The synthesis of cathode materials into carbon nanofiber structure is relatively new yet promising. The challenge with the synthesis of these cathode/CNFs materials is balancing concentration of polymer-gel solution and cathode material. The right amount of the polymer plays a critical role in maintaining the fiber-structure[215], while the cathode materials determines the electrochemical properties of the composite electrode. Therefore more work needs to be done to addresses these pertinent issues.

5.1. Composite nanofibers for Li/S battery cathode

Lithium-sulfur batteries have attracted much attention and are considered as good candidates for alternative energy storage systems, largely on account of their ultra-high capacity, high theoretical specific power and energy density, easiness in handling and processing, and environmentally benign [216-223]. A Li-S battery consists of a Li metal anode, an organic electrolyte and a sulfur composite cathode (porous), wherein S (existing as S_8) undergoes a series

of electrochemical reactions to give Li sulfide (Li_2S) with each S atom accepting two lithium atoms [216, 217]. The application of composite nanofibers have been investigated severally as an alternative means to improve the microstructure of the cathode electrode in Li/S batteries. The advantage of using these carbon nanofibers with sulfur as cathode for Li/S stem from their unique structure; porous/ hollow structures, and high specific surface area. These properties of the carbon nanofiber-sulfur based cathodes form ideal inter wound reservoir-like matrices that accommodate active sulfur [123, 153, 224-240], while the porous structure ideally confine/trap the active sulfur and its soluble polysulfides, which can greatly reduce the shuttle effect. In addition, the carbon nanofibers improve the mechanical/ structural integrity of the composite electrode as well as the conductivity, [232, 233, 238] that further enhances electrons/ Li^+ transfer and improves sulfur utilization in Li-S batteries [123, 153, 224-240] and by extension, improves the batteries electrochemical performance. The challenge however, on the use of these carbon nanofiber-sulfur-based cathodes in Li-S batteries is the inconsistency of the fiber surface area, particularly those produced by electrospinning [225, 226, 241, 242]. A relatively small surface area and a large pore volume size can lead to sulfur being exposed outside the porous structure, which can cause serious polysulfide dissolutions at prolonged battery cycling. Additionally, notwithstanding the fact that the microstructure of these carbon nanofibers provide porous / robust conductive networks, compared to graphite (~10 micron in particle size), their surface area and pore volumes are much lower, which can limited the amount sulfur loading in the electrode. To countenance these challenges, several morphologies and electrode architectures have been designed including hollow carbon nanofiber-encapsulated sulfur[243], amphiphilic surface modification of hollow carbon nanofibers[244], highly mineralized chitin-protein fibers as biotemplates [245], bimodal mesoporous carbon nanofibers[246], impregnation of

microporous activated carbon fibers with elemental melted sulfur (ACF-S), infiltration sulfur into a microporous CNFs/CNTs composite[237], functionalization of nitrogen-doped porous carbon nanofiber/sulfur composites [247, 248] and hollow carbon nanofiber hybrid nanostructure anchored with titanium dioxide (HCNF@TiO₂) [239] (Fig.9). All these electrode architectures and designs are either aimed at improving the crystal structure of the sulfur hosting composite electrode [249, 250], minimizing sulfur dissolution, increase specific capacity or energy density (Fig. 10), reduce cost, or to improve safety of Li-S batteries [12, 244-246, 251-254]. On the separator front for Li-S batteries, there is surprisingly not much attention or interest compared to the active dynamics of cathode research. The few that exist focus on the modification of existing polypropylene and polyethylene commercial separators. Nonwoven PVdF- nanofibers, nanofibers from ceramic precursors have been coated on the mono layer of PP and PE Celgard separators in a bit to inhibit the diffusion of polysulfide and its intermediates onto the anode in order reduce the shuttle effects on Li-S battery performance [255-258]. The subtle absence of wholly nonwoven nanofiber separators from polymeric materials is due partly to their low strength and loose and open structure that might compound the plating of sulfur products on the Li metal anode from sulfur dissolution (shuttle effect).

5.2. Composite nanofibers for Li-air battery cathodes

There are very few publications that explore the use of composite nanofibers as cathode material for Li-air batteries. The most common Li-air cathode material designed with carbon is Co₃O₄ [227, 259, 260] and few reports on RuO₂/CNFs, α MnO₂/CNFs[15, 261-265]. The motivation for the use of carbon nanofibers as against carbon has been the higher surface area as well as the higher pores volume that carbon nanofibers present [266],[15]. The porosity and 3-phase

structure of air-cathode is one key and critical determining factor for the Li-air battery electrochemical performance (Fig. 11). The higher pore volume and surface area of a typical composite NFs Li-Air cathode, increase the contact area of the electrode/electrolyte interface while the pores provides a high diffusion path for both ions and oxygen necessary for the electrochemical reaction to form species such as Li_2O_2 and Li_2O [259, 262, 264, 265]. These composite nanofiber cathodes record an impressive electrochemical performance over several cycles far better than the commercial RuO_2 , Co_3O_4 , and αMnO_2 Li-Air cathode [15, 260-264, 267] as shown in a typical electrochemical performance plots of composite CNFs electrode for Li-Air battery in Figure 12. The downside, however of the open structure of the carbon nanofibers tends to decrease the conductivity due to occasional discontinuity in the electrical path. This challenge, notwithstanding, the pore structure provides room for the precipitation of insoluble Li_2O_2 species and insulating it from further access of reactants products such as O_2 and Li^+ [259, 260]. The high capacity of the Li-Air batteries chemistry has been established to directly depend on the presence and amount Li_2O_2 in the cathode structure [227]. Nanofibers as cathode materials seem to be in its infancy and it expected to see a growing interest in the not distance future. Nanofibers and composite nanofibers mainly prepared by electrospinning have been also used in sodium ion batteries as cathodes and separators. The discussion of these NFs is beyond the scope of this review and we refer the reader to reference [13] for more details on the structure and performance of these composite NFs.

6. Polymeric Nanofiber Separators

The commonly used separators in lithium-ion batteries are the microporous membrane separators made from , polypropylene, polyethylene, polyvinylidene difluoride (PVdF) or PVdF-coated

microporous polyolefin separators [268-270]. Several companies such as Celgard, Asahi, Toray, Entek Membrane, Ube industries, DSM, etc. have been designed and developed commercial separators for the over \$4billion lithium ion batteries market [271], these mostly consist of polymer materials such as polyolefin microporous membranes developed by Celgard, DSM, and Asahi and a tri-layer of polypropylene/polyethylene/polypropylene from Celgard and Ube industries. High performance separators must have 1) more porosity, 2) safer to puncture and shorts, 3) higher melt stability, 4) thinner structure to allow for more active material, 5) very thin layer to allow for composite structures of ceramic coatings, 6) very thin and porous nonwoven to be filled with polymer electrolyte, 7) High thermal stability, and 8) lower cost for used in hybrid vehicles automobile [268, 270, 271]. However, several studies [79, 270, 272-276] have pointed to these polymer-based battery separators to have less impressive key performance indices such as: high interface resistance, low thermal stability, and low electrolyte uptake. The severe thermal shrinkage of polyolefin separators can cause serious internal electrical short circuit leading to a fire disaster or battery explosion when the cells are exposed to abnormal operating conditions. Some battery separator producers such as Celgard Inc., have made several improvement to its polypropylene (PP) mono layer polymer separator by designing a three layer separator comprising of the polypropylene/ polyethylene / polypropylene (i.e. PP/PE/PP) thereby improving the deficiency of its mono layer separators Celgard [35, 36, 38, 49, 52, 68, 77]. Nonetheless, the performance of the non-woven nanofibers separators are gradually being considered better alternatives.

6.1 Nonwoven fibrous polymer separators

Lithium ion battery separators most often are classified into three categories; microporous membranes, non-woven mats and inorganic composite membrane separators. In all, they are usually characterized by their thinness, excellent thermal stability and the high porosity that gives them their ion transport characteristics [37, 54-57, 61-63, 277-284]. The increasing vulnerability of the lithium battery to thermal runaway requires a separator with greater mechanical integrity above 130°C [285, 286] to provide a greater margin of safety to the battery. The nonwoven nanofiber separator membrane fibers have shown to be much better stability in the redox environment compared to other polymeric based separators[287] (Fig. 13). The nonwoven category such as cellulosic fibers, PVdF, ceramic fibers, nanocomposite polymer have been extensively studied. The PVdF itself has been extensively used as a polymer electrolyte [288-293] by virtue of its appealing electrochemical properties. Generally, the PVdF based polymer electrolytes are anodically stable in the redox environment in the lithium ion battery due partly to the strong electron-withdrawing of the C-F functional groups on the polymer backbone [294, 295]. The PVdF category of nonwoven nanofiber separators show improved electrochemical performance relative to the commonly used polypropylene/ polyethylene (i.e. PP/PE) polymeric separators (Fig.14). In the same vein, the cellulosic fibers have never been used successfully in commercial (mostly in laboratory cells) lithium batteries due to their hygroscopic nature of cellulosic papers and films, their tendency to degrade in contact with lithium metal, and their susceptibility to pinhole formation at thicknesses of about 100 µm [54, 65, 277-279]. This notwithstanding, the cellulosic separators still maintain some level of research interest due largely to the various morphologies of the cellulose membrane (Fig.15) that offer stability at higher temperatures compared to separators made of polyolefin or can be coupled

with the other polymeric separator materials with low melting properties as a polymeric laminate material [277, 278].

The non-woven fibrous mats, despite their remarkable properties, have less mechanical strength compared to their PP counterparts[296] and are also yet to be used in commercial lithium ion batteries as separators. The drawback in their application is often attributed to their open structure and their rough surface which cannot effectively prevent micro short circuits and dendrites penetration [278], but mainly used in other battery chemistries such as alkaline batteries such as nickel–cadmium and nickel–metal–hydride batteries. In lithium ion batteries, these non-woven fiber mats are widely used as supporting framework architecture to make gel power electrolyte due largely to their high porosity and large pore size [35, 52] as shown in Figure 15 and 16.

6.2. Improvement Trends

6.2.1 Coating separators with ceramic particles

As many researchers identified the short coming of these microporous polymer separators, has paved the way for many research efforts geared towards improving especially the mono layer PP separator for lithium ion batteries, while very viable alternative separators materials are sought. Ceramic coatings such as TiO_2 are deposited on the Tri-layer polymeric separator [270], Al_2O_3 and hydrophilic poly(lithium-4-styrenesulfonate) onto the porous polyethylene membrane [276], and SiO_2 coating on polyethylene [297, 298]. These ceramic coating on the polymeric separator not only afford the separator its dimensional stability, but they also improve the porous structure of the separator that allow higher ion transport to improve ionic conductivity and low inner resistance [54, 299].

6.2.2 Coating separators with polymer nanofiber (NFs)

The mono layer polypropylene separator has also been improved using various polymer coatings such as polymers and polymer NFs coatings. Among these polymers include the use of poly(vinylidene fluoride-co-hexafluoropropylene), and poly(ethyleneglycol) dimethacrylate (PVDF-HFP) to modify the monolayer polypropylene separator (Fig.17.) [35, 36, 49, 52, 273, 299], ethylcellulose and a thermally stable and renewable biomass materials also used on the tri-layer (i.e. PP/PE/PP) polymer separator [65]. These coated polymers improve the Celgard mono layer PP separator qualities by acting as pores multipliers, improving the close niche nanofibrous structure and thus significantly reducing the thermal shrinkage of the separator, and improving the electrolyte uptake and its adhesion to the electrode[47, 300, 301]. To improve both the thermal, ionic conductivity, and interfacial properties with lithium electrodes of these nonwoven fibrous separator mat, inert ceramic oxides fillers such as silicon dioxide (SiO_2), titanium dioxide (TiO_2) and alumina (Al_2O_3) are generally incorporated into the base polymer matrix [54, 298, 302-306]. The enhancement in the electrochemical properties of these nanocomposite separators is generally attributed to the decrease of the polymer crystallinity in the presence of these nanoparticles and the interactions of the ceramic particles with the Lewis-acids in the electrolyte[279]. However, they are often not suitable for high-rate performance and cycle performance class of lithium ion batteries due to their nano-porous structure (Fig. 15&16) and the flow property of gel polymer electrolytes at high temperatures [305, 307].

For lithium-ion battery applications, microporous polyolefin membranes, and non-woven composite membrane separators should have the ability to absorb and retain electrolyte in order to transport lithium ions between the anode and cathode. Unique techniques such as self-assembly and atomic layer deposition have employed to prepare advanced separators from

polymeric materials for used in lithium-ion batteries. Inadvertently, all these techniques have their drawbacks, hence additional work is needed for the continual development of new separator structures to meet the high performance and energy density of advanced secondary batteries. More details on the discussion of these techniques and methods reported on the current challenges and prospects of electrospun nanofibers used in advanced secondary batteries can be found in these two references [308, 309]

7. Conclusions

The development of improved energy storage materials has often been a challenge in meeting the current and future energy requirement. Re-designing the architecture of these materials into nanofiber from various techniques have received attention. Various lithium batteries components; electrodes and separators in particular have been produced with nanofiber structure that showed remarkable electrochemical performance. The findings from the various CNFs electrode and separator point to a revolution in the energy materials with higher energy density and longer cycle life. The major challenges that confront this new frontier is the seemingly lack of scalable method among the various techniques used to make these nanofibers. Most of these methods are lab scale in nature, thus making the commercialization of this new developed materials an illusion. However, there could be an end in sight for this problem with the coming on stream of the forspinning and electrospinning method with the capability to mass produce nanofibers with good fiber yield from variety of materials. The labyrinth structure of the nanofibers also pose new challenge specially for separator materials as pin-hole size in the

materials could be a major headache as these can lead to dendrite penetration leading to an old problem of battery thermal runaway from electrode short circuits. These drawbacks notwithstanding, the nanofiber revolution hold a great promise to the energy storage industry.

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Figure Caption:

Figure 1a: A pictorial view of the Forcespinning machine and a schematic drawing of a typical setup inside the machine showing the collectors, the spinneret and the substrate/fan assembly for fiber production.

Figure 1b: A schematic drawing of nanofiber making process using electrospinning. Reproduced with permission from Journal of Materials Science [51].

Figure 2: A typical Pictorial view of the As-forcespun Sn/PAN precursor nanofiber (a) and the carbonized Sn/C at 800°C for 3hrs (b).

Figure 3: SEM micrographs showing the morphology of the baseline as forcespun PAN fibers (a) and the carbonized PAN CNFs (b), the forcespun Sn/PAN fibers(c) and the Carbonized Sn/C nanofiber (d) nanofibers showing pores on the fibers strands.

Figure 4: A plot showing typical cycling performance of the base CNFs electrode, Sn/CNFs composite electrode and Si/CNFs composite electrode cells. Si/CNFs anodes show capacity fading because of the volume change.

Figure 5: Rate performance of Sn/C, SnO₂/C, and Fe₂O₃/C composite electrode cycled between 0.01- 3.0V vs Li/Li⁺

Figure 6: SEM micrograph of a typical (a) Fe₃O₄/PAN/PS precursor fibers and cross-section of the nanofiber showing the pore structure and hollowness of the finished of Fe₃O₄/CNFs.[182] Reproduced with permission from Carbon.

Figure 7: A plot showing typical cycling performance of the ferriferrous oxide/carbon nanofibers composite electrode and cathode materials cells.

Figure 8: SEM images (a) as-spun LiFePO_4 precursor/PAN nanofibers (b) ASL-PAN after 300°C heat treatment, (c) LiFePO_4/C composite nanofibers after calcination at 800°C , and (d) high magnification of the region marked with a square in (c)[214]. Reproduced with permission from the Int. J. Electrochem. Sci.

Figure 9: SEM images of hollow carbon nanofiber-Sulfur composite electrode (a,b) [222], Nitrogen doped carbon nanofiber web/sulfur composite electrode (c)[247] and CNFs with sulfur coating(d) [230]. Reproduced with permission from Power Sources, Electrochimica Acta and Nano Lett.

Figure 10: A typical plots showing the effect of CNFs/S microstructure [247] on cell performance (a) and the rate capability of these of the S-CNF nanocomposite with (G-S-CNFs) composite electrodes [230] (b). Reproduced with permission from Nano. Lett. and Electrochimica Acta .

Figure 11: Microstructure of mesoporous silica coated carbon nanofibers (a,b) [15] and mesoporous flower-like cobalt oxide/carbon nanofiber composites with shell–core structure (c,d) [264] composite electrodes for Li-Air batteries. Reproduced with permission from Applied Surf. Sci. and Carbon

Figure 12: A typical electrochemical discharge/charge curves at a current density of 100 mA g^{-1} (a) and rate performance at varying current densities (b) from 200 mA g^{-1} to 1000 mA g^{-1} of CNFs/ RuO_2 composite Li-Air electrode[4]. Reproduced with permission from J.Power Sources

Figure 13: A plots showing a comparison of the stability of the separator in the redox environment from the cellulose, PAN nanofiber membrane and some polymeric materials like PP and tri-layer of PP/PE.

Figure 14: A plot showing typical cycling performance of the base Cellulose, PAN, PVdF and modified PP/PE coated separators for use in lithium ion batteries.

Figure 15: Various morphologies of nanofiber cellulose membrane separator mats for use in the lithium ion batteries.

Figure 16: A typical SEM micrographs showing fibrous separator made from PAN membrane showing a fiber average diameter of $<2\mu\text{m}$ with fibers with a lot of pores on the fiber strands.

Figure 17: SEM images of uncoated (a, c) Monolayer polypropylene (PP) separator, (b, d) Monolayer PP coated with PVDF-co-CTFE and PVDF-co-HFP. Reproduced with permission from Journal of Solid State Electrochemistry [49]

References

1. Fang, S., L. Shen, Z. Tong, H. Zheng, F. Zhang, and X. Zhang, *Si nanoparticles encapsulated in elastic hollow carbon fibres for Li-ion battery anodes with high structural stability*. *Nanoscale*, 2015. **7**(16): p. 7409-7414.10.1039/c5nr00132c
2. Feng, J., Z. Zhang, L. Ci, W. Zhai, Q. Ai, and S. Xiong, *Chemical dealloying synthesis of porous silicon anchored by in situ generated graphene sheets as anode material for lithium-ion batteries*. *Journal of Power Sources*, 2015. **287**: p. 177-183.10.1016/j.jpowsour.2015.04.051
3. Gomez-Camer, J.L., H. Thuv, and P. Novak, *Electrochemical study of Si/C composites with particulate and fibrous morphology as negative electrodes for lithium-ion batteries*. *Journal of Power Sources*, 2015. **294**: p. 128-135.10.1016/j.jpowsour.2015.06.067
4. Guo, Z., D. Zhou, H. Liu, X. Dong, S. Yuan, A. Yu, Y. Wang, and Y. Xia, *Synthesis of ruthenium oxide coated ordered mesoporous carbon nanofiber arrays as a catalyst for lithium oxygen battery*. *Journal of Power Sources*, 2015. **276**: p. 181-188.10.1016/j.jpowsour.2014.11.145
5. Jiang, H., Y. Ge, K. Fu, Y. Lu, C. Chen, J. Zhu, M. Dirican, and X. Zhang, *Centrifugally-spun tin-containing carbon nanofibers as anode material for lithium-ion batteries*. *Journal of Materials Science*, 2015. **50**(3): p. 1094-1102.10.1007/s10853-014-8666-5
6. Kim, H., X. Huang, Z. Wen, S. Cui, X. Guo, and J. Chen, *Novel hybrid Si film/carbon nanofibers as anode materials in lithium-ion batteries*. *Journal of Materials Chemistry A*, 2015. **3**(5): p. 1947-1952.10.1039/c4ta05804f
7. Kim, H., Y. Son, C. Park, M.-J. Lee, M. Hong, J. Kim, M. Lee, J. Cho, and H.C. Choi, *Germanium Silicon Alloy Anode Material Capable of Tunable Overpotential by Nanoscale Si Segregation*. *Nano letters*, 2015. **15**(6): p. 4135-4142.10.1021/acs.nanolett.5b01257
8. Kim, Y.-J., H. Lee, D.J. Lee, J.-K. Park, and H.-T. Kim, *Reduction of Charge and Discharge Polarization by Cobalt Nanoparticles-Embedded Carbon Nanofibers for Li-O₂ Batteries*. *ChemSusChem*, 2015. **8**(15): p. 2422-2422.10.1002/cssc.201500924
9. Kong, J., X. Yao, Y. Wei, C. Zhao, J.M. Ang, and X. Lu, *Polydopamine-derived porous nanofibers as host of ZnFe₂O₄ nanoneedles: towards high-performance anodes for lithium-ion batteries*. *Rsc Advances*, 2015. **5**(18): p. 13315-13323.10.1039/c4ra16460a
10. Lee, H.-G., A.-I. Gopalan, G. Sai-Anand, B.-C. Lee, S.-W. Kang, and K.-P. Lee, *Facile synthesis of functionalized graphene-palladium nanoparticle incorporated multicomponent TiO₂ composite nanofibers*. *Materials Chemistry and Physics*, 2015. **154**: p. 125-136.10.1016/j.matchemphys.2015.01.055
11. Park, S.H. and W.J. Lee, *Coaxial carbon nanofiber/NiO core-shell nanocables as anodes for lithium ion batteries*. *Rsc Advances*, 2015. **5**(30): p. 23548-23555.10.1039/c4ra15147j
12. Wu, Y.Z., C.V.R. Bobba, and S. Ramakrishna, *Research and Application of Carbon Nanofiber and Nanocomposites via Electrospinning Technique in Energy Conversion Systems*. *Current Organic Chemistry*, 2013. **17**(13): p. 1411-1423
13. Wang, H.G., S. Yuan, D.L. Ma, X.B. Zhang, and J.M. Yan, *Electrospun materials for lithium and sodium rechargeable batteries: from structure evolution to electrochemical performance*. *Energy & Environmental Science*, 2015. **8**(6): p. 1660-1681.10.1039/c4ee03912b
14. Luo, L., Y.Q. Fei, K. Chen, D.W. Li, X. Wang, Q.Q. Wang, Q.F. Wei, and H. Qiao, *Facile synthesis of one-dimensional zinc vanadate nanofibers for high lithium storage anode material*. *Journal of Alloys and Compounds*, 2015. **649**: p. 1019-1024.10.1016/j.jallcom.2015.07.265
15. Song, M.J. and M.W. Shin, *Fabrication and characterization of carbon nanofiber@mesoporous carbon core-shell composite for the Li-air battery*. *Applied Surface Science*, 2014. **320**: p. 435-440.<http://dx.doi.org/10.1016/j.apsusc.2014.09.100>

16. Gao, D.W., L.L. Wang, C.X. Wang, and Q.F. Wei, *Electrospinning of Porous Carbon Nanocomposites for Supercapacitor*. *Fibers and Polymers*, 2015. **16**(2): p. 421-425.10.1007/s12221-015-0421-2
17. He, Y.T., L.X. Wang, D.Z. Jia, and H.Y. Zhao, *Coal-based Carbon Nanofibers Prepared by Electrospinning for Supercapacitor*. *Chemical Journal of Chinese Universities-Chinese*, 2015. **36**(1): p. 157-164.10.7503/cjcu20140455
18. Xiong, X., W. Luo, X. Hu, C. Chen, L. Qie, D. Hou, and Y. Huang, *Flexible Membranes of MoS₂/C Nanofibers by Electrospinning as Binder-Free Anodes for High-Performance Sodium-Ion Batteries*. *Scientific Reports*, 2015. **5**.925410.1038/srep09254
19. Aravindan, V., J. Sundaramurthy, P.S. Kumar, Y.-S. Lee, S. Ramakrishna, and S. Madhavi, *Electrospun nanofibers: A prospective electro-active material for constructing high performance Li-ion batteries*. *Chemical Communications*, 2015. **51**(12): p. 2225-2234.10.1039/c4cc07824a
20. Koo, J.B., B.Y. Jang, S.S. Kim, K.S. Han, D.H. Jung, and S.H. Yoon, *Physical mixtures of Si nanoparticles and carbon nanofibers as anode materials for lithium-ion batteries*. *Japanese Journal of Applied Physics*, 2015. **54**(8).08500110.7567/jjap.54.085001
21. Luo, L., R. Cui, K. Liu, H. Qiao, and Q. Wei, *Electrospun preparation and lithium storage properties of NiFe₂O₄ nanofibers*. *Ionics*, 2015. **21**(3): p. 687-694.10.1007/s11581-014-1213-1
22. McCormac, K., I. Byrd, R. Brannen, B. Seymour, J. Li, and J. Wu, *Preparation of porous Si and TiO₂ nanofibres using a sulphur-templating method for lithium storage*. *Physica Status Solidi a-Applications and Materials Science*, 2015. **212**(4): p. 877-881.10.1002/pssa.201431834
23. Peng, Y.-T. and C.-T. Lo, *Effect of Microstructure and Morphology of Electrospun Ultra-Small Carbon Nanofibers on Anode Performances for Lithium Ion Batteries*. *Journal of the Electrochemical Society*, 2015. **162**(6): p. A1085-A1093.10.1149/2.0061507jes
24. Shi, X., W. Zhou, D. Ma, Q. Ma, D. Bridges, Y. Ma, and A. Hu, *Electrospinning of Nanofibers and Their Applications for Energy Devices*. *Journal of Nanomaterials*, 2015.14071610.1155/2015/140716
25. Cho, J.S., Y.J. Hong, and Y.C. Kang, *Design and Synthesis of Bubble-Nanorod-Structured Fe₂O₃-Carbon Nanofibers as Advanced Anode Material for Li-Ion Batteries*. *Acs Nano*, 2015. **9**(4): p. 4026-4035.10.1021/acs.nano.5b00088
26. Jing, S., H. Jiang, Y. Hu, J. Shen, and C. Li, *Face-to-Face Contact and Open-Void Coinvolved Si/C Nanohybrids Lithium-Ion Battery Anodes with Extremely Long Cycle Life*. *Advanced Functional Materials*, 2015. **25**(33): p. 5395-5401.10.1002/adfm.201502330
27. Zhang, J., Y. Liang, Q. Zhou, Y. Peng, and H. Yang, *Enhancing electrochemical properties of silicon-graphite anodes by the introduction of cobalt for lithium-ion batteries*. *Journal of Power Sources*, 2015. **290**: p. 71-79.10.1016/j.jpowsour.2015.05.003
28. Li, B., S. Yang, S. Li, B. Wang, and J. Liu, *From Commercial Sponge Toward 3D Graphene-Silicon Networks for Superior Lithium Storage*. *Advanced Energy Materials*, 2015. **5**(15).150028910.1002/aenm.201500289
29. Tang, W.S., J.N. Chotard, and R. Janot, *Synthesis of Single-Phase LiSi by Ball-Milling: Electrochemical Behavior and Hydrogenation Properties*. *Journal of the Electrochemical Society*, 2013. **160**(8): p. A1232-A1240.10.1149/2.089308jes
30. Xu, S., K. Kan, Y. Yang, C. Jiang, J. Gao, L. Jing, P. Shen, L. Li, and K. Shi, *Enhanced NH₃ gas sensing performance based on electrospun alkaline-earth metals composited SnO₂ nanofibers*. *Journal of Alloys and Compounds*, 2015. **618**: p. 240-247.10.1016/j.jallcom.2014.08.153

31. Kumar, P.S., J. Sundaramurthy, S. Sundarrajan, V.J. Babu, G. Singh, S.I. Allakhverdiev, and S. Ramakrishna, *Hierarchical electrospun nanofibers for energy harvesting, production and environmental remediation*. Energy & Environmental Science, 2014. **7**(10): p. 3192-3222.10.1039/c4ee00612g
32. Lee, J.-H., A. Katoch, S.-W. Choi, J.-H. Kim, H.W. Kim, and S.S. Kim, *Extraordinary Improvement of Gas-Sensing Performances in SnO₂ Nanofibers Due to Creation of Local p-n Heterojunctions by Loading Reduced Graphene Oxide Nanosheets*. ACS Applied Materials & Interfaces, 2015. **7**(5): p. 3101-3109.10.1021/am5071656
33. Li, M., Y. Xiong, X. Liu, X. Bo, Y. Zhang, C. Han, and L. Guo, *Facile synthesis of electrospun MFe₂O₄ (M = Co, Ni, Cu, Mn) spinel nanofibers with excellent electrocatalytic properties for oxygen evolution and hydrogen peroxide reduction*. Nanoscale, 2015. **7**(19): p. 8920-8930.10.1039/c4nr07243j
34. Garcia, E., Q. Li, X. Sun, K. Lozano, and Y. Mao, *TiO₂ Fibers: Tunable Polymorphic Phase Transformation and Electrochemical Properties*. Journal of Nanoscience and Nanotechnology, 2015. **15**(5): p. 3750-3756.10.1166/jnn.2015.9545
35. Lee, H., M. Alcoutlabi, J.V. Watson, and X.W. Zhang, *Electrospun nanofiber-coated separator membranes for lithium-ion rechargeable batteries*. Journal of Applied Polymer Science, 2013. **129**(4): p. 1939-1951.10.1002/app.38894
36. Lee, H., M. Alcoutlabi, J.V. Watson, and X.W. Zhang, *Polyvinylidene fluoride-co-chlorotrifluoroethylene and polyvinylidene fluoride-co-hexafluoropropylene nanofiber-coated polypropylene microporous battery separator membranes*. Journal of Polymer Science Part B: Polymer Physics, 2013. **51**(5): p. 349-357.10.1002/polb.23216
37. Nunes-Pereira, J., C.M. Costa, R. Leones, M.M. Silva, and S. Lanceros-Mendez, *Li-ion battery separator membranes based on poly(vinylidene fluoride-trifluoroethylene)/carbon nanotube composites*. Solid State Ionics, 2013. **249**: p. 63-71.Doi 10.1016/j.ssi.2013.07.021
38. Weng, B.C., F.H. Xu, M. Alcoutlabi, Y.B. Mao, and K. Lozano, *Fibrous cellulose membrane mass produced via forcespinning(A (R)) for lithium-ion battery separators*. Cellulose, 2015. **22**(2): p. 1311-1320.10.1007/s10570-015-0564-8
39. Weng, B.C., F.H. Xu, and K. Lozano, *Mass Production of Carbon Nanotube- Reinforced Polyacrylonitrile Fine Composite Fibers*. Journal of Applied Polymer Science, 2014. **131**(11).Artn 40302Doi 10.1002/App.40302
40. Weitz, R.T., L. Harnau, S. Rauschenbach, M. Burghard, and K. Kern, *Polymer nanofibers via nozzle-free centrifugal spinning*. Nano Letters, 2008. **8**(4): p. 1187-1191.10.1021/nl080124q
41. Loordhuswamy, A.M., V.R. Krishnaswamy, P.S. Korrapati, S. Thinakaran, and G.D.V. Rengaswami, *Fabrication of highly aligned fibrous scaffolds for tissue regeneration by centrifugal spinning technology*. Materials Science & Engineering C-Materials for Biological Applications, 2014. **42**: p. 799-807.10.1016/j.msec.2014.06.011
42. Xu, H.Z., H.H. Chen, X.L. Li, C. Liu, and B. Yang, *A Comparative Study of Jet Formation in Nozzle- and Nozzle-Less Centrifugal Spinning Systems*. Journal of Polymer Science Part B-Polymer Physics, 2014. **52**(23): p. 1547-1559.10.1002/polb.23596
43. Badrossamay, M.R., H.A. McIlwee, J.A. Goss, and K.K. Parker, *Nanofiber Assembly by Rotary Jet-Spinning*. Nano Letters, 2010. **10**(6): p. 2257-2261.10.1021/nl101355x
44. Alcoutlabi, M. and G.B. McKenna, *Effects of confinement on material behaviour at the nanometre size scale*. Journal of Physics-Condensed Matter, 2005. **17**(15): p. R461-R524.Doi 10.1088/0953-8984/17/15/R01

45. Ron, L.Y. and S.P. Kotha, *Centrifugal jet spinning for highly efficient and large-scale fabrication of barium titanate nanofibers*. Materials Letters, 2014. **117**: p. 153-157.DOI 10.1016/j.matlet.2013.11.103
46. Sarkar, K., C. Gomez, S. Zambrano, M. Ramirez, E. de Hoyos, H. Vasquez, and K. Lozano, *Electrospinning to Forcespinning™*. Materials Today, 2010. **13**(11): p. 12-14.[http://dx.doi.org/10.1016/S1369-7021\(10\)70199-1](http://dx.doi.org/10.1016/S1369-7021(10)70199-1)
47. Zhang, J.Q., S.Q. Chen, X.Q. Xie, K. Kretschmer, X.D. Huang, B. Sun, and G.X. Wang, *Porous poly(vinylidene fluoride-co-hexafluoropropylene) polymer membrane with sandwich-like architecture for highly safe lithium ion batteries*. Journal of Membrane Science, 2014. **472**: p. 133-140.10.1016/j.memsci.2014.08.049
48. Zhang, X. and Y. Lu, *Centrifugal Spinning: An Alternative Approach to Fabricate Nanofibers at High Speed and Low Cost*. Polymer Reviews, 2014. **54**(4): p. 677-701.10.1080/15583724.2014.935858
49. Lee, H., M. Alcoutlabi, O. Toprakci, G.J. Xu, J.V. Watson, and X.W. Zhang, *Preparation and characterization of electrospun nanofiber-coated membrane separators for lithium-ion batteries*. Journal of Solid State Electrochemistry, 2014. **18**(9): p. 2451-2458.10.1007/s10008-014-2501-4
50. Klankowski, S.A., G.P. Pandey, B.A. Cruden, J. Liu, J. Wu, R.A. Rojas, and J. Li, *Anomalous capacity increase at high-rates in lithium-ion battery anodes based on silicon-coated vertically aligned carbon nanofibers*. Journal of Power Sources, 2015. **276**: p. 73-79.10.1016/j.jpowsour.2014.11.094
51. Alcoutlabi, M., L.W. Ji, B.K. Guo, S.L. Li, Y. Li, S. Zhang, O. Toprakci, and X.W. Zhang, *Electrospun Nanofibers for Energy Storage*. Aatcc Review, 2011. **11**(6): p. 45-51
52. Alcoutlabi, M., H. Lee, J.V. Watson, and X.W. Zhang, *Preparation and properties of nanofiber-coated composite membranes as battery separators via electrospinning*. Journal of Materials Science, 2013. **48**(6): p. 2690-2700.10.1007/s10853-012-7064-0
53. Ji, L.W., Z. Lin, M. Alcoutlabi, and X.W. Zhang, *Recent developments in nanostructured anode materials for rechargeable lithium-ion batteries*. Energy & Environmental Science, 2011. **4**(8): p. 2682-2699.10.1039/c0ee00699h
54. Kim, Y.J., C.H. Ahn, M.B. Lee, and M.S. Choi, *Characteristics of electrospun PVDF/SiO₂ composite nanofiber membranes as polymer electrolyte*. Materials Chemistry and Physics, 2011. **127**(1-2): p. 137-142.DOI 10.1016/j.matchemphys.2011.01.046
55. Yanilmaz, M., Y. Lu, Y. Li, and X.W. Zhang, *SiO₂/polyacrylonitrile membranes via centrifugal spinning as a separator for Li-ion batteries*. Journal of Power Sources, 2015. **273**: p. 1114-1119.DOI 10.1016/j.jpowsour.2014.10.015
56. Kim, Y.J., H.S. Kim, C.H. Doh, S.H. Kim, and S.M. Lee, *Technological potential and issues of polyacrylonitrile based nanofiber non-woven separator for Li-ion rechargeable batteries*. Journal of Power Sources, 2013. **244**: p. 196-206.DOI 10.1016/j.jpowsour.2013.01.166
57. Khan, W.S., R. Asmatulu, V. Rodriguez, and M. Ceylan, *Enhancing thermal and ionic conductivities of electrospun PAN and PMMA nanofibers by graphene nanoflake additions for battery-separator applications*. International Journal of Energy Research, 2014. **38**(15): p. 2044-2051.Doi 10.1002/Er.3188
58. Lee, H., J. Yun, H. Choi, D. Kim, and H. Byun, *The preparation of primary battery separator using polyamide nonwoven and nanofiber*. Applied Energy Technology, Pts 1 and 2, 2013. **724-725**: p. 1079-1082.DOI 10.4028/www.scientific.net/AMR.724-725.1079
59. Ren, L.Y., R. Ozisik, S.P. Kotha, and P.T. Underhill, *Highly Efficient Fabrication of Polymer Nanofiber Assembly by Centrifugal Jet Spinning: Process and Characterization*. Macromolecules, 2015. **48**(8): p. 2593-2602.10.1021/acs.macromol.5b00292

60. Golecki, H.M., H.Y. Yuan, C. Glavin, B. Potter, M.R. Badrossamay, J.A. Goss, M.D. Phillips, and K.K. Parker, *Effect of Solvent Evaporation on Fiber Morphology in Rotary Jet Spinning*. Langmuir, 2014. **30**(44): p. 13369-13374.10.1021/la5023104
61. Lee, J.H., J. Manuel, H. Choi, W.H. Park, and J.-H. Ahn, *Partially oxidized polyacrylonitrile nanofibrous membrane as a thermally stable separator for lithium ion batteries*. Polymer, (0).<http://dx.doi.org/10.1016/j.polymer.2015.04.055>
62. Raghavan, P., J. Manuel, X. Zhao, D.S. Kim, J.H. Ahn, and C. Nah, *Preparation and electrochemical characterization of gel polymer electrolyte based on electrospun polyacrylonitrile nonwoven membranes for lithium batteries*. Journal of Power Sources, 2011. **196**(16): p. 6742-6749.DOI 10.1016/j.jpowsour.2010.10.089
63. Subramania, A., N.T.K. Sundaram, A.R.S. Priya, and G.V. Kumar, *Preparation of a novel composite micro-porous polymer electrolyte membrane for high performance Li-ion battery*. Journal of Membrane Science, 2007. **294**(1-2): p. 8-15.10.1016/j.memsci.2007.01.025
64. Zhou, X.H., L.P. Yue, J.J. Zhang, Q.S. Kong, Z.H. Liu, J.H. Yao, and G.L. Cui, *A Core-Shell Structured Polysulfonamide-Based Composite Nonwoven Towards High Power Lithium Ion Battery Separator*. Journal of the Electrochemical Society, 2013. **160**(9): p. A1341-A1347.Doi 10.1149/2.003309jes
65. Sohn, J.Y., J.S. Im, S.J. Gwon, J.H. Choi, J. Shin, and Y.C. Nho, *Preparation and characterization of a PVDF-HFP/PEGDMA-coated PE separator for lithium-ion polymer battery by electron beam irradiation*. Radiation Physics and Chemistry, 2009. **78**(7-8): p. 505-508.DOI 10.1016/j.radphyschem.2009.03.035
66. Sohn, J.Y., J.S. Im, J. Shin, and Y.C. Nho, *PVDF-HFP/PMMA-coated PE separator for lithium ion battery*. Journal of Solid State Electrochemistry, 2012. **16**(2): p. 551-556.DOI 10.1007/s10008-011-1379-7
67. Aravindan, V., J. Sundaramurthy, P.S. Kumar, N. Shubha, W.C. Ling, S. Ramakrishna, and S. Madhavi, *A novel strategy to construct high performance lithium-ion cells using one dimensional electrospun nanofibers, electrodes and separators*. Nanoscale, 2013. **5**(21): p. 10636-10645.10.1039/c3nr04486f
68. Liang, Y.Z., L.W. Ji, B.K. Guo, Z. Lin, Y.F. Yao, Y. Li, M. Alcoutlabi, Y.P. Qiu, and X.W. Zhang, *Preparation and electrochemical characterization of ionic-conducting lithium lanthanum titanate oxide/polyacrylonitrile submicron composite fiber-based lithium-ion battery separators*. Journal of Power Sources, 2011. **196**(1): p. 436-441.10.1016/j.jpowsour.2010.06.088
69. Cao, C.Y., L. Tan, W.W. Liu, J.Q. Ma, and L. Li, *Polydopamine coated electrospun poly(vinylidene fluoride) nanofibrous membrane as separator for lithium-ion batteries*. Journal of Power Sources, 2014. **248**: p. 224-229.DOI 10.1016/j.jpowsour.2013.09.027
70. Souza, M.A., J.E. Oliveira, E.S. Medeiros, G.M. Glenn, and L.H.C. Mattoso, *Controlled Release of Linalool Using Nanofibrous. Membranes of Poly(lactic acid) Obtained by Electrospinning and Solution Blow Spinning: A Comparative Study*. Journal of Nanoscience and Nanotechnology, 2015. **15**(8): p. 5628-5636.10.1166/jnn.2015.9692
71. Balogh, A., B. Farkas, K. Farago, A. Farkas, I. Wagner, I. Van Assche, G. Verreck, Z.K. Nagy, and G. Marosi, *Melt-Blown and Electrospun Drug-Loaded Polymer Fiber Mats for Dissolution Enhancement: A Comparative Study*. Journal of Pharmaceutical Sciences, 2015. **104**(5): p. 1767-1776.10.1002/jps.24399
72. Yao, Y.F., Z. Lin, Y. Li, M. Alcoutlabi, H. Hamouda, and X.W. Zhang, *Superacidic Electrospun Fiber-Nafion Hybrid Proton Exchange Membranes*. Advanced Energy Materials, 2011. **1**(6): p. 1133-1140.10.1002/aenm.201100435

73. Chen, W., Y. Liu, Y. Ma, J. Liu, and X. Liu, *Improved performance of PVdF-HFP/PI nanofiber membrane for lithium ion battery separator prepared by a bicomponent cross-electrospinning method*. Materials Letters, 2014. **133**: p. 67-70.10.1016/j.matlet.2014.06.163
74. Han, L., C. Lu, P. Chen, W. Qi, and Q. Yu, *The Effects OF in situ generated titanium dioxide on the mechanical and electrochemical properties of electrospun polyvinylidene fluoride seperator for lithium-ion battery*. Acta Polymerica Sinica, 2012(11): p. 1319-1325.10.3724/sp.j.1105.2012.12053
75. Sencadas, V., J.C. Rodriguez Hernandez, C. Ribeiro, J.L. Gomez Ribelles, and S. Lanceros-Mendez, *Poly(vinylidene fluoride) Electrospun Fibers for Electroactive Scaffold Applications: Influence of the Applied Voltage on Morphology and Polymorphism*, in *Advances in Material Design for Regenerative Medicine, Drug Delivery and Targeting/Imaging*, V.P. Shastri, et al., Editors. 2009. p. 203-208.
76. Tonurist, K., T. Thomberg, A. Jaenes, T. Romann, V. Sammelselg, and E. Lust, *Polymorphic Behavior and Morphology of Electrospun Poly(vinylidene Fluoride) Separator Materials for Non-aqueous Electrolyte Based Electric Double Layer Capacitors*. Batteries and Energy Technology (General Session) - 222nd Ecs Meeting/Prime 2012: In Honor of James Mcbreen, 2013. **50**(45): p. 49-58.10.1149/05045.0049ecst
77. Weng, B.C., F.H. Xu, G. Garza, M. Alcoutlabi, A. Salinas, and K. Lozano, *The Production of Carbon Nanotube Reinforced Poly(vinyl) Butyral Nanofibers by the Forcespinning (R) Method*. Polymer Engineering and Science, 2015. **55**(1): p. 81-87.10.1002/pen.23872
78. Weng, B.C., F.H. Xu, A. Salinas, and K. Lozano, *Mass production of carbon nanotube reinforced poly(methyl methacrylate) nonwoven nanofiber mats*. Carbon, 2014. **75**: p. 217-226.Doi 10.1016/j.carbon.2014.03.056
79. Yanilmaz, M., C. Chen, and X.W. Zhang, *Fabrication and Characterization of SiO₂/PVDF Composite Nanofiber-Coated PP Nonwoven Separators for Lithium-Ion Batteries*. Journal of Polymer Science Part B-Polymer Physics, 2013. **51**(23): p. 1719-1726.Doi 10.1002/Polb.23387
80. Yanilmaz, M. and X.W. Zhang, *Polymethylmethacrylate/Polyacrylonitrile Membranes via Centrifugal Spinning as Separator in Li-Ion Batteries*. Polymers, 2015. **7**(4): p. 629-643.Doi 10.3390/Polym7040629
81. Mihut, D.M., K. Lozano, and H. Foltz, *Fabrication and characterization of silver- and copper-coated Nylon 6 forspun nanofibers by thermal evaporation*. Journal of Vacuum Science & Technology A, 2014. **32**(6).Artn 061401Doi 10.1116/1.4896752
82. McEachin, Z. and K. Lozano, *Production and characterization of polycaprolactone nanofibers via forcespinning (TM) technology*. Journal of Applied Polymer Science, 2012. **126**(2): p. 473-479.Doi 10.1002/App.36843
83. Agubra, V.A., Zuniga, L. , De la Garza, D., Gallegos, L., Pokhrel, M., Alcoutlabi, M., *Forcespinning: A new method for the mass production of Sn/C composite nanofiber anodes for lithium ion batteries*. Solid State Ionics, 2015. **Accepted**
84. Agubra, V.A., D. De la Garza, L. Gallegos, and M. Alcoutlabi, *ForceSpinning of polyacrylonitrile for mass production of lithium-ion battery separators*. Journal of Applied Polymer Science, 2016. **133**(1).Artn 4284710.1002/App.42847
85. Sarkar, K.L.a.K., *inventors Super fine Fiber Creating Spinneret and Uses Thereof*, in *US Patent*, U.p. Office, Editor. 2009: USA
86. Padron, S., R. Patlan, J. Gutierrez, N. Santos, T. Eubanks, and K. Lozano, *Production and characterization of hybrid BEH-PPV/PEO conjugated polymer nanofibers by forcespinning (TM)*. Journal of Applied Polymer Science, 2012. **125**(5): p. 3610-3616.10.1002/app.36420
87. Hooper, J.P., *Centrifugal Spinneret*, in *US paptent* U.p. Office, Editor. 1924: USA

88. Khamforoush, M. and T. Asgari, *A Modified Electro-Centrifugal Spinning Method to Enhance the Production Rate of Highly Aligned Nanofiber*. Nano, 2015. **10**(2).Artn 1550016Doi 10.1142/S1793292015500162
89. Dabirian, F., S.A.H. Ravandi, and A.R. Pischevar, *Investigation of Parameters Affecting PAN Nanofiber Production Using Electrical and Centrifugal Forces as a Novel Method*. Current Nanoscience, 2010. **6**(5): p. 545-552
90. Dabirian, F., S.A.H. Ravandi, A.R. Pischevar, and R.A. Abuzade, *A comparative study of jet formation and nanofiber alignment in electrospinning and electrocentrifugal spinning systems*. Journal of Electrostatics, 2011. **69**(6): p. 540-546.Doi 10.1016/j.elstat.2011.07.006
91. Dabirian, F., S.A.H. Ravandi, and A.R. Pischevar, *The effects of operating parameters on the fabrication of polyacrylonitrile nanofibers in electro-centrifuge spinning*. Fibers and Polymers, 2013. **14**(9): p. 1497-1504.Doi 10.1007/s12221-013-1497-1
92. Aravindan, V., J. Sundaramurthy, E.N. Kumar, P.S. Kumar, W.C. Ling, R. von Hagen, S. Mathur, S. Ramakrishna, and S. Madhavi, *Does carbon coating really improves the electrochemical performance of electrospun SnO₂ anodes?* Electrochimica Acta, 2014. **121**(0): p. 109-115.<http://dx.doi.org/10.1016/j.electacta.2013.12.141>
93. Wang, W., Y. Xiao, X. Wang, B. Liu, and M. Cao, *In Situ Encapsulation of Germanium Clusters in Carbon Nanofibers: High-Performance Anodes for Lithium-Ion Batteries*. ChemSusChem, 2014. **7**(10): p. 2914-2922.10.1002/cssc.201402304
94. Liu, X., D. Teng, T. Li, Y. Yu, X. Shao, and X. Yang, *Phosphorus-doped tin oxides/carbon nanofibers webs as lithium-ion battery anodes With enhanced reversible capacity*. Journal of Power Sources, 2014. **272**: p. 614-621.10.1016/j.jpowsour.2014.08.084
95. Liu, Z., D. Fu, F. Liu, G. Han, C. Liu, Y. Chang, Y. Xiao, M. Li, and S. Li, *Mesoporous carbon nanofibers with large cage-like pores activated by tin dioxide and their use in supercapacitor and catalyst support*. Carbon, 2014. **70**: p. 295-307.10.1016/j.carbon.2014.01.011
96. Simon, G.K., B. Maruyama, M.F. Durstock, D.J. Burton, and T. Goswami, *Silicon-coated carbon nanofiber hierarchical nanostructures for improved lithium-ion battery anodes*. Journal of Power Sources, 2011. **196**(23): p. 10254-10257.<http://dx.doi.org/10.1016/j.jpowsour.2011.08.058>
97. Zhao, Y., X. Li, B. Yan, D. Li, S. Lawes, and X. Sun, *Significant impact of 2D graphene nanosheets on large volume change tin-based anodes in lithium-ion batteries: A review*. Journal of Power Sources, 2015. **274**(0): p. 869-884.<http://dx.doi.org/10.1016/j.jpowsour.2014.10.008>
98. Alcoutlabi, M., L. Banda, S. Kollengodu-Subramanian, J. Zhao, and G.B. McKenna, *Environmental Effects on the Structural Recovery Responses of an Epoxy Resin after Carbon Dioxide Pressure Jumps: Intrinsic Isopiestic, Asymmetry of Approach, and Memory Effect*. Macromolecules, 2011. **44**(10): p. 3828-3839.10.1021/ma1027577
99. Alcoutlabi, M., L. Banda, and G.B. McKenna, *A comparison of concentration-glasses and temperature-hyperquenched glasses: CO₂-formed glass versus temperature-formed glass*. Polymer, 2004. **45**(16): p. 5629-5634.10.1016/j.polymer.2004.04.004
100. Lee, M., M. Alcoutlabi, J.J. Magda, C. Dibble, M.J. Solomon, X. Shi, and G.B. McKenna, *The effect of the shear-thickening transition of model colloidal spheres on the sign of N-1 and on the radial pressure profile in torsional shear flows*. Journal of Rheology, 2006. **50**(3): p. 293-311.10.1122/1.2188567
101. Li, T., C. Wei, Y.-M. Wu, F.-D. Han, Y.-X. Qi, H.-L. Zhu, N. Lun, and Y.-J. Bai, *Simple Preparation of Carbon Nanofibers with Graphene Layers Perpendicular to the Length Direction and the Excellent Li-Ion Storage Performance*. Acs Applied Materials & Interfaces, 2015. **7**(9): p. 5107-5115.10.1021/am508862e

102. Li, W., M. Li, M. Wang, L. Zeng, and Y. Yu, *Electrospinning with partially carbonization in air: Highly porous carbon nanofibers optimized for high-performance flexible lithium-ion batteries*. Nano Energy, 2015. **13**: p. 693-701.10.1016/j.nanoen.2015.03.027
103. Ramos, A., I. Camean, N. Cuesta, and A.B. Garcia, *Graphitized stacked-cup carbon nanofibers as anode materials for lithium-ion batteries*. Electrochimica Acta, 2014. **146**: p. 769-775.10.1016/j.electacta.2014.09.035
104. Zhu, J., L. Chen, Z. Xu, and B. Lu, *Electrospinning preparation of ultra-long aligned nanofibers thin films for high performance fully flexible lithium-ion batteries*. Nano Energy, 2015. **12**: p. 339-346.10.1016/j.nanoen.2014.10.026
105. He, D., F. Bai, L. Li, L. Shen, H.H. Kung, and N. Bao, *Fabrication of Sandwich-structured Si Nanoparticles-Graphene Nanocomposites for High-performance Lithium-ion Batteries*. Electrochimica Acta, 2015. **169**: p. 409-415.10.1016/j.electacta.2015.04.090
106. Omampuliyur, R.S., M. Bhuiyan, Z. Han, Z. Jing, L. Li, E.A. Fitzgerald, C.V. Thompson, and W.K. Choi, *Nanostructured Thin Film Silicon Anodes for Li-Ion Microbatteries*. Journal of Nanoscience and Nanotechnology, 2015. **15**(7): p. 4926-4933.10.1166/jnn.2015.9831
107. Yue, H., S. Wang, Z. Yang, Q. Li, S. Lin, and D. He, *Ultra-thick porous films of graphene-encapsulated silicon nanoparticles as flexible anodes for lithium ion batteries*. Electrochimica Acta, 2015. **174**: p. 688-695.10.1016/j.electacta.2015.06.042
108. Zhu, H., F. Lyu, M. Du, M. Zhang, Q. Wane, J. Yao, and B. Guo, *Design of Two-Dimensional, Ultrathin MoS₂ Nanoplates Fabricated Within One-Dimensional Carbon Nanofibers With Thermosensitive Morphology: High-Performance Electrocatalysts For The Hydrogen Evolution Reaction*. Acs Applied Materials & Interfaces, 2014. **6**(24): p. 22126-22137.10.1021/am505544g
109. Zhang, X.W., L.W. Ji, O. Toprakci, Y.Z. Liang, and M. Alcoutlabi, *Electrospun Nanofiber-Based Anodes, Cathodes, and Separators for Advanced Lithium-Ion Batteries*. Polymer Reviews, 2011. **51**(3): p. 239-264.10.1080/15583724.2011.593390
110. Guo, J., B. Jiang, X. Zhang, and H. Liu, *Monodisperse SnO₂ anchored reduced graphene oxide nanocomposites as negative electrode with high rate capability and long cyclability for lithium-ion batteries*. Journal of Power Sources, 2014. **262**(0): p. 15-22.<http://dx.doi.org/10.1016/j.jpowsour.2014.03.085>
111. Lu, Y., K. Fu, S. Zhang, Y. Li, C. Chen, J. Zhu, M. Yanilmaz, M. Dirican, and X. Zhang, *Centrifugal spinning: A novel approach to fabricate porous carbon fibers as binder-free electrodes for electric double-layer capacitors*. Journal of Power Sources, 2015. **273**: p. 502-510.10.1016/j.jpowsour.2014.09.130
112. Meschini, I., F. Nobili, M. Mancini, R. Marassi, R. Tossici, A. Savoini, M.L. Focarete, and F. Croce, *High-performance Sn@carbon nanocomposite anode for lithium batteries*. Journal of Power Sources, 2013. **226**(0): p. 241-248.<http://dx.doi.org/10.1016/j.jpowsour.2012.11.004>
113. Fleaca, C.T. and F. Le Normand, *Ni-catalysed carbon nanotubes and nanofibers assemblies grown on TiN/Si(100) substrates using hot-filaments combined with d.c. plasma CVD*. Physica E-Low-Dimensional Systems & Nanostructures, 2014. **56**: p. 435-440.10.1016/j.physe.2012.11.026
114. Ghavanini, F.A., M.E.L. Damian, D. Rafieian, and P. Lundgren, *Growth characterization of vertically aligned carbon nanofibers on top of TiN buffer layer for nanoelectromechanical devices*, in *Eurosensors Xxiv Conference*, B. Jakoby and M.J. Vellekoop, Editors. 2010. p. 1115-1118.
115. Kim, W.S., Y. Hwa, J.H. Jeun, H.J. Sohn, and S.H. Hong, *Synthesis of SnO₂ nano hollow spheres and their size effects in lithium ion battery anode application*. Journal of Power Sources, 2013. **225**: p. 108-112.10.1016/j.jpowsour.2012.10.030

116. Park, H., T. Song, H. Han, and U. Paik, *Electrospun Li₄Ti₅O₁₂ nanofibers sheathed with conductive TiN/TiO_xNy layer as an anode material for high power Li-ion batteries*. Journal of Power Sources, 2013. **244**(0): p. 726-730.<http://dx.doi.org/10.1016/j.jpowsour.2012.11.078>
117. Tran, T., K. McCormac, J. Li, Z. Bi, and J. Wu, *Electrospun SnO₂ and TiO₂ Composite Nanofibers for Lithium Ion Batteries*. Electrochimica Acta, 2014. **117**(0): p. 68-75.<http://dx.doi.org/10.1016/j.electacta.2013.11.101>
118. Trinca, R.B., G.A. Abraham, and M.I. Felisberti, *Electrospun nanofibrous scaffolds of segmented polyurethanes based on PEG, PLLA and PTMC blocks: Physico-chemical properties and morphology*. Materials science & engineering. C, Materials for biological applications, 2015. **56**: p. 511-7.10.1016/j.msec.2015.07.018
119. Yang, H., T. Song, S. Lee, H. Han, F. Xia, A. Devadoss, W. Sigmund, and U. Paik, *Tin indium oxide/graphene nanosheet nanocomposite as an anode material for lithium ion batteries with enhanced lithium storage capacity and rate capability*. Electrochimica Acta, 2013. **91**(0): p. 275-281.<http://dx.doi.org/10.1016/j.electacta.2012.12.070>
120. El-Gendy, H., M. Alcoutlabi, M. Jemmett, M. Deo, J. Magda, R. Venkatesan, and A. Montesi, *The Propagation of Pressure in a Gelled Waxy Oil Pipeline as Studied by Particle Imaging Velocimetry*. Aiche Journal, 2012. **58**(1): p. 302-311.10.1002/aic.12560
121. Yun, Q., X. Qin, W. Lv, Y.-B. He, B. Li, F. Kang, and Q.-H. Yang, *"Concrete" inspired construction of a silicon/carbon hybrid electrode for high performance lithium ion battery*. Carbon, 2015. **93**: p. 59-67.10.1016/j.carbon.2015.05.032
122. Zeng, L., Y. Jiang, J. Xu, M. Wang, W. Li, and Y. Yu, *Flexible copper-stabilized sulfur-carbon nanofibers with excellent electrochemical performance for Li-S batteries*. Nanoscale, 2015. **7**(25): p. 10940-10949.10.1039/c5nr01861g
123. Zhang, G., J. Zhu, W. Zeng, S. Hou, F. Gong, F. Li, C.C. Li, and H. Duan, *Tin quantum dots embedded in nitrogen-doped carbon nanofibers as excellent anode for lithium-ion batteries*. Nano Energy, 2014. **9**: p. 61-70.10.1016/j.nanoen.2014.06.030
124. Zhou, H., X. Ding, G. Liu, Y. Jiang, Z. Yin, and X. Wang, *Preparation and Characterization of Ultralong Spinel Lithium Manganese Oxide Nanofiber Cathode via Electrospinning Method*. Electrochimica Acta, 2015. **152**: p. 274-279.10.1016/j.electacta.2014.11.147
125. Zhuang, W., L. Li, J. Zhu, R. An, L. Lu, X. Lu, X. Wu, and H. Ying, *Facile Synthesis of Mesoporous MoS₂-TiO₂ Nanofibers for Ultrastable Lithium Ion Battery Anodes*. Chemelectrochem, 2015. **2**(3): p. 374-381.10.1002/celc.201402358
126. Zou, M., J. Li, W. Wen, Y. Lin, H. Lai, and Z. Huang, *Free-standing anode of N-doped carbon nanofibers containing SnO_x for high-performance lithium batteries*. Materials Research Bulletin, 2014. **60**: p. 868-871.10.1016/j.materresbull.2014.09.086
127. Hoque, M.A., D.C. Higgins, F.M. Hassan, J.-Y. Choi, M.D. Pritzker, and Z. Chen, *Tin oxide - mesoporous carbon composites as platinum catalyst supports for ethanol oxidation and oxygen reduction*. Electrochimica Acta, 2014. **121**(0): p. 421-427.<http://dx.doi.org/10.1016/j.electacta.2013.12.075>
128. Wang, J.W., Y. He, F. Fan, X.H. Liu, S. Xia, Y. Liu, C.T. Harris, H. Li, J.Y. Huang, S.X. Mao, and T. Zhu, *Two-Phase Electrochemical Lithiation in Amorphous Silicon*. Nano Letters, 2013. **13**(2): p. 709-715.10.1021/nl304379k
129. Bridel, J.-S., S. Grugeon, S. Laruelle, J. Hassoun, P. Reale, B. Scrosati, and J.-M. Tarascon, *Decomposition of ethylene carbonate on electrodeposited metal thin film anode*. Journal of Power Sources, 2010. **195**(7): p. 2036-2043.10.1016/j.jpowsour.2009.10.038
130. Inose, T., D. Watanabe, H. Morimoto, and S.-I. Tobishima, *Influence of glyme-based nonaqueous electrolyte solutions on electrochemical properties of Si-based anodes for rechargeable lithium cells*. Journal of Power Sources, 2006. **162**(2): p. 1297-1303.10.1016/j.jpowsour.2006.08.005

131. Mukhopadhyay, A. and B.W. Sheldon, *Deformation and stress in electrode materials for Li-ion batteries*. Progress in Materials Science, 2014. **63**: p. 58-116.10.1016/j.pmatsci.2014.02.001
132. Bonino, C.A., L. Ji, Z. Lin, O. Toprakci, X. Zhang, and S.A. Khan, *Electrospun Carbon-Tin Oxide Composite Nanofibers for Use as Lithium Ion Battery Anodes*. Acs Applied Materials & Interfaces, 2011. **3**(7): p. 2534-2542.10.1021/am2004015
133. Jang, B.-O., S.-H. Park, and W.-J. Lee, *Electrospun Co-Sn alloy/carbon nanofibers composite anode for lithium ion batteries*. Journal of Alloys and Compounds, 2013. **574**: p. 325-330.<http://dx.doi.org/10.1016/j.jallcom.2013.05.063>
134. Kim, D., D. Lee, J. Kim, and J. Moon, *Electrospun Ni-Added SnO₂-Carbon Nanofiber Composite Anode for High-Performance Lithium-Ion Batteries*. Acs Applied Materials & Interfaces, 2012. **4**(10): p. 5408-5415.10.1021/am301328u
135. Zhao, Y., X. Li, L. Dong, B. Yan, H. Shan, D. Li, and X. Sun, *Electrospun SnO₂-ZnO nanofibers with improved electrochemical performance as anode materials for lithium-ion batteries*. International Journal of Hydrogen Energy, 2015. **40**(41): p. 14338-14344.<http://dx.doi.org/10.1016/j.ijhydene.2015.06.054>
136. Fu, Z.R., X.F. Li, and G.R. Xu, *Novel electrospun SnO₂@carbon nanofibers as high performance anodes for lithium-ion batteries*. Crystal Research and Technology, 2014. **49**(7): p. 441-445.10.1002/crat.201300211
137. Ara, M., K. Wadumesthrige, T. Meng, S.O. Salley, and K.Y. Simon Ng, *Effect of microstructure and Sn/C ratio in SnO₂-graphene nanocomposites for lithium-ion battery performance*. Rsc Advances, 2014. **4**(39): p. 20540-20547.10.1039/c4ra00851k
138. Shen, Z., Y. Hu, Y. Chen, X. Zhang, K. Wang, and R. Chen, *Tin nanoparticle-loaded porous carbon nanofiber composite anodes for high current lithium-ion batteries*. Journal of Power Sources, 2015. **278**: p. 660-667.10.1016/j.jpowsour.2014.12.106
139. Wang, J., W.L. Song, Z.Y. Wang, L.Z. Fan, and Y.F. Zhang, *Facile Fabrication of Binder-free Metallic Tin Nanoparticle/Carbon Nanofiber Hybrid Electrodes for Lithium-ion Batteries*. Electrochimica Acta, 2015. **153**: p. 468-475.10.1016/j.electacta.2014.12.026
140. Li, W., R. Yang, J. Zheng, and X.G. Li, *Tandem plasma reactions for Sn/C composites with tunable structure and high reversible lithium storage capacity*. Nano Energy, 2013. **2**(6): p. 1314-1321.10.1016/j.nanoen.2013.06.012
141. Chen, C.-M. and P.-Y. Shih, *A peculiar composite structure of carbon nanofibers growing on a micro-sized tin whisker*. Journal of Materials Research, 2008. **23**(10): p. 2668-2673.10.1557/jmr.2008.0326
142. Lee, B.-S., S.-B. Son, K.-M. Park, W.-R. Yu, K.-H. Oh, and S.-H. Lee, *Anodic properties of hollow carbon nanofibers for Li-ion battery*. Journal of Power Sources, 2012. **199**(0): p. 53-60.<http://dx.doi.org/10.1016/j.jpowsour.2011.10.030>
143. Tian, Q., Y. Tian, Z. Zhang, L. Yang, and S.-i. Hirano, *Facile synthesis of ultrasmall tin oxide nanoparticles embedded in carbon as high-performance anode for lithium-ion batteries*. Journal of Power Sources, 2014. **269**(0): p. 479-485.<http://dx.doi.org/10.1016/j.jpowsour.2014.07.019>
144. Chen, J., L. Yang, S. Fang, Z. Zhang, A. Deb, and S.-i. Hirano, *Sn-contained N-rich carbon nanowires for high-capacity and long-life lithium storage*. Electrochimica Acta, 2014. **127**(0): p. 390-396.<http://dx.doi.org/10.1016/j.electacta.2014.02.066>
145. Duan, B., W. Wang, K. Yuan, A. Wang, H. Zhao, and Y. Yang, *Preparation and Electrochemical Properties of Sn/C Composite Anode Materials*. Rare Metal Materials and Engineering, 2012. **41**: p. 496-499
146. Kim, I.S., P.N. Kumta, and G.E. Blomgren, *Chemically derived nano-encapsulated tin-carbon composite anodes for Li-ion batteries*, in *Developments in Solid Oxide Fuel Cells and Lithium Ion Batteries*, A. Manthiram, et al., Editors. 2005. p. 131-140.

147. Reale, P., M. Morcrette, and J. Hassoun, *In-Situ X-Ray Diffraction Study of the Li-Alloying Electrochemical Process in a Tin-Carbon Nanocomposite Electrode*. Nanoscience and Nanotechnology Letters, 2012. **4**(2): p. 132-135.10.1166/nnl.2012.1295
148. Zhu, J., G.H. Zhang, S.Z. Gu, and B.G. Lu, *SnO₂ Nanorods on ZnO Nanofibers: A New Class of Hierarchical Nanostructures Enabled by Electrospinning as Anode Material for High-Performance Lithium-Ion Batteries*. Electrochimica Acta, 2014. **150**: p. 308-313.10.1016/j.electacta.2014.10.149
149. Jang, B.O., S.H. Park, and W.J. Lee, *Electrospun Co-Sn alloy/carbon nanofibers composite anode for lithium ion batteries*. Journal of Alloys and Compounds, 2013. **574**: p. 325-330.10.1016/j.jallcom.2013.05.063
150. Xie, W., S. Li, S. Wang, S. Xue, Z. Liu, X. Jiang, and D. He, *N-Doped Amorphous Carbon Coated Fe₃O₄/SnO₂ Coaxial Nanofibers as a Binder-Free Self-Supported Electrode for Lithium Ion Batteries*. Acs Applied Materials & Interfaces, 2014. **6**(22): p. 20334-20339.10.1021/am505829v
151. Lei, D., B. Qu, H.-T. Lin, and T. Wang, *Facile approach to prepare porous GeO₂/SnO₂ nanofibers via a single spinneret electrospinning technique as anodes for Lithium-ion batteries*. Ceramics International, 2015. **41**(8): p. 10308-10313.<http://dx.doi.org/10.1016/j.ceramint.2015.04.085>
152. Chan, C.K., H. Peng, G. Liu, K. McIlwrath, X.F. Zhang, R.A. Huggins, and Y. Cui, *High-performance lithium battery anodes using silicon nanowires*. Nat Nano, 2008. **3**(1): p. 31-35.http://www.nature.com/nnano/journal/v3/n1/supinfo/nnano.2007.411_S1.html
153. Li, W., M. Li, Z. Yang, J. Xu, X. Zhong, J. Wang, L. Zeng, X. Liu, Y. Jiang, X. Wei, L. Gu, and Y. Yu, *Carbon-Coated Germanium Nanowires on Carbon Nanofibers as Self-Supported Electrodes for Flexible Lithium-Ion Batteries*. Small, 2015. **11**(23): p. 2762-2767.10.1002/sml.201403533
154. Liu, S.K., W. He, X.D. Zhang, H.M. Li, S.Z. Zhang, and Y. Wang, *Novel Nanostructure Designs for High-Performance Silicon Based Anodes*. Energy and Environment Focus, 2015. **4**(3): p. 178-190.10.1166/eef.2015.1169
155. Ge, M., S. Kim, A. Nie, R. Shahbazian-Yassar, M. Mecklenburg, Y. Lu, X. Fang, C. Shen, J. Rong, S.Y. Park, D.S. Kim, J.Y. Kim, and C. Zhou, *Capacity retention behavior and morphology evolution of SixGe1-x nanoparticles as lithium-ion battery anode*. Nanotechnology, 2015. **26**(25).25570210.1088/0957-4484/26/25/255702
156. Jamnongkan, T., S.K. Sukumaran, M. Sugimoto, T. Hara, Y. Takatsuka, and K. Koyama, *Towards novel wound dressings: antibacterial properties of zinc oxide nanoparticles and electrospun fiber mats of zinc oxide nanoparticle/poly(vinyl alcohol) hybrids*. Journal of Polymer Engineering, 2015. **35**(6): p. 575-586.10.1515/polyeng-2014-0319
157. Zhou, M., X. Li, B. Wang, Y. Zhang, J. Ning, Z. Xiao, X. Zhang, Y. Chang, and L. Zhi, *High-Performance Silicon Battery Anodes Enabled by Engineering Graphene Assemblies*. Nano letters, 2015. **15**(9): p. 6222-8.10.1021/acs.nanolett.5b02697
158. Polat, B.D. and O. Keles, *The effect of copper coating on nanocolumnar silicon anodes for lithium ion batteries*. Thin Solid Films, 2015. **589**: p. 543-550.<http://dx.doi.org/10.1016/j.tsf.2015.06.038>
159. Xu, K.Q., L.B. Ben, H. Li, and X.J. Huang, *Silicon-based nanosheets synthesized by a topochemical reaction for use as anodes for lithium ion batteries*. Nano Research, 2015. **8**(8): p. 2654-2662.10.1007/s12274-015-0772-4
160. Wang, W., Y. Wang, L. Gu, R. Lu, H. Qian, X. Peng, and J. Sha, *SiC@Si core-shell nanowires on carbon paper as a hybrid anode for lithium-ion batteries*. Journal of Power Sources, 2015. **293**: p. 492-497.10.1016/j.jpowsour.2015.05.103
161. Zhou, H., X. Wang, and D. Chen, *Li-Metal-Free Prelithiation of Si-Based Negative Electrodes for Full Li-Ion Batteries*. ChemSusChem, 2015. **8**(16): p. 2737-2744.10.1002/cssc.201500287

162. Wang, M.S., W.L. Song, J. Wang, and L.Z. Fan, *Highly uniform silicon nanoparticle/porous carbon nanofiber hybrids towards free-standing high-performance anodes for lithium-ion batteries*. Carbon, 2015. **82**: p. 337-345.10.1016/j.carbon.2014.10.078
163. Nguyen Trung, H., J. Suk, D.W. Kim, O.H. Chung, J.S. Park, and Y. Kang, *Silicon nanoparticle and carbon nanotube loaded carbon nanofibers for use in lithium-ion battery anodes*. Synthetic Metals, 2014. **198**: p. 36-40.10.1016/j.synthmet.2014.09.021
164. Park, E., H. Yoo, J. Lee, M.-S. Park, Y.-J. Kim, and H. Kim, *Dual-Size Silicon Nanocrystal-Embedded SiO_x Nanocomposite as a High-Capacity Lithium Storage Material*. Acs Nano, 2015. **9**(7): p. 7690-7696.10.1021/acs.nano.5b03166
165. Wang, X., M. Xi, F. Zheng, B. Ding, H. Fong, and Z. Zhu, *Reduction of crack formation in TiO₂ mesoporous films prepared from binder-free nanoparticle pastes via incorporation of electrospun SiO₂ or TiO₂ nanofibers for dye-sensitized solar cells*. Nano Energy, 2015. **12**: p. 794-800.10.1016/j.nanoen.2015.01.045
166. Choi, Y.S., M. Pharr, K.H. Oh, and J.J. Vlassak, *A simple technique for measuring the fracture energy of lithiated thin-film silicon electrodes at various lithium concentrations*. Journal of Power Sources, 2015. **294**: p. 159-166.10.1016/j.jpowsour.2015.06.063
167. Li, J. and J. Huang, *A nanofibrous polypyrrole/silicon composite derived from cellulose substance as the anode material for lithium-ion batteries*. Chemical communications (Cambridge, England), 2015. **51**(78): p. 14590-3.10.1039/c5cc05300e
168. Pandey, G.P., S.A. Klankowski, Y. Li, X.S. Sun, J. Wu, R.A. Rojas, and J. Li, *Effective Infiltration of Gel Polymer Electrolyte into Silicon-Coated Vertically Aligned Carbon Nanofibers as Anodes for Solid-State Lithium-Ion Batteries*. Acs Applied Materials & Interfaces, 2015. **7**(37): p. 20909-18.10.1021/acsami.5b06444
169. Schmuelling, G., M. Winter, and T. Placke, *Investigating the Mg-Si Binary System via Combinatorial Sputter Deposition As High Energy Density Anodes for Lithium-Ion Batteries*. Acs Applied Materials & Interfaces, 2015. **7**(36): p. 20124-33.10.1021/acsami.5b05382
170. Yamano, A., M. Morishita, H. Yamauchi, T. Nagakane, M. Ohji, A. Sakamoto, M. Yanagida, and T. Sakai, *Electrochemical and safety performance of Li pre-doping free cell using tin-phosphate glass-silicon composite anode*. Journal of Power Sources, 2015. **292**: p. 31-38.10.1016/j.jpowsour.2015.05.026
171. Chou, C.-Y., J.-H. Seo, Y.-H. Tsai, J.-P. Ahn, E. Paek, M.-H. Cho, I.-S. Choi, and G.S. Hwang, *Anomalous Stagewise Lithiation of Gold-Coated Silicon Nanowires: A Combined In Situ Characterization and First-Principles Study*. Acs Applied Materials & Interfaces, 2015. **7**(31): p. 16976-16983.10.1021/acsami.5b01930
172. Liu, J., P. Kopold, P.A. van Aken, J. Maier, and Y. Yu, *Energy Storage Materials from Nature through Nanotechnology: A Sustainable Route from Reed Plants to a Silicon Anode for Lithium-Ion Batteries*. Angewandte Chemie-International Edition, 2015. **54**(33): p. 9632-9636.10.1002/anie.201503150
173. Dirican, M., Y. Lu, K. Fu, H. Kizil, and X. Zhang, *SiO₂-confined silicon/carbon nanofiber composites as an anode for lithium-ion batteries*. Rsc Advances, 2015. **5**(44): p. 34744-34751.10.1039/c5ra03129j
174. Lee, B.-S., H.-S. Yang, H. Jung, S.-Y. Jeon, C. Jung, S.-W. Kim, J. Bae, C.-L. Choong, J. Im, U.I. Chung, J.-J. Park, and W.-R. Yu, *Novel multi-layered 1-D nanostructure exhibiting the theoretical capacity of silicon for a super-enhanced lithium-ion battery*. Nanoscale, 2014. **6**(11): p. 5989-5998.10.1039/c4nr00318g
175. Li, Q., L. Yin, J. Ma, Z. Li, Z. Zhang, A. Chen, and C. Li, *Mesoporous silicon/carbon hybrids with ordered pore channel retention and tunable carbon incorporated content as high performance*

- anode materials for lithium-ion batteries. *Energy*, 2015. **85**: p. 159-166.10.1016/j.energy.2015.03.090
176. Wang, M., D. Jia, J. Li, and J. Huang, *Nanofibrous silicon/carbon composite sheet derived from cellulose substance as free-standing lithium-ion battery anodes*. *Rsc Advances*, 2014. **4**(64): p. 33981-33985.10.1039/c4ra05820h
 177. Wang, Y., J. Chen, and S. Wang, *Mesoporous silicon/carbon nanofibers composites anode materials for Li-ion battery*. *Abstracts of Papers of the American Chemical Society*, 2014. **247**
 178. Wu, Q., T. Tran, W. Lu, and J. Wu, *Electrospun silicon/carbon/titanium oxide composite nanofibers for lithium ion batteries*. *Journal of Power Sources*, 2014. **258**: p. 39-45.10.1016/j.jpowsour.2014.02.047
 179. Zhang, C., R. Yu, T. Zhou, Z. Chen, H. Liu, and Z. Guo, *Mass production of three-dimensional hierarchical microfibers constructed from silicon-carbon core-shell architectures with high-performance lithium storage*. *Carbon*, 2014. **72**: p. 169-175.10.1016/j.carbon.2014.01.069
 180. Zhang, H., X. Qin, J. Wu, Y.-B. He, H. Du, B. Li, and F. Kang, *Electrospun core-shell silicon/carbon fibers with an internal honeycomb-like conductive carbon framework as an anode for lithium ion batteries*. *Journal of Materials Chemistry A*, 2015. **3**(13): p. 7112-7120.10.1039/c4ta06044j
 181. Zhang, M., X. Hou, J. Wang, M. Li, S. Hu, Z. Shao, and X. Liu, *Interweaved Si@C/CNTs&CNFs composites as anode materials for Li-ion batteries*. *Journal of Alloys and Compounds*, 2014. **588**: p. 206-211.10.1016/j.jallcom.2013.10.160
 182. Chen, P.-C., J. Xu, H. Chen, and C. Zhou, *Hybrid silicon-carbon nanostructured composites as superior anodes for lithium ion batteries*. *Nano Research*, 2011. **4**(3): p. 290-296.10.1007/s12274-010-0081-x
 183. Choi, J.W., L. Hu, L. Cui, J.R. McDonough, and Y. Cui, *Metal current collector-free freestanding silicon-carbon 1D nanocomposites for ultralight anodes in lithium ion batteries*. *Journal of Power Sources*, 2010. **195**(24): p. 8311-8316.10.1016/j.jpowsour.2010.06.108
 184. Guo, J., A. Sun, X. Chen, C. Wang, and A. Manivannan, *Cyclability study of silicon-carbon composite anodes for lithium-ion batteries using electrochemical impedance spectroscopy*. *Electrochimica Acta*, 2011. **56**(11): p. 3981-3987.10.1016/j.electacta.2011.02.014
 185. Wang, J.W., X.H. Liu, K. Zhao, A. Palmer, E. Patten, D. Burton, S.X. Mao, Z. Suo, and J.Y. Huang, *Sandwich-Lithiation and Longitudinal Crack in Amorphous Silicon Coated on Carbon Nanofibers*. *Acs Nano*, 2012. **6**(10): p. 9158-9167.10.1021/nn3034343
 186. Wang, W. and P.N. Kumta, *Nanostructured Hybrid Silicon/Carbon Nanotube Heterostructures: Reversible High-Capacity Lithium-Ion Anodes*. *Acs Nano*, 2010. **4**(4): p. 2233-2241.10.1021/nn901632g
 187. Ji, L.W., O. Toprakci, M. Alcoutlabi, Y.F. Yao, Y. Li, S. Zhang, B.K. Guo, Z. Lin, and X.W. Zhang, *alpha-Fe₂O₃ Nanoparticle-Loaded Carbon Nanofibers as Stable and High-Capacity Anodes for Rechargeable Lithium-Ion Batteries*. *Acs Applied Materials & Interfaces*, 2012. **4**(5): p. 2672-2679.10.1021/am300333s
 188. Kim, J.H., Y.J. Hong, Y.C. Kang, Y.J. Choi, and Y.S. Kim, *Superior electrochemical properties of alpha-Fe₂O₃ nanofibers with a porous core/dense shell structure formed from iron acetylacetonate-polyvinylpyrrolidone composite fibers*. *Electrochimica Acta*, 2015. **154**: p. 211-218.10.1016/j.electacta.2014.11.181
 189. Li, J., W. Wen, G. Xu, M. Zou, Z. Huang, and L. Guan, *Fe-added Fe₃C carbon nanofibers as anode for Li ion batteries with excellent low-temperature performance*. *Electrochimica Acta*, 2015. **153**: p. 300-305.10.1016/j.electacta.2014.12.008
 190. Luo, L., R. Cui, H. Qiao, K. Chen, Y. Fei, D. Li, Z. Pang, K. Liu, and Q. Wei, *High lithium electroactivity of electrospun CuFe₂O₄ nanofibers as anode material for lithium-ion batteries*. *Electrochimica Acta*, 2014. **144**: p. 85-91.10.1016/j.electacta.2014.08.048

191. Wan, Y., Z. Yang, G. Xiong, R. Guo, Z. Liu, and H. Luo, *Anchoring Fe₃O₄ nanoparticles on three-dimensional carbon nanofibers toward flexible high-performance anodes for lithium-ion batteries*. Journal of Power Sources, 2015. **294**: p. 414-419.10.1016/j.jpowsour.2015.06.057
192. Zou, M., J. Li, W. Wen, L. Chen, L. Guan, H. Lai, and Z. Huang, *Silver-incorporated composites of Fe₂O₃ carbon nanofibers as anodes for high-performance lithium batteries*. Journal of Power Sources, 2014. **270**: p. 468-474.10.1016/j.jpowsour.2014.07.119
193. Ji, L., O. Toprakci, M. Alcoutlabi, Y. Yao, Y. Li, S. Zhang, B. Guo, Z. Lin, and X. Zhang, *alpha-Fe₂O₃ Nanoparticle-Loaded Carbon Nanofibers as Stable and High-Capacity Anodes for Rechargeable Lithium-Ion Batteries*. ACS Applied Materials & Interfaces, 2012. **4**(5): p. 2672-2679.10.1021/am300333s
194. Wu, C., X. Li, W. Li, B. Li, Y. Wang, Y. Wang, M. Xu, and L. Xing, *Fe₂O₃ nanorods/carbon nanofibers composite: Preparation and performance as anode of high rate lithium ion battery*. Journal of Power Sources, 2014. **251**: p. 85-91.10.1016/j.jpowsour.2013.11.030
195. Zhang, X., H. Liu, S. Petnikota, S. Ramakrishna, and H.J. Fan, *Electrospun Fe₂O₃-carbon composite nanofibers as durable anode materials for lithium ion batteries*. Journal of Materials Chemistry A, 2014. **2**(28): p. 10835-10841.10.1039/c3ta15123a
196. Büyükyazi, M. and S. Mathur, *3D nanoarchitectures of α-LiFeO₂ and α-LiFeO₂/C nanofibers for high power lithium-ion batteries*. Nano Energy, 2015. **13**: p. 28-35.<http://dx.doi.org/10.1016/j.nanoen.2015.02.005>
197. Qiao, H., L. Luo, K. Chen, Y. Fei, R. Cui, and Q. Wei, *Electrospun synthesis and lithium storage properties of magnesium ferrite nanofibers*. Electrochimica Acta, 2015. **160**: p. 43-49.10.1016/j.electacta.2015.02.012
198. Qin, X.Y., H.R. Zhang, J.X. Wu, X.D. Chu, Y.B. He, C.P. Han, C. Miao, S.A. Wang, B.H. Li, and F.Y. Kang, *Fe₃O₄ nanoparticles encapsulated in electrospun porous carbon fibers with a compact shell as high-performance anode for lithium ion batteries*. Carbon, 2015. **87**: p. 347-356.10.1016/j.carbon.2015.02.044
199. Kalluri, S., W.K. Pang, K.H. Seng, Z. Chen, Z. Guo, H.K. Liu, and S.X. Dou, *One-dimensional nanostructured design of Li_{1+x}(Mn_{1/3}Ni_{1/3}Fe_{1/3})O₂ as a dual cathode for lithium-ion and sodium-ion batteries*. Journal of Materials Chemistry A, 2015. **3**(1): p. 250-257.10.1039/c4ta04271a
200. Kim, C., B.R. Kim, and J.T. Son, *Synthesis mechanism of new morphology LiMnPO₄ nanofibers using electrospinning process*. Journal of Electroceramics, 2014. **33**(1-2): p. 7-11.10.1007/s10832-014-9893-5
201. Xu, G., J. Li, X. Li, H. Zhou, X. Ding, X. Wang, and F. Kang, *Understanding the electrochemical superiority of 0.6Li Li_{1/3}Mn_{2/3}O₂-0.4Li Ni_{1/3}Co_{1/3}Mn_{1/3}O₂ nanofibers as cathode material for lithium ion batteries*. Electrochimica Acta, 2015. **173**: p. 672-679.10.1016/j.electacta.2015.05.083
202. Yan, B., X. Li, Z. Bai, M. Li, L. Dong, D. Xiong, and D. Li, *Superior lithium storage performance of hierarchical porous vanadium pentoxide nanofibers for lithium ion battery cathodes*. Journal of Alloys and Compounds, 2015. **634**: p. 50-57.10.1016/j.jallcom.2015.01.292
203. Mai, L., L. Xu, C. Han, X. Xu, Y. Luo, S. Zhao, and Y. Zhao, *Electrospun Ultralong Hierarchical Vanadium Oxide Nanowires with High Performance for Lithium Ion Batteries*. Nano letters, 2010. **10**(11): p. 4750-4755.10.1021/nl103343w
204. Li, Z., G. Liu, M. Guo, L.-X. Ding, S. Wang, and H. Wang, *Electrospun porous vanadium pentoxide nanotubes as a high-performance cathode material for lithium-ion batteries*. Electrochimica Acta, 2015. **173**: p. 131-138.<http://dx.doi.org/10.1016/j.electacta.2015.05.057>
205. Whittingham, M.S., *Lithium Batteries and Cathode Materials*. Chemical Reviews, 2004. **104**(10): p. 4271-4302.10.1021/cr020731c

206. Du Pasquier, A., C.C. Huang, and T. Spitler, *Nano Li₄Ti₅O₁₂–LiMn₂O₄ batteries with high power capability and improved cycle-life*. Journal of Power Sources, 2009. **186**(2): p. 508-514.<http://dx.doi.org/10.1016/j.jpowsour.2008.10.018>
207. Belharouak, I., Y.-K. Sun, W. Lu, and K. Amine, *On the Safety of the Li₄Ti₅O₁₂/LiMn₂O₄ Lithium-Ion Battery System*. Journal of the Electrochemical Society, 2007. **154**(12): p. A1083-A1087.10.1149/1.2783770
208. Cheng, X.B., Q. Zhang, H.F. Wang, G.L. Tian, J.Q. Huang, H.J. Peng, M.Q. Zhao, and F. Wei, *Nitrogen-doped herringbone carbon nanofibers with large lattice spacings and abundant edges: Catalytic growth and their applications in lithium ion batteries and oxygen reduction reactions*. Catalysis Today, 2015. **249**: p. 244-251.10.1016/j.cattod.2014.10.047
209. Liu, Q., D. Mao, C. Chang, and F. Huang, *Phase conversion and morphology evolution during hydrothermal preparation of orthorhombic LiMnO₂ nanorods for lithium ion battery application*. Journal of Power Sources, 2007. **173**(1): p. 538-544.10.1016/j.jpowsour.2007.03.077
210. Molenda, J., M. Ziemnicki, J. Marzec, W. Zajac, M. Molenda, and M. Bucko, *Electrochemical and high temperature physicochemical properties of orthorhombic LiMnO₂*. Journal of Power Sources, 2007. **173**(2): p. 707-711.10.1016/j.jpowsour.2007.05.054
211. Thackeray, M.M., L.A. de Picciotto, A. de Kock, P.J. Johnson, V.A. Nicholas, and K.T. Adendorff, *Spinel electrodes for lithium batteries — A review*. Journal of Power Sources, 1987. **21**(1): p. 1-8.[http://dx.doi.org/10.1016/0378-7753\(87\)80071-X](http://dx.doi.org/10.1016/0378-7753(87)80071-X)
212. Matsushima, T., *Deterioration estimation of lithium-ion cells in direct current power supply systems and characteristics of 400-Ah lithium-ion cells*. Journal of Power Sources, 2009. **189**(1): p. 847-854.10.1016/j.jpowsour.2008.08.023
213. Deng, B.H., H. Nakamura, and M. Yoshio, *Capacity fading with oxygen loss for manganese spinels upon cycling at elevated temperatures*. Journal of Power Sources, 2008. **180**(2): p. 864-868.10.1016/j.jpowsour.2008.02.071
214. Xu, H., X. Hu, Y. Sun, W. Luo, C. Chen, Y. Liu, and Y. Huang, *Highly porous Li₄Ti₅O₁₂/C nanofibers for ultrafast electrochemical energy storage*. Nano Energy, 2014. **10**: p. 163-171.10.1016/j.nanoen.2014.09.003
215. Lin, H.-Y., S.-M. Yeh, and J.-S. Chen, *Physical and Electrochemical Properties of LiFePO₄/C Nanofibers Synthesized by Electrospinning*. International Journal of Electrochemical Science, 2014. **9**(12): p. 6936-6948
216. Manthiram, A., S.H. Chung, and C.X. Zu, *Lithium-Sulfur Batteries: Progress and Prospects*. Advanced Materials, 2015. **27**(12): p. 1980-2006.10.1002/adma.201405115
217. Manthiram, A., Y.Z. Fu, S.H. Chung, C.X. Zu, and Y.S. Su, *Rechargeable Lithium-Sulfur Batteries*. Chemical Reviews, 2014. **114**(23): p. 11751-11787.10.1021/cr500062v
218. Scheers, J., S. Fantini, and P. Johansson, *A review of electrolytes for lithium-sulphur batteries*. Journal of Power Sources, 2014. **255**: p. 204-218.10.1016/j.jpowsour.2014.01.023
219. Bresser, D., S. Passerini, and B. Scrosati, *Recent progress and remaining challenges in sulfur-based lithium secondary batteries - a review*. Chemical Communications, 2013. **49**(90): p. 10545-10562.10.1039/c3cc46131a
220. Lin, Z. and C.D. Liang, *Lithium-sulfur batteries: from liquid to solid cells*. Journal of Materials Chemistry A, 2015. **3**(3): p. 936-958.10.1039/c4ta04727c
221. Mikhaylik, Y.V. and J.R. Akridge, *Low temperature performance of Li/S batteries*. Journal of the Electrochemical Society, 2003. **150**(3): p. A306-A311.10.1149/1.1545452
222. Agostini, M. and J. Hassoun, *A lithium-ion sulfur battery using a polymer, polysulfide-added membrane*. Scientific Reports, 2015. **5**.Artn 759110.1038/Srep07591

223. Li, Q., Z. Zhang, K. Zhang, J. Fang, Y. Lai, and J. Li, *A simple synthesis of hollow carbon nanofiber-sulfur composite via mixed-solvent process for lithium-sulfur batteries*. Journal of Power Sources, 2014. **256**: p. 137-144.<http://dx.doi.org/10.1016/j.jpowsour.2014.01.063>
224. Chen, Y.M., X.Y. Li, K.S. Park, J.H. Hong, J. Song, L.M. Zhou, Y.W. Mai, H.T. Huang, and J.B. Goodenough, *Sulfur encapsulated in porous hollow CNTs@CNFs for high-performance lithium sulfur batteries*. Journal of Materials Chemistry A, 2014. **2**(26): p. 10126-10130.10.1039/c4ta01823k
225. Huang, L., J.L. Cheng, G.X. Qu, X.D. Li, Y. Hu, W. Ni, D.M. Yuan, Y. Zhang, and B. Wang, *Porous carbon nanofibers formed in situ by electrospinning with a volatile solvent additive into an ice water bath for lithium-sulfur batteries*. Rsc Advances, 2015. **5**(30): p. 23749-23757.10.1039/c4ra14680h
226. Ji, L.W., M.M. Rao, S. Aloni, L. Wang, E.J. Cairns, and Y.G. Zhang, *Porous carbon nanofiber-sulfur composite electrodes for lithium/sulfur cells*. Energy & Environmental Science, 2011. **4**(12): p. 5053-5059.10.1039/c1ee02256c
227. Kim, D.S. and Y.J. Park, *Buckypaper electrode containing carbon nanofiber/Co₃O₄ composite for enhanced lithium air batteries*. Solid State Ionics, 2014. **268, Part B**: p. 216-221.<http://dx.doi.org/10.1016/j.ssi.2014.03.010>
228. Li, X. and X.A. Sun, *Nitrogen-doped carbons in Li-S batteries: materials design and electrochemical mechanism*. Frontiers in Energy Research, 2014. **2**.10.3389/fenrg.2014.00049
229. Li, Z., J.T. Zhang, and X.W. Lou, *Hollow Carbon Nanofibers Filled with MnO₂ Nanosheets as Efficient Sulfur Hosts for Lithium-Sulfur Batteries*. Angewandte Chemie-International Edition, 2015. **54**(44): p. 12886-12890.10.1002/anie.201506972
230. Lu, S.T., Y. Chen, X.H. Wu, Z.D. Wang, L.Y. Lv, W. Qin, and L.X. Jiang, *Binder-free cathodes based on sulfur-carbon nanofibers composites for lithium-sulfur batteries*. Rsc Advances, 2014. **4**(35): p. 18052-18064.10.1039/c4ra02122c
231. Lu, S.T., Y.W. Cheng, X.H. Wu, and J. Liu, *Significantly Improved Long-Cycle Stability in High-Rate Li-S Batteries Enabled by Coaxial Graphene Wrapping over Sulfur-Coated Carbon Nanofibers*. Nano Letters, 2013. **13**(6): p. 2485-2489.10.1021/nl400543y
232. Rao, M.M., W.S. Li, and E.J. Cairns, *Porous carbon-sulfur composite cathode for lithium/sulfur cells*. Electrochemistry Communications, 2012. **17**: p. 1-5.10.1016/j.elecom.2011.12.022
233. Rao, M.M., X.Y. Song, and E.J. Cairns, *Nano-carbon/sulfur composite cathode materials with carbon nanofiber as electrical conductor for advanced secondary lithium/sulfur cells*. Journal of Power Sources, 2012. **205**: p. 474-478.10.1016/j.jpowsour.2012.01.047
234. Tang, H., S.S. Yao, M.X. Jing, X. Wu, J.L. Hou, X.Y. Qian, D.W. Rao, X.Q. Shen, X.M. Xi, and K.S. Xiao, *Mg_{0.6}Ni_{0.4}O hollow nanofibers prepared by electrospinning as additive for improving electrochemical performance of lithium-sulfur batteries*. Journal of Alloys and Compounds, 2015. **650**: p. 351-356.10.1016/j.jallcom.2015.07.264
235. Ye, J., F. He, J. Nie, Y.L. Cao, H.X. Yang, and X.P. Ai, *Sulfur/carbon nanocomposite-filled polyacrylonitrile nanofibers as a long life and high capacity cathode for lithium-sulfur batteries*. Journal of Materials Chemistry A, 2015. **3**(14): p. 7406-7412.10.1039/c4ta06976e
236. Zeng, L.C., Y. Jiang, J. Xu, M. Wang, W.H. Li, and Y. Yu, *Flexible copper-stabilized sulfur-carbon nanofibers with excellent electrochemical performance for Li-S batteries*. Nanoscale, 2015. **7**(25): p. 10940-10949.10.1039/c5nr01861g
237. Zeng, L.C., F.S. Pan, W.H. Li, Y. Jiang, X.W. Zhong, and Y. Yu, *Free-standing porous carbon nanofibers-sulfur composite for flexible Li-S battery cathode*. Nanoscale, 2014. **6**(16): p. 9579-9587.10.1039/c4nr02498b

238. Zhang, W.H., D. Qiao, J.X. Pan, Y.L. Cao, H.X. Yang, and X.P. Ai, *A Li⁺-conductive microporous carbon-sulfur composite for Li-S batteries*. *Electrochimica Acta*, 2013. **87**: p. 497-502.10.1016/j.electacta.2012.09.086
239. Zhang, Z., Q. Li, S.F. Jiang, K. Zhang, Y.Q. Lai, and J. Li, *Sulfur Encapsulated in a TiO₂-Anchored Hollow Carbon Nanofiber Hybrid Nanostructure for Lithium-Sulfur Batteries*. *Chemistry-a European Journal*, 2015. **21**(3): p. 1343-1349.10.1002/chem.201404686
240. Zhou, F., S. Xin, H.-W. Liang, L.-T. Song, and S.-H. Yu, *Carbon Nanofibers Decorated with Molybdenum Disulfide Nanosheets: Synergistic Lithium Storage and Enhanced Electrochemical Performance*. *Angewandte Chemie-International Edition*, 2014. **53**(43): p. 11552-11556.10.1002/anie.201407103
241. Fu, K., Y.P. Li, M. Dirican, C. Chen, Y. Lu, J.D. Zhu, Y. Li, L.Y. Cao, P.D. Bradford, and X.W. Zhang, *Sulfur gradient-distributed CNF composite: a self-inhibiting cathode for binder-free lithium-sulfur batteries*. *Chemical Communications*, 2014. **50**(71): p. 10277-10280.10.1039/c4cc04970e
242. Wu, Y.H., M.X. Gao, X. Li, Y.F. Liu, and H.G. Pan, *Preparation of mesohollow and microporous carbon nanofiber and its application in cathode material for lithium-sulfur batteries*. *Journal of Alloys and Compounds*, 2014. **608**: p. 220-228.10.1016/j.jallcom.2014.04.073
243. Zheng, G.Y., Y. Yang, J.J. Cha, S.S. Hong, and Y. Cui, *Hollow Carbon Nanofiber-Encapsulated Sulfur Cathodes for High Specific Capacity Rechargeable Lithium Batteries*. *Nano Letters*, 2011. **11**(10): p. 4462-4467.10.1021/nl2027684
244. Zheng, G.Y., Q.F. Zhang, J.J. Cha, Y. Yang, W.Y. Li, Z.W. Seh, and Y. Cui, *Amphiphilic Surface Modification of Hollow Carbon Nanofibers for Improved Cycle Life of Lithium Sulfur Batteries*. *Nano Letters*, 2013. **13**(3): p. 1265-1270.10.1021/nl304795g
245. Yao, H.B., G.Y. Zheng, W.Y. Li, M.T. McDowell, Z.W. Seh, N.A. Liu, Z.D. Lu, and Y. Cui, *Crab Shells as Sustainable Templates from Nature for Nanostructured Battery Electrodes*. *Nano Letters*, 2013. **13**(7): p. 3385-3390.10.1021/nl401729r
246. He, G., B. Mandlmeier, J. Schuster, L.F. Nazar, and T. Bein, *Bimodal Mesoporous Carbon Nanofibers with High Porosity: Freestanding and Embedded in Membranes for Lithium-Sulfur Batteries*. *Chemistry of Materials*, 2014. **26**(13): p. 3879-3886.10.1021/cm403740r
247. Yang, J., J. Xie, X.Y. Zhou, Y.L. Zou, J.J. Tang, S.C. Wang, F. Chen, and L.Y. Wang, *Functionalized N-Doped Porous Carbon Nanofiber Webs for a Lithium-Sulfur Battery with High Capacity and Rate Performance*. *Journal of Physical Chemistry C*, 2014. **118**(4): p. 1800-1807.10.1021/jp410385s
248. Zhou, L., X.J. Lin, T. Huang, and A.S. Yu, *Nitrogen-doped porous carbon nanofiber webs/sulfur composites as cathode materials for lithium-sulfur batteries*. *Electrochimica Acta*, 2014. **116**: p. 210-216.10.1016/j.electacta.2013.11.041
249. Elazari, R., G. Salitra, A. Garsuch, A. Panchenko, and D. Aurbach, *Sulfur-Impregnated Activated Carbon Fiber Cloth as a Binder-Free Cathode for Rechargeable Li-S Batteries*. *Advanced Materials*, 2011. **23**(47): p. 5641-+.10.1002/adma.201103274
250. Wang, C., J.H. Jheng, and F.C. Chiu, *Electrospun nylon-4,6 nanofibers: solution rheology and Brill transition*. *Colloid and Polymer Science*, 2013. **291**(10): p. 2337-2344.10.1007/s00396-013-2970-5
251. Choi, Y.J., K.W. Kim, H.J. Ahn, and J.H. Ahn, *Improvement of cycle property of sulfur electrode for lithium/sulfur battery*. *Journal of Alloys and Compounds*, 2008. **449**(1-2): p. 313-316.10.1016/j.jallcom.2006.02.098
252. Singhal, R., S.H. Chung, A. Manthiram, and V. Kalra, *A free-standing carbon nanofiber interlayer for high-performance lithium-sulfur batteries*. *Journal of Materials Chemistry A*, 2015. **3**(8): p. 4530-4538.10.1039/c4ta06511e

253. Wang, J.G., Y. Yang, and F.Y. Kang, *Porous carbon nanofiber paper as an effective interlayer for high-performance lithium-sulfur batteries*. *Electrochimica Acta*, 2015. **168**: p. 271-276.10.1016/j.electacta.2015.04.055
254. Zhao, B., N.W. Li, H.L. Lu, Z.X. Lin, and M.B. Zheng, *Mesoporous Carbon Nanofiber-Sulfur Cathode for Lithium-Sulfur Batteries*. *Chinese Journal of Inorganic Chemistry*, 2014. **30**(4): p. 733-740
255. Chen, L. and L.L. Shaw, *Recent advances in lithium-sulfur batteries*. *Journal of Power Sources*, 2014. **267**: p. 770-783.10.1016/j.jpowsour.2014.05.111
256. Vizintin, A., M.U.M. Patel, B. Genorio, and R. Dominko, *Effective Separation of Lithium Anode and Sulfur Cathode in Lithium-Sulfur Batteries*. *Chemelectrochem*, 2014. **1**(6): p. 1040-1045.10.1002/celc.201402039
257. Yin, Y.X., S. Xin, Y.G. Guo, and L.J. Wan, *Lithium-Sulfur Batteries: Electrochemistry, Materials, and Prospects*. *Angewandte Chemie-International Edition*, 2013. **52**(50): p. 13186-13200.10.1002/anie.201304762
258. Zhang, Z.Y., Y.Q. Lai, Z.A. Zhang, K. Zhang, and J.E. Li, *Al₂O₃-coated porous separator for enhanced electrochemical performance of lithium sulfur batteries*. *Electrochimica Acta*, 2014. **129**: p. 55-61.10.1016/j.electacta.2014.02.077
259. Ryu, W.-H., T.-H. Yoon, S.H. Song, S. Jeon, Y.-J. Park, and I.-D. Kim, *Bifunctional Composite Catalysts Using Co₃O₄ Nanofibers Immobilized on Nonoxidized Graphene Nanoflakes for High-Capacity and Long-Cycle Li-O₂ Batteries*. *Nano Letters*, 2013. **13**(9): p. 4190-4197.10.1021/nl401868q
260. Song, M.J., I.T. Kim, Y.B. Kim, and M.W. Shin, *Self-standing, binder-free electrospun Co₃O₄/carbon nanofiber composites for non-aqueous Li-air batteries*. *Electrochimica Acta*, 2015. **182**: p. 289-296.<http://dx.doi.org/10.1016/j.electacta.2015.09.100>
261. Guo, Z., C. Li, J. Liu, X. Su, Y. Wang, and Y. Xia, *A core-shell-structured TiO₂(B) nanofiber@porous RuO₂ composite as a carbon-free catalytic cathode for Li-O₂ batteries*. *Journal of Materials Chemistry A*, 2015. **3**(42): p. 21123-21132.10.1039/c5ta06850a
262. Kalubarme, R.S., H.S. Jadhav, D.T. Ngo, G.-E. Park, J.G. Fisher, Y.-I. Choi, W.-H. Ryu, and C.-J. Park, *Simple synthesis of highly catalytic carbon-free MnCo₂O₄@Ni as an oxygen electrode for rechargeable Li-O₂ batteries with long-term stability*. *Scientific Reports*, 2015. **5**: p. 13266.10.1038/srep13266<http://www.nature.com/articles/srep13266#supplementary-information>
263. Mitchell, R.R., B.M. Gallant, C.V. Thompson, and Y. Shao-Horn, *All-carbon-nanofiber electrodes for high-energy rechargeable Li-O₂ batteries*. *Energy & Environmental Science*, 2011. **4**(8): p. 2952-2958.10.1039/c1ee01496j
264. Zhang, G.Q., J.P. Zheng, R. Liang, C. Zhang, B. Wang, M. Au, M. Hendrickson, and E.J. Plichta, *α -MnO₂/Carbon Nanotube/Carbon Nanofiber Composite Catalytic Air Electrodes for Rechargeable Lithium-air Batteries*. *Journal of The Electrochemical Society*, 2011. **158**(7): p. A822-A827.10.1149/1.3590736
265. Zhang, G.Q., J.P. Zheng, R. Liang, C. Zhang, B. Wang, M. Hendrickson, and E.J. Plichta, *Lithium-Air Batteries Using SWNT/CNF Buckypapers as Air Electrodes*. *Journal of The Electrochemical Society*, 2010. **157**(8): p. A953-A956.10.1149/1.3446852
266. Park, S.H. and W.F. Lee, *Hierarchically mesoporous flower-like cobalt oxide/carbon nanofiber composites with shell-core structure as anodes for lithium ion batteries*. *Carbon*, 2015. **89**: p. 197-207.10.1016/j.carbon.2015.03.039
267. Yang, G., Y. Li, H. Ji, H. Wang, P. Gao, L. Wang, H. Liu, J. Pinto, and X. Jiang, *Influence of Mn content on the morphology and improved electrochemical properties of Mn₃O₄/MnO@carbon*

- nanofiber as anode material for lithium batteries. *Journal of Power Sources*, 2012. **216**: p. 353-362. <http://dx.doi.org/10.1016/j.jpowsour.2012.05.092>
268. Huang, X.S., *Separator technologies for lithium-ion batteries*. *Journal of Solid State Electrochemistry*, 2011. **15**(4): p. 649-662. DOI 10.1007/s10008-010-1264-9
 269. Lee, S.W., S.W. Choi, S.M. Jo, B.D. Chin, D.Y. Kim, and K.Y. Lee, *Electrochemical properties and cycle performance of electrospun poly(vinylidene fluoride)-based fibrous membrane electrolytes for Li-ion polymer battery*. *Journal of Power Sources*, 2006. **163**(1): p. 41-46. DOI 10.1016/j.jpowsour.2005.11.102
 270. Yang, C.R., Z.D. Jia, Z.C. Guan, and L.M. Wang, *Polyvinylidene fluoride membrane by novel electrospinning system for separator of Li-ion batteries*. *Journal of Power Sources*, 2009. **189**(1): p. 716-720. DOI 10.1016/j.jpowsour.2008.08.060
 271. Arora, P. and Z.M. Zhang, *Battery separators*. *Chemical Reviews*, 2004. **104**(10): p. 4419-4462. Doi 10.1021/Cr020738u
 272. Nunes-Pereira, J., C.M. Costa, and S. Lanceros-Mendez, *Polymer composites and blends for battery separators: State of the art, challenges and future trends*. *Journal of Power Sources*, 2015. **281**: p. 378-398. DOI 10.1016/j.jpowsour.2015.02.010
 273. Cho, T.H., M. Tanaka, H. Ohnishi, Y. Kondo, M. Yoshikazu, T. Nakamura, and T. Sakai, *Composite nonwoven separator for lithium-ion battery: Development and characterization*. *Journal of Power Sources*, 2010. **195**(13): p. 4272-4277. DOI 10.1016/j.jpowsour.2010.01.018
 274. Lee, Y.M., J.W. Kim, N.S. Choi, J.A. Lee, W.H. Seol, and J.K. Park, *Novel porous separator based on PVdF and PE non-woven matrix for rechargeable lithium batteries*. *Journal of Power Sources*, 2005. **139**(1-2): p. 235-241. DOI 10.1016/j.jpowsour.2004.06.055
 275. Li, S.L., X.P. Ai, H.X. Yang, and Y.L. Cao, *A polytriphenylamine-modified separator with reversible overcharge protection for 3.6 V-class lithium-ion battery*. *Journal of Power Sources*, 2009. **189**(1): p. 771-774. DOI 10.1016/j.jpowsour.2008.08.006
 276. Lee, Y.S., Y.B. Jeong, and D.W. Kim, *Cycling performance of lithium-ion batteries assembled with a hybrid composite membrane prepared by an electrospinning method*. *Journal of Power Sources*, 2010. **195**(18): p. 6197-6201. DOI 10.1016/j.jpowsour.2009.11.012
 277. Xiong, M., H. Tang, Y. Wang, and M. Pan, *Ethylcellulose-coated polyolefin separators for lithium-ion batteries with improved safety performance*. *Carbohydrate Polymers*, 2014. **101**(0): p. 1140-1146. <http://dx.doi.org/10.1016/j.carbpol.2013.10.073>
 278. Kuribayashi, I., *Characterization of composite cellulosic separators for rechargeable lithium-ion batteries*. *Journal of Power Sources*, 1996. **63**(1): p. 87-91. Doi 10.1016/S0378-7753(96)02450-0
 279. Zhang, S.S., *A review on the separators of liquid electrolyte Li-ion batteries*. *Journal of Power Sources*, 2007. **164**(1): p. 351-364. 10.1016/j.jpowsour.2006.10.065
 280. Jiang, W., Z.H. Liu, Q.S. Kong, J.H. Yao, C.J. Zhang, P.X. Han, and G.L. Cui, *A high temperature operating nanofibrous polyimide separator in Li-ion battery*. *Solid State Ionics*, 2013. **232**: p. 44-48. DOI 10.1016/j.ssi.2012.11.010
 281. Kritzer, P., *Nonwoven support material for improved separators in Li-polymer batteries*. *Journal of Power Sources*, 2006. **161**(2): p. 1335-1340. <http://dx.doi.org/10.1016/j.jpowsour.2006.04.142>
 282. Kim, J.H., J.H. Kim, E.S. Choi, H.K. Yu, J.H. Kim, Q.L. Wu, S.J. Chun, S.Y. Lee, and S.Y. Lee, *Colloidal silica nanoparticle-assisted structural control of cellulose nanofiber paper separators for lithium-ion batteries*. *Journal of Power Sources*, 2013. **242**: p. 533-540. DOI 10.1016/j.jpowsour.2013.05.142
 283. Chun, S.J., E.S. Choi, E.H. Lee, J.H. Kim, S.Y. Lee, and S.Y. Lee, *Eco-friendly cellulose nanofiber paper-derived separator membranes featuring tunable nanoporous network channels for*

- lithium-ion batteries. *Journal of Materials Chemistry*, 2012. **22**(32): p. 16618-16626. Doi 10.1039/C2jm32415f
284. Zhang, J.J., L.P. Yue, Q.S. Kong, Z.H. Liu, X.H. Zhou, C.J. Zhang, S.P. Pang, X.J. Wang, J.H. Yao, and G.L. Cui, *A Heat-Resistant Silica Nanoparticle Enhanced Polysulfonamide Nonwoven Separator for High-Performance Lithium Ion Battery*. *Journal of the Electrochemical Society*, 2013. **160**(6): p. A769-A774. Doi 10.1149/2.043306jes
285. Cho, T.-H., M. Tanaka, H. Onishi, Y. Kondo, T. Nakamura, H. Yamazaki, S. Tanase, and T. Sakai, *Battery performances and thermal stability of polyacrylonitrile nano-fiber-based nonwoven separators for Li-ion battery*. *Journal of Power Sources*, 2008. **181**(1): p. 155-160. <http://dx.doi.org/10.1016/j.jpowsour.2008.03.010>
286. Ye, W., J. Zhu, X. Liao, S. Jiang, Y. Li, H. Fang, and H. Hou, *Hierarchical three-dimensional micro/nano-architecture of polyaniline nanowires wrapped-on polyimide nanofibers for high performance lithium-ion battery separators*. *Journal of Power Sources*, 2015. **299**: p. 417-424. <http://dx.doi.org/10.1016/j.jpowsour.2015.09.037>
287. Cho, T.H., T. Sakai, S. Tanase, K. Kimura, Y. Kondo, T. Tarao, and M. Tanaka, *Electrochemical Performances of Polyacrylonitrile Nanofiber-Based Nonwoven Separator for Lithium-Ion Battery*. *Electrochemical and Solid-State Letters*, 2007. **10**(7): p. A159-A162. 10.1149/1.2730727
288. Jeschke, S., M. Mutke, Z. Jiang, B. Alt, and H.-D. Wiemhoefer, *Study of Carbamate-Modified Disiloxane in Porous PVDF-HFP Membranes: New Electrolytes/Separators for Lithium Ion Batteries*. *Chemphyschem*, 2014. **15**(9): p. 1761-1771. 10.1002/cphc.201400065
289. Li, H., Y.-M. Chen, X.-T. Ma, J.-L. Shi, B.-K. Zhu, and L.-P. Zhu, *Gel polymer electrolytes based on active PVDF separator for lithium ion battery. I: Preparation and property of PVDF/poly(dimethylsiloxane) blending membrane*. *Journal of Membrane Science*, 2011. **379**(1-2): p. 397-402. 10.1016/j.memsci.2011.06.008
290. Li, H., C.-E. Lin, J.-L. Shi, X.-T. Ma, B.-K. Zhu, and L.-P. Zhu, *Preparation and characterization of safety PVDF/P(MMA-co-PEGMA) active separators by studying the liquid electrolyte distribution in this kind of membrane*. *Electrochimica Acta*, 2014. **115**: p. 317-325. 10.1016/j.electacta.2013.10.183
291. Xi, J.Y., X.P. Qiu, and L.Q. Chen, *PVDF-PEO/ZSM-5 based composite microporous polymer electrolyte with novel pore configuration and ionic conductivity*. *Solid State Ionics*, 2006. **177**(7-8): p. 709-713. 10.1016/j.ssi.2006.01.032
292. Xi, J.Y., X.P. Qiu, J. Li, X.Z. Tang, W.T. Zhu, and L.Q. Chen, *PVDF-PEO blends based microporous polymer electrolyte: Effect of PEO on pore configurations and ionic conductivity*. *Journal of Power Sources*, 2006. **157**(1): p. 501-506. 10.1016/j.jpowsour.2005.08.009
293. Zhai, W., H.-j. Zhu, L. Wang, X.-m. Liu, and H. Yang, *Study of PVDF-HFP/PMMA blended microporous gel polymer electrolyte incorporating ionic liquid BMIM BF₄ for Lithium ion batteries*. *Electrochimica Acta*, 2014. **133**: p. 623-630. 10.1016/j.electacta.2014.04.076
294. Wang, H.P., H.T. Huang, and S.L. Wunder, *Novel microporous poly(vinylidene fluoride) blend electrolytes for lithium-ion batteries*. *Journal of the Electrochemical Society*, 2000. **147**(8): p. 2853-2861. 10.1149/1.1393616
295. Song, J.Y., Y.Y. Wang, and C.C. Wan, *Review of gel-type polymer electrolytes for lithium-ion batteries*. *Journal of Power Sources*, 1999. **77**(2): p. 183-197. 10.1016/S0378-7753(98)00193-1
296. Yoshio, M., R.J. Brodd, and A. Kozawa, *Lithium-ion batteries : science and technologies*. 2009, New York: Springer. xxvi, 452 p.
297. Juang, R.-S., C.-T. Hsieh, P.-A. Chen, and Y.-F. Chen, *Microwave-assisted synthesis of titania coating onto polymeric separators for improved lithium-ion battery performance*. *Journal of Power Sources*, 2015. **286**(0): p. 526-533. <http://dx.doi.org/10.1016/j.jpowsour.2015.04.023>

298. Choi, J.A., S.H. Kim, and D.W. Kim, *Enhancement of thermal stability and cycling performance in lithium-ion cells through the use of ceramic-coated separators*. Journal of Power Sources, 2010. **195**(18): p. 6192-6196.DOI 10.1016/j.jpowsour.2009.11.020
299. Jeong, H.S. and S.Y. Lee, *Closely packed SiO₂ nanoparticles/poly(vinylidene fluoride-hexafluoropropylene) layers-coated polyethylene separators for lithium-ion batteries*. Journal of Power Sources, 2011. **196**(16): p. 6716-6722.DOI 10.1016/j.jpowsour.2010.11.037
300. Zhang, Z.A., Z.Y. Zhang, J. Li, and Y.Q. Lai, *Polydopamine-coated separator for high-performance lithium-sulfur batteries*. Journal of Solid State Electrochemistry, 2015. **19**(6): p. 1709-1715.10.1007/s10008-015-2797-8
301. Fang, L.F., J.L. Shi, H. Li, B.K. Zhu, and L.P. Zhu, *Construction of Porous PVDF Coating Layer and Electrochemical Performances of the Corresponding Modified Polyethylene Separators for Lithium Ion Batteries*. Journal of Applied Polymer Science, 2014. **131**(21).4103610.1002/app.41036
302. Liu, H., Z. Dai, J. Xu, B. Guo, and X. He, *Effect of silica nanoparticles/poly(vinylidene fluoride-hexafluoropropylene) coated layers on the performance of polypropylene separator for lithium-ion batteries*. Journal of Energy Chemistry, 2014. **23**(5): p. 582-586.10.1016/s2095-4956(14)60188-1
303. Liu, H., J. Xu, B. Guo, and X. He, *Effect of Al₂O₃/SiO₂ composite ceramic layers on performance of polypropylene separator for lithium-ion batteries*. Ceramics International, 2014. **40**(9): p. 14105-14110.10.1016/j.ceramint.2014.05.142
304. Prasanna, K., C.-S. Kim, and C.W. Lee, *Effect of SiO₂ coating on polyethylene separator with different stretching ratios for application in lithium ion batteries*. Materials Chemistry and Physics, 2014. **146**(3): p. 545-550.10.1016/j.matchemphys.2014.04.014
305. Shi, C., P. Zhang, L. Chen, P. Yang, and J. Zhao, *Effect of a thin ceramic-coating layer on thermal and electrochemical properties of polyethylene separator for lithium-ion batteries*. Journal of Power Sources, 2014. **270**: p. 547-553.10.1016/j.jpowsour.2014.07.142
306. Wang, J., Z. Hu, X. Yin, Y. Li, H. Huo, J. Zhou, and L. Li, *Alumina/Phenolphthalein Polyetherketone Ceramic Composite Polypropylene Separator Film for Lithium Ion Power Batteries*. Electrochimica Acta, 2015. **159**: p. 61-65.10.1016/j.electacta.2015.01.208
307. Xiao, W., L. Zhao, Y. Gong, S. Wang, J. Liu, and C. Yan, *Preparation of high performance lithium-ion batteries with a separator-cathode assembly*. Rsc Advances, 2015. **5**(43): p. 34184-34190.10.1039/c5ra03769g
308. Jung, Ji-Won, Lee C.L, Yu, S and Kim Il-Doo, *Electrospun nanofibers as a platform for advanced secondary batteries: a comprehensive review*, J. Mater. Chem. A, 2016, 4, 703, DOI: 10.1039/c5ta06844d
309. Lee, H., Yanilmaz, M., Toprakci, O., Fu, K., Zhang, XW., *A review of recent developments in membrane separators for rechargeable lithium-ion batteries*, Energy Environ. Sci., 2014, 7, 3857, DOI: 10.1039/c4ee01432d

Figure(s)

Figures

Figure 1a:

Figure 1b:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6:

Figure 7:

Figure 8:

Figure 9

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Figure 11

Figure 12:

Figure 13:

Figure 14:

Figure 15:

Figure 16:

Figure 17: