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Development of field effect transistor based on single graphene ribbon prepared by a modified unzipping process of MWCNT

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ABSTRACT

Here we report the synthesis of graphene ribbon by unzipping the carbon nanotubes and investigate its performance as a field effect transistor. The produced graphene ribbons were characterized by transmission electron microscopy (TEM), Raman spectroscopy, X-ray photoelectron microscopy (XPS) and atomic force microscopy (AFM). A single layer graphene ribbon with average width of 600 ± 20 nm was obtained. This ribbon was drop casted on a silicon substrate coated by 300 nm silicon oxide layer with patterned gold electrode by lithography system. The developed single graphene FET showed very high saturation current density of 2.8A/mm, electrons mobility of 4000 cm^2/V.s and holes mobility of 3200 cm^2/V.s. These values are higher than the values obtained from FET based graphene prepared by CVD and chemical exfoliation methods. The enhancement of the saturation current value and obtaining high mobility for FET based on single graphene ribbon will open a new avenue to develop a new generation of FET for future applications.

1. Introduction

The Integrated circuits are the workhorse of all electronic devices. Thereby the miniaturization of these integrated circuits is considered one of the paramount concerns of the scientific researcher to be introduced into the electronics industry. To make it possible, there is a real need to scale down the size of the field effect transistor (FET) which is the heart-core of the integrated circuits [1]. Several efforts were employed to reduce the size of FET to the nanoscale based on the carbon nanotubes and semiconductor nanowires [2–4]. The domination of the short channel effect for FET based on these materials hinders the ability to continue further scaling down these FET devices [5]. Recently, new materials have been shown up in the horizon for the future nanoscale FET's. Among these materials, the graphene showed a great encouragement as alternative material for the electronic devices owing to its unique properties such as high mobility ($\sim 2 \times 10^5$ cm^2/V s) [6], high transparency (~97%) along the whole visible light region [7], its ability to endure current density of 10^8 A/cm^2 [8], high thermal conductivity (5×10^3 W/m K) [9] and it has only one atom thick [10]. Graphene was prepared by various techniques such as non-chemical [11], mechanical exfoliation of graphite by scotch tape [12], Hummer method which based on the exfoliation of graphite flakes by harsh oxidation and thermal exfoliation in the presence of acids either by conventional thermal oven or microwave [13]. Most of the produced graphene by these methods has not a uniform shape and causes chirality problem [14], which affects the performance of using graphene as an active material in the electronic industry. Later, the chemical vapor deposition technique was used to produce graphene on wafer by using catalyst followed by the removing of this catalyst by chemical etching and the transfer of the graphene layer on silicon substrate. Although this method gives the highest quality graphene compared to the other, it suffers from the high cost and damage of graphene layer during the transfer process. Herein we report the synthesis of graphene ribbon by unzipping the CNT and investigate its performance as a field effect transistor. The growth parameters were optimized to get a uniform graphene ribbon. This ribbon was drop casted on a silicon substrate coated by 300 nm silicon oxide layer. Gold electrode was patterned on the surface of SiO_2 layer by lithography system. The characteristics of single graphene nanoribbon were investigated in detail to examine its performance as FET device.

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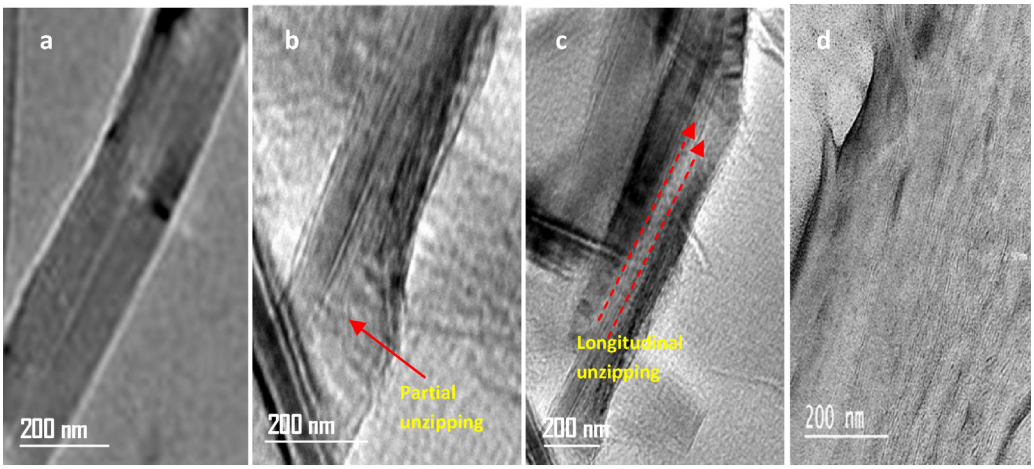

Fig. 1. TEM images during the unzipping process. (a) MWCNT before unzipping (b) after unzipping at 300 wt%, (c) 500 wt% and (d) 700 wt% of $KMnO_4$.

2. Experimental

The unzipping process of the MWCNT to graphene ribbons were performed as follow. The as-received MWCNTs from Sigma-Aldrich (150 nm average diameter, 7 μm average length and density of 1.7 g mL^{-1}) were first dispersed into hydrochloric acid (2 M, 20 mL) for 24 h to remove the residual catalyst materials. The treated MWCNT was filtered and washed several times to remove the excess of acid and left to dry at ambient conditions. The treated MWCNT was dispersed into 20 mL of oxalic acid (1 M) and left for 24 h to ensure the intercalation of the oxalic acid among the interior surfaces of the MWCNTs. Then, 20 mg of the interclated MWCNT is added to 50 mL of H_2SO_4 (2 M) solution. This suspension is stirred for 7 h at room temperature. After the 6 h of stirring, potassium permanganate ($KMnO_4$) was added step by step until about 700 wt% while the while mixture kept stirring at 70 °C for 1 h. Then, 250 mL of ice water (~4 °C) was added to quench the reaction followed by adding of 2 mL of H_2O_2 (33%). The produced graphene oxide ribbons were reduced by adding 5 mg of graphene oxide ribbons into 10 mL of de-ionized water, 30 mL of aqueous ammonia and 1 mL of hydrazine and kept stirring for 4 h at 90 °C until black suspension was obtained. The supernatant was collected by centrifuge at 15000 rpm for 10 min and washed with de-ionized water many times and left to dry in an electric oven at 50 °C under vacuum for 8 h. The produced graphene ribbons were examined by JEOL JEM1010 transmission electron microscope, XPS measurements (PHI-Versa-Probe-II) and Horiba Jobin-Yvon: Lab-RAM HR800 UV-Raman microscope (laser wavelength of 327 nm, laser power of 30 mW and integrating time 5 s). The electrical measurement was carried out in open air by the Agilent-B1500A-semiconductor parameter analyzer.

3. Results and discussion

Fig. 1 depicts the TEM images during the unzipping process of MWCNTs. Fig. 1a shows the MWCNTs before unzipping which showed an average diameter of 200 ± 10 nm. Fig. 1b showed the morphology of the MWCNT after addition of 300 wt% of $KMnO_4$. A partial cleavage is observed. Further addition of $KMnO_4$ to 500 wt% resulted in a lengthwise cutting of the MWCNT (Fig. 1c). Once the amount of $KMnO_4$ was increased to 700 wt%, a complete unzipping was achieved and graphene ribbon was obtained (Fig. 1d). The produced graphene ribbon showed an average width of 600 ± 20 nm. It is interesting to observe that the MWCNT is almost uniformly unzipped without any destruction during the unzipping process. This is mainly argued to the intercalation of MWCNTs with oxalic acid. This oxalic acid acts as a functional linker among the walls of MWCNT, where it diffuses among the CNT walls and combined them together. Once the oxidizing agent starts to attack the surface of the outer tube, a lengthwise cutting takes place and a uniform wall by wall unzipping process is smoothly achieved as indicated in the schematic diagram of Fig. 2. This can easily be observed from TEM images and from a simple calculation based on the width of the graphene ribbon. The width of graphene ribbon was found 600 ± 20 nm and the diameter of MWCNT was about 200 ± 10 nm. Since the width of graphene

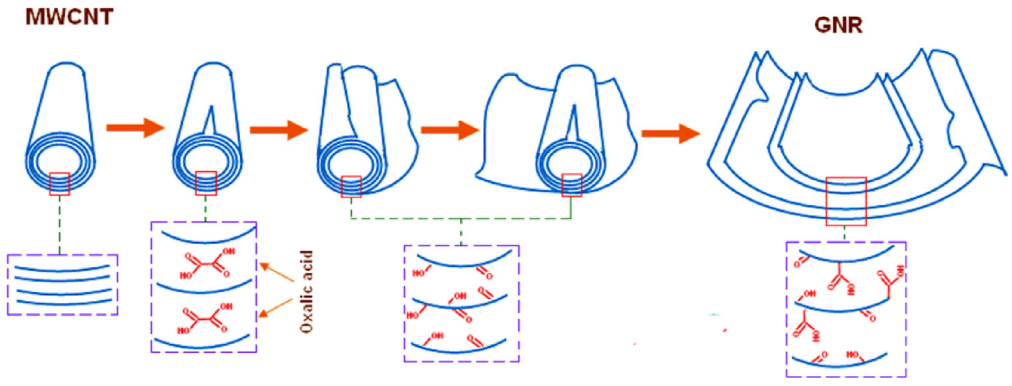

Fig. 2. A schematic diagram showed the mechanism of unzipping steps of MWCNT to graphene ribbons.