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Characterization of All Printed Single-Wall Carbon Nanotube Based Thin-Film Transistor on Plastic Foils Using Displacement Current Measurement

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1. Introduction

All printed thin-film transistors (PTFTs) using organic semiconductor as active layer have been applied in the field of macroelectronic devices such as radio frequency identification tags (RFID), flexible displays and e-papers. However, the organic semiconductors have many disadvantages in mobility, stability and operation voltage comparing amorphous Si based TFTs. Therefore, to overcome those disadvantages recently single wall carbon nanotubes (SWCNTs) have been used as active layer to attain high mobility and stability under ambient condition. For the practical use of SWCNTs based printed TFTs (SWCNT-TFTs) in macroelectronic devices, the understand of the carrier injection properties between the interfaces of network structured SWCNTs and drain/source electrodes of SWCNT-TFTs is one of the most important issues because the all practical parameters of SWCNT-TFTs such as mobility, threshold voltage, and tansconductance tends to depend on carrier injection properties. The carrier injection properties of SWCNT-TFTs will be used to precisely evaluate those parameters.

In this paper, we demonstrate transfer curve and displacement current in all printed single-wall carbon nanotube based thin-film transistors (SWCNT-TFTs) on plastic foils and evaluate the field-effect mobility (μ), threshold voltage (V_{th}), and injection properties from the measured transfer curve and displacement current.

2. Experimental Methods

In displacement current measurement (DCM), the displacement current (I_{dis}) through a SWCNT-TFTs structure is measured while a triangular wave of external bias voltage, V_{GS} and a constant bias voltage of V_{DS}, are applied as show in Fig. 1. The displacement currents at the drain (I_{disD}) and source (I_{disS}) electrodes are given by

$$I_{dis} = I_{disD} + I_{disS} = \frac{dQ(t)}{dt} + (C_S + C_D)\frac{dV_{GS}}{dt}$$

$$Q(t) = \int_0^L \sigma(x,t) W dx$$

$$I_{disD,disS} = C_{S,D}\frac{dV_{GS}}{dt} + \frac{dQ}{dt} \qquad (1)$$

Q(t) : total charge at the channel

σ(x, t) : carrier density at position x

where $C_{D,S}$ consists of the capacitances of the gate dielectric layer under the drain and source electrodes, respectively.[1] I_{DS} is expressed in the saturation region as [2]

$$I_{DS} = \mu C_i \frac{W(V_{GS}-V_{th})^2}{2L} \qquad (2)$$

where L is the channel length, W is the channel width, also I_{dis} and I_{DS} are expressed by measured I_D and I_S as [1]

$$I_{dis} = I_{disD} + I_{disS} = I_D + I_S \qquad (3)$$

and

$$I_{DS} = \frac{-I_D + I_S}{2} \qquad (4)$$

respectively, when it is assumed that I_{disS} has the same value as I_{disD}, I_{dis} and I_{DS} can be evaluated from the simultaneously measured I_D and I_S by using these equations.[3]

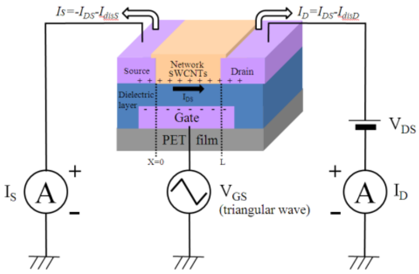

Fig. 1 Schematic diagram of the displacement current measurement (I_{dis}) and channel current (I_{DS}) in SWCNT-TFTs.

In the work, we printed bottom-contact SWCNTs based TFTs (SWCNT-TFTs) using an inkjet printer (Dimatrix DMP-2800 Fuji) for printing drain-source electrodes and an inkjet printer (UJ 2100, Unijet Co Korea) for printing active layers on Roll-to-Roll (R2R) gravure printed dielectric layer using barium titanate blending with epoxy (ε_r=14) with 2.5 μm thickness. The drain-source electrodes were printed using bundle SWCNTs based ink. The reason for using the bundle SWCNTs for the drain and source electrodes is to avoid Shottkey contact to semiconducting SWCNTs. For formulating bundle SWCNTs ink, 0.37 g of crude SWCNTs (HiPco) were dispersed in 1 L of water/SDS (10 g) using an ultrasonic homogenizer (Polyscience X-520, 750-Watt) for 1 h. The solution was then filtered (syringe filter with 5 μm of pore size, PALL) to remove aggregated SWCNTs; the filtrate had a viscosity of 0.79 cp and was used as a conducting ink to print the drain and source electrodes. The printed drain and source electrodes had sheet resistances of 4-4.5 KΩ/sq. The semiconductive ink was formulated using surface modifies SWCNTs (SM-SWCNTs) (0.001 g/L).[4] The formulated semiconducting inks were simply adjusting surface tension to maintain good printed quality on R2R gravure printed dielectric layer. The surface tensions of formulated inks were all about 34 mN/m. The active layers, with a width of 3890 *μ*m and channel lengths of 280 *μ*m, were printed on the R2R gravure printed dielectric layer per each of semiconducting inks. The resulting printed TFTs were dried under ambient condition at 60 °C for 1 h. Drain (I_D) and source (I_S) currents were simultaneously measured using a digital phosphor oscilloscope (Tektronix DPO 4054) during the applications of a constant drain voltage (V_{DS}) and a triangular-wave gate voltage (V_{GS}) in the bottom-contact all printed SWCNT-TFTs at 300K. V_{GS} was applied as three cycles of triangular waves with amplitudes of ±10V at 100Hz. Before the simultaneous measurements of I_D and I_S, V_{GS} was maintained at -10V. During all the measurements, V_{DS} was maintained at 0 or -9V.

3. Results and Discussion

In Figs. 2(a)-2(c), we show V_{GS}-*t*, I_S-*t*, and I_D-*t* relationships at a constant V_{DS} of -9 V, respectively. We used forward bias (from -10 to 10 V) and backward bias (from 10 to -10 V) of V_{GS} for displacement current measurement.

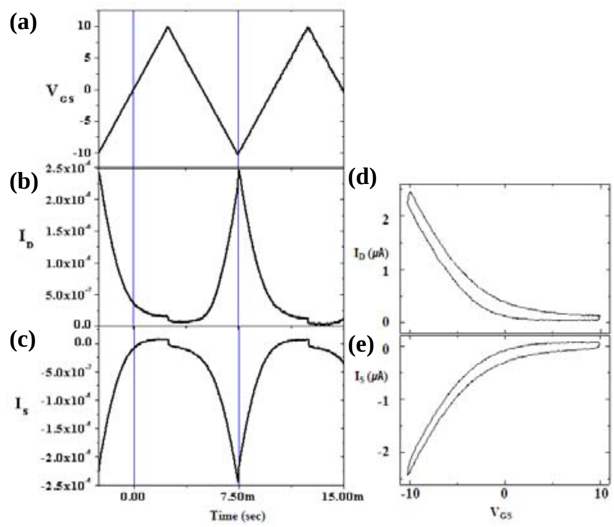

Fig. 2 Schematic diagram V_{GS}-*t* (a), I_D-*t* (b), I_S-*t* (c), I_D-V_{GS} (d), and I_S-V_{GS} (e) relationships at V_{DS} =- 9V in SWCNT-TFTs.

The data are converted into I_D-V_{GS} and I_S-V_{GS} relationships, as shown in Figs. 2(d) and 2(e). As a result, the maximum I_{DS} and displacement currents are 2.5 and 0.34 μA as show in Figs. 3(a) and 3(b), respectively.

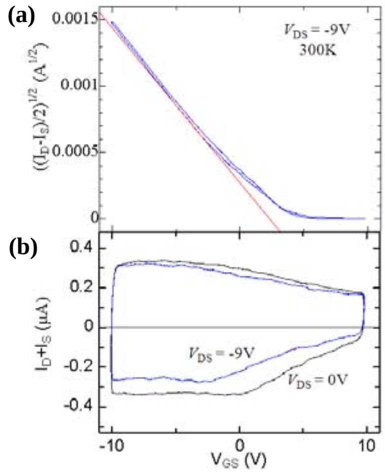

Fig. 3 Typical experimental of I_{dis}-V_{GS} (a) and $I_{DS}^{1/2}$-V_{GS} (b) characteristics of SWCNT-TFTs.

Furthermore, the squared root of the channel current $I_{DS}^{1/2}$-V_{GS} relationship shown in Fig. 3(a) and I_{DS} is calculated using eq. (4) and no hysteresis is observed in transfer curve. We calculated that the field-effect mobility and threshold voltages are respectively calculated to 0.39 cm^2/Vs and 2.8V using eq. (2). At the backward bias sweep, displacement current has plateaus at -0.26 μA, and -0.34 μA with the V_{DS} of -9, and 0 V. The decrease in the displacement current at -9 V indicates saturated region of the SWCNT-TFTs operation.

4. Conclusions

In summary, we have measured transfer curve and displacement currents in bottom-contact all printed SWCNT-TFTs. Using displacement current measurement method, we have been evaluated that the field effect mobility and threshold voltage of SWCNT-TFTs were 0.39 cm^2/Vs and 2.8 V from the channel current.

Acknowledgements

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Appendix