Cost Effective and Scalable Synthesis of MnO$_2$ Doped Graphene in a Carbon Fiber/PVA: Superior Nanocomposite for High Performance Flexible Supercapacitors

Mohammad Javad Taghizadeh$^1$, Behzad Poorbadiei$^2$, Esmail Soholi$^1$

$^1$Department of Chemistry, School of Sciences University of Imam Hossein, Tehran, Iran

$^2$Faculty of Chemistry, University of Sharif, Tehran, Iran

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Abstract

In the current study, we report new flexible, free standing and high performance electrodes for electrochemical supercapacitors developed through a scalable but simple and efficient approach. Highly porous structures based on carbon fiber and poly (vinyl alcohol) (PVA) were used as a pattern. The electrochemical performances of Carbon fiber/GO-MnO$_2$/CNT supercapacitors were characterized using cyclic voltammetry, galvanostatic charge/discharge and impedance spectroscopy techniques. The porosity of the electrode material was determined by scanning electron microscopy. The electrode specific capacitance was calculated to be 68Fcm$^{-1}$-150 mv/s from cyclic voltammetry. The prepared films could be directly used as flexible supercapacitor electrodes and exhibited a highly specific capacitance and good cycle stability. The porous structures of films pave the way for emission without blocking for electrolyte ions and increase the specific area of the material. The electrochemical analysis confirms that the Carbon fiber/GO-MnO$_2$/CNT has improved particular capacitance compared to Carbon fiber/GO-MnO$_2$ and Carbon fiber/MnO$_2$. This study offers a new extremely light, conductive, inexpensive and environmentally friend electrode material that are promising for future flexible and efficient electrochemical supercapacitors.

Keywords: Supercapacitors, Superior Nanocomposite, Graphene, Carbon Fiber/PVA.

*Corresponding author: Mohammad Javad Taghizadeh, Department of Chemistry, School of Sciences University of Imam Hossein, Tehran, Iran, E-mail: mohammadjavataghizadeh31@yahoo.com.*
Introduction

The growing demand for the energy and environmental challenges facing the world leading to use of renewable energy sources such as batteries and supercapacitors (SPs). Over the past few years, SPs have paid close attention to wide range of applications including power utility applications and as back up energy storage due to their superior properties such as fast charging/discharging rates, high power performance, long cycle life and excellent environmental safety [1,2]. Today, flexible energy storage devices are widely considered to be used in portable and wearable electronic systems in varied fields. SPs are classified into two groups: electrochemical double layer capacitors (EDLC) and pseudocapacitors. Pseudocapacitors can possess higher capacitance per gram than EDLCs. Therefore, it has been attempted to make lightweight, low cost and large-scale manufacturing of materials with pseudocapacitance properties [3,4].

Recently, many efforts have been made to investigate new electrode materials to enhance cyclic stability and increasing the capacitance of the SPs. There are three major types of electrode materials: 1) carbon source materials such as CNT, graphene, activated carbon, nanodiamonds with high specific surface area based on double layer capacitance mechanism; 2) conducting polymers and 3) metallic oxides transmitted with pseudocapacitance or Faradic process. Nowadays, hybrid capacitors are designed using both high-surface area carbonaceous materials and pseudocapacitance materials comprehensively in a single electrode. Rapid replacement of inherent redox switching and low weight. Among these, MnO$_2$ has received much research attention due to its facile synthesis, low cost, high specific capacitance and long-term stability [5,6]. At present, there is an increasing demand for low-cost, environmentally friendly and renewable electronic devices derived to fabricating biobased as well as flexible, scalable and efficient energy storage devices such as SPs [7-9]. For instance, Dominko and his co-workers, developed low surface area graphene/cellulose composite a host matrix for Li/S batteries [10]. Shao and his co-workers used cellulose nanofibers paper as the SP substrate [11]. In the other related study, Deng et al. made solid-state and flexible PANI/Ag/cellulose aerogel supercapacitors [12]. It is worth noting that the drawback associated with metal oxides is its poor conductivity. Therefore, different approaches have been developed to achieve high performance, lightweight and conductivity composites of metal oxides. Polyvinyl alcohol (PVA), has been widely used as the gel electrolyte of SPs due to its availability, hydrophilicity, chemical resistance properties as well as excellent mechanical properties and good film forming [13,14].

Herein, we report a simple strategy for producing Carbon fiber/GO-MnO$_2$/CNT ternary hybrid nanocomposite with potential application as electrode for SPs (scheme 1). The porous and paper-like carbon fiber was used to support the MnO$_2$ nanoparticles. PVA was used as the polymer matrix.
and stabilizer of GO-MnO$_2$ and CNT on the carbon fiber sheets. To the best of our knowledge, a flexible electrode material based on carbon fiber has not been studied yet. The ternary composite material exhibited excellent specific capacitance up to 168 F/cm$^2$ and good cycling stability. It has been observed that the porous structure and addition of CNT increase the electrochemical capacitance of the electrode. Therefore, excellent mechanical properties of PVA, the high specific surface area of carbon based materials and pseudocapacitance of MnO$_2$ prepared low cost and scalable electrode in potential energy storage devices.

Scheme 1. producing Carbon fiber/GO-MnO$_2$/CNT ternary hybrid nanocomposite.

Experimental

Materials and Methods
Poly (vinyl alcohol) with molecular weight of 145000, Carbon fiber (CF) (from China), natural graphite powder, potassium permanganate (KMnO$_4$) (from Merck) sulfuric acid (H$_2$SO$_4$, 98%), hydrochloric acid (HCl, 37%), phosphoric acid (H$_3$PO$_4$, 85%) and hydrogen peroxide (H$_2$O$_2$ 30%) were purchased from Merck Company and used without further purification, NaOH, Mn(OAc)$_2$, Citric acid, NH$_3$, CNT (from Merck).

Fabrication of the nanocomposite
Purification of graphite
10g impure graphite was dissolved in NaOH 25% (5g NaOH was loaded into a beaker and then H₂O was added to a total mass of 20 g). Then, impure graphite was poured into a porcelain crucible and NaOH solution was added, following it the solution was stirred to obtain a homogeneous solution. Porcelain crucible was placed in furnace at 300 °C for 1 h, then obtained lump was milled by a mortar. The resulting graphite was washed with H₂O and HCl 5% several times to obtain a neutral pH and was dried at 60 °C.

**Synthesis of GO**

GO was synthesized by modified hummer method[15,16]. First of all, 3g purified graphite was poured into a flask containing 360 mL H₂SO₄ (98%). Then 40 mL H₃PO₄ was added, following 18g KMnO₄ was added for 30 min. The resulted solution was stirred for 12 h at 55 °C. Then 150 mL distilled water was added and temperature of the solution was reduced to 4 °C by an ice bath. Next, 4 mL H₂O₂ (30%) was added dropwise to the solution until there is no bubbles. Following stage, the solution was washed with HCl (5%) and water then it was centrifuged and dried at 40 °C for 24 h.

**Synthesis of manganese oxide nanoparticles**

1g Mn(OAc)₂ and 1.74g acid citric was dissolved in deionized water then pH was fixed in 6 by NH₃ and stirred at 80 °C for 2 h. The obtained gel was heated at 380 °C for 12 h in the furnace to form manganese oxide nanoparticles. Next, for the purification, it was stirred in H₂SO₄ 2M, for 1 h. After filtration and washing, the resulted sediment was dried at 100 °C to obtain brown sediment.

**Synthesis of GO doped to manganese oxide nanoparticles**

200 mg resulted graphene oxide was stirred in the aqueous solution of 0.02 M KMnO₄ under reflux conditions for 12 h. Then it was washed several times with water and was dried at 55 °C.

**Preparation of PVA solution**

At the first, 0.3g PVA was weighed and was poured in 10 mL deionized water then it was stirred at 95 °C under reflux conditions for 2 h to obtain homogenous solution of PVA 3%.

**Preparation of carbon fiber-manganese oxide fiber (CF/MnO₂)**

10 ml of 3% PVA solution was loaded onto a 25 ml baker and then 0.1 g of MnO nanoparticles were dispersed in PVA solution by sonication for 2 h. Then, a carbon fiber (1 × 1 cm², 0.001 g) was immersed in the solution. After drying of the fiber the same procedure was done two times again and
at last, it was completely dried at 60°C for 20 h. Preparation of carbon fiber-manganese oxide-graphene oxide (CF/G-MnO₂). This electrode was also prepared by the previous method.

**Preparation of carbon fiber - manganese oxide – graphene oxide - carbon nanotube (CF/CNT/G-MnO₂)**

First 0.05 g CNT was dispersed in 20 mL ethanol solution for 2 h under ultrasonication. Then carbon fiber (1×1 cm², 0.001 g) was immersed in the solution then it was dispersed for other 30 min until CNT is dispersed on yarn. 0.1 g of G-MnO₂ was added to the 10 mL of PVA solution (3 wt%) and then dispersed via ultrasonic irradiation in 30 min. CF/CNT papers were immersed in the above solution and dried in room temperature. this process was repeated three times. The sample preparation method was used for electrochemical analysis of silver paste to attach each of the electrodes to a thin copper wire and dried overnight at 40 °C.

**Characterization**

In order to verify the chemical structure of the products, FTIR spectra over a frequency range of 500–4000 cm⁻¹ obtained at room temperature using a FTIR spectrometer (ABB Bomem MB-100). The thermal properties of samples were conducted using a thermogravimetric analyzer (TGA-DSC1/Mettler Toledo) ranging from room temperature to 700°C at a rate of 15°C/min under N₂ atmosphere. The surface morphology of the fibers was observed by scanning electron microscope (SEM) of model Vegall-Tescan. Cyclic voltammetry (CV) was performed using a standard three-electrode electrochemical cell utilizing an Autolab/GPES interface (Metrohm) with the sample as the working electrode, a platinum wire as the counter electrode and a 3 M KCl-saturated Ag/AgCl electrode as the reference electrode in a 0.5 M Na₂SO₄ electrolyte. The specific capacitance (C) of the active electrode materials was also determined from the charge/discharge curves using the equation:

\[ C = \frac{i \times \Delta t}{m \times \Delta V} \]

where \( i \) is discharging current, \( \Delta t \) is the discharging time, \( m \) the mass of active electrode materials on a single side, and \( \Delta V \) is the voltage drop upon discharging.

**Results and discussion**

FTIR is a powerful tool for characterization of chemical structure of materials. FTIR spectra of GO, MnO₂ and GO/MnO₂ composite are shown in Figure 1. FTIR spectrum of GO demonstrates C=O stretching band of carboxylic acid groups in 1716 cm⁻¹. The main peak of MnO₂ nanoparticles has
appeared at 500 cm\(^{-1}\) corresponding to the Mn-O stretching vibration. The main peak of MnO\(_2\) at 500 cm\(^{-1}\) in FTIR spectrum of GO/MnO\(_2\) nanocomposite indicates that MnO\(_2\) nanoparticles have been synthesized on the surface of GO.

![Figure 1. FT-IR of GO, MnO\(_2\), GO-MnO\(_2\).](image1)

The TGA curves of the synthesized materials in the temperature range between 30 to 750 °C are shown in Figure 2. The adsorbent water molecules were removed to 150 °C in all samples. The decomposition of PVA and carboxylate groups of GO take place from 150 to 500 °C. It has been observed that there are approximately 10 % of MnO\(_2\) in CF/MnO\(_2\) composite by comparing with TGA curve of CF at temperature range of 500-750 °C. Addition of CNT increased the thermal stability of the CF/G-MnO\(_2\)/CNT nanocomposite.

![Figure 2. TGA curves of the CF, CF/MnO\(_2\), CF/G-MnO\(_2\), CF/G-MnO\(_2\)/CNT.](image2)

SEM images of the synthesized MnO\(_2\) nanoparticles are shown in Figure 3a. The rodshaped nanoparticles with 25 nm in diameter and 300 nm in length have completely covered the
surface of GO (Figure 3b). The filament of bare CF and functionalized CF with GO/MnO$_2$ are shown in Figure 3c and d respectively. It is observed that CFs have successfully functionalized with GO/MnO$_2$ as shown in section SEM image with 500 nm resolution.

![SEM images](image)

Figure 3. (a) SEM images of MnO$_2$ nanoparticles, (b) GO/MnO$_2$, (c) CF, (d) CF/GO/MnO$_2$.

Figure 4 shows the cyclic voltammograms (CV) of three different electrodes in 1M KOH electrolyte at the scan rate of 100 mV/s. Calculated specific capacitance are 17.8, 20.7 and 40.6 F/g for MnO$_2$, GO/MnO$_2$ and GO/MnO$_2$/CNT electrodes respectively. The curves clearly show that the redox currents increases with the addition of G-MnO$_2$ instead of MnO$_2$ alone. CNT help to enlarge the area of the curves enclosed in CV curves because of improving the conductivity of the electrode.
Figure 4. Cyclic voltammograms (CV) of for MnO$_2$, GO/MnO$_2$ and GO/MnO$_2$/CNT.

The cyclic stability of the electrode was tested as illustrated in Figure 5a. After 500 consecutive cycles, the specific capacitance of the electrode decreases from 40.6 F/g at first cycle to 28.5 F/g, with retention of 70% specific capacitance. The electrochemical impedance spectroscopy (EIS) measurements were evaluated with the frequency ranging from 100 kHz to 100 mHz in KOH 1M aqueous as electrolyte.

Nyquist plots of the EIS data for the three prepared electrodes are shown in Figure 5b. The EIS of the MnO$_2$ and G-MnO$_2$ electrodes indicate well resolved semicircles in the high frequency range indicates same charge transfer resistance at both electrode/electrolyte interface. No distinct semicircle in the G-MnO$_2$/CNT sample curve indicates a very low charge transfer resistance in this electrode which could be attributed to the conductive nature of the CNT that enclose with G-MnO$_2$.

The straight line observed in the lower frequencies represents the Warburg impedance resulting from diffusive resistance of the electrolyte in the electrode materials. It is evident that G-MnO$_2$ and G-MnO$_2$/CNT plots at low frequency area demonstrate straight line indicates that these electrodes have low diffusion resistance compared with MnO$_2$ alone. Galvanostatic charge/discharge is a very important procedure to evaluate the electrochemical capacitance of the material under controlled current conditions. Galvanostatic charge/discharge experiments, with current density from 0.5 to 10 mA are shown in Figure 5d. These curves show a small IR drop once discharging began, indicating internal resistance between G-MnO$_2$ and CF. The specific capacitance is calculated to be 166 and 71 F/g at 0.5 and 5 mA/g for the electrode normalized by MnO$_2$ weight. This result is in good accordance with the CV tests. At lower current, the electrolyte ions can be diffused sufficiently into
the interior electrode. Therefore, due to the limitation of emission, decrease in specific capacity is caused by increasing current density.

Figure 5. (a) Cyclic stability of the electrode, (b) The EIS data for the three prepared electrodes, (c) electrochemical properties of the G-MnO$_2$/CNT/PVA electrode, (d) Galvanostatic charge/discharge experiments.

To evaluate the electrochemical properties of the G-MnO$_2$/CNT/PVA electrode, Cyclic voltammetry was performed at different scan rates in KOH 1M, see Figure 5c which shows the first scans. This electrode represents CV curves of a nearly rectangular shaped that exhibits atypical capacitive behavior under the measured scan rates. Specific capacitance calculated from CV curves was 8 F/g at scan rate of 5 mV/s. The value gradually declined to 40.6 F/g when scan rate increased to 100 mV/s. The high electrochemical activity of MnO$_2$ and conductivity of CNT results in high capacitance at the electrode. The presence of graphene oxide in the composite provides high surface area for electrochemical reactions. There is a redox peak in 0.24 V observed a scan rate of 5 mV/s which gradually decreased to the 0.12 V at 100 mV/s. The specific capacitance decreases as potential scan increases because at higher scan rate electrolyte ions cannot diffuse completely into the inner active sites of material hence, electrochemical reactions could not perform completely.
Table 1 summarizes the Carbon fiber/GO-MnO$_2$/CNT supercapacitors with those of other previously reported GO-MnO$_2$ materials in the literature. Comparison of the Carbon fiber/GO-MnO$_2$/CNT with other proposed methods clearly shows that the Specific capacitance at the carbon fiber/GO-MnO$_2$/CNT used is higher than other electrodes.

<table>
<thead>
<tr>
<th>Current collector</th>
<th>Working electrode</th>
<th>Electrolyte (M)</th>
<th>Specific capacitance (F/g)</th>
<th>References</th>
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<tr>
<td>nickel foam</td>
<td>GO/MnO$_2$</td>
<td>0.5M Na$_2$SO$_4$</td>
<td>145.7</td>
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<td>GO(3D)/MnO$_2$</td>
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<td>[18]</td>
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<td>GR/MCNTs/MnO$_2$</td>
<td>0.5M Na$_2$SO$_4$</td>
<td>126</td>
<td>[19]</td>
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<tr>
<td>stainless steel</td>
<td>GO/MnO$_2$</td>
<td>0.5M Na$_2$SO$_4$</td>
<td>127</td>
<td>[20]</td>
</tr>
<tr>
<td>nickel foam</td>
<td>GO/MnO$_2$ precursor</td>
<td>0.5M Na$_2$SO$_4$</td>
<td>81.25</td>
<td>[21]</td>
</tr>
<tr>
<td>nickel foam</td>
<td>MnO$_2$/MnCO$_3$/rGO</td>
<td>0.5M Na$_2$SO$_4$</td>
<td>123.6</td>
<td>[22]</td>
</tr>
<tr>
<td>Carbon fiber</td>
<td>GO-MnO$_2$/CNT</td>
<td>0.5M Na$_2$SO$_4$</td>
<td>168</td>
<td>This work</td>
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</table>

Conclusion

In summary, we have successfully investigated the efficiency of carbon fibers membranes as flexible electrode materials for high performance supercapacitors. In this approach, MnO$_2$ nanoparticles were prepared and mixed with PVA solution to attachment into the carbon fibers. In order to improvement of the electrode, two different flexible thin film supercapacitors with G-MnO$_2$ and G-MnO$_2$/CNT composition were successfully fabricated. The proper electrochemical analysis was performed and it was concluded that the later nanocomposite (i.e. G-MnO$_2$/CNT) presented high specific capacitance and good cycling stability after 500 cycles. Furthermore, the proposed electrode showed great potential for the development of effective and low-cost flexible electrodes in energy storage devices.

References