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Synthesis and Characterization of Carbon Nanoparticle Using Arc Discharge Plasma

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Abstract: Carbon nanoparticles (CNP) were synthesized in arc plasma discharge using a simple, low-cost and toxic-free precursor gas. The structural and electrical characteristics were examined. SEM image showed existence of a high density and uniform nanostructures within the cylindrical bulk CNP tube. The tube diameter and its length was 28.5 µm and 316.7 µm, respectively. The average diameter of the nanoparticles grown in the tube was 600 nm. The electrical characteristics revealed low resistance with R = 7.23 kΩ with Cu electrodes. In addition, the device exhibited a high conductivity of 3.6 x 10^7 Scm^{-1}. These results indicate the potential of CNP material for power device applications.

Keywords: Arc Discharge, Carbon Nanoparticle, Current density, hydrocarbon precursor

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1. INTRODUCTION

The research in carbon based devices such as graphene and carbon nanotube has been rising tremendously with improved performance for diverse applications including sensors and power devices [1-3]. Therefore, carbon-based nanomaterials with unique electrical properties are not new in the research field. However, further studies on their electrical characteristics especially for carbon nanotube (CNT) based transistor show that CNT can produce a massive mobility as high as 100 000 cm^2/Vs [4]. In addition, CNT can carry a higher current load up to 10^8 A/cm^2 which is higher in comparison to other materials [5]. Similar properties for graphene as their mobility and current density can reach up to 20 000 cm^2/Vs and 200 µA μm^{-1}, respectively [6]. These excellent features of CNT and graphene encourage us to investigate another carbon allotropes known as carbon nanoparticles (CNPs).

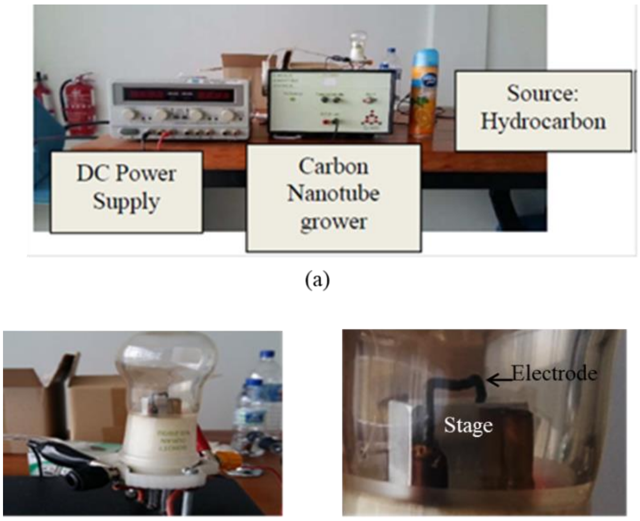
The CNPs can appear within two conditions either metallic or semiconductor. These condition occur with depending their chirality and diameter [7]. Also the CNPs able to become a new light emitting diode (LED) device after silicon. This new application are explored by Ahmadi *et al*. where they successfully demonstrates their CNPs which can emit light after applied high current and electric field towards the CNPs [8]. The CNPs can be fabricated using arc discharge plasma which was explored by a group of researchers who investigated the radiation detector technology [9]. Their arc discharge has two electrodes that made of conducting materials and two pipes that were connected to a chamber. One pipe is for the input where the gas can be inserted in while another pipe is connected to a bubbling system to prevent the re-entry of air molecules into the glass chamber. A CNP is synthesized between these two electrodes which will have different potential. Due to the difference in the potential, electrical current will be conducted. However, the electrical characteristics of these CNPs are not widely explored thus necessitates the study to unleash the material potential. In addition, previous arc discharge techniques to grow CNPs employed toxic gases such as butane and carbon monoxide. Although the synthesis was executed in a closed chamber, possible leakage of the gases can cause harm to the environment. Therefore, it is essential to use a non-toxic gas as precursor to grow these CNPs.

In this article, CNPs are grown using arc discharge method which are low cost, catalyst-free and using non-toxic gas as a precursor. The structural, electrical and chemical characteristics of the CNPs grown are examined. The high conductivity achieved (~10^5 Scm^{-1}) of the material indicates its feasibility towards power device applications.

2. METHODOLOGY

A p-Si wafer was diced into 1 cm x 1 cm dimension. Then, the diced substrates were dipped into acetone and ultrasonic bath for 5 minutes. The substrates were rinsed in de-ionized water before dipping into ethanol and ultrasonic bath for another 5 minutes. Another cycle of rinsing was executed before dipping into DI water and ultrasonic for 5 minutes.

The cleaned substrate was placed inside the arc chamber to grow the CNPs. Figure 1(a) shows the arc discharge setup in the laboratory. There are two pipes for input and output of hydrocarbon that connected to the side of chamber. The output pipe was connected to a bubbling system to prevent the re-entry of air molecules into the glass chamber. The hydrocarbon gas enters the chamber through the input pipes. The DC power supply was connected to the chamber to conduct the electricity by providing a potential difference across two electrodes in the presence of gas. The gas chamber is in atmospheric pressure.



(b) (c)

Figure 1. (a) Experimental setup for CNPs growth (b) Glass chamber in Arc Discharge (c) Enlarged view of stage and sample inside the glass chamber

A DC power supply is used to generate the DC voltage to the circuit system in order to enable the constant current flow for the plasma sparking. The growth of CNPs needs a hydrocarbon gas with inserted the gas into the glass chamber. A freshener fragrance which contains hydrocarbon gas was used in this project to grow the CNPs between the copper electrodes.

Figure 1(c) shows the glass chamber where the CNPs will be grown. To separate the carbon nanotube from the electrodes, a cube sized stage with a dimension of 1 cm x 0.8 cm x 1.4 cm and a substrate with 1 cm x 1 cm was added into the glass chamber.

After a cleaned substrate is loaded into the glass chamber, hydrocarbon gas was introduced into the chamber for about 10 s. The power supply was turned on at 12.7 V and current at 0.01 A. Once the power supply was turned on, plasma will be generated indicating the growth of CNPs has started. The plasma will be continuously glow until end of CNPs growth. When the glow has disappeared, the chamber was monitored if CNPs has been grown across the electrodes.

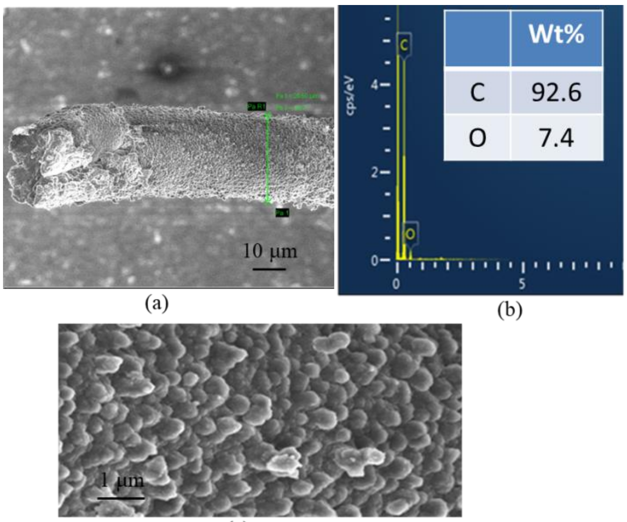
The CNPs was characterized in Scanning Electron Microsope for imaging the dimensions and morphology. The I-V characteristics were measured using Semiconductor Parameter Analyzer, Keysight B1500.

3. RESULTS & DISCUSSION

Figure 2(a) shows the SEM image of the CNPs grown using the arc discharge method after the CNPs was separated from the electrodes. From the image, the diameter and length of the CNPs grown are 28.5 µm and 316.7 µm, respectively. The length corresponds well with the distance between the two copper electrodes. Figure 2(b) shows the the EDX results of the CNPs. The results indicate 92.6 % of carbon element and 7.4% of oxygen element on the CNPs which confirms the sample is carbon based material. Figure 2(c) shows the magnified image of the CNPs surface. It reveals the existence of many nanostructures grown on the surface of the cylindrical bulk CNPs from the arc discharge method. The average diameter of the nanoparticles is 600 nm. The nanoparticles appear to be dense and uniformly distributed. The morphology of the grown CNPs as observed in SEM is comparable to other research who used similar method to synthesize the CNPs [9-12]. In particular, Ref[9] obtain similar result with us. Both have evenly distributed of the nanoparticles in the bulk. However, the CNPs produced in this work have low density compared to the obtained in Ref [9]. This is an important features of the material for many electronic applications which include sensors and power devices.

Figure 3 shows the current-voltage, I-V measurement of the CNPs with Cu electrodes as the metal contacts. The result shows a linear curve with current, I = 138 µA at V = 1V. From this result, the resistance of the CNPs is extracted to be 7.23 kΩ. The resistance value is higher compared to previous work by Kasani *et al*. in which the resistance of their CNPs was 0.18 kΩ [9]. This can be due to the highly dense nanoparticles produced in this work which impede the movement of electrons, hence affecting the resistance value.

From the plot, the current density was calculated, J = 22 A/cm^2 at V = 1 V. This is higher compared to the value obtained from [13] which only achieved a value of 0.1 A/cm^2 but lower compared to [9] which achieved a density of 302 A/cm^2 in their work.



(c)

Figure 2 (a) SEM image of the grown CNPs (b) EDX results of the CNPs (c) Enlarged image of the CNPs

In addition, the conductivity, σ was calculated from Equation (1).

$$\sigma = RL/A \qquad (1)$$

where R is the resistance of the CNPs, L is the length of the device in cm and A is the cylindrical area of the bulk CNPs in cm^2. It was found the $\sigma = 3.6 \times 10^7$ Scm^{-1}. This value is five orders higher than pristine CNT [14] (~10^2 Scm^{-1}) and a three order higher than pure CNT fibre [15] (10^4 Scm^{-1}).

The low current density achieved in this work can be due to the weakly bonded of the carbon atoms in the CNPs. As shown in SEM image, the morphology of the CNPs consists of nanostructures with different sizes of grains. The high conductivity achieved in this work is due to the free electrons produced from the weakly bonded atomic structure. According to Subramaniam *et al.* work who have mapped the current density against conductivity for various relevant materials, the performance of our CNPs agree well with metallic materials such as Ti and Pb [5].

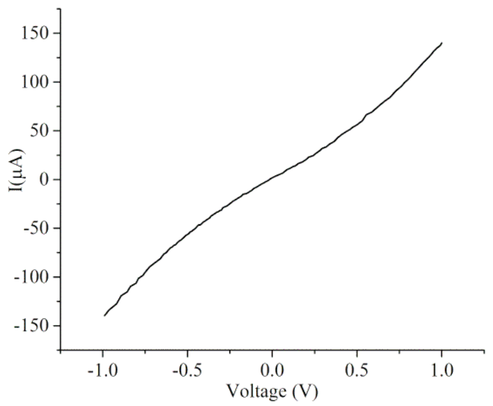


Figure 3 I-V characteristics of the CNPs-Cu device.

3. CONCLUSION

In summary, CNPs were grown using arc discharge technique using a simple, low cost and toxic-free gas as a precursor. The surface of the material was characterized in SEM which shows a high density of nanostructures on CNPs. The electrical characteristics revealed a low resistance (7.23 kΩ) with Cu electrodes and high conductivity of 3.6×10^7 Scm^{-1} was achieved. These results indicate the potential of CNPs material for power device applications.

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