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Thin film transistors with length-sorted single-wall carbon nanotubes

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Abstract

Length-sorting of SWCNTs is important for the parametric analysis of property in their applications. SWCNTs with different average length were prepared using size exclusion chromatography (SEC) and the effects of SWCNT length on the performance of SWCNT thin film transistors (SWCNT-TFTs) were investigated. Higher device performances were obtained in longer SWCNTs and it was found that the average SWCNT length is an important factor to determine the device performance.

1. Introduction

SWCNTs have attracted much attention for the application in electronic device. In particular, semiconducting property of SWCNTs are useful for a channel of TFTs [1] which enables the fabrication of flexible, large-area, and low-cost electronic devices by printed electronics techniques.

Recently, we had reported SWCNT-TFTs using mono-dispersed and length-sorted SWCNTs prepared by DNA wrapping and SEC [2]. By using this method, homogeneous SWCNT networks with length-sorted SWCNTs can be formed, and high on/off ratio can be obtained by controlling of the SWCNT density according to the percolation theory even though the electric property of SWCNTs

The electronic transport mechanism of SWCNT-TFTs roughly follows the percolation theory. Therefore, it is thought that SWCNT length affect the performance of SWCNT-TFTs because SWCNT length is related to the percolation threshold. In this study, we have fabricated the SWCNT–TFTs with length-sorted SWCNTs with various length distributions and investigate the relation between SWCNT length and the device performances. Furthermore, we have normalized SWCNT density using a percolation threshold and compared TFT performance between different SWCNT lengths on the basis of the normalized density.

2. Experimental

SWCNTs were synthesized by gas-phase chemical vapor deposition growth using the enhanced direct-injection pyrolytic synthesis method [3]. The average diameter of synthesized SWCNTs characterized by UV-vis-NIR spectroscopy was determined to be ca. 1.3 nm. SWCNTs were dispersed in a 1 mg/ml of DNA (salmon sperm DNA) aqueous solution by sonication, and mono-dispersed SWCNTs were obtained by ultracentrifugation. After the dispersing process, SWCNT length was sorted by SEC (COSMOSIL CNT 3000) using a high performance liquid chromatography (HPLC) system. The length distributions of SWCNTs after SEC were measured using an atomic force microscope (AFM).

For the fabrication of SWCNT channels of TFTs, length-sorted SWCNTs dispersion was dropped on the amino-functionalized silicon wafer and formed their networks on it. Morphology of SWCNT networks was also observed using AFM, and SWCNTs were counted from the AFM images to characterize the SWCNT density. After that Au electrodes were deposited through a patterned shadow mask. The channel length (L) and channel width (W) were 50 μm and 500 μm, respectively [Fig. 2 (a)]. Transport characteristics of SWCNT-TFTs were measured at room temperature in dry air using a semi-automatic probe system and a semiconductor parameter analyzer.

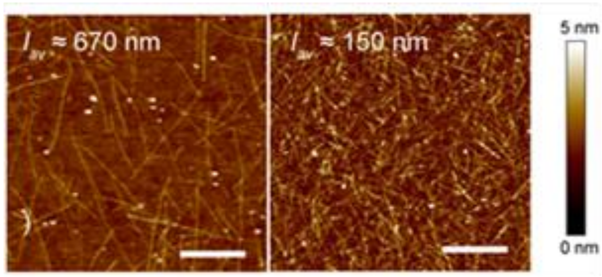

Fig. 1 Typical AFM images of SWCNT networks with different average SWCNT length (l_{av} = 670, 150 nm) and similar normalized density. Scale bars are 500 nm.

3. Results and discussion

In this study, we prepared four samples with different average length by SEC (Table I). Fig. 1 shows typical AFM images of SWCNT networks fabricated by using longest (left) and shortest (right) length samples. According to percolation theory in the linear stick model [4], percolation threshold (N) is given by following equation;

$$N=\frac{1}{\pi}\left(\frac{4.236}{l}\right)^2 \qquad (1)$$

Table I Average SWCNT length (l_{av}) and percolation threshold (N) of prepared four samples.

	A	B	C	D
l_{av} (nm)	668	432	264	153
N (tubes/μm^2)	13	31	82	244

where l is the SWCNT length. Because of the inverse proportionto the square of the SWCNT length, the percolation threshold varies a great deal depending on l. Furthermore, we have defined ''normalized density (D)'' as a comparable density. The normalized density, D, was calculated using an equation containing the percolation threshold (N) and the practical density (n);

$$D = \frac{n}{N} \qquad (2)$$

where N was deduced from the SWCNT length, and n were measured by counting the number of SWCNTs per area in AFM images. As shown in Fig. 1, long SWCNTs make space networks (D = 1.1) and short SWCNTs make dense networks (D = 1.2) at almost the same normalized density. Here, we have investigated the property of SWCNT-TFTs with the normalized density, D, from 1 to 2.5 for four samples.

Fig. 2 (b) shows typical transfer characteristics of SWCNT-TFTs with different SWCNT length distributions which exhibit on/off ratios of more than 10^3. By analyzing the transfer characteristics of a number of SWCNT-TFTs statistically, we have investigated the various device performances from the viewpoint of SWCNT lengths. Fig. 3 demonstrates the significant effect of the SWCNT length on the off-current that results in the low on/off ratio in the shorter SWCNTs, although the carrier mobility slightly varies within one decade.

For further study, the relation between on-current and normalized density was plotted and we confirmed that the dependence of on-current on the normalized density ap proximately follows percolation theory, independently of the SWCNT length. On the other hand, the behaviors of off-current and on/off ratio showed the considerably differrent dependence among SWCNT lengths. It was found that

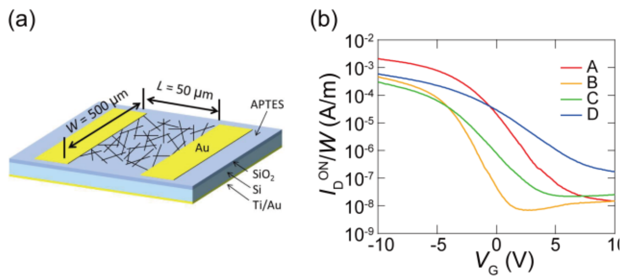

Fig. 2 (a) Schematic illustration of SWCNT-TFTs. (b) Typical transfer characteristics of SWCNT-TFTs measured at V_{DS} = -1 V.

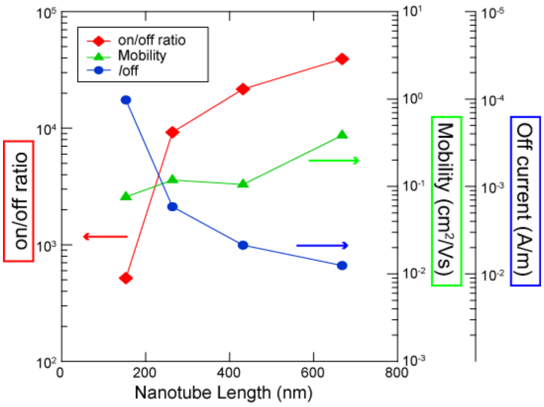

Fig. 3 Device performance of SWCNT-TFTs with different SWCNT length. Carrier mobility, off-current, and on/off ratio are plotted as a function of SWCNT length.

the decrease of the SWCNT length increases the off-current level, which causes to short-circuit SWCNT-TFTs at much lower SWCNT density than that estimated from the percolation theory.

4. Conclusions

SWCNT-TFTs fabricated using length-sorted SWCNTs. It was found that the total device performance improves with increasing the average length of SWCNTs. The detailed analyses confirmed that the effect of SWCNT length on SWCNT-TFTs clearly appeared in the variations of off-state properties, such as the off-current and on/off ratio.

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