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Full Length Article

On/off ratio enhancement in single-walled carbon nanotube field-effect transistor by controlling network density via sonication

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ABSTRACT

Single-walled carbon nanotube (SWCNT) is generally used as a networked structure in the fabrication of a field-effect transistor (FET) since it is known that one-third of SWCNT is electrically metallic and the remains are semiconducting. In this case, the presence of metallic paths by metallic SWCNT (m-SWCNT) becomes a significant technical barrier which hinders the networks from achieving a semiconducting behavior, resulting in a low on/off ratio. Here, we report on an easy method of controlling the on/off ratio of a FET where semiconducting SWCNT (s-SWCNT) and m-SWCNT constitute networks between source and drain electrodes. A FET with SWCNT networks was simply sonicated under water to control the on/off ratio and network density. As a result, the FET having an almost metallic behavior due to the metallic paths by m-SWCNT exhibited a p-type semiconducting behavior. The on/off ratio ranged from 1 to 9.0×10^4 along sonication time. In addition, theoretical calculations based on Monte-Carlo method and circuit simulation were performed to understand and explain the phenomenon of a change in the on/off ratio and network density by sonication. On the basis of experimental and theoretical results, we found that metallic paths contributed to a high off-state current which leads to a low on/off ratio and that sonication formed sparse SWCNT networks where metallic paths of m-SWCNT were removed, resulting in a high on/off ratio. This method can open a chance to save the device which has been considered as a failed one due to a metallic behavior by a high network density leading to a low on/off ratio.

1. Introduction

Since the discovery by Iijima in 1991 [1], carbon nanotube has attracted attention for several decades due to its superior mechanical [2], thermal [3], and electrical [4] properties. Especially, single-walled carbon nanotube (SWCNT) has received much attention in the field of electronics since it can be classified to electrically metallic and semiconducting characteristics depending on the tube chirality [5–8]. Among them, semiconducting SWCNT (s-SWCNT) was considered as a prospective channel material to replace Si in the fabrication of a field-effect transistor (FET). And, such interests led to the effort to separate metallic SWCNT (m-SWCNT) and s-SWCNT from synthesized SWCNT to obtain highly sorted SWCNT. As a result, various separation methods such as gel-based separation [9], sequence-dependent DNA assembly [10], and density differentiation [11] have been developed and highly pure s- and m-SWCNT are selectively available depending on the application purposes.

No matter how superior the electrical properties are, SWCNT is rarely used as an individual tube itself in the applications. Due to its short length, SWCNT is mostly used in the form of networks where an individual tube is connected to constitute an electrical path. When SWCNT is utilized in the channel of a FET, it can be also used as a networked structure between source and drain electrodes of the FET. In this case, highly separated s-SWCNT is required for a good device performance such as a high on/off ratio. However, we cannot avoid the existence of a small amount of m-SWCNT even in separated s-SWCNT in spite of the high purity. And, the m-SWCNT included in the network inevitably influences the on/off ratio of the FET, by forming a metallic path. This phenomenon particularly appears when the network of pure s-SWCNT becomes dense, leading to a low on/off ratio. Needless to say, it happens in the case that unsorted SWCNT constitutes the channel of a FET. And, centrifuging at a high speed is necessarily accompanied to obtain s-SWCNT networks [12–16]. Of course, the centrifuged SWCNT can exhibit a metallic behavior at a dense network.

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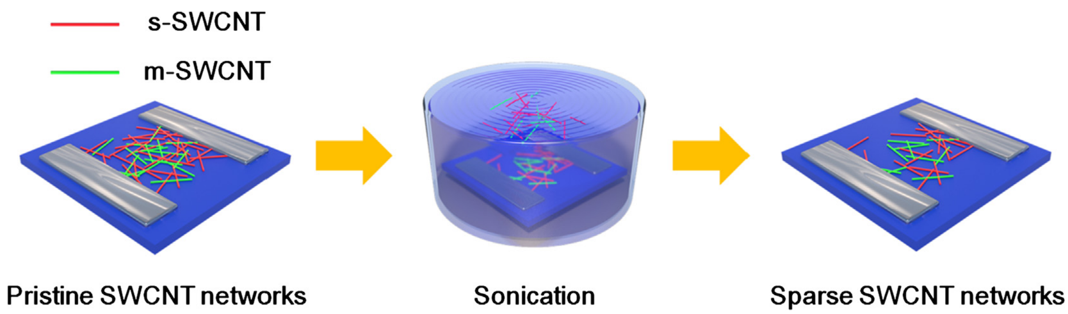

Fig. 1. Schematic illustration of controlling the network density of SWCNT by sonicating a FET under water to achieve a wide range of an on/off ratio.

Hence, a way of controlling network density of SWCNT should be considered and developed in parallel to separation techniques. There were studies on the relationship between the density of SWCNT networks and electrical properties [17–21]. And, these works commonly focus on the step of forming networks on a FET rather than already formed networks in the channel. When a FET is prepared by mistake to have a low on/off ratio because of dense networks containing m-SWCNT, the device should be disposed of in spite of laborious efforts spent in device fabrication. Therefore, it is attractive to control SWCNT networks which are already formed in the channel of a FET.

In this study, we demonstrate a simple way of controlling SWCNT networks which are already formed in the channel of a FET and show a low on/off ratio due to dense networks. The main reason of the low on/off ratio is attributed to metallic paths by m-SWCNT existing in the dense SWCNT networks. Hence, the best way to obtain a high on/off ratio is to eliminate metallic paths connecting source-drain electrodes of a FET. To realize this, we simply removed metallic paths from a dense network formed between the two electrodes by sonicating a SWCNT FET. Fig. 1 shows a schematic illustration of controlling SWCNT networks connecting source-drain electrodes irrespective of purity. The idea of achieving a high on/off ratio from a bad performance is to constitute sparse SWCNT networks containing few metallic paths by sonicating a FET in water. This resulted in a well-controlled on/off ratio from less than 10 to approximately 10^5, depending on sonication time. This method was available to control network density in both cases of SWCNT and highly sorted s-SWCNT networks, indicating that sonication of a FET with a bad performance can enhance an on/off ratio by controlling network density.

To assure if the on/off ratio change is due to a variation of network density, we carried out theoretical calculations based on Monte-Carlo method. From randomly generated SWCNT networks, transfer characteristic curves were obtained by using NGSPICE circuit simulator.

We highlight that our method can be applied to even unsorted SWCNT where s- and m-SWCNT are present at the same time. Moreover, this method can open a chance to save the device which has been considered as a failed one due to a metallic behavior by a high network density leading to a low on/off ratio.

2. Experimental and calculations

2.1. Device fabrication

To study the effect of sonication on network density, SWCNT powder including m-SWCNT and s-SWCNT and highly sorted s-SWCNT solution were shipped from Raymor (C-SWNT) and NanoIntegris (purity: 99%), respectively. These samples were used as received without any further purification. In the case of SWCNT powder, a well-dispersed solution of SWCNT was prepared by sonicating 0.02 g of SWCNT in 20 ml of 10 wt.% sodium dodecyl sulfate solution. Then, 3 µl of the solution was dropped between source and drain electrodes on a Si substrate which has a SiO_2 layer with a thickness of 300 nm as a gate insulator. The channel length was defined to be 120 µm by the electrodes. To form SWCNT networks between the electrodes, the FET was stagnated until water was totally evaporated from the network. Next, the SWCNT networks were washed by using de-ionized (DI) water to remove the surfactant, followed by air blowing for drying. These processes were repeated until a multimeter read some resistance value from the source and drain electrodes. The same procedure was repeated to prepare highly sorted s-SWCNT networks in the channel of a FET.

2.2. Device characterization

Before sonication, the electrical characteristics of SWCNT and highly sorted s-SWCNT networks were measured by using semiconducting parameter analyzer (Agilent, 4155C). Gate voltage (V_G) was swept from −20 to 20 V at source-drain voltage (V_{SD}) of 5 V. And, source-drain current (I_{SD}) was recorded in the swept range. To control the networks formed between the electrodes, bath sonication was conducted on all devices after putting each FET separately in DI water. In the case of a FET with SWCNT networks, the sonication for 2 min was sequentially carried out 21 times. Meanwhile, sonication for 30 min was also performed on a FET with s-SWCNT networks in the channel. The transfer characteristic curves of all devices were measured after each sonication to monitor a change in an on/off ratio. Atomic force microscopy (AFM, Park XE100, Park Systems) and optical microscope were used to observe the morphology of networks by density change before and after sonication.

2.3. Theoretical calculations

To understand a change of the on/off ratio by different network densities, theoretical calculations based on Monte-Carlo method were carried out. By using MATLAB, random networks were generated by 1500 SWCNTs with a length of 500 ± 50 nm. The centre of all generated SWCNTs was positioned in the channel area, and the angle of the SWCNTs with respect to the horizontal axis was not restricted in random network generation. To avoid unreasonable calculation time, the length of a channel was determined to be 2 µm defined by source and drain electrodes and the width of the channel was fixed to be 10 µm. The portion of m-SWCNT was fixed to be one-third while two-thirds of the generated SWCNTs were assigned as s-SWCNT. To simulate sonication effect on SWCNT networks ranging from a high to low density, the number of SWCNT for random networks was regularly decreased by 15 from 1500 to 315.

Theoretical transfer characteristic curves of all generated random networks were obtained by using NGSPICE circuit simulator.