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Length dependent performance of single-wall carbon nanotube thin film transistors

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ABSTRACT

The effects of the length of single-wall carbon nanotubes (SWCNTs) on their thin film transistors (TFTs) were investigated by using SWCNTs sorted in length using size exclusion chromatography. Higher device performances were obtained in longer SWCNTs and it was found that the average length of the SWCNTs is an important factor to determine the device performance. Detailed analyses, in which the SWCNT density was normalized using percolation threshold, confirmed that the dependence of on-current on the normalized density approximately follows percolation theory, independently of the SWCNT length. On the other hand, the behaviors of off-current and on/off ratio showed the considerably different dependence among SWCNT lengths.

1. Introduction

Single-wall carbon nanotubes (SWCNTs) are promising electronic materials because of their outstanding conducting properties and unique characteristics. One of the most advantageous features of SWCNTs is their semiconducting application in thin film transistors (SWCNT–TFTs) [1] that enables the fabrication of flexible [2], large-area [3–5], and low-cost electronic devices by a printed electronics technique [6,7]. It has been reported that SWCNT–TFTs can be adopted in chemical/biological sensors [8], digital logic gates [9], ring oscillators [10], and computers [11].

In SWCNT–TFTs, SWCNTs form random network structures as the channel. So far, it has been proved that the electronic transport mechanism of such SWCNT–TFTs with the random SWCNT network roughly follows the percolation theory. However, as the non-negligible factors, the structures of individual SWCNTs are also important for understanding the electronic transport properties of SWCNT–TFTs. The performance of SWCNT–TFTs has been investigated as a function of single SWCNT structures, such as length [12,13], diameter [14], chirality [15], and electrical properties [16,17]. The morphology of SWCNT networks also affects the performance of SWCNT–TFTs. For instance, the effects of surfactant type [18], junction geometry [19], nanotube alignment [20], and nanotube density [14] has been reported.

As discussed above, many factors impact the performance of SWCNT–TFTs, because individual SWCNTs are classified in various structures. In general, SWCNTs are produced as a mixture of various SWCNT types. Moreover, SWCNTs easily form bundle structures. Thus, there are still challenges to controlling the morphology of SWCNT networks. It remains difficult to investigate each factor independently in actual SWCNT–TFT devices.

Recently, we had reported SWCNT–TFTs using monodispersed and length-sorted SWCNTs prepared by DNA

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wrapping and size exclusion chromatography (SEC) [21]. In this previous work, it was shown that the control of the SWCNT density leads to high on/off ratio according to the percolation theory even though the electric property of SWCNTs was still unseparated. By using this length-sorted SWCNTs with DNA wrapping, homogeneous SWCNT networks can be formed and it is possible to investigate the properties of SWCNT–TFTs based on the SWCNT length and density. More recently, we had investigated the specific diameter dependence of the off-current behaviors on SWCNT–TFTs of DNA-wrapped SWCNTs with different tube diameters [14].

The SWCNT length is related to the percolation threshold and should affect the total contact resistances between SWCNTs. However, to date there were a few experimental reports regarding the SWCNT length [12,13], and the detailed effects of SWCNT length on the performance of SWCNT–TFTs is still unclear. Here, we have fabricated the SWCNT–TFTs of length-sorted SWCNTs with various length distributions to 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 lengths of SWCNTs at the same normalized density.

2. Experimental

SWCNTs were synthesized by gas-phase chemical vapor deposition growth using the enhanced direct-injection pyrolytic synthesis method [22]. The synthesized SWCNTs with an average diameter of 1.3 nm were characterized by the measurements of Raman spectra (NRS-5100, Jasco) and UV–vis-NIR absorption spectra (U-4100, Hitachi) as shown in Fig. S1.

In order to prepare mono-dispersed SWCNTs, 3 mg of SWCNTs was dispersed in 10 mL of DNA (salmon sperm DNA, WAKO) aqueous solutions with the concentration of 1 mg/mL by ultrasonication (VCX500, SONICS, 200 W 10 min), and then ultracentrifuged (himac CS120FNX, Hitachi, 100,000×*g*). After the dispersing process, SWCNTs were sorted in length by SEC (COSMOSIL CNT 3000, 7.5 mm × 300 mm, Nacalai Tesque Inc.) using a high performance liquid chromatography (HPLC) system (SSC-3461 and SSC-5410, Senshu Scientific Co., Ltd.). A 1/15 M phosphate buffer (pH 7.0) was used for the elution phase, and the flow rate and injection volume were 1.0 mL/min and 0.5 mL, respectively. For the measurement of chromatogram in SEC, the detection wavelengths of 280 nm and 425 nm that are suitable for DNA and SWCNTs, respectively, were adopted (see Fig. 1(a)). The fractions were collected every 30 s during the separation by SEC. The length distributions of length-sorted samples were measured using an atomic force microscope (AFM) (Dimension Icon, Bruker AXS K.K.). For a comparison with length-sorted SWCNTs, we also prepared a mixture sample having SWCNTs with a wide distribution of lengths.

The SWCNT networks were formed on amino functionalized silicon wafers (highly Sb doped) with 100-nm-thick SiO_2 by soaking the solutions of length-sorted SWCNTs. The samples were rinsed with water to remove DNA, dried by N_2 blow, and then baked at 180 °C for 30 min. The SWCNT networks were also observed using AFM, and SWCNTs were counted from the AFM images to characterize the SWCNT density.

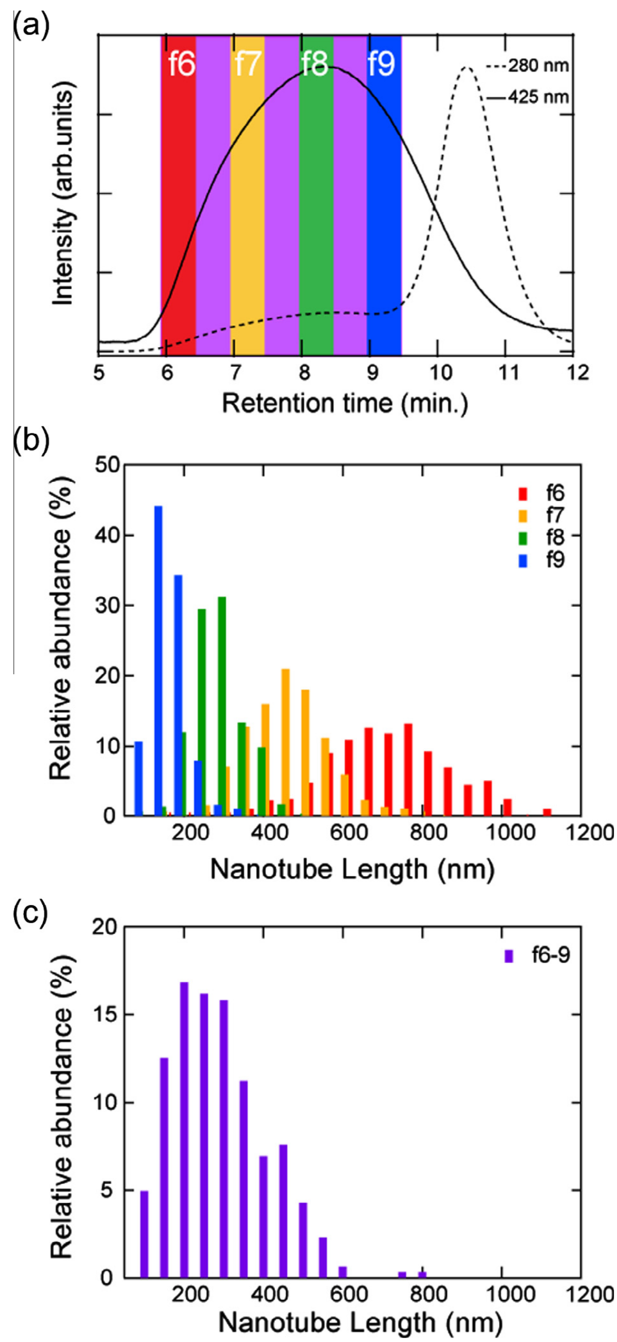

Fig. 1 – (a) Chromatogram monitored in the SEC separation of DNA-wrapped SWCNTs. The detection UV wavelengths of 280 nm (dash line) and 425 nm (solid line) were adopted. The length-sorted fractions (f6, f7, f8, and f9) were collected intermittently as highlighted. From the chromatogram of 280 nm, the elution of excessive amounts of free DNA consisting in solution is confirmed from 9′ to 12′. (b and c) Length distribution of each SWCNT fraction measured from AFM images.

For the fabrication of SWCNT–TFTs, Au electrodes were deposited on the SWCNT networks through a patterned