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Hybrid-type Complementary Inverters using Semiconducting Single Walled Carbon Nanotube Networks and In-Ga-Zn-O Nanofibers

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Abstract

In this study, we fabricated complementary inverters using solution-processed semiconducting single-walled carbon nanotube (scSWCNT) random networks and electrospun In-Ga-Zn-O (IGZO) nanofibers as p-type and n-type TFT channels, respectively. The IGZO nanofiber n-type TFT and scSWCNT random network p-type TFT have an on-off current ratios of 2.55×10^5 and 1.38×10^5, a threshold voltage of -7.6 and 9.5 V, a subthreshold swing of 380 and 391 mV/dec, and field effect mobilities of 1.96 and 5.67 $cm^2/V{\cdot}s$ for electrons and holes respectively. In addition, this hybrid-type complementary inverters consisting of n-channel TFT and p-channel TFT have excellent CMOS operation characteristics. Therefore, we expect that the hybrid CMOS-type inverters using scSWCNT random networks and IGZO naofibers to be useful technologies for transparent and flexible digital logic circuits.

1. Introduction

Complementary inverters composed of n-channel and p-channel field-effect transistors (FETs) are widely used in digital circuits because they have advantages such as low static power consumption, large noise margins and full voltage swing. Recently, In-Ga-Zn-O (IGZO) as an n-type TFT channel has been intensively studied as a substitute for a conventional Si-based TFTs because of its excellent electrical characteristics and transparency. However, the IGZO film is limited in terms of mechanical flexibility. Overcome this problem, functional IGZO structures in the form of nanowires or nanotubes are being studied [1,2]. Among them, IGZO nanofibers fabricated using the electrospinning method are attracting much attention due to flexibility in one-dimensional (1D) form, large area in volume and excellent transfer characteristics [3,4]. On the other hand, as p-type TFT channel, oragnic semiconductor or carbon nanotube (CNT) have been studied extensively. Organic semiconductor TFTs are being studied because they have the advantage of being mechanically flexible and easy to manufacture at low cost. However, the stability of operation is poor due to the low chemical stability and sensitivity to the surrounding environment. Meanwhile, semiconducting single-walled carbon nanotubes (scSWCNTs) have been studied extensively as channel layer of p-type TFTs because of their excellent electrical and mechanical properties. Compared to conventional channel materials such as poly-Si, amorphous Si or metal oxide semiconductors, scSWCNT is capable of room temperature solution processing and has advantages in transparency, excellent flexibility, and high carrier mobility. Therefore, in this study, we fabricated a hybrid-type complementary inverter using scSWCNT network for p-type TFT and IGZO nanofiber for n-type TFT. The electrical characteristics of the fabricated scSWCNT network TFTs and IGZO nanofiber TFTs were measured and the characteristics of the CMOS inverter were evaluated.

2. General Instructions

On the p-type Si wafer, SiO_2 100 nm was thermally grown and standard RCA cleaning was performed. To form an n-channel layer, IGZO nanofibers were electrospun on a substrate using an IGZO precursor solution and then calcined by microwave irradiation at 1000 W to remove the polymer matrix and improve electrical properties. Then, photolithography and 30:1 BOE etching of IGZO nanofiber were performed to form the active region of the n-type TFTs. Subsequently, a uniform scSWCNT random network layer was deposited using a SWCNT solution (diameter range of 1.2-1.7 nm, length range of 300 nm) as a p-channel layer and photolithography and O_2 plasma ashing were performed to form the active region of the p-type TFTs. Finally, the hybrid CMOS-type inverters composed of scSWCNT network / IGZO nanofiber were fabricated by depositing 100-nm-thick Ti with E-beam evaporator and forming S/D electrode of TFTs by lift-off method.

Fig. 1 shows the optical transmittance spectra of the IGZO nanofibers and scSWCNT random networks. The average transmittance in the visible region (400 to 700 nm) of the IGZO nanofibers is 93.3%, and the scSWCNT random network is 97.3% higher in transparency.

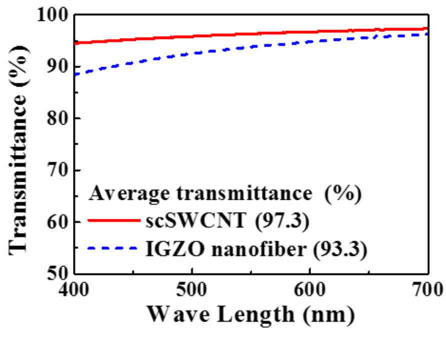

Fig. 1 Optical transmittance spectra of the IGZO nanofibers and scSWCNT random networks.

Fig. 2 shows the schematic structure of fabricated hybrid CMOS-type inverters composed of IGZO nanofiber n-chennal TFT and scSWCNT network p-channel TFT.

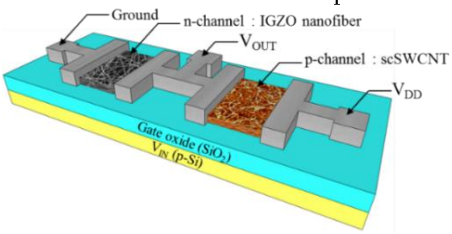

Fig. 2 Schematic structure of fabricated hybrid scSWCNT random network/IGZO nanofiber complementary inverters.

Fig. 3 show (a) optical microscope image of fabricated devices, (b) SEM image of n-type IGZO nanofibers, and (c) AFM image of scSWCNT networks, respectively. It is found that the electrospun IGZO nanofibers and the solution processed scSWCNT is well-formed. We have also found through the SEM and AFM images that the density of IGZO nanofibers and scSWCNT are 9.8×10^7 units/cm^2 and 4.2×10^9 unit/cm^2, respectively. The diameters of IGZO nanofibers and scSWCNT were found to be approximately 150 nm and less than 1 nm, respectively.

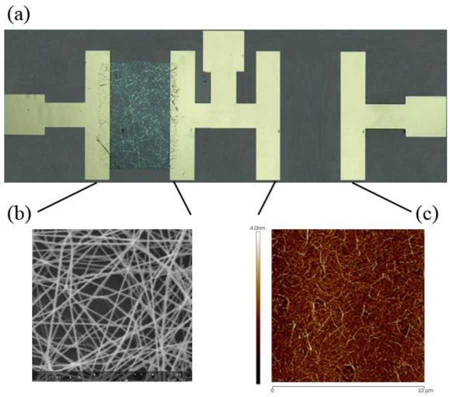

Fig. 3 (a) Optical microscope image of hybrid CMOS-type inverter. (b) SEM image of IGZO nanofibers in the n-channel region. (c) AFM image of scSWCNT network in the p-channel region.

Fig. 4 shows (a) I_{DS}-V_{GS} and (b) I_{DS}-V_{DS} curves of scSWCNT network/IGZO nanofiber complementary inverter. IGZO nanofiber (n-type) and scSWCNT network (p-type) TFTs have nearly symmetric electrical characteristics, an on-off current ratio of 2.55×10^5 and 1.38×10^5, a threshold voltage of 9.5 and -7.6 V, a subthreshold swing of 391.01 and 380.13 mV/dec at V_D = 1, -1 V. The field effect mobilities are 1.957, 5.674 cm^2/V·s respectively.

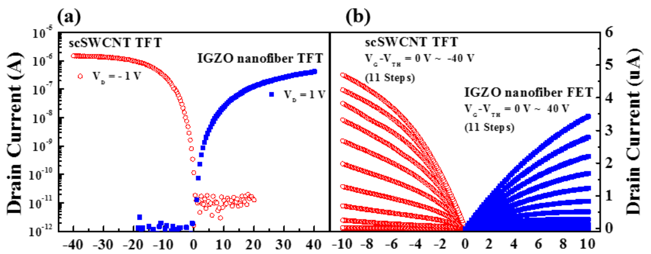

Fig. 4 (a) Transfer and (b) output characteristic curves of scSWCNT network and IGZO nanofiber FETs.

Fig. 5(a) shows the voltage transfer (V_{OUT}-V_{IN}) curve to evaluate the fabricated complementary inverter. As input voltage is swept from '0' (-20 V) state to '1' state (40 V), the output voltage changes from '1' (10 V) state to '0' (0 V) state. The output level (9.99 V) was almost equal to the input V_{DD} value (10 V), and the low output level showed excellent characteristics close to 0 V. At the same time, the I_D-V_{IN} characteristics of the complementary inverter were also shown with closed square. The I_D rapidly increased and decreased only in switching range, and it was close to 0 A at V_{OUT} near '0' and '1'. The voltage gain increased steeply as shown with open triangle. In addition as shown in Fig. 5(b), the inverter was measured in a square wave pulse having a period of 50 ms with '1' (20 V) and '0' (0 V). It is found that the inverter operates without delay at this frequency.

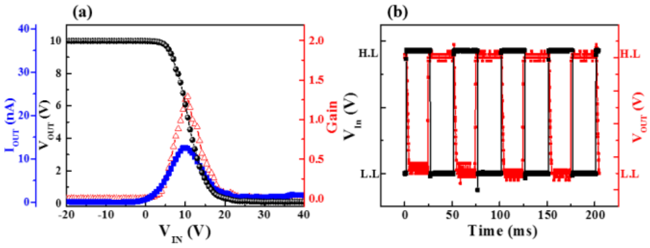

Fig. 5 (a) V_{out}-V_{in}, switching current and gain characteristics of inverter measured with V_{DD} = 10 V, (b) V_{out}-V_{in} characteristics at input signal of 20 V square wave (20 Hz).

3. Conclusions

We sucessfully fabricated complementary inverters using solution-processed scSWCNT random networks and electrospun IGZO nanofibers as p-type and n-type TFT channels, respectively. The IGZO nanofiber and scSWCNT random network TFTs showed an on-off current ratios of 2.55×10^5 and 1.38×10^5, a threshold voltage of -7.6 and 9.5 V, a subthreshold swing of 380 and 391 mV/dec, and field effect mobilities of 1.96 and 5.67 cm^2/V·s, respectively. In addition, this hybrid-type complementary inverters consisting of n-channel TFT and p-channel TFT demonstrate excellent CMOS operation characteristics. We expect that the hybrid CMOS-type inverters using scSWCNT random networks and IGZO nanofibers is promising for future transparent and flexible digital logic circuits.

Acknowledgements

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