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High-Yield Fabrication of n-Type Carbon Nanotube Thin-Film Transistors on Plastic Substrate

Fu-Wen Tan[1], Jun Hirotani[1], Tomohiro Yasunishi[1], Shigeru Kishimoto[1], and Yutaka Ohno[1,2]

[1]Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[2]Institute of Material and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Phone: +81-52-789-5387, E-mail: yohno@nagoya-u.jp

Abstract

Carbon nanotube thin-film transistors (CNT TFTs) are promising active device for various flexible/stretchable devices because CNTs exhibit excellent mechanical and electrical properties. As-fabricated CNT TFTs normally show p-type characteristics, thus n-type TFTs are necessary to construct complementary metal-oxide-semiconductor-based devices. We have fabricated more than 800 air-stable, n-type CNT TFTs on a flexible plastic substrate with high yield by chemical doping technique. We confirmed 99.5 % of devices changed from p- to n-type characteristics with small hysteresis.

1. Introduction

Single-walled carbon nanotubes (CNTs) are suitable materials for high-performance future electronic devices due to its highly desirable electrical and mechanical properties. In particular, a thin film of randomly arranged CNTs can be used as the conductive channel for thin-film transistors (TFTs) on flexible substrates, [1,2] which meets the demands of wearable healthcare/medical electronic devices.

As-fabricated CNT TFT devices are normally p-type, due to the adsorption of oxygen molecules in the ambient air [3]. However, devices with n-type characteristics are required to realize complementary metal-oxide-semiconductor (CMOS)-based circuits because of its good noise margin and low power consumption [4,5].

There are several methods to fabricate n-type CNT TFTs, in particular, solution based chemical doping with poly(ethylene) imine (PEI) [6] combined with surface passivation offers stability of dopant in air and ease of controlling the doping level [7]. However, the yield of n-type devices is still one of the unresolved issues.

In this work, we have fabricated more than 800 n-type CNT TFTs on a flexible substrate with high yield on the basis of PEI doping combined with surface passivation.

2. Experimental

Semiconducting CNTs extracted by gel chromatography [8] were used as channel material. The mean diameter and length of individual CNTs were estimated to be 1.3 nm and 0.52 μm respectively by absorption spectroscopy and atomic force microscopy.

We have adopted poly(ethylene naphthalate) (PEN) as a flexible and transparent substrate. The schematic device structure of a bottom gate TFT is shown in Figure 1(a). Channel length and width are 100 μm. The Ti/Au (10/100 nm) electrodes were formed by conventional photolithography, electron-beam evaporation, and lift-off process. A 40-nm-thick Al_2O_3 gate oxide layer was deposited by atomic layer deposition (ALD) process. A CNT film was formed on the Al_2O_3 layer by transfer process and patterned by oxygen plasma [9]. Before chemical doping with PEI, electrical characteristics of the CNT TFTs were measured. Concentration-optimized PEI (Sigma Aldrich, MW = 800) dissolved in methanol was spin-coated onto the substrate for n-type doping. Subsequently, an Al_2O_3 passivation layer was formed by ALD and patterned by photolithography and reactive ion etching. The fabricated array of CNT TFTs with bottom-gate structure is shown in Fig. 1(b). More than 800 devices were fabricated on a PEN film.

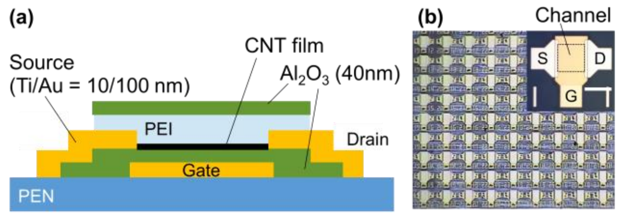

Fig.1 (a) Schematic structure of a typical n-type device.
(b) Optical micrograph of CNT TFT device with channel length and width of 100 μm. (scale bar: 100 μm) (inset) and an array of CNT TFTs.

Their characterization was performed in ambient air. Transfer characteristics were measured by sweeping gate voltage (V_{GS}) from 2 V to -2 V. On-current was evaluated at the saturation region (V_{DS} = 4 V) of I_D-V_{DS} characteristics.

3. Results and Discussion

In the first phase of the fabrication process, the 831 devices showed p-type behavior with good on/off ratio of 10^4 and relatively uniform characteristics. The second phase involved n-type doping and Al_2O_3 passivation onto the p-type devices. The output and transfer characteristics of a device before and after doping are shown in Fig. 2. The device characteristics changed from p- to n-type without significant degradation of on-current and mobility. Hysteresis was reduced as a result of Al_2O_3 passivation.

Figure 3 shows the transfer characteristics of 827 operational devices after PEI doping. 99.5 % of 831 devices were converted to n-type behavior by our n-type doping method. Four devices did not work after doping due to gate leakage current or damage during measurement. A majority of the TFTs maintain a good on/off ratio of 10^4, with an average hysteresis width of 0.25 V. However, low on/off ratio and threshold voltage shift toward the normally-on condition are

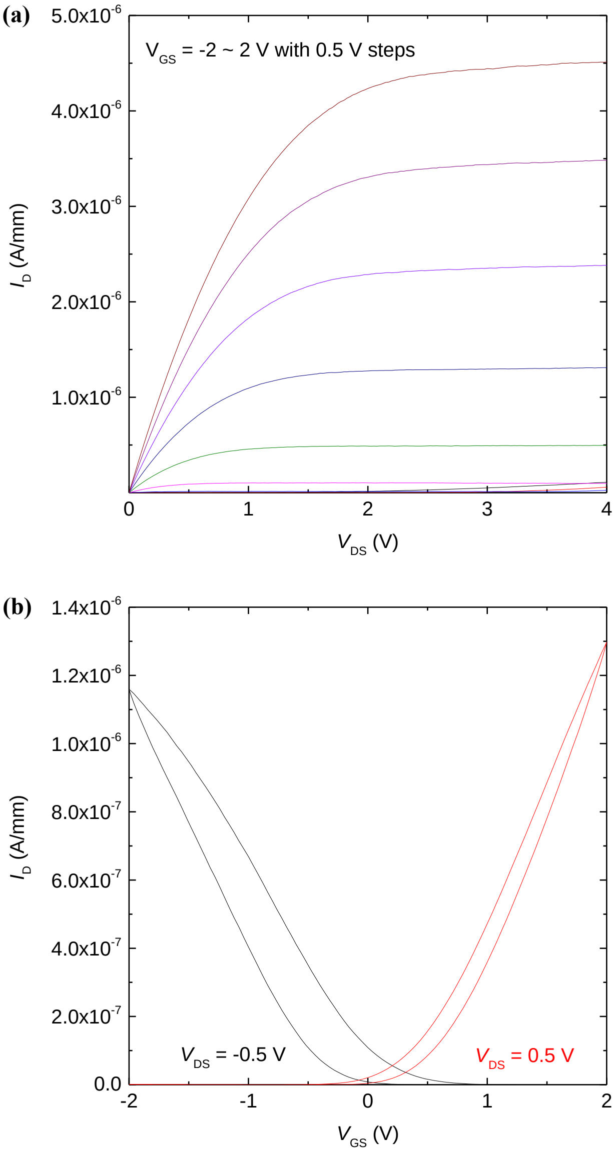

Fig. 2 (a) Typical I_D-V_{DS} curves of an n-type device. (b) Typical I_D-V_{GS} curves of a TFT before and after doping. After PEI doping and Al_2O_3 passivation, the device shows a small hysteresis.

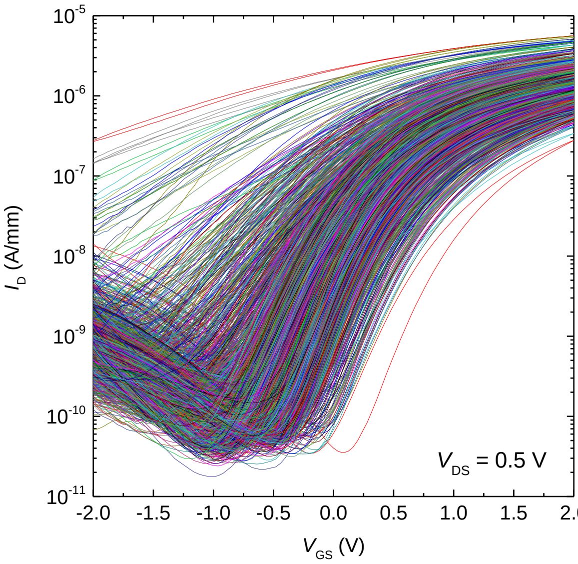

Fig. 3 I_D-V_{GS} curves at V_{DS} = 0.5 V of 827 n-type devices.

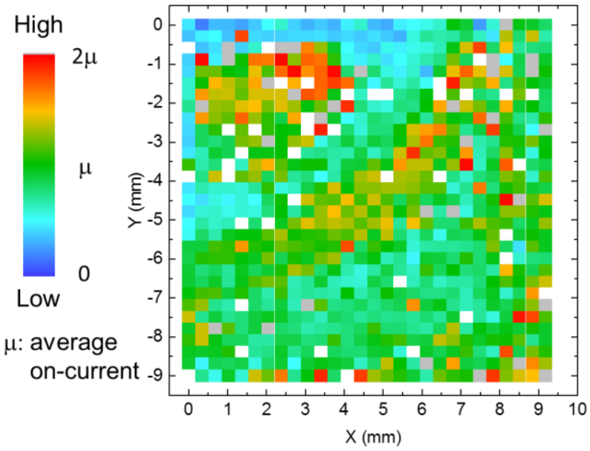

Fig. 4 On-current map at V_{DS} = 4 V.

exhibited by a few percentages of devices. This is probably due to non-uniformity of doping levels caused by spin coating method, which is in agreement with the on-current map in Fig. 4. Improvement in doping process should be able to yield better overall homogeneity in the n-type characteristics.

4. Conclusions

We have fabricated n-type CNT TFTs on a flexible plastic substrate with high yield. The n-type doping was performed by PEI coating with Al_2O_3 passivation. Although threshold voltage of some devices shifted to normally-on side due to non-uniformity of doping levels, majority of the devices kept a good on/off ratio of 10^4. A 99.5% highly efficient n-type conversion and reduction of hysteresis were achieved.

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References

[1] Q. Cao *et al.*, *Nature* **454**, 495 (2008).
[2] D.-M. Sun *et al.*, *Nat. Nanotechnol.* **6**, 156 (2011).
[3] E. S. Snow *et al.*, *Appl. Phys. Lett.*, **82**, 2145 (2003).
[4] M. L. Geier *et al.*, *Nat. Nanoechnol.* **10**, 944 (2015).
[5] Y. Zhao *et al.*, *ACS Nano* **10**, 2193 (2016).
[6] M. Shim *et al.*, *J. Am. Chem. Soc.*, **123**, 11512 (2001).
[7] T. Yasunishi *et al.*, *Jpn. J. Appl. Pys.* **53**, 05FD01 (2014).
[8] T. Tanaka *et al.*, *Appl. Phys. Express*, **1**, 114001 (2008).
[9] J. Hirotani *et al.*, *Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials* (2015) 722.