Improvement of contact resistance in transparent thin film transistor by applying an Al/SWCNTs bilayer as electrodes

Su Jeong Lee[*], Yun Cheol Kim[*],Tae Il Lee[**], Jung Han Kim[***], Chul-Hong Kim[***], Gee Sung Chae[***] and Jae-Min Myoung[*]

[*] Department of Materials Science and Engineering, Yonsei University, Korea, jmmyoung@yonsei.ac.kr
[**] Department of BioNano Technology and Gachon BioNano Research Institute, Gachon University, Seoul, Korea, t2.lee77@gachon.ac.kr
[***] LCD Research and Development Center, LG Display, Seongnam, Korea, junghan.kim@lgdisplay.com

ABSTRACT

Contact resistance has an important effect on the electrical characteristics of the thin film transistor (TFT). In the solution process, we present a study on the improvement of contact resistance between the single-walled carbon nanotubes (SWCNTs) and indium oxide (In_2O_3). In order to reduce the high carrier injection barrier for SWCNTs, aluminum (Al) was deposited as a contact layer between the SWCNTs and In_2O_3 films. Integrated device consisting of Al/SWCNT bilayers, In_2O_3 and hafnium oxide (HfO_2) as source and drain electrodes, channel layers and gate insulator, respectively, were fabricated on indium tin oxide (ITO) glass, bottom gate, structure. The threshold voltage of 0.53 V, sub-threshold swing of 0.39 Vdec^{-1}, field-effect mobility of 3.18 cm^2 V^{-1}s^{-1} and I_{on} / I_{off} ratio of ~10^6 were obtained. Furthermore, a transmittance of 69.82% was obtained.

Keywords: single-walled carbon nanotubes (SWCNTs), contact resistacne, spray coating, Al/SWCNT bilayer electrodes, tranceparent thin film transistor (TTFT)

1 BACK GROUND

SWCNTs show excellent heat transfer characteristics and the elastic strength, electrical and optical properties.[1-5] Due to these characteristics, SWCNTs have being studied as an alternative with which could replace indium-tin-oxide (ITO).[6,7] Because of the asymmetry of molecules, SWCNTs have various bandgaps so that they show metal as well as semiconductor characteristic. However, it is difficult to separate the metallic and the semi-conducting SWCNTs. Also, the high contact resistance at the interface between SWCNTs and the channel causes loss of carrier mobility and of electrical properties of device. In order to preserve the excellent performance of device, it is essential to make the contact resistance lower.[8,9]

In this study, we fabricated the Al/SWCNT bilayer electrodes and applied this structure to fabricated transparent thin film transistor (TTFT) for reducing the contact resistance. HfO_2 film as a gate insulator was deposited on ITO glass by atomic layer deposition (ALD) and In_2O_3 was spin-coated on it as channel layer. 7 nm-thick Al films were thermally deposited and the SWCNTs were spray-coated on channel to form bilayer electrodes and to complete TTFT. To evaluate the contact resistance between the In_2O_3 channel and the SWCNTs electrodes, Transmission Line Method (TLM) was applied. Furthermore, optical property was measured by ultraviolet-visible- near infrared spectrophotometer.

2 CURRENT RESULTS

Fig. 1 shows schmatic illustrations of TFTs with SWCNTs electrodes and 7 nm-thick Al/SWCNTs bilayer electrodes.

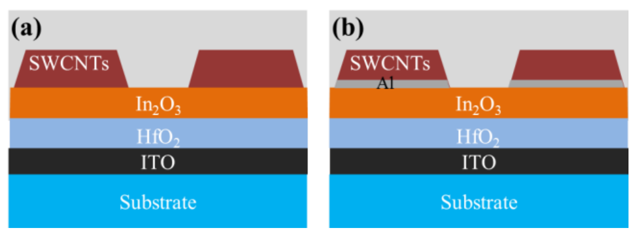

Figure 1: Schmatic illustrations of the bottom gate top contact TFT structures with (a) SWCNTs electrodes and (b) 7 nm-thick Al/SWCNTs bilayer electrodes.

ITO glass substrate was washed using acetone, isopropyl alcohol and deionized water, respectively. For the HfO_2 gate insulator layer, the HfO_2 film was deposited by commercial ALD chamber (NCD Co., Lucida M100-PL). $HfCl_4$ precursors were evaporated at 170 ℃ and the delivery lines were heated to 15 ℃ to prevent the Hf precursor condensation. Precursor vapor was brought into the reaction chamber by Ar carrier gas. Ar gas was also used to purge superfluity of gas molecules and byproducts between each precursor and reactant exposure step. Substrate temperature was retained at 250 ℃. For the In_2O_3 channel layer, 0.1 M of indium nitrate hydrate [$In(NO_3)_3$•xH_2O] was dissolved in deionized water. The In_2O_3 solution was stirred for 1 day, and filtered through polytetrafluoroethylene (PTFE) syringe filters before spin-coating. The In_2O_3 solution on the HfO_2 gate insulator layer was spin-coated at 3000 rpm for 20 sec and annealed at 250 ℃.[10] For the Al/SWCNTs bilayer source and drain electrodes, Al was deposited by evaporator and the film thicknesses were 7 nm. The SWCNTs were provided from Nano Solution Co. Ltd. (SA-210). To prevent aggregation, SWCNTs were dispersed in SDS (sodium dodecyl sulfate) surfactant and deionized water. The SWCNTs were spray-coated on Al contact layer at 115.5 ℃. After then, surfactant was removed using deionized water for 5 min. Finally, source and drain electrodes were patterned by using photo-lithography and lift-off process. The thicknesses of the HfO_2, In_2O_3, Al, and SWCNTs layers were 50, 15, 7, and 100 nm, respectively.[9]

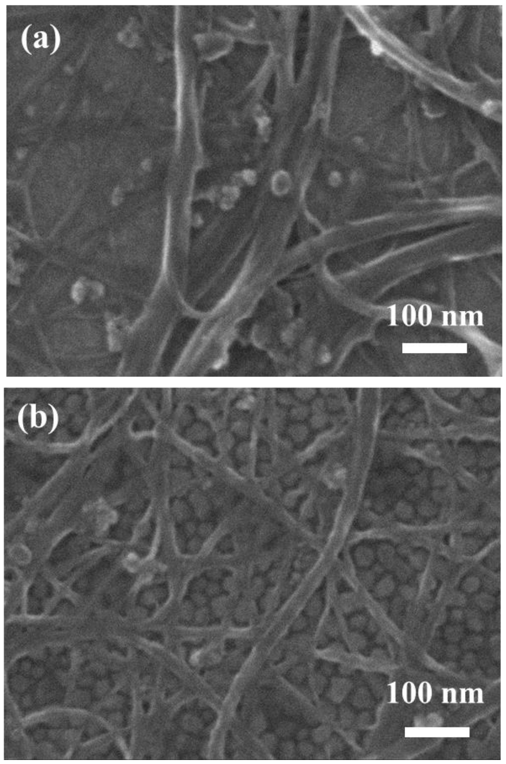

Figure 2: The SEM images of source and drain electrodes on In_2O_3 channel layer. (a) SWCNTs electrodes. (b) 7 nm-thick Al/SWCNTs bilayer electrodes.

Fig. 2(a), (b) show the field-emission scanning electron microscopy (FE-SEM, JSM-7001, JEOL) images of SWCNTs electrodes and 7 nm-thick Al/SWCNTs bilayer electrodes. The SWCNTs films were induced small contact area with the In_2O_3 channel layer. Also, small contact area disturbed the movement of carrier transport for channel layer. When 7 nm-thick Al contact layer was deposited under the SWCNTs film, the contact area increased so that the smooth movement of the carrier transport was possible.

The contact properties of SWCNTs electrodes and 7 nm-thick of Al/SWCNTs bilayer electrodes shown in Fig. 3 were estimated by using the TLM. The TLM patterns were defined as channel length was changed from 50 to 250 µm and channel width was defiend as 400 µm. And then, gate voltage varied from 5 to 20 V. The contact resistacne (R_CW) was estimated at L=0 and width normalized resistance (RW) point of intersection for each gate voltages.[11] The R_CW value for SWCNTs-electrode TFT was indicated at 429.3 KΩ to 2.29 MΩ with various gate voltages from 5 to 20 V in Fig 3(a). And the R_CW value for 7 nm-thick Al/SWCNTs bilayer TFT was indicated at 59.3 to 481.4 KΩ in Fig 3(b). 7 nm-thick Al/SWCNTs bilayer-electrode TFT was lower R_CW than that of SWCNTs-electrodes TFT because Al contact layer reduced the contact resistance between SWCNT electrodes and In_2O_3 channel layer.

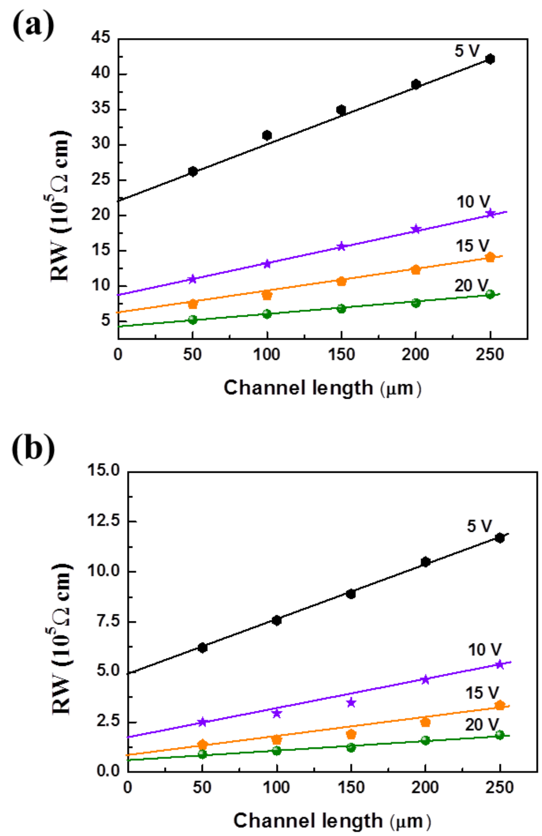

Figure 3: Width normalized resistance (RW) and width normalized contact resistance (R_CW) for (a) SWCNTs-electrode TFT and (b) 7 nm-thick Al/SWCNTs bilayer-electrode TFT with various gate voltages.

The electrical characteristics of SWCNTs electrodes and 7 nm-thick Al/SWCNTs bilayer electrodes shown in figure 4 were measured by semiconductor parameter analyser (Agilent B1500A, Agilent Technologies). The source and drain electrodes were fixed with a 150 µm channel width (W) and 20 µm channel lengths (L), respectively. The dielectric constant of HfO_2 is 18. Threshold voltage (V_{th}) was determined from the intersection of the square root of I_{DS}-V_{GS}. The field-effect mobility (μ_e) and sub-threshold swing (S) were calculated by the following formulas:[12]

$$I_{DS} = \left(\frac{C_i W \mu_{sat}}{2L}\right)(V_{GS} - V_{th})^2 \quad (1)$$

$$S = \left[\frac{d(\log_{10} I_{DS})}{dV_{GS}} \right]^{-1} \quad (2)$$

From transfer curve, the SWCNTs-electrode TFT with drain voltage (V_D) of 5 V has threshold voltage of 0.81 V, sub-threshold swing of 0.68 $Vdec^{-1}$, field-effect mobility of 1.73 $cm^2\ V^{-1}s^{-1}$ and I_{on} / I_{off} ratio of ~10^5. The 7 nm-thick Al/SWCNTs bilayer-electrode TFT with drain voltage (V_D) of 5 V has threshold voltage of 0.53 V, sub-threshold swing of 0.39 $Vdec^{-1}$, field-effect mobility of 3.18 $cm^2\ V^{-1}s^{-1}$ and I_{on} / I_{off} ratio of ~10^6.

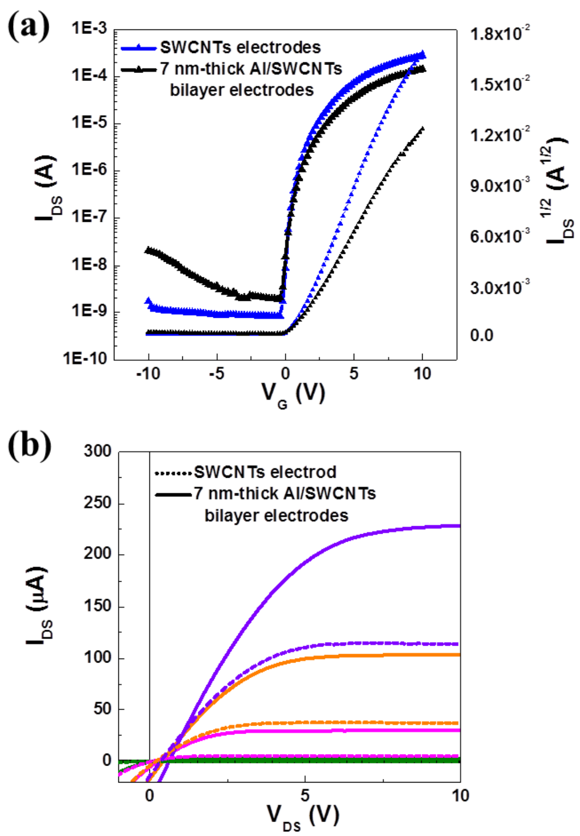

Figure 4: Electrical characteristics of TFTs. (a) Transfer curves of SWCNTs (black line) and 7 nm-thick Al/SWCNTs bilayer (blue line)-electrode TFT. (b) Output curves of SWCNTs (dashed line) and 7 nm-thick of Al/SWCNTs bilayer (soild line)-electrode TFT with V_{GS}= 0 to 8 V.

Figure 5 shows optical trasnsmittance spectra 7 nm-thick of Al/SWCNTs bilayer-electrode TFT in visible range at 550 nm. The optical transparency was evaluated by ultraviolet-visible-near infrared (UV-vis-NIR, V-650, JASCO) spectrophotometer. The transmittances were obtained 69.82% at 550 nm and 73.62% at an average of 350 to 780 nm.

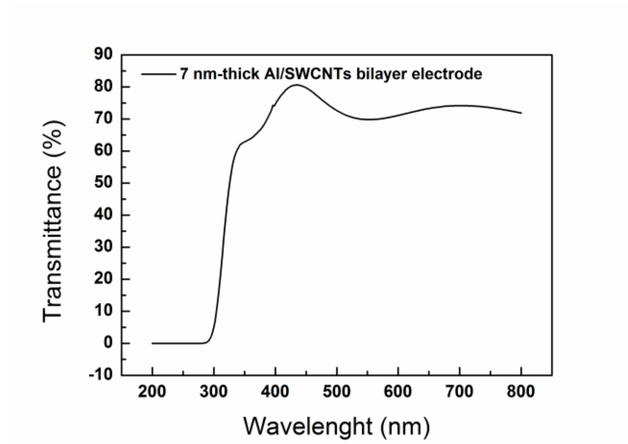

Figure 5: Optical transmittance spectra 7 nm-thick of Al/SWCNTs bilayer-electrode TFT.

In summary, we have reported transparent metal oxide TFT with 20 μm channel length and 7 nm-thick Al/SWCNTs bilayer-electrodes. High contact resistance of SWCNT induces carrier injection barrier, so that carrier hardly injects from electrode to semiconductor. Further, small contact area between SWCNTs disturbs the movement of carriers from electrodes to the channel. Al contact layer improves device performance of SWCNTs electrode TFT. The expansion on contact area of the electrode and inducement of ohmic contact between electrode and semiconductor make the contact resistance decrease by lowering the electron injection barrier in order for the carrier to move smoothly. The device performance exhibits excellent properties for a TFT with the 7 nm-thick Al/SWCNTs bilayer as a transparent electrodes.

REFERENCES

[1] S. Iijima and T. Ichihara, "Single-shell carbon nanotubes of 1-nm diameter", Nature, 363, 603-605, 1993.

[2] V. N. Popov, "Carbon nanotubes: properties and application" Mater. Sci. Eng. R, 43, 61-102, 2004.

[3] H. Kataura, Y. Kumazawa, Y. Maniwa, I. Uemezu, S. Suzuki, Y. Ohtsuka and Y. Achiba, "Optical properties of single-wall carbon nanotubes", Synt. Met. 103, 2555-2558, 1999.

[4] R. S. Ruoff, D. Qian and W. K. Liu, " Mechanical properties of carbon nanotubes: theoretical predictions and experimental measurements," C. R. Physique, 4, 993-1008, 2003.

[5] J. Hone, M. Whitney, C. Piskoti, and A. Zettl, "Thermal conductivity of single-walled carbon nanotubes", A. Phys. ReV. B, 59, R2514-R2516, 1999.

[6] D. S. Hecht, L. Hu and G. Irvin, "Emerging Transparent Electrodes Based on Thin Films of Carbon Nanotubes, Graphene, and Metallic Nanostructures", Adv.Mater., 23, 1482-1513, 2011.

[7] L. Hu, D. S. Hecht and G. Gru¨ne, "Carbon Nanotube Thin Films: Fabrication, Properties, and Applications", Chem. Rev., 110, 5790-5844, 2010.
[8] J. Jeon, T. I. Lee, J. H. Choi, J. P. Kar, W. J. Choi, H. K. Baik and J. M. Myoung, "Performance Enhanced Carbon Nanotube Films by Mechanical Pressure for a Transparent Metal Oxide Thin Film Field Effect Transistor", Electrochem. Solid-State Lett., 14, H76, 2011.
[9] J. H. Park, S. J. Lee, T. I. Lee, J. H. Kim, C. H. Kim, G. S. Chae, M. H. Ham, H. K. Baik, and J. M. Myoung, "All-solution-processed, transparent thin-film transistors based on metal oxides and single-walled carbon nanotubes", J. Mater. Chem. C, 1,1840-1845, 2013.
[10] J. H. Park, Y. B. Yoo, K. H. Lee, W. S. Jang, J. Y. Oh, S. S. Chae, H. W. Lee, S. W. Han, and H. K. Baik, "Boron-Doped Peroxo-Zirconium Oxide Dielectric for High-Performance, Low-Temperature, Solution-Processed Indium Oxide Thin-Film Transistor", ACS Appl. Mater. Interfaces., 5, 8067-8075, 2013.
[11] G. B. Blanchet, C. R. Fincher, M. Lefenfeld and J. A. Rogers, "Contact resistance in organic thin film transistors", Appl. Phys. Lett., 84, 296-298, 2004.
[12] B. G. Streetman and S. Banerjee, "Solid State Electronic Devices 6th edn (Upper Saddle River, NJ: Pearson Education)", 2006.