### Abstract

The contact resistance between source/drain electrodes and semiconductor layer is an important parameter affecting electron transporting performance in the thin film transistor (TFT). In this work, we introduced a transparent and the solution processable single-walled carbon nanotube (SWCNT)/Al-doped ZnO nano particle (AZO NP) bilayer electrodes showing low contact resistance with indium-oxide (In$_2$O$_3$) sol gel thin film. By inserting low work function AZO NPs into the interface between the SWCNTs and the In$_2$O$_3$, which has a high energy barrier, we could obtain an electrical Ohmic contact between them. Finally, with the SWCNT-AZO NP bilayer electrodes, we successfully fabricated a TFT showing a field effect mobility of 5.38 cm$^2$/V·s at 250°C.

### Keywords

Single-walled carbon nanotube (SWCNT), Al-doped ZnO (AZO) nanoparticle, contact resistance, Thin-film transistor (TFT).

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### I. INTRODUCTION

Flexible transparent electrode is an essential component for flexible displays, touch screens, smart windows, LCD, OLED and the solar cell. The material for application of transparent electrode should processes electrical characteristics and high optical properties [1]-[4]. Generally, indium tin oxide (ITO) is widely used as transparent electrodes for electronic devices. ITO shows a high optical transmittance and electrical conductivity. Nevertheless, ITO requires high deposition temperature and its mechanical flexibility is limited for application of flexible electronics. Also, indium, one of material consisting ITO, is too expensive [5], [6]. Various materials like Ag metal nanowires network, CNTs, and graphene was considered as the alternative of ITO. These materials like Ag metal nanowires network, CNTs, and graphene were considered as the alternative of ITO. These materials have superior electrical characteristics and high optical properties [11], [12]. Therefore, it causes degradation of the electrical characteristics of the transparent electrode [10]. On the contrary, the single-wall carbon nanotubes (SWCNTs) have excellent heat transfer characteristics and high oxidized temperature, mechanical, optical, and electrical properties [11], [12]. However, the high contact resistance between the SWCNTs and the semiconductor deteriorates the performance of electronic devices [13].

In order to solve this problem, we introduce a solution processable single-walled carbon nanotube (SWCNT)/Al-doped ZnO nano particle (AZO NP) bilayer electrode. An Ohmic contact could be formed by the AZO NPs and then the contact resistance was significant reduced. We experimentally investigated the electrical properties of the SWCNT/AZO NP bilayer electrodes and its contact resistance with the indium-oxide (In$_2$O$_3$) channel layer. As a result, an Ohmic contact could be formed so that it is possible to reduce the contact resistance and high performance In$_2$O$_3$ TFT could be achieved.

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### II. RESULT AND DISCUSSION

Fig. 1 (a) illustrates a scheme of bottom gate type TFT with the SWCNTs electrodes and the SWCNT/AZO NP bilayer electrodes. A heavily doped p-type Si (100) substrate with a thermally oxidized 300 nm thick SiO$_2$ layer was used. The substrate was washed using a piranha solution ($\text{H}_2\text{SO}_4$:$\text{H}_2\text{O}_2=3:1$) to remove organic residues. The In$_2$O$_3$ aqueous solution for the channel layer was prepared using 0.1 M of indium nitrate hydrate [$\text{In(NO}_3)_3\cdot\text{xH}_2\text{O}$] in deionized (DI) water and then purified the polytetrafluoroethylene (PTFE) syringe filters with 0.2 μm pores to filter out impurities before spin coating. The In$_2$O$_3$ channel layer was deposited by spin coating at 3000 rpm for 20 s and annealed at 250°C for 2 h [14]. The source and drain electrodes were formed by using the SWCNT/AZO NP bilayer electrodes. 0.1 wt% AZO NPs (Sigma-Aldrich) was dispersed in ethanol by sonication for 1 h.

AZO NPs solution was deposited by spin coating at 2000 rpm for 30 s and annealed at 100 °C for 5 min. This coating procedure was repeated 3 times. The SWCNTs (SA-210, Nano Solution Co. Ltd.) were dispersed in DI water with using a surfactant as sodium dodecyl sulfate. The SWCNTs solution was sprayed at 115°C and then rinsing with DI water. The photo lithography and lift-off process were used to define the source and drain electrodes [15]. Finally, 7 nm In$_2$O$_3$ film and 100 nm SWCNT/AZO NP bilayers were obtained.
AZO NPs were deposited on the SWCNT film, the contact area of the electrodes increased so that the smooth movement of the carrier was possible, as shown in Figs. 1 (c) and (d).

Fig. 2 shows characteristic transmittance-sheet resistance curves of the SWCNT film and the SWCNT/AZO NP bilayer film as a function of coating times with a thickness of 50 nm. When the SWCNTs thickness increased from 50 to 100 nm, sheet resistance dramatically decreased because interconnecting network formed percolation path between the SWCNTs and the movement of carriers was enhanced. However, the optical transmittance decreased by the increase of the thickness from 94.4 to 58.1%, as shown in Fig. 2 (a), whereas the average transmittance of the SWCNT/AZO NP bilayer film was maintained at 83.4%, as shown in Fig. 2 (b).

Fig. 3 shows the sheet resistance change after the bending test of the SWCNT/AZO NP bilayer film with a radius of curvature of 3 mm. The SWCNT/AZO NP bilayer film was retained stability electrical conductivities during repetitive bending cycles. Moreover, it is notable that the AZO NPs were not removed on the SWCNT film even after 3000 bending cycles.

Fig. 4 shows the electrical contact properties of the SWCNT and the SWCNT/AZO NP bilayer electrodes. To investigate the improvement of the contact resistance in the SWCNT/AZO NP bilayer electrodes, electrical resistance between the channel layer and the electrodes was evaluated by using a transmission line method (TLM).

The TLM patterns from 50 to 250 μm on the In<sub>2</sub>O<sub>3</sub> channel layer were formed. Also, the gate voltage increased from 5 to 20 V. The contact resistance (R<sub>c</sub>W) of the devices was estimated by plotting the width normalized resistance (RW) as a function of channel length. The intersection at L=0 provides the R<sub>c</sub>W for each gate voltages [16].

Fig. 4 (a) shows the R<sub>c</sub>W value of the SWCNT electrode. The R<sub>c</sub>W was changed from 11.5 to 2.62 MΩ as a function of channel length. Fig. 4 (b) shows the R<sub>c</sub>W value of the SWCNT/AZO NP electrode. The R<sub>c</sub>W was changed from 328.4 to 50.6 KΩ as a function of channel length. The SWCNT/AZO NP bilayer electrode showed lower R<sub>c</sub>W than
that of the SWCNT electrode because AZO NPs reduced the energy barrier height between the SWCNT electrodes and the In$_2$O$_3$ channel layer.

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I_{ds} = (WC_i/2L) \cdot \mu_{eff} (V_G - V_T)^2
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where, \(C_i\) is the gate dielectric capacitance per unit area, \(W\) is channel width, \(L\) is channel length. The threshold voltage \(V_{th}\) was calculated by linearly fitting the square root of \(I_{ds}\) vs \(V_{gs}\).

As a result, the \(\mu_\tau, V_{th}\), a sub-threshold slope (S) and \(I_{on}/I_{off}\) ratio of SWCNT electrode TFT were measured by 2.93 cm$^2$/V·s, -1.36 V, 5.87 V/decade and \(\sim 10^3\) at a \(V_D\) of 20 V, respectively. And the \(\mu_\tau, V_{th}\), a sub-threshold slope (S) and \(I_{on}/I_{off}\) ratio of SWCNT/AZO NP bilayer electrode TFT were 5.35 cm$^2$/V·s, 1.52 V, 2.58 V/decade and \(\sim 10^3\) at a \(V_D\) of 20 V, respectively.

In summary, a solution processable SWCNT/AZO NP bilayer electrode was introduced. To overcome the high contact resistance of the p-type SWCNTs with n-type In$_2$O$_3$ channel layer, the AZO NPs having a low work function was inserted between the SWCNT and the In$_2$O$_3$ channel layer. As a result, an Ohmic contact was successfully obtained between source/drain electrodes and channel layer and high performance In$_2$O$_3$ TFT could be achieved. This study has a significant technological impact and motivates deeper studies related to the fabrication and characterization of the SWCNT electrode based electronic devices in the aspect of lowering the energy barrier height between the n-type semiconductor and the p-type SWCNT by inserting a low work function conductive NP.

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REFERENCES


