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Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp722-723

Wafer-Scale Statistical Characterization of Carbon Nanotube Thin-Film Transistors

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Abstract

Carbon nanotube thin-film transistors are attracting much attention as promising active components for flexible and wearable devices. However, the large characteristic variation is a critical issue for their practical applications. In this work, we have statistically investigated the characteristics for more than 4,000 devices with varying the number density of carbon nanotubes in the channel to clarify causes of characteristic variation. Although there is a non-negligible long-range variation in the wafer scale due to the film formation process, a quite small variation in on-current (~5 %) can be obtained in an area of ~9 mm^2.

1. Introduction

Carbon nanotubes (CNTs) provide great potential for high-performance flexible devices because of exceptional intrinsic electrical and mechanical properties. While individual CNT is considered to be one of the ideal materials for nanoelectronics, CNT thin film takes advantage for ease of processing and for mass fabrication on various substrates [1], which is configured as thin-film transistors (TFTs). CNT TFTs can be utilized as promising components for flexible displays and electrical circuits in wearable healthcare devices. Though great efforts have been made to achieve high-performance CNT TFTs [2], device-to-device variation in the electrical characteristics is still one of unresolved issues towards their practical applications.

Two dimensional percolation theory predicts that on-current variation is expected to diminish as the number of CNTs, hence the number of current paths in the channel, increases by averaging the amount of current which is different for different current path. Though simple percolation theory is good tool for qualitative evaluations of on-current variation, characteristic variation of CNT TFTs is also caused by fabrication process. Vacuum filtration and film transfer method are considered to be advantageous for relatively uniform and large-area film formation on various substrate rather than spin coating, drop casting, and so on.

In this work, we have investigated electrical performance and characteristic variation of CNT TFTs with changing the number density of CNTs in the channel. On-current variation are statistically discussed on the basis of spatial autocorrelation analysis.

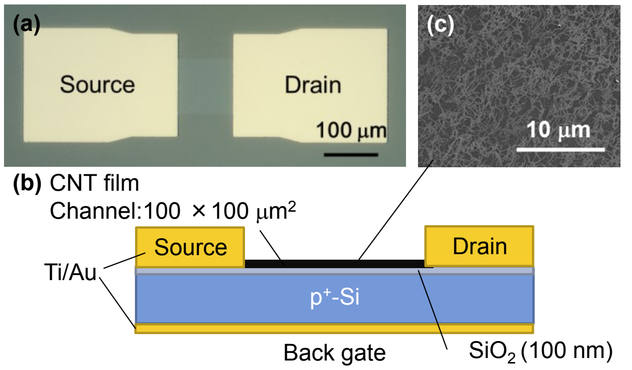

Fig. 1 Fabricated CNT TFT. (a) Optical image, (b) schematic structure, (c) SEM image of CNT film.

2. CNT Characterization and Device Fabrication

High-purity semiconducting single-walled CNTs are used to avoid a formation of short paths of metallic SWNTs in a high-density CNT film. The starting material were synthesized by chemical vapor deposition (KH SWCNT, KH Chemicals), and separated by gel chromatography [3]. The CNTs were dispersed in an aqueous solution with two types of surfactant as sodium dodecyl sulfate (0.3 wt%) and sodium cholate (1 wt%). High G/D ratio (>30) was confirmed by Raman spectroscopy. The mean diameter and length of individual CNTs were respectively estimated to be 1.3 nm and 0.52 μm by the absorption spectroscopy and atomic force microscopy. From the average length of CNTs, percolation threshold, ρ_{th} was estimated to be 21.2 μm^{-2}.

Back-gate CNT TFTs were fabricated on a SiO_2/Si wafer as shown in Fig. 1. The channel length and width are both 100 μm, easily achievable by future high-throughput printing process. The number density of CNT film was varied from 52 to 342 μm^{-2}, which corresponds to $2.5\rho_{th}$ ~ $16\rho_{th}$. Transfer characteristics of TFTs were measured by sweeping V_{GS} from 5 V to -5 V in both linear (V_{DS} = -1 V) and saturation (V_{DS} = -5 V) regions. On-current variation was assessed from standard derivation divided by average current in saturated region at V_{GS} = -5 V. Hole mobility was estimated from the maximum transconductance in the linear region.

3. Results and Discussion

As CNT density increased, the on-current density was increased to be in the order of 10^{-4} A/mm, and the variation in on-current tends to be eliminated. The on/off ratio, however, decreased with an increase in CNT density above 86 μm^{-2}, probably due to the bundling of CNTs. In a bundle of CNTs, the gate field may be screened by the outer CNTs, which causes the leakage current flowing through the inner CNTs at off-state. I_D-V_{GS} characteristics of 507 devices with a CNT density of 150 μm^{-2} is shown in Fig. 2, which shows a good balance between the characteristic variation and on/off ratio. The typical on/off ratio is 10^5, and the mobility is 14.1 cm^{2}V^{-1}s^{-1} in average. The inset of Fig. 2 shows the histogram of on-currents in the saturation region. The on-current variation of overall devices is rather small as 20 % in standard deviation, which is almost comparable to previous works [4,5].

There exists a long-range special distribution in on-current as can be seen in the mapping data of the inset of Fig. 3. This is probably caused by non-uniformity in CNT density, which originates from the vacuum filtration process. We adopt spatial autocorrelation analysis (Moran's *I*) [6] to investigating similarities between distant CNT TFTs. The spatial autocorrelation is calculated by

$$I = \frac{N\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}(x_i - x_{ave})(x_j - x_{ave})}{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}\sum_{i=1}^{N}(x_i - x_{ave})^2} \qquad (1)$$

Here, N is the number of samples, $x_{i,j}$ is the on-current of sample i and j, x_{ave} is the average on-current of total samples. We employ inverse-distance-weighted factor, $w_{ij}= 1/d_{ij}$. in Eq. (1). The spatial autocorrelation is plotted as a function of distance in Fig. 3. As distances between CNT TFTs increase, spatial autocorrelation decreases, which means that nearby TFTs have similar on-current rather than distant ones. Therefore, local on-current variation could be smaller than the whole variation. We investigated the on-current variation in an area smaller than the range of the long-range distribution (~15 mm) to clarify the expectable uniformity without the non-uniformity in the filtration process. A small on-current variation as ~5 % in standard deviation was obtained in an area of 9 mm^2.

3. Conclusions

We developed a technique for wafer-scale fabrication of CNT TFTs. More than 4,000 CNT TFTs were measured to investigate statistically on-current, on/off ratio, and mobility for various CNT densities. The on-current variation overall devices was rather small as 20 % for the optimal CNT density. Spatial autocorrelation analysis showed an existence of a long-range variation, probably originating from the filtration process. A small on-current variation (~5%) was shown in an area of 9 mm^2.

Acknowledgements

The semiconducting CNTs were provided by TASC. This work was partially supported by Grant-in-Aid by MEXT, JST/SICORP, and JST/ALCA.

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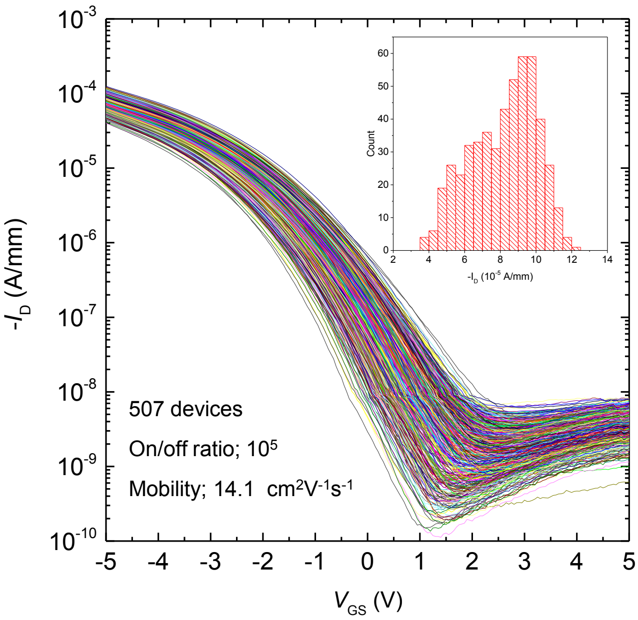

Fig. 2 Transfer curve of 507 devices. Insets: histogram of on-current.

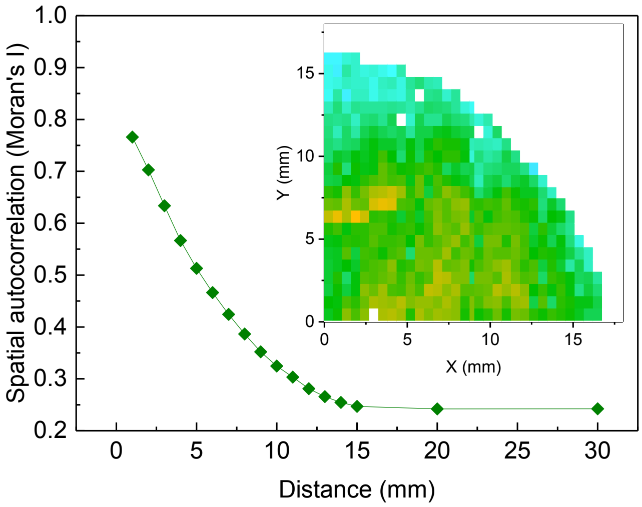

Fig. 3 Spatial autocorrelation (Moran's *I*) versus distances between devices. The inset shows the on-current map with a CNT density of 150 μm^{-2}.