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Review Article

Progress in Application of CNTs in Lithium-Ion Batteries

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The lithium-ion battery is widely used in the fields of portable devices and electric cars with its superior performance and promising energy storage applications. The unique one-dimensional structure formed by the graphene layer makes carbon nanotubes possess excellent mechanical, electrical, and electrochemical properties and becomes a hot material in the research of lithium-ion battery. In this paper, the applicable research progress of carbon nanotubes in lithium-ion battery is described, and its future development is put forward from its two aspects of being not only the anodic conductive reinforcing material and the cathodic energy storage material but also the electrically conductive framework material.

1. Introduction

New energy technology is of great importance for the sustainable development of human society. Li-ion batteries (LIBs) have been developing robustly due to their advantages such as high energy density, long cycle life, low self-discharge, nonmemory effect, and environmental friendliness since they were developed by SONY corp. in 1990. And they have been widely applied in many fields including mobile phone, laptop, and auto power batteries. Meanwhile, it is anticipated that they can be used on a large scale in the storage of clean electric energy that is produced by solar energy and wind energy [1, 2]. Carbon nanotubes (CNTs) can serve as one-dimensional nanomaterials and they can be made into two kinds of CNTs—single-walled carbon nanotube (SWCNT) rolled up by one-layer graphene and multiwalled carbon nanotube (MWCNT) rolled up by multilayer graphene. CNTs have excellent mechanical, electrical, and chemical properties due to their light weight and perfect connection in their hexagon structure. In recent years, with the progress in the research on CNTs and nano materials, the prospect of wide application of CNTs is emerging [3–6], because of its excellent electrochemical properties, (10^6 Sm^{-1} at 300 K for single-walled CNTs (SWCNTs) and $>10^5$ Sm^{-1} for multiwalled nanotubes (MWCNTs)), low density, high rigidity, and high tensile strength [7]. CNTs are widely used in lithium-ion batteries, both as the anode material and the conductive additive in the composite electrodes. In this paper, the progress of latest research on the application of CNTs in anode and cathode materials is discussed.

2. Application of CNTs in Anode Materials

CNTs have the typical hollow structure of multilayer and are the coaxial circular tube mainly composed of a dozen of layers of carbon atoms arrayed in hexagon. There is a certain distance, 0.34 nm, between two neighboring layers with the diameter ranging from 2 nm to 20 nm. The low density of carbon atom and the typical structure of CNTs allow the imbedding of Li-ion. Thanks to the structure defect on the surface and edge of CNTs, as well as the nanoscale slit between walls, Li-ion can be imbedded not only anywhere on CNTs wall, but also between layers [8]. Udomvech et al. [9] have found out that it is easy for Li/Li^+ to spread along the wall inside; however, it is easier for Li/Li^+ to be imbedded on the location of C6 on the surface outside; thus, an effective opening on the end or adding more defects will help Li/Li^+ to spread inside. Nishidate and Hasegawa [10] have discovered after calculating that the defect on the surface of SWNT facilitates the entrance of Li^+ and the entrance of Li^+ can add more defects in turn, which deepens the imbedding of Li^+ and shortens the process; as a result, Li^+ can be imbedded not only anywhere inside the tube, but also in the gap. Studies on electron density have revealed that complete charge transfer happens between Li^+ and CNTs after Li^+ is imbedded in

the tube. Meanwhile, the imbedding causes slight structural deformations in the CNTs. And inside CNTs, the gap between layers allow Li^+ to enter [11]. Wu et al. [12] found that the structures of the CNT played major roles in both specific capacity and cycle life. Slightly graphitized CNT showed a specific capacity of 640 mAh g^{-1} during the first charge and after 20 charge/discharge cycles the charge capacity of the slightly graphitized samples degraded to 65.3%, whereas well-graphitized carbon nanotubes showed a specific capacity of 282 mAh g^{-1} during the first charge and 91.5% of their original charge capacities after 20 charge/discharge cycles.

2.1. Raw CNTs as Anode Materials. The graphite structure of CNTs allows that CNTs can be used as the electrode material in the place of graphite. As is often the case, the specific capacity of SWCNT is 400–460 mAh g^{-1}, but it can reach above 1000 mAh g^{-1} after introducing defects on the surface. The solid electrolyte interface (SEI) can be formed at around 0.9 V, which can remarkably reduce the specific capacity during the first electrochemical cycle. Landi et al. [13] discover that although the melting point of propene carbonate (PC) is quite low, the graphitic layer can be peeled off when graphite is used as the anode material, and if SWCNT is used as the anode material, when PC is added to the system consisting of ethylene carbonate (EC) and dimethyl carbonate (DMC), the reversible specific capacity can be improved effectively, retaining 95% with the specific capacity of 520 mAh g^{-1} at the 10th cycle. A layer of 3,4-ethylenedioxythiophene (PEDOT) with good conductivity and electrochemical activity has been polymerized on the top of MWCNT array by Chen et al. [14] to improve the conductivity between the CNTs. A layer of polymer as thick as 0.5 μm can be formed by painting 10% PVDF in acetonitrile solvent on the layer of PEDOT, and the intensity can peel the array completely off the silicon substrate. As the anode material, a specific capacity of 265 mAh g^{-1} could be reached without noticeable fading of capacity after 50 cycles. Pushparaj et al. [15] have built a multilayer nanocomposite serving as the thin power storage device with electrode, separator, current collector, and electrolyte in a way similar to that of building blocks. An even interface that can be peeled off can be formed after the mixture of cellulose and 1-butyl 3-methyl imidazole chloride which is a PTIL permeating into the CNTs array. The interface can be used as the electrode to assemble supercapacitors or lithium-ion batteries or to assemble the double-layer device by capacitors and lithium batteries. As the lithium-ion battery, the working voltage is 2.1 V, and the specific capacity of CNTs is 430 mAh g^{-1} after the first charge and discharge while that will drop to 110 mAh g^{-1} after 10 cycles. The specific capacity of 373 mAh g^{-1} and good cyclability have been realized by Zhang et al. [16] through using the CNTs array as the electrode. He also discusses the lithium storage mechanism of carbon tube. It is believed that the graphite in the inner layer provides better conducting passages so as to avoid the loss of active material in the process of charge and discharge. Therefore, the performance of cycle is good. There are many defects on the graphene layer on the surface of carbon tube. During the process of charging, Li^+ can insert between graphite layers through these defects, which will deform the graphene layer close to these defects, especially on the top of CNTs, as shown in Figure 1 where the deformation is quite obvious. More defects on the top will be produced in the period of nucleation growth of carbon tube. The reversible specific capacity of 279 mAh g^{-1} is lower than that of graphene (372 mAh g^{-1}), corresponding to a chemical composition of about $Li_{0.75}C_6$. The diffusion distance of Li^+ inside the wall of carbon tube is very short, less than 10 nm, which avoids the damages to the inner layer and the section far from defects. This frame with high mechanical strength can avoid the damage on materials in the process of charge and discharge, guaranteeing its cyclability.

The resistance of CNTs array is 1–5 kΩ/cm^2, which hinders the electron transportation and generates heat. Therefore, the CNTs growing directly on the current collector have attracted people's concern. The CNTs can grow on the carbon layer which is loaded on metal foil by Chen et al. [17]. The resistance between carbon and copper foil is only 1-2 Ω; this resistance of carbon tube is similar to that of carbon, which can be ignored. After 100 cycles, the specific capacity is 572 mAh g^{-1} and the compound between Li and graphite layer is $Li_{1.6}C_6$. Carbon sheet CNTs composite electrode material is produced by Chen et al. [18] through chemical vapor deposition (CVD) on carbon fiber sheet. There is good contact between CNTs and carbon fiber sheet and the CNTs have put their advantage of large specific surface, so it has good low-temperature stability and chemical stability. Its specific capacity was retained at 546 mAh g^{-1} after 50 cycles. The catalyst of Ti-Ni thin layer (20–25 nm) on copper foil has been loaded by Lahiri et al. [19] through magnetron sputtering and thus carbon tubes can directly grow on the copper foil through CVD method, which produces the electrode free of adhesive. The carbon tube is tightly connected to the copper foil which is used as the substrate and current collector with good conductivity, which makes the specific capacity of electrode (900 mAh g^{-1}, 1 C) three times as that of graphite. Even at high charge/discharge current densities of 3 C rate, the electrode still keeps good curve. It shows negligible capacity decay with capacity retention of 99% after 50 cycles.

As a flexible electrode, CNT fiber or CNT paper can be used as active material and current collector, which can effectively reduce the contact resistance and electrode weight. With the development of wearable electrode application, the material of thread binding energy storage has attracted researchers' attention [20, 21]. The self-supporting CNT paper has some strength and stability without any adhesion, so it can be used as the electrode material of flexible device and helps improve the specific capacity of electrode. Ng et al. [22] have produced SWNT agents through the ultrasound of SWNT and Triton X-100 in water; the unsupported SWNT paper serving as the electrode of lithium-ion batteries has also been produced through pressure filtration method in which poly (vinylidene luoride) (PVDF) membrane with the aperture of 0.22 μm is used as filter membrane. The electrolyte is 1 mol/L $LiPF_6$ in ethylene carbonate (EC) and dimethyl carbonate (DMC) (1 : 1), and its specific capacity

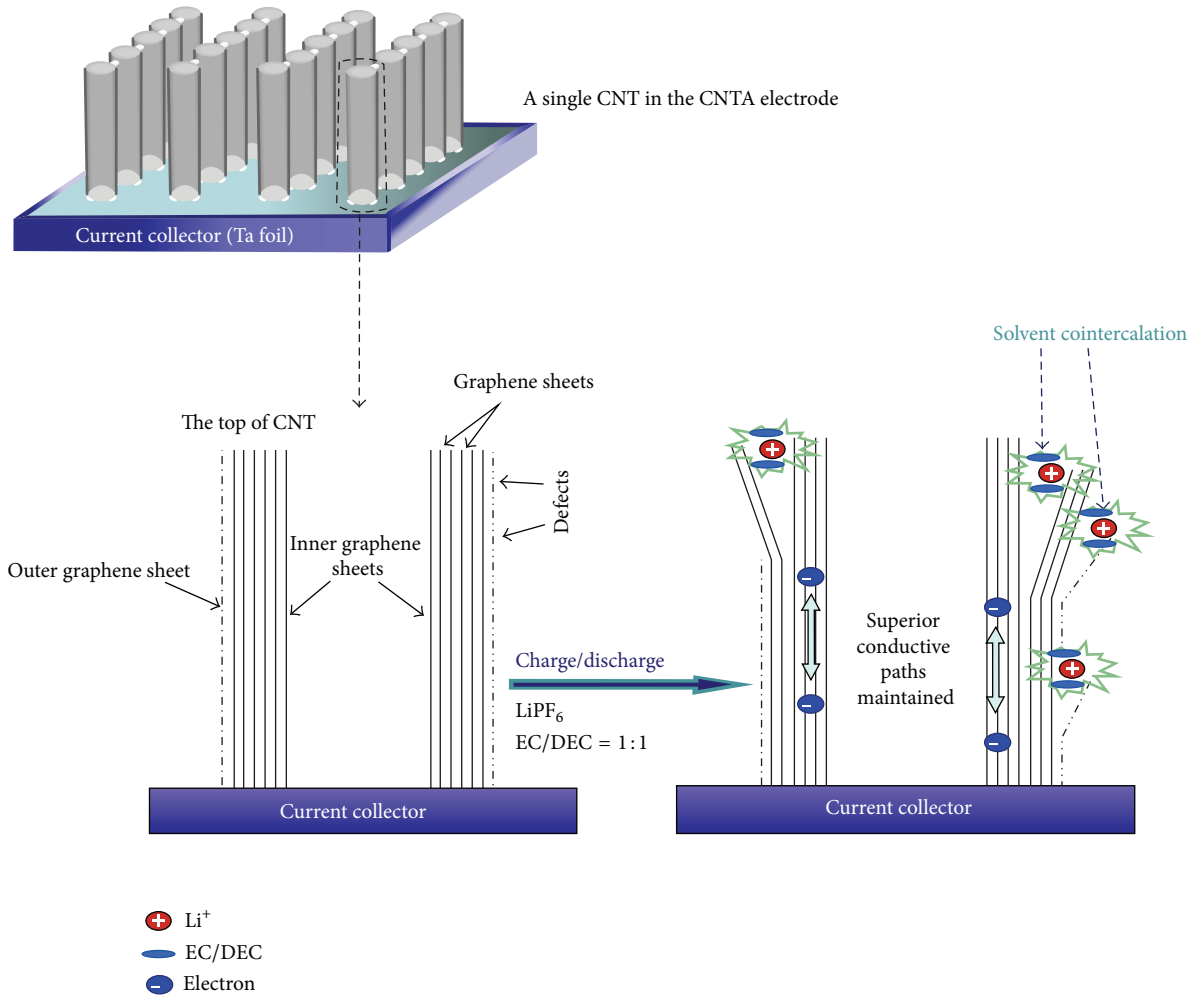

FIGURE 1: Schematic representation of the microstructure and energy storage characteristics of the CNTA anodes.

is 180 mAh g^{-1} which will be raised to about 230 mAh g^{-1} with good cyclicity when loaded on Ni layer. Chew et al. [23] have produced self-supported CNT film with this method and the performances of SWCNTs, DWCNTs, and MWCNTs are compared. In the study on oxidation process, MWCNTs display good reversibility and the Li/Li^+ redox peaks appear at about the potential of 0.15 V. As for graphite material, the peaks correspond to lithium insertion and extraction. In particular, the 10–20 nm hollow MWCNTs facilitate the spread of Li^+. Oxidation peak of Li/Li^+ appears at the position of 1.2 V in SWCNTs and DWCNTs, which means Li^+ has reacted with the oxygen-containing functional groups on the surface to produce COO^-Li^+ or Li^+ has reacted with hydrogen in the CNTs. Li^+ can mainly penetrate the place between the external walls of SWCNTs and DWCNTs and their inner walls. Comparatively speaking, MWCNT is more suitable for lithium-ion batteries.

2.2. Composite of CNTs as the Anode Material. In the past decades, to improve the performance of CNT electrode, materials with high specific capacity such as metallic oxide and Si are combined with CNTs in many studies, which play its advantage of huge specific surface area and the role of supporting and conducting as the frame. Ren et al. [24] have produced flexible fibrous lithium-ion batteries through spinning CNTs into fibers on which MnO_2 was deposited, which is shown in Figure 2. As an N-type wide-band-gap semiconductor (300 k, Eg = 3.6 eV), SnO_2 is one kind of anode material of great application potential [25]. However large volume change during lithiation/delithiation process makes the electrochemical active particles crack and lose the electrical contact, which results in fast decline of reversible capacity. MWCNTs composite material coated by a layer of even SnO_2 is produced by Wang et al. [26] through thioglycolic acid assisted hydrothermal method and the thickness of SnO_2 can be controlled by reaction conditions. After the SEI interface is formed in the first cycle, the specific capacity is improved and the stability is quite good. After 50 cycles of complete charge and discharge of 0.2 C rate, the specific capacity stays at 435 mAh g^{-1} which is higher than that of graphite. $SnCl_{0.5}$ and Sb nanoparticles are produced on the external wall of CNTs through reduction reaction by Chen et al. [27]. When the weight ratio of Sb is 36 wt%, the specific capacity is 462 mAh g^{-1} while when the weight ratio of SnSb

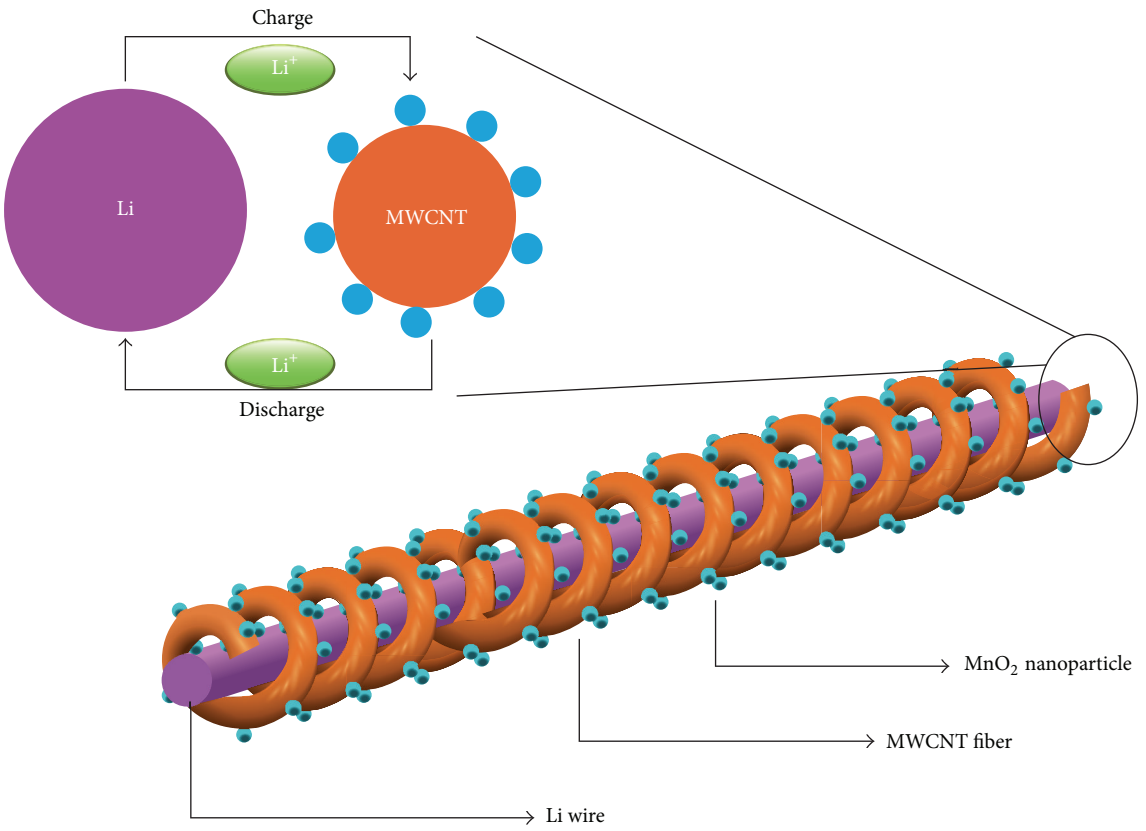

FIGURE 2: Schematic illustration to the wire-shaped lithium-ion battery fabricated by twisting an aligned MWCNT/MnO_2 composite fiber and Li wire as positive and negative electrodes, respectively.

is 56 wt%, the specific capacity is 518 mAh g^{-1}. After 30 cycles, the capacity retention is 62.1% and 67.2%, respectively. As a buffer, CNTs reduce the damage on nanoparticles during lithiation/delithiation. Zhang et al. [28] have produced the CNTs array with CVD before drawing the array into a CNT film on which nano SnO_2 is produced. The specific capacity is as high as 850 mAh g^{-1}, and it retains 100% after 65 cycles at 0.01–3 V voltage range. The Co_3O_4 was reported to show a high theoretic reversible specific capacity of 890 mAh g^{-1} [29]. Park et al. [30] fabricated vertically aligned mesoporous carbon nanotubes (MCTs) by a dual template method: a hard template-assisted sol-gel process. And this kind of carbon nanotubes was filled with Co_3O_4 nanoparticles (NPs). As an anode material, it shows a high reversible capacity of about 627 mAh g^{-1} after the 50th discharge. The small-size of Co_3O_4 NPs improved electrochemical performance of Co_3O_4/MCT and the rapid diffusion of Li-ions was induced by the three-dimensional structure of the MCT. Therefore, the 3D nanostructure can be widely applied to other promising 11 conversion reaction electrodes to improve LIB performance.

Si and Lithium can produce Si-Li alloy phase of Li_2Si_5 whose specific capacity can reach 4200 mAh g^{-1}, having great potential of replacing graphite; thus, the study on silicon nanowire, porous silicon, and carbon fiber covering amorphous silicon has been accelerated. One-dimensional composite material has been produced by Wang and Kumta [31] through depositing nanocrystalline silicon on CNTs array with simple two-step pouring liquor into chemical vapor deposition. Nano silicon clusters connect tightly with CNTs, which minimize the loss when the silicon connects with and desorbs from Li^+. This novel structure has good rate capability, high reversible capacity (2050 mAh g^{-1}), and good stability (after 25 cycles, only 20% has been reduced). The capacity loss results mainly from the damage on the boundary between the silicon and CNTs as well as the hindering of Li^+ transport by SEI's weakening. Rong et al. [32] proposed a kind of anode material—a layer of silicon formed on SWNTs. This method can effectively improve the performance of silicon electrode easily. A rough surface can be formed on SWNT which produces a layer of buffer between copper foil current collector and silicon layer. At 0.1 C rate, the specific capacity is 2221 mAh g^{-1} after 40 cycles, which is 3.6 times as that of silicon layer directly covering the copper foil and 11 times as that of SWNT. And after 40 cycles, a stable porous structure can be formed. Kawasaki et al. [33] add 9,10-Dihydroanthracene, β-carotene and hexabenzobenzene to form pod structure which obtained high irreversible specific capacity (>900 mAh g^{-1}). Compared with that of pure CNTs, the specific capacity of CNTs added with organics can be improved 2.5 times. Wang et al. [34] reported that super-aligned CNT films could be used as current collectors for LIBs. The CNT current collectors are with excellent flexibility, extremely low density, stronger adhesion, lower contact resistance, and higher energy density than those with metal

current collectors. Fu et al. [35] used the super-aligned CNT sheet as the current collector on which the silicon active material is deposited. The aligned CNT structure provides significant uniform deposition of silicon coatings. The charge capacity was 1494 mAh g^{-1} after 45 cycles with a capacity retention of over 94%. The CE for each cycle was stabilized above 98%. Lin et al. [36] reported the development of novel wire-shaped lithium-ion batteries fabricated by twisted, aligned multiwalled MWCNT/Si composite fiber anodes for flexibility. The Si exhibited a high capacity and remained at 1648 mAh g^{-1} in 30 cycles at 0.6 C (1 A g^{-1}). Weng et al. [37] used a new type anode which was fabricated by three-dimensionally aligned CNT/Si hybrid to develop for LIB. The LIBs have high specific capacity and cyclic stability which were retained at 1055 mAh g^{-1} after 1000 13 cycles at 5 A g^{-1}.

3. Application of CNTs in Cathode Material

Cathode material is the provider of Li^+. Currently, the materials in lithium-ion batteries are mainly inorganic salts including $LiCoO_2$ of hexagonal layered structure, $LiMn_2O$ of spinel structure, and $LiFePO_4$ of olivine structure. In the circle of research, the conducting polymer used as the cathode material of lithium-ion batteries has got more and more attention. The cathode materials determine the safety performance of batteries and a major technical bottleneck of improving the specific capacity of batteries as well.

$LiFePO_4$ is a kind of cathode material which has been widely studied and applied because of its low price, environmental compatibility, high theory specific capacity (170 mAh g^{-1}), proper working voltage (3.42 V versus Li^+/Li), and secure safety. However, in the structure of $LiFePO_4$, the PO_4 tetrahedral between the octahedron limits the change in the capacity of crystal lattice, influencing the intercalation of Li-atom and de-Li atom, which slows down the spread of ions of $LiFePO_4$. Meanwhile, since there is no a continuous network of octahedron, electric conductor cannot be formed, which lowers the electronic conductivity of $LiFePO_4$. Therefore, studies on the modification of $LiFePO_4$ all focus on how to improve the conductivity. $LiFePO_4$/MWCNTs have been produced through hydrothermal by Jin et al. [38] who have explored the electrical property of batteries at room temperature. The conductivity of composite material at RT is 1.08×10^{-1} S/cm, 8 times as that of pure $LiFePO_4$. The CNTs added can not only improve the electronical conductivity, but also improve the Li^+ diffusion coefficient, reducing the crystallite size and transportation resistance. For the diffusion of Li^+ into $LiFePO_4$, it has to pass a 1-dimensional passage in which the defect of $LiFePO_4$ will hinder the diffusion of Li^+. As a result, how to reduce the defects is an important direction in the study on $LiFePO_4$. On one hand, it is admitted that defects of amorphous substances such as $FePO_4$ cannot affect the diffusion of Li^+, but the speed of Li^+' intercalation and deintercalation can be influenced by the low conductivity of $FePO_4$. Core-shell nanowire has been produced from CNT-amorphous $FePO_4$ and been used in making anode by Kim et al. [39]. At 3.4 V, a smooth discharge voltage plateau appears and the specific capacity is 149 mAh g^{-1}, so it is of good stability. Similarly, Hosono et al. [40] has produced spinning $LiFePO_4$ whose core is MWCNTs and complex shell of $LiFePO_4$ and amorphous carbon, and this nanowire is used as cathode of lithium-ion batteries through electrostatic spinning. CNTs play a leading role in the electron transportation and inhibition the oxidization of Fe^{2+}. At 0.1 A g^{-1}, the specific capacity is 130 mAh g^{-1}, and the rate capability and cycle properties are excellent. $LiMn_2O_4$-MWCNTs composite material has been produced by Liu et al. [41] with sol-gel method. As the 1-dimensional conductor in nanocomposite material, CNTs facilitate the transport of electron; the resistance of composite material is far lower than that of $LiMn_2O_4$ of spinel structure and displays high cycle stability after 20 cycles; the capacity retention is 99% while that of pure $LiMn_2O_4$ is only 9%. Xia et al. [42] synthesized ultrafine $LiMn_2O_4$/carbon nanotube (CNT) nanocomposite by a one-step hydrothermal treatment. In the nanocomposite, the CNTs not only provide a conductive matrix, but also effectively reduce agglomeration of $LiMn_2O_4$ nanoparticles which between 10–20 nm in diameters are well crystallized and uniformly distributed in the CNT matrix. The nanocomposite with unique structural and morphological features exhibits superior high-rate capability and long term cycling stability, delivering discharge capacities of 116 mAh g^{-1} (92% retention) after 500 cycles at 1 C rate and 77 mAh g^{-1} (77% retention) even after 1000 cycles at 10 C. Porous material provides channels for a rapid diffusion of Li^+ and the scattered conductive network can effectively guarantee the supply of electron (Figure 3), which improves the diffusion speed of Li^+. Porous $LiFePO_4$-CNT composite material has been synthesized by Zhou et al. with sol-gel method [43]. The oxidation peak and reduction peak appear at 3.51 V and 3.38 V, respectively, and the potential difference is 0.13 V which improves the irreversibility and reaction activity.

Due to the innovative work of Tarascon which revealed a new strategy for high capacity electrodes by exhibiting that metal oxides can store more than one Li ion per transition metal atom, many researchers have investigated various conversion reaction compounds, such as metal nitrides, sulfides, fluorides, and oxides [44–46]. As a kind of novel cathode material, Vanadium pentoxide (V_2O_5) obtains the characteristics of low cost and being earth-rich and shows much higher energy density than traditional $LiMn_2O_4$, $LiCoO_2$, and $LiFePO_4$ materials [47]. But the multiphase transitions of V_2O_5 in the charge/discharge process correspond to the multiple voltage plateaus, which caused repeated damages to the structure of V_2O_5. To improve the structural stability of V_2O_5, Zhou et al. [48] synthesized vanadium oxide nanosheet-MWCNT composite via sol-gel method and subsequent hydrothermal treatment process. This nanosheet-MWCNT composite with distinct single phase transition feature displays high specific capacity and good cycling stability owing to its sheet-like nanostructure and uniform adding of MWCNTs, which makes this novel composite quite suitable. Cao and Wei [49] prepared V_2O_5/SWNT hybrid films with mesoporous structure by a simple floating CVD method. Li^+ diffusivity can be promoted by 2 to 4 orders due to SWNTs. The hybrid films as cathodes for lithium-ion

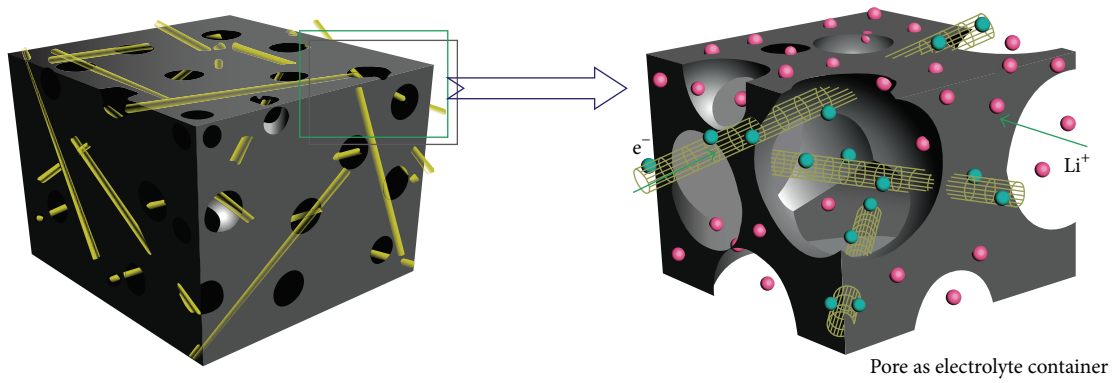

FIGURE 3: Schematic illustrations of the porous $LiFePO_4$-CNT composite. (b) is an enlarged zone from (a), showing the corresponding electron transport and ion diffusion mechanisms.

batteries demonstrate a high rate capacity of 548 mAh g^{-1} at the discharge rate of 1 C. Kim et al. [46] fabricated nanoarchitectures composed of FeF_3 nanoflowers on CNT branches by functionalizing the surfaces of CNT with FeF_3. Electron transport made the nanostructured cathode deliver more than 210 mAh g^{-1} at a current rate of 20 mA g^{-1} with the specific energy about 650 Wh kg^{-1} under these conditions of average discharge voltage of about 3.1 V in the voltage range 2.0–4.5 V, which was higher than conventional cathode materials.

In recent years, researchers have made a wide range of investigation on rechargeable lithium-sulfur (Li-S) batteries due to theoretically high specific capacity (1675 mAh g^{-1}), low cost, and environmentally benign sulfur. The rechargeable Li-S cell works through reducing S at the cathode on discharge to form various polysulphides combining with Li to finally produce Li_2S [50, 51]. The commercialization of lithium-sulfur batteries is hindered by inadequate electrode rechargeability and limited rate capability induced by sulfur active material loss and polysulfide shuttle reaction through dissolution into electrolyte. Wang et al. [51] synthesized three-dimensional carbon nanotube frameworks with bipyramidal sulfur particles by simple mixing of multiwalled carbon nanotubes (MWCNTs), sulfur powder, and capping agents in water/tetrahydrofuran. The Li-S cells deliver a specific discharge capacity of ≈1600 mAh g^{-1} at 0.05 C on the first cycle. Guo et al. [52] fabricated disordered carbon nanotubes (DCNTs) due to a template wetting technique which means impregnating sulfur into DCNTs as cathode material for Li-S batteries. The superior cyclability (showed better stability of 72.9% retention after 100 cycles except the first one,) and Coulombic efficiency (at 0.25 C rate were averagely at 89% and 96% during 100 cycles) were demonstrated in the obtained sulfur-carbon tube cathodes.

As the cathode material of lithium batteries, conducting polymer has many characteristics such as being safe and easy to use. The conducting polymer such as polyacetylene and polypyrrole has great application potential. However, compared with inorganic cathode material, there is a problem of low working voltage. Poly-PMT has drawn wide attention with its high oxidative potential (3.6 V versus Li/Li^+). With in situ polymerization, Kim et al. [53] have synthesized poly(PMT)/MCNT; PMT/CNT is used as the cathode while incombustible 1-Ethyl-3-methylimidazolium Tetrafluoroborate ($EMIBF_4$) and $LiBF_4$ make up the ionic liquid electrolyte. Polymer lithium-ion batteries of high safety and high voltage have been produced with the porous membrane of *P* (VdF-co-HFP) and the specific capacity at 1.0 C is 80 mAh g^{-1}. The specific capacity can be reduced dramatically by the degradation of or damage on polymer because of the contraction and swelling of polyaniline during the charge and discharge process. With the method of in situ polymerization, Sivakkumar and Kim [54] have produced PAN/CNT composite electrode material. The charge voltage remains at 3.7 V after 250 cycles; in the potential range of 2.0–3.9 V, the cell delivered a maximum discharge capacity of 86 mAh g at the 80th cycle with an average Coulombic efficiency of 98%.

After carboxylation and amination, CNTs have been assembled as the cathode of lithium batteries by Horn with layer-by-layer method [55], and the thickness ranges from 20 nm to 30 μm or even more thicker. The output power, 10 times as that of ordinary lithium batteries, can reach 100 kW Kg^{-1} and the specific capacity preserves at the original one—about 200 mAh g^{-1} after 1000 cycles. This is the first report in which CNTs have been used as the cathode of lithium-ion batteries, and the reaction mechanism of $C = O_{LBL\text{-}MWNT} + Li^+ \leftrightarrow C\text{-}OLi_{LBL\text{-}MWNT}$ is different from LixC formed by graphite material and Li^+. This has widened and deepened the application of CNTs in lithium-ion batteries.

4. Prospect

As an electrode material for lithium-ion batteries, CNTs have promising prospect of application. Although the study on CNTs has made much progress, there is great potential. In future studies and researches, more efforts and energy should be invested in the following aspects. Firstly, it is necessary

to further the study on the lithium storage mechanism of CNTs. The influence of the tubes' length, diameter, number of walls, and defects on the wall on the performance of lithium storage should be analyzed and tested both theoretically and empirically in order to minimize the loss of specific capacity after the formation of SEI and to improve the stability and cycle performance. Secondly, the study on composite material of CNTs as electrode should be expended. As the surface template and conductive frame with high specific capacity, CNTs can give greater play. Thirdly, the cost should be cut down, technology be simplified, and performance be stabilized in the real application of CNTs in electrode material.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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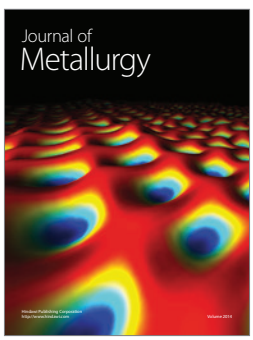
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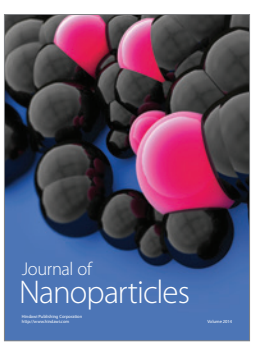
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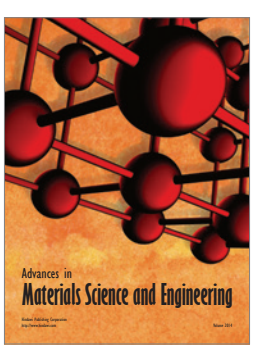
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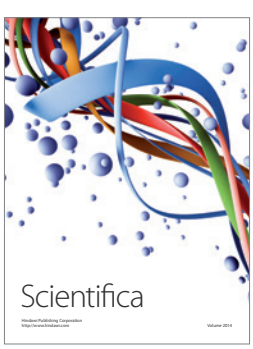
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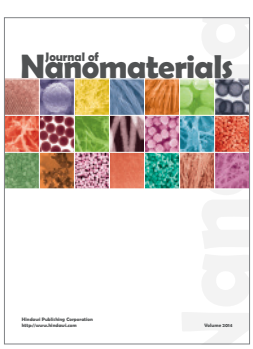
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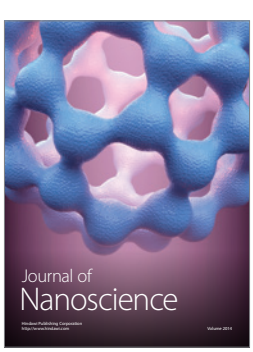
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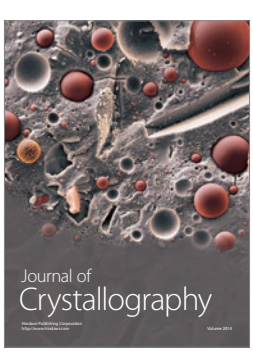
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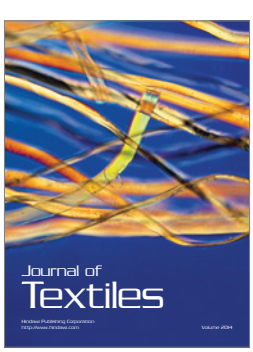
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