Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp1112-1113

Evaluation of Dynamic Performance of CNT Random Network Transistors

Noriyuki Tonouchi[1,4], Hiroyuki Endoh[1,4], Takashi Manako[1,4]
Fumiyuki Nihey[2], Hideaki Numata[2], Tomoyuki Yokota[3], Tsuyoshi Sekitani[3], and Takao Someya[3,4]

[1] Smart Energy Research Laboratories, NEC Corporation, Tsukuba 305-8501, Japan
Phone: +81-29-850-1157 E-mail: n-tonouchi@ab.jp.nec.com
[2] Technology Research Association for Single Wall Carbon Nanotubes (TASC), Tsukuba 305-8565, Japan
[3] Department of Electrical Engineering, School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan
[4] Institute for Nano Quantum Information Electronics, Tokyo 153-8505, Japan

Abstract

A carbon nanotube (CNT) [1] random network channel was fabricated with dispenser printing on a substrate on which electrodes were patterned to reduce the gate capacitance by using super inkjet technology. The dynamic performance of the CNT thin-film transistor (CNT-TFT) was evaluated. As a result, on-off switching action up to 100 kHz was achieved. The authors demonstrated the high potential of CNTs as printable semiconductive materials.

1. Introduction

We have promoted research and development on CNT-TFTs as promising devices toward achieving applications for printed electronics [2–4]. Organic semiconductors have mainly been studied thus far as printable channel materials. However, the mobility of organic TFTs is 1 cm^2/Vs or lower. Thus, the possible device frequency has been estimated to be 100 kHz at most. However, CNTs have high electrical properties and the mobility of CNT-TFTs has achieved 1–10 cm^2/Vs or more even though their channels have been fabricated with printing processes [5–8]. Therefore, CNT-TFTs are expected to have the potential to achieve printed devices that are high performance such as those that require operating frequencies over 100 kHz (e.g., scanning line drivers for display panels).

Until now, CNT-TFTs have been evaluated by only focusing on their static performance. Therefore, there have been few researchers who have actually evaluated their dynamic performance.

We evaluated the dynamic performance of CNT-TFTs in the present work whose channels had been fabricated with a printing process. We aimed at demonstrating switching action up to 100 kHz.

2. Experiments and Results

CNTs with a diameter of 1.0 nm were used for this study. The CNTs were dispersed into deuterium oxide by using a nonionic surfactant of polyoxyethylene stearyl ether. Then, the dispersed solution was treated by sonication followed by ultracentrifugation to obtain mono-dispersed CNT solution. After treatment, metallic and semiconducting CNTs were repeatedly separated by using the method of electric-field-induced layer formation (ELF). The optical absorbance spectra revealed that metallic peaks were suppressed after treatment. This indicated that metallic CNTs had effectively been removed from the solutions. The purity of semiconducting CNTs was estimated to be more than 96% from the spectra [9].

First, we fabricated a CNT-TFT whose channels were patterned with dispenser printing on a substrate on which electrodes had been formed by using the method of vapor deposition. Figure 1 has a cross-sectional view of the CNT-TFT and Figure 2 plots its transport characteristics. Typical p-type semiconducting properties were obtained and mobility was estimated to be 0.28 cm^2/Vs.

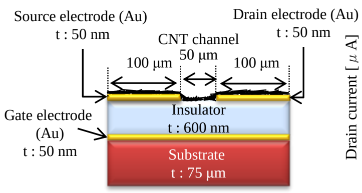

Fig. 1. Cross section of TFT

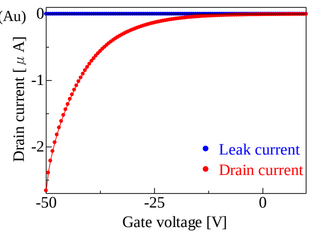

Fig. 2. Transport characteristics (Vapor deposition)

The detailed results for dynamic properties are presented below. Figure 3 plots the data at a gate frequency of 25 Hz, and Figure 4 plots those at 1 kHz. The blue dots represent data with a drain voltage of 0 V, where a sinusoidal signal was observed. This signal formed unwanted background current against the on-off signal of the CNT channel. The red dots indicate detected current with a drain voltage of 5 V. An obvious on-off signal can be identified at 25 Hz even though the sinusoidal background current is superimposed on the on-off signal of the CNT channel. However, the background

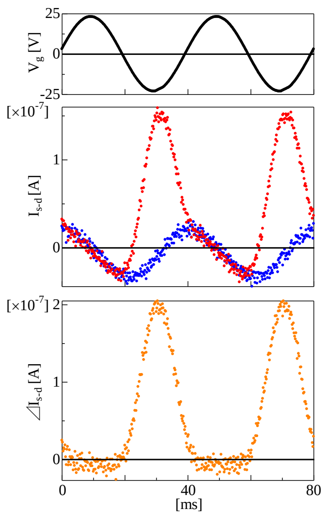

Fig. 3. Switching action at 25 Hz (Vapor-deposition)

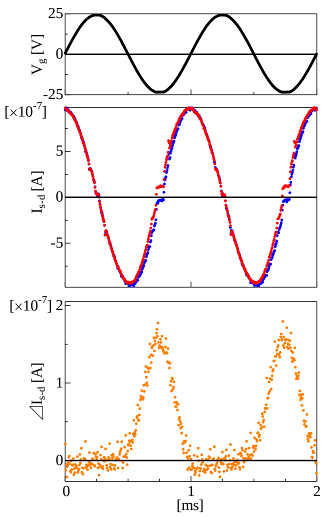

Fig. 4. Switching action at 1 kHz (Vapor-deposition)

current increases as the gate frequency increases, and becomes larger than the on-off signal at 1 kHz (Figure 4). The orange dots plot the extracted on-off signal of the CNT channel obtained by background subtraction. Although clear on-off action is seen even at 1 kHz, degradation in the S/N ratio is also observed. Sinusoidal background current is due to displacement current through the gate capacitance formed by the overlap between drain and gate electrodes. The amplitude of displacement current is generally linearly dependent on the frequency of applied voltage. Thus, its amplitude is estimated to be ~100 μA or more at 100 kHz. Since this value is 100–1000 times that of the on-current value of this CNT-TFT, no reliable verification of on-off action could be achieved even if background subtraction had been done. That is, verification of 100 kHz on-off action requires an improved S/N ratio.

Two main methods of improving the S/N ratio are listed below:

(1) Reduction in gate capacitance
1. To make the drain electrode narrower
2. To rearrange electrodes

(2) Enhancement of on-current
1. To increase CNT density
2. To make the channel narrower

We examined making the drain electrode narrower (1)-1 and increasing CNT density (2)-1 in this study.

We patterned the source-drain electrodes with super inkjet (SIJ) technology to make the electrodes narrower [9]. The structure of this TFT was the same as the former wide electrode CNT-TFTs (WE-TFTs) with a bottom-contact bottom gate structure. We used a silicon substrate and the gate insulator was made of SiO_2 (250 nm). The channel length was 50 μm. The width of the electrodes was confirmed to be 2–3 μm from the SEM image. Figure 5 plots the dependence of the amplitudes of displacement current of each CNT-TFT on frequency. Compared to the WE-TFTs, the amplitude of displacement current of the CNT-TFT is suppressed to ~1/10. We fabricated the channel with CNT ink that had been treated to reduce the surfactant through dialysis to increase CNT density. Reducing the surfactant enabled us to increase the relative content of CNTs. Figure 6 plots the transport characteristics of this TFT with a drain voltage of 5 V.

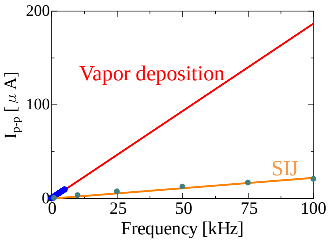

Fig. 5. Suppression of the displacement current by SIJ technology.

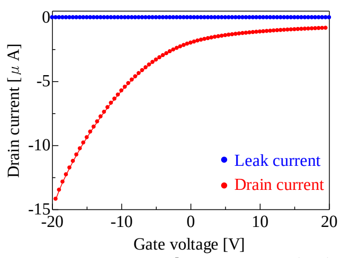

Fig. 6. Transport characteristics (SIJ)

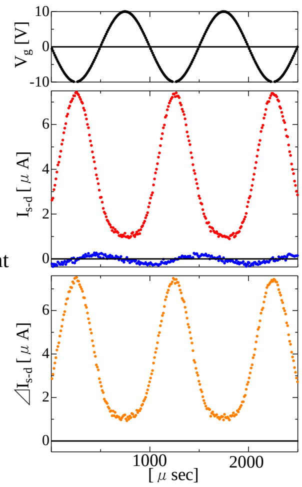

Fig. 7. Switching action at 1 kHz (SIJ)

Mobility was estimated to be 1.8 cm^2/Vs. When the gate voltage was -20 V, drain current reached over 10 μA, which was about 100 times larger than that of WE-TFTs.

As the result of making the drain electrode narrower (1)-1 and increasing CNT density (2)-1, the S/N ratio was about 1000 times higher than that of the WE-TFTs. Figure 7 plots the dynamic properties of this TFT at 1 kHz. Displacement current is suppressed to the extent that it does not affect the switching action of the CNT-TFT. Clear switching action can be identified even at 100 kHz (Figure 8). The amplitude of this switching action is ~6 μA at 1 kHz, and ~5 μA at 100 kHz. Since no predominant decrease in amplitude was observed, the CNT channel definitely operated up to 100 kHz.

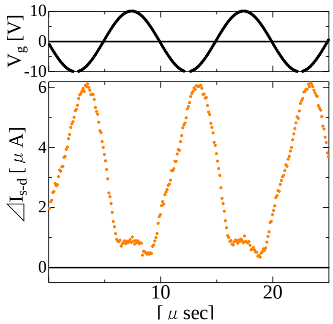

Fig. 8. Switching action at 100 kHz (SIJ)

3. Conclusions

First, we evaluated the dynamic performance of a CNT-TFT whose the electrodes had been patterned with a method of vapor deposition and found it was necessary to improve the S/N ratio. We enhanced on-current by using improved CNT ink and suppressed displacement current by patterning narrower electrodes to obtain a higher S/N ratio. Consequently, we achieved a ~1000 times higher S/N ratio than previously, and verified switching action in CNT channels up to 100 kHz. This study confirmed the superiority of CNTs as printable channel materials and suggested the possibility of pioneering fields of application for printed electronics by using CNT-TFTs.

Acknowledgment

The authors would like to thank Dr. Shinichi Yorozu and Ms. Mayumi Kosaka for helpful discussions. This work was supported by Project for Developing Innovation Systems of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References

[1] S. Iijima and T. Ichihashi, *Nature* **363** (1993) 603.
[2] M. Ishida and F. Nihey, *Appl. Phys. Lett.* **92** (2008) 163507.
[3] H. Numata *et al.*, *Appl. Phys. Express* **5** (2012) 055102.
[4] H. Endoh, *J.Photopoly.Sci.Tech* **25** (2012) 281.
[5] E. S. Snow *et al.*, *Appl. Phys. Lett*, **82** (2003) 2145.
[6] E. S. Snow *et al.*, *Appl. Phys. Lett*, **86** (2005) 033105.
[7] P. Beecher *et al.*, *J. Appl. Phys.* **102** (2007) 043710.
[8] T. Takenobu *et al.*, *Appl. Phys. Express* **2** (2009) 025005.
[9] K. Murata *et al.*, *Microsyst. Technol.* **12** (2005) 2.