Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp581-582

Electrical Performance Improvement of Carbon Nanotube Network Transistors by Direct Microwave Treatment

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1. Introduction

Thin-film transistors (TFTs) of randomly networked single-walled carbon nanotubes (SWNTs) have recently drawn attention for having the potential to overcome two major current challenges in electronic device applications using single nanotubes: (1) chirality dependence issues relating to the separation of semiconducting and metallic nanotubes and (2) position control issues [1]. This transistor scheme may also provide a new type of nanotube-based material for a semiconductor thin film for future electronic devices in transparent or flexible electronics [2]. However, geometrically, these systems have commonly been considered percolating systems with a random mixture of semiconducting (S-) and metallic (M-) nanotubes in the active area of the transistor channel. A reasonable on-off ratio (~ 10^3 - 10^4) was only obtained at very low tube densities (<1 tube/μm^2) [3] or very large channel lengths (L_c~100μm) [4]. This result is attributed to the percolation threshold governed by the existence of metallic paths along long nanotubes (which are not sufficiently shorter than L_c) as well as the fraction of M-tubes, i.e. about 33%, in a random chiral distribution. In spite of improvement for the preferential growing method of semiconducting nanotubes, difficulty in controlling chirality still represents a limit of nanotube density in order to avoid the metallic paths in the thin films of SWNTs. A zero fraction of M- nanotubes in the SWNT system is ideal for transistor applications but is not possible at present.

In this work, we report improved I-V characteristics of carbon nanotube network transistors having much larger nanotube density (100 tubes/μm^2) by direct expose of microwave. As a result, the nanotube transistors whose on-off ratios were less than 10 with metallic behavior showed the increased on-off ratios up to 10^5 after the microwave treatment.

2. Experiment and result

As shown in Fig. 1, a mixed solution of ferrocene and a conventional photoresist (AZ 5214E) were spin-coated onto SiO_2 (400 nm)/Si substrates to prepare iron catalyst nanoparticles. After the standard photolithographic processes, the defined active areas were formed for the nanotube transistor channels by additional burning of the photoresist in an oxygen flow of 500 sccm (1.5 Torr) in order to remove organic materials. A homemade radio frequency (13.56 MHz) remote PECVD system was used for nanotube growth. After allowing for the stabilization of the substrate temperature (450 ℃), methane (60 sccm) was introduced. Then, water plasma (15 W) was ignited and kept for 180 seconds to form clean nanotubes, which were selectively grown on the pre-patterned catalyst. The resulting nanotubes form a continuous SWNT random network whose density is ~100/μm^2 with lengths of 0.5~1μm and diameters of 0.8~1.3 nm. Analysis of optical absorption in UV-Vis-Near IR region and Raman spectroscopy were routinely performed to evaluate the diameter and chiral distribution of SWNTs.

SWNT thin film transistors were fabricated on the SWNT networks at the defined active areas, with formation of the source and drain electrodes from Ti(10 nm)/Au(50 nm) by a standard lift-off method. Si substrate was employed as the gate electrodes in the back-gate structure to simplify preparation by eliminating a processing step. Two hundred individual TFTs were formed as one test sample.

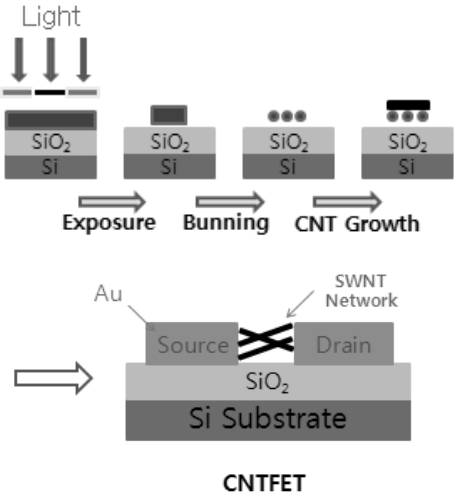

Fig. 1. The fabrication and structure of carbon nanotube field effect transistor with single walled carbon nanotube networks which are operated as channel between source and drain.

The microwave treatment performed directly in a microwave oven that has operating conditions of 700 W at 2450 MHz. The samples were placed in the center of the oven holder. Exposing time was taken as 5, 10, 20, 30 minutes.

Fig. 2 shows the transistor characteristics before and after the microwave treatment for the SWNT network transistors with 10μm of channel length and 50μm of width. The transistor was intentionally taken to have metallic paths with high density of nanotubes. All transistors exhibit low on-off ratios of 10~100 with the fixed drain voltages of 0.5V. The on-off switching in the transistor characteristic is attributed to heterogeneous percolating networks of metallic and semiconducting nanotubes. Snow et al. showed that a random network of nanotubes is electrically conductive above the percolation threshold of $0.3/\mu m^2$ for nanotube density with its length of 1~3 μm since the SWNTs form a continuous conductive path with metallic nanotubes [3]. However, the on-off ratios are dramatically increased to 10^5 after the microwave treatments. It indicates that absence of a metallic path in networks with SWNTs above the percolation threshold can be found to explain the smaller metallic fraction by removing metallic tubes. Although the basic mechanism is still ambiguous, it is understood that the microwave treatment seems to be an effective method for selective removing of metallic SWNTs.

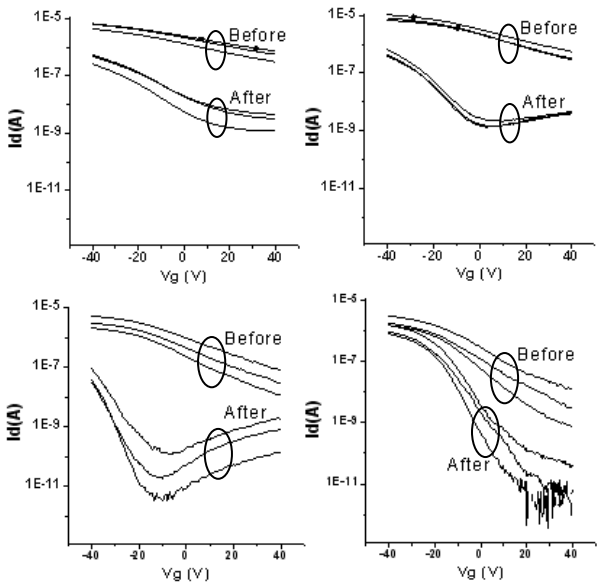

FiG. 2. I-V characteristics of carbon nanotube network transistors after (a) 5 minutes (b) 10 minutes (c) 20 minutes (d) 30 minutes treatment by microwave irradiation. The upper curves and lower curves represent before and after microwave treatment, respectively.

Fig. 3 shows the radial breathing modes (RBM) of Raman spectroscopy for excitation frequency of 633nm which are obtained from the nanotube networks in the transistor channels before and after the microwave treatment. As well known, resonance peaks of metallic and semiconducting nanotubes are separated to the two different Raman shifts: 170-230 cm^{-1} and 230-300 cm^{-1}, respectively. Absence of the metallic peak is observed after the microwave treatment. This observation agrees with the previous works by Shim et. al [5].

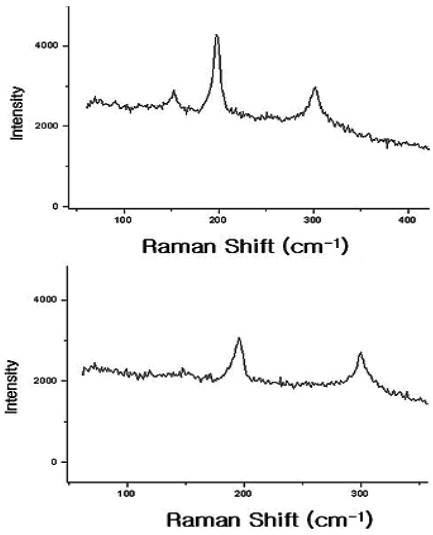

Fig. 3. The radial breathing modes (RBM) of Raman spectroscopy for excitation frequency of 633nm before (upper spectrum) and after (lower spectrum) the microwave treatment. The peak at 300 cm^{-1} is a unique peak from silicon substrate.

In spite of the obvious improvement of I-V characteristics and absence of metallic peak, selective destruction of metallic tube by microwave irradiation is still ambiguous at present. But, it is noted that thermal effect on the nanotube/metal junction could be ruled out as an origin of the variation of the on-off ratios since the independent analysis showed no increase of the on-off ratio by heating effect up to 300℃. The nanotube density lowing to percolation threshold can induce the high on-off ratio, but there is no meaningful density reduction by comparison with SEM images before and after the microwave treatment.

More importantly, the microwave treatment is the damage free process for the SWNT network transistors.

3. Conclusions

We present a microwave irradiation effect on I-V characteristics of carbon nanotube network transistors. The microwave treatment dramatically increases on-off ratio by removing metallic paths formed in the transistor channel. It could be useful as a curing method for the failed transistors without damage in the device form.

Acknowledgements

This work was supported by HY-SDR Research Center at Hanyang University under the ITRC program of Ministry of Knowledge Economy, Korea.

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