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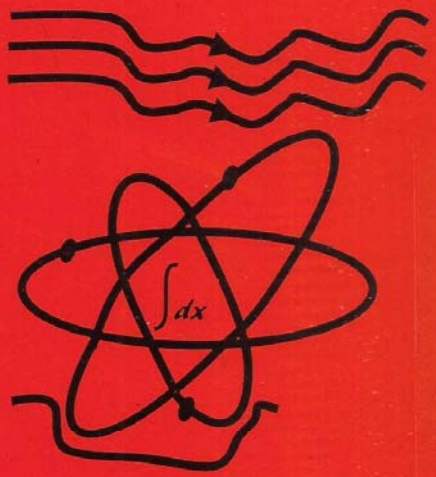

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SYNTHESIS AND ELECTROCHEMISTRY OF 3D NA_xSNO_{1-x}/G $(0.3 \leq x \leq 0.4)$ COMPOSITE ELECTRODE FOR SUPERCAPACITOR APPLICATION.

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Abstract

Studying the electrochemistry of Na_xSnO_{1-x}/G composite $(0.3 \leq x \leq 0.4)$ as an electrode material for supercapacitor application, the reduce graphene oxide (G) was synthesized using an improved modified Hummer's method and the composites electrode material using hydrothermal reduction method. The electrode Na_xSnO_{1-x} $(x = 0.4)$ gives the highest specific capacitance of 103.5 F/g, energy density of 26.4Wh/kg and power density of 205.9 W/kg after one cycle and after 1000 cycles CV test, it gives the highest capacitance efficiency, equivalent to 94.7 % capacitance retention. The electrode Na_xSnO_{1-x} $(x = 0.3)$ gives the lowest specific capacitance of 102.6 F/g, energy density of 25.5Wh/kg and power density of 152.1 W/kg after one cycle and after 1000 cycles CV test, it gives the lowest capacitance efficiency, equivalent to 93.9 % capacitance retention. This research highlighted the importance of introducing Na doped SnO in the network of the reduce graphene oxide in order to enhance the electrochemistry of the composite electrode for supercapacitor application.

Keywords: Reduce Graphene Oxide, Capacitance, Energy density, Power density, Electrode

I. Introduction

The increasing demand for a reliable and sustainable source of energy for technological growth and development has facilitated increase in funding energy related research. The increase in the world population and advancement in technology has also created an increase in the global demand for energy use ranging from small scale domestic applications (in terms of personal use) to large scale industrial applications for transport and manufacturing purposes.

This has led to an increasing interest in renewable energy-based research for generating a much cleaner and safer energy generation/conversion system. Therefore, there is also a need to build a reliable and efficient energy storage system to preserve the excess generated power for use when required for specific applications. Such storage system must possess high energy and high power densities in order to provide a robust storage capacity alone with an instantaneous/rapid delivery capability respectively. Nowadays, semiconductor metal oxides, carbon materials, and conducting polymers are applied as basic pillars for electrodes [1], [2]. The carbonaceous substances indicate best physical and chemical properties while the polymers with conductivity properties present high pseudo capacitance, low cost, conductivity, best energy density. However, EDLCs have the best pore-size and surface area. Then, pseudocapacitors with transition metal oxides materials can present excellent specific capacitance and energy storage density. Carbon materials have been applied as framework to support Na-ion host materials, such as phosphorous [3], Sn-based compounds [4], in order to increase the electronic conductivity of electrode materials during charge/discharge processes. Graphene has been widely used as effective building blocks for these purposes, owing to its high electronic conductivity, two-dimensional structure with high surface area, and flexibility. In order to meet the demand of high energy storage, numerous efforts have been devoted to enhancing the electrochemical performance of the graphene-based composite materials based on rational material manipulations [5].

It is very important to note that among tin oxide compounds, tin dioxide (SnO_2) and tin monoxide (SnO) have attracted much attention due to their potential applications in optoelectronic devices such as solar cells, displays, sensors, and complementary oxide-thin film transistors [6]. The existence of different oxidation states in tin ion makes it more beneficial to have non stoichiometric tin oxide phases. SnO_2 is generally an n-type semiconductor due

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to the existence of intrinsic defects such as oxygen deficiencies and tin interstitials, but SnO exhibits p-type conductivity and relatively high hole mobility originated from the tin vacancy. From the literature concerned, most research work in the past has paid attention to SnO_2, whereas experimental reports on SnO are fewer because of its meta-stability and tendency to transform into SnO_2at high oxygen pressures [7]. However, interest in SnO has been recently resurged because of the difficulty in obtaining high quality p-type oxide semiconductor such as p-type-doped NiO and CuO. It is believed that the p-type conductivity of SnO can be further improved by proper doping [8], [9].

Pure graphene can be modified by oxygen or other heteroatoms to show increased electrochemical capacitance. Such a gain is attributed to the redox activity enabled by the hetero atoms, known as pseudocapacitance which is the same as or comparable with the common capacitive behaviour that is featured by rectangular cyclic voltammograms[10]. It is commonly considered to result from electrode surface confined electron transfer reactions and hence is Faradaic in nature [11]. However, the rectangular CVs of pseudocapacitance are in contrast to those peak-shaped CVs that can be predicted from the Nernst Law for single or multiple electron transfer reactions in surface confined battery-type materials. The differences between the Faradaic capacitive and Faradaic Nernstian electrode reactions are claimed to result from, respectively, the transfer of partially delocalised and localised valence electrons, although no theoretically justified explanation has yet been reported [12]. However, current studies on laboratory made graphene oxides (GOs) have not yet revealed well-defined atomic structures which bring difficulties to resolve the electronic structures. Further, oxygen in GOs is known to only exist in a few forms [13].

2. Experiment

2.1 Methods

The Reduced Graphene Oxide was synthesis using modified Hummer's methods and the composite material using hydrothermal reduction method at Advanced Chemistry Laboratory, Sheda Science and Technology Complex (SHESTCO) Abuja, Nigeria. All apparatus for the synthesis were washed with distilled water and then dried in an electric oven at 60 ^{0}C for 30 mins before used.

2.1.1 Synthesis of Reduced Graphene Oxide (G)

5g of graphite, 2.5g of $NaNO_3$ and 115 mL H_2SO_4, (98%) were added together and stirred for 30 min using a magnetic stirrer. The mixture was then transfer into an ice bath, then 15 g $KMnO_4$, was added slowly to mixture and maintained at below 20 ^{0}C, after the $KMnO_4$ was added, the temperature was then raise to 35 ^{0}C and stirred again for another 30 min. 230 mL of distilled water and ascorbic acid (5 mg dispersed in 10 mL of water to produce a 0.5 mg mL^{-1}) to aid reduction was then added slowly to the mixture and temperature raised to 98 ^{0}C and stirred for another 15 min. At the end of the 15 min, 400 mL distilled water and 50 mL H_2O_2at 30% was added to the mixture then filtered and then wash with 1 M HCl then with 100 mL DI water and we get a cake of the reduced graphene oxide and dried in an electric oven for 60 min.

2.1.2 Synthesis of Na doped SnO reduced graphene oxide (Na_xSnO_{1-x}/G) composite ($0.3 \leq x \leq 0.4$)

10 mg of the G was dispersed in 20 mL of water to produce a 0.5 mg mL^{-1} completely water dispersed G.

i. G solution (0.5 mg mL^{-1}) was mixed with 10 mL of water containing (7 mg $SnCl_2.2H_2O$ and3 mg $NaNO_3$),ascorbic acid (5 mg dispersed in 10 mL of water to produce a 0.5 mg mL^{-1}) to aid reduction and 10 mL of ethanol to aid homogeneity for the synthesis of $Na_{0.3}SnO_{0.7}$/G composite

ii. G solution (0.5 mg mL^{-1}) was mixed with 10 mL of water containing (6 mg $SnCl_2.2H_2O$ and4 mg $NaNO_3$), ascorbic acid (5 mg dispersed in 10 mL of water to produce a 0.5 mg mL^{-1}) to aid reduction and 10 mL of ethanol to aid homogeneity for the synthesis of $Na_{0.4}SnO_{0.6}$/G composite.

The whole mixtures in (i. ii.) were sonicated at 60 ^{0}C for 3 h in a bath sonicator. After sonication the sample is then dried in an electric oven at 60 ^{0}C for 60 min.

2.1.3 Electrochemical Analysis

The electrochemical analyses of the samples were carried using Cyclic Voltammetry and Electrochemical Impedance Spectroscopy (EIS) tests from a CH1604E Electrochemical Analyser, controlled by EC-Lab VIO.37 software. The CH1604E Electrochemical Analyser is an electronic instrument designed to control the potential difference (E) applied to the working electrode (WE) with a current flow (in form of either a half cell or a full cell), a reference electrode (RE) with no current and the counter electrode (CE) through which current leaves the electrolyte while measuring the potential difference between the WE and RE.

The CH1604E Electrochemical Analyser generates characteristic cyclic voltammetry curves which give us information on the possible thermodynamics of electrochemical reactions of the system. All tests in this study were carried out in a three electrode configuration with the active material serving as the working electrode, a carbon rod serving as the counter electrode and Ag/AgCl serving as the reference. A 2 M KOH aqueous solution serve as the electrolyte which provides a medium for current flow and ion interaction. Although the nature of electrolyte is very important for an efficient enhancement of the performance of supercapacitors, comparison of different electrolyte types is not within the scope of this work.

3. Results and Discursion

3.1 Results and Discussion on Structural properties

The structural properties of the composite materials were analysed using the following characterisation; the Raman analysis and SEM.

3.1.1 Raman analysis

Figure 1 gives the Raman spectra of the Na_xSnO_{1-x} ($0.3 \leq x \leq 0.4$) graphene composites.

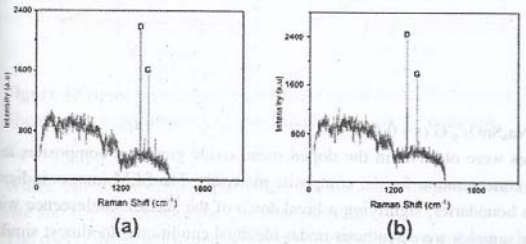

Figure 1 Raman spectra for (a)Na_xSnO_{1-x}/G (x=0.3), (b) Na_xSnO_{1-x}/G (x=0.4)

The Raman spectra for the samples were obtained using OriginPro 2018 software and provide the best signature for characterisation of graphene samples and composites. The D band is the defects and disorder mode in the reduced graphene oxide and its composite material, while the G band is the sp^2-bonded vibration from carbon atoms (hexagonal lattice of graphite). The G and the D band are due to the bond stretching of all pairs of sp^2 atoms and the vibrating modes of the sp^2 bond [5]

From figure 1, the Raman shift for the composites give a D band value of about 1348 cm^{-1} and a G band value of about 1500 cm^{-1}. The Raman shift gives the I_D/I_G intensity ratio of 1.04. From figure 1 a shift of the D band intensity was observed for all the composites. This shift may have originated from structural distortion of the reduce graphene oxide [12] this may have been caused by the different bond distances of C–C atom and C-Na, C-Sn atoms owing to the introduction of the 3D doped

metal oxide in graphene networks. The Na dopants interact with the Sn^{4+} providing additional active sites in the composite material which results in a strong coupling between the metal species and the reduce graphene oxide, resulting in shift in the D band. The shift in the D band intensity may also be due to slight change in temperature during the synthesis of the composite material.

From the relative high intensities of the D and G band, it can be concluded that the size of the sp^2 domains increase during the reduction of the graphene oxide. From figure 1, decrease in the intensities of the G band relative to the D band was also observed for the composite material, this demonstrated that defect are more easily introduced into thinner reduced graphene oxide sheet which is as a result of the stretching of the sp^2atom, which can be attributed to the presents of the 3D doped metal oxide within the layers of the graphene, this agrees with the report by [14]. This decrease in the G band intensities relative to D band in the composites materials reveals the disorder present in the sample, which can facilitate the trapping of ions from the electrolyte. The present of only D and G band in the composite material is a clear indication of the incorporation of the doped metal oxide into the reduce graphene oxide and this reflect the good crystallinity of the doped metal oxide in the composite material.

3.1.2 SEM Analysis

Figure 2 give the SEM images ofNa_xSnO_{1-x}/G (x-=0.3), Na_xSnO_{1-x}/G (x= 0.4),

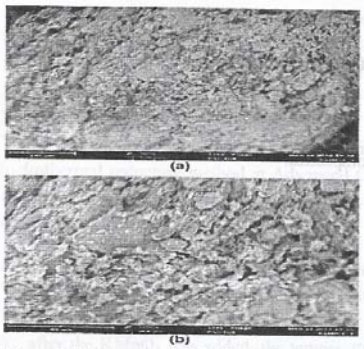

Figure2SEM images for (a) Na_xSnO_{1-x}/G (x-=0.3) (b) Na_xSnO_{1-x}/G (x= 0.4)

Figure 2, a relatively uniform porous surface structures were observedin the doped metal oxide graphene composites and were observed to increase with increase in the doping concentration for the composite materials. The SEM images indicate that there was a slight increase in the number of grain boundaries, signifying a breakdown of the surface coalescence with increasing dopant concentration. However, since all the samples were synthesis under identical conditions, an almost similar microstructure and surface morphology was seen in all the doped metal reduce graphene electrode composites irrespective of the doping concentration.

Graphene layers interacting by means of van der Waals forces [15] and form an open pore system, through which electrolyte ions can easily access the surfaces of the graphene, which facilitate the formation of electric double layers and improve the electrochemical utilization of Na, and Sn nanoparticles into the network of the composite electrode. The doped metal oxides improve the accessibility due to their metal-cation and regular 3D dispersion in the structure of the electrode. Agglomeration adversely affects the performance of the reduced graphene oxide as an electrode by preventing electrolyte ions from penetrating into the reduced graphene oxide layers [16]. The doped metal oxide is being used as a spacer to prevent agglomeration, and thus avoid the loss of their high active surface area which ensures high electrochemical utilisation of the reduced graphene oxide and also contribute to the total capacitance. The SEM images in figures 2 shows that the doped metal oxide is sandwiched chemically within the layers of the reduced graphene oxide, resulting into 3D architecture material and reveals good quality dispersion. The lateral grain size of the reduced graphene oxide and composites material exhibits a wide distribution, ranging from 80 μm to 100 μm.

3.2 Results and Discussion on Electrochemical Analysis

The electrochemical properties of the composite materials were analysed using Cyclic Voltammetry (CV) and the Electrochemical Impedance Spectroscopy (EIS) analysis.

The cyclic voltammograms from the Cyclic Voltammetry analysis for Na_xSnO_{1-x}/G (x=0.3) and Na_xSnO_{1-x}/G (x=0.4)at a scan rate of 100 mVs^{-1}. current density of 100 mA/g is given in figure 3. The Nyquist plot from the Electrochemical Impedance Spectroscopy analysis for Na_xSnO_{1-x}/G (x=0.3) and Na_xSnO_{1-x}/G (x=0.4) composites electrode materials is given in figure 4

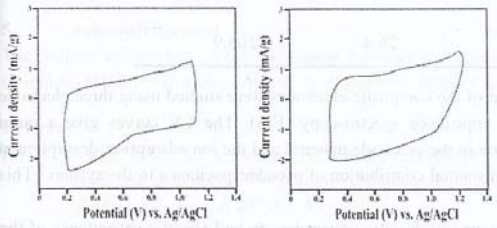

Figure 3 Cyclic Voltammogram for (a) Na_xSnO_{1-x}/G (x-=0.3) (b) Na_xSnO_{1-x}/G (x= 0.4

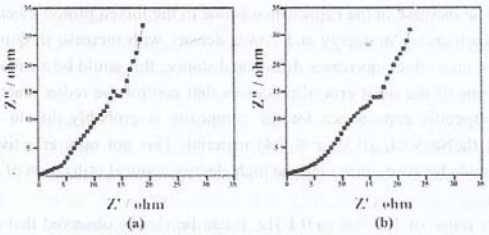

Figure 4 Nyquist plot for (a) Na_xSnO_{1-x}/G (x-=0.3) (b) Na_xSnO_{1-x}/G (x= 0.4)

The specific capacitance (C_{sp}) was calculated using the equation;

$$C_{sp} = \frac{S}{2mk(E)} \quad (1)$$

Where $C_{sp}$is the specific capacitance, S is the total charge surface area, m is the mass of the electrode material, k is the scan rate and E is the value of the electrode potential.

The energy density (E_D) and power density (P_D) were calculated using equations

$$E_D = \frac{1}{8} C_{sp} V^2 \quad (2)$$

Where C is the specific capacitance in F/g, V is the electrode potential in volts

The power is the energy expended per unit time and since the capacitor usually consists of the current collector, electrode and dielectric material, there will be an associated equivalent series resistance (ESR) from these extra components. As such; the associated maximum power density the cell can deliver is expressed as:

$$P_D = \frac{1}{4X(ESR)} \frac{V^2}{M} \quad (3)$$

Where ESR is the equivalent series resistance and M is the total mass of active material. The values of the equivalent series resistance (ESR) for the composites electrodes were obtained from theNyquist plot in figure 4. The summary of the results from the electrochemical analysis is given in table 1.

Table 1 Summary of results from electrochemical analysis for one cycle

Composite	Mass (g)	C_{sp}(F/g)	ERS (Ω)	E_D (Wh/kg)	P_D (W/kg)
Na_xSnO_{1-x}/G (x=0.3)	0.151	102.6	4.0	25.5	152.1
Na_xSnO_{1-x}/G (x=0.4)	0.161	103.5	3.0	26.4	205.9

The electrochemical properties and capacitance measurement of the composite electrodes were studied using three electrode system by cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). The CV curves give a quasi-rectangular shape due to the kinetics of electron transportation in the electrode material and the ion adsorption-desorption at the electrode and electrolyte interface and also due to the substantial contribution of pseudocapacitance to the system. This also agrees with report from [17].

From table 1, it was observed that there was increase in the energy density, power density and specific capacitance of the composites electrodes with increase in doping concentration of the cations (Na) in the composite electrodes. This is due the expansion of the active sites when the 3D Na_xSnO_{1-x}, ($0.3 \leq x \leq 0.4$) materials were introduced into the network of the reduce graphene oxide. This agrees with the work of [8]. The increase in the capacitance is due to the mixed proton-electron conductivity from the cations and the electrolyte ions. This increase in energy and power density with increase in doping concentration is also attributed to increase in charge surface area which decreases diffusion distance; this could be attributed to high Na^+ diffusion coefficient, since ions diffusion is one of the most crucial processes that control the redox reaction within the electrode material [3]. The greatly enhanced specific capacitance for the composite is probably due to the synergetic effect between the reduce graphene oxide and theNa_xSnO_{1-x}($0.3 \leq x \leq 0.4$) material. This not only effectively inhibit the stacking/agglomeration of the reduce graphene oxide but also improving the high electrochemical utilization of the composites electrodes.

EIS measurement was carried within the probed frequency range of 100,000 to 0.1 Hz. It can be clearly observed that the impedance curves from the figure 4consist of an arc and followed by a slanted line in the low frequency region. While in the high frequency region, the intercept of the semi circle on the real axis of the Nyquist plot represent the solution equivalent series resistance which can be correlated to the Ohmic resistance of the electrolyte in the system and the charge transfer resistance between interface of the electrode materials and the electrolyte. The Warburg impedance is related to the diffusional impedance of the electrochemical system which is employed to fit the straight line at the intermediate frequency, followed by a near vertical line at the lower frequency region [18-23]. From table 1, a decrease in ESR for all composite with increase in doping concentration was observed. This is due to the increase in the current response with increase in doping concentration. The decrease in the value of the ESR implies, the improve conductivity of the composite electrode and this enhances their capacitive performance, which is in accordance to the results obtained from the CV measurement. This decrease in ESR resulted in the increase in power density for the composite electrodes.

The cyclic stability of the electrode material is a crucial and important parameter to rank the performance of the energy storage application [19, 24]. The electrochemical stability of the composites electrodes were evaluated by repeating the CV test between 0.0 and 1.3 V at a scan rate of 100 mV/s for 1000 cycles under the same condition of the electrochemical set-up applied for one cycle. The composites electrode showed a greatly improved cycling stability and demonstrated the positive synergistic effect of Na_xSnO_{1-x} ($0.3 \leq x \leq 0.4$) material with the reduce graphene oxide as composite electrode to meet the requirement for high energy and power density. The electrodeshowed greatly improved cycling stability and demonstrated the positive synergistic effect of Na_xSnO_{1-x} ($0.3 \leq x \leq 0.4$) material with the reduce graphene oxide as composite electrode to meet therequirement for high energy and power density. The electrode Na_xSnO_{1-x}/G(x = 0.4) after 1000 cycles CV test, it gives 98.0 F/g with the highest capacitance efficiency, equivalent to 94.7 % capacitance retention. The electrode Na_xSnO_{1-x}(x=0.3) after 1000 cycles CV test, it gives 96.3 F/g with the lowest capacitance efficiency, equivalent to 93.9 % capacitance retention.

4. Conclusion

The electrode Na_xSnO_{1-x} (x = 0.4) gives the highest specific capacitance of 103.5 F/g, energy density of 26.4Wh/kg and power density of 205.9 W/kg after one cycle and after 1000 cycles CV test, it gives the least capacitance efficiency, equivalent to 94.7 % capacitance retention.

The electrode Na_xSnO_{1-x} ($x = 0.3$) gives the lowest specific capacitance of 102.6 F/g, energy density of 25.5Wh/kg and power density of 152.1 W/kg after one cycle and after 1000 cycles CV test, the electrode material Na_xSnO_{1-x} ($x = 0.3$) gives the highest capacitance efficiency, equivalent to 93.9 % capacitance retention.

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