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Fabrication and Electrical Characterization of InZnO:N Thin Film Transistors Prepared by Radio Frequency Magnetron Sputtering

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The fabrication and electrical characterization of InZnO:N thin film transistors (TFTs) were investigated in this work. The InZnO:N film was deposited on SiO_2/*p*-type Si substrates by radio frequency magnetron sputtering as the active layer of the TFTs at room temperature. In order to optimize the performance of the InZnO:N TFTs, the effect of the oxygen contents in the preparation of the active layer is investigated. We found that an appropriate O_2/Ar gas flow ratio is very beneficial for the InZnO:N TFTs, and when the O_2/Ar gas flow ratio is at 1/30, the transistor exhibited a high field-effect mobility of 39.3 cm^2/Vs, a threshold voltage of 2.4 V and a $I_{ON/OFF}$ ratio of 1.1×10^7.

Key words: InZnO:N, thin film transistor, field-effect mobility, $I_{ON/OFF}$ ratio

INTRODUCTION

In the past decades, amorphous silicon (a-Si) and poly silicon (p-Si) thin film transistors (TFTs) have been widely applied in flat panel displays. Nevertheless, they are non-transparent in the range of visible light. Meanwhile, the field-effect mobility of a-Si TFTs are generally less than 1 cm^2/Vs of field-effect mobility and the p-Si TFTs suffer from non-uniformity against large-area preparation.[1–4] Recently, the metal oxide-based TFTs have attracted particular attention to solve these problems due to their advantages such as high optical transparency in the visible light region and higher field-effect mobility. Among the metal oxide-based TFTs, the InGaZnO TFTs have been widely explored and basically industrialized, due to their high field-effect mobilities (>10 cm^2/Vs).[5–8] But, their field-effect mobilities still can't meet the demands of the next generation of displays, which is expected to have the characteristics of high resolution, high speed, large size, and three dimensionality (3D).

It is well known that the In-doped ZnO films have benefits of carrier transport and enhancement of field-effect mobility. The 5*s* orbital of metal ions with an electronic configuration of $(n-1)d^{10}ns^0$ seems to play a dominant role in providing good conductivity.[9–11] And N, as a suitable candidate for substituting O (N_O), was used to improve the electrical properties of ZnO TFTs by intentional adding into the active layers. However, there have been low saturation field-effect mobilities μ_{SAT} (2–20.9 cm^2/Vs) for ZnO:N TFTs in the earlier literature.[12–14] Nevertheless, so far, there are no reports about InZnO:N TFTs.

In this work, we fabricated bottom-gate-type InZnO:N TFTs by radio frequency (RF) magnetron sputtering. Furthermore, the effect of the oxygen contents in the preparation of the active layer on the electrical properties of the InZnO:N TFTs was investigated. And when the O_2/Ar gas flow ratio is 1/30, the InZnO:N TFTs exhibited better electrical characteristics with a high field-effect mobility of 39.3 cm^2/Vs, an $I_{ON/OFF}$ ratio of over 10^7 and a V_{TH} of 2.4 V.

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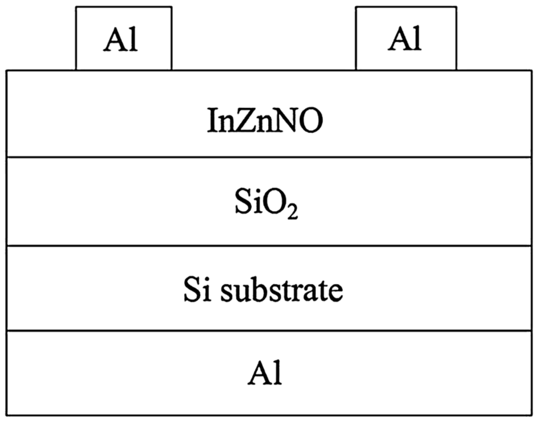

Fig. 1. Cross-sectional schematic diagram of the InZnO:N TFTs structure.

EXPERIMENT

A diagram of the N-doped InZnO TFT structure employed in this paper is shown in Fig. 1. First, 250-nm-thick SiO_2 layers were deposited on Si and acted as the gate dielectrics. The 30-nm-thick InZnO:N films were deposited as an active layer on SiO_2/*p*-type Si substrates by RF magnetron sputtering. The RF sputtering power was 100 W, and the sputtering time was 900 s. The deposition was done at room temperature in a mixed atmosphere of Ar and O_2 with the O_2/Ar gas flow ratio varied as 0/30, 1/30, 2/30, 3/30, 4/30, and the Ar gas flow was fixed at 30 standard cubic centimeter per minute (SCCM). The deposition process was performed at a working pressure of 2×10^{-2} Pa. The InZnO:N targets were prepared with the ZnO-In_2O_3-Zn_3N_2 ceramic target with 1% molar ratio of N/Zn and 50% molar ratio of Zn/In. The source was 100-nm thick aluminum (Al) layers and drain electrodes were thermally evaporated onto the active layer through a shadow mask with the gate length (L) and width (W) of the fabricated InZnO:N TFTs were 70 and 140 μm, respectively. And 100-nm thick Al also was patterned on the back side of p-Si to serve as gate contact. The electrical characteristics were measured by a Keithley 4200-SCS at room temperature in ambient air.

RESULTS AND DISCUSSION

Figure 2 shows the output characteristics of InZnO:N TFT with the O_2/Ar gas flow ratio of 1/30. The curves are very stable and smooth. The device exhibits typical field effect transistor characteristics and is an *n*-type transistor for the increased drain current with positive gate voltage. Furthermore, many other characteristics were observed which is very desirable for practical applications of transistors, such as clear pinch-off, high on-current, saturation characteristics at higher drain-source voltage.

Figure 3 shows the transfer characteristics of InZnO:N TFT with an O_2/Ar gas flow ratio of 1/30

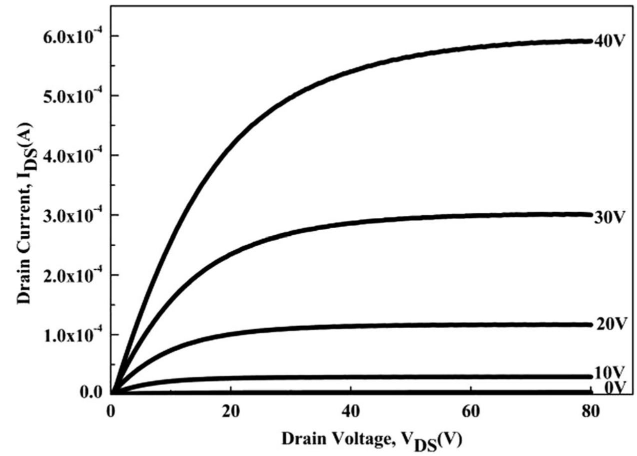

Fig. 2. Output characteristics of InZnO:N TFT with V_{GS} = 0 to 40 V.

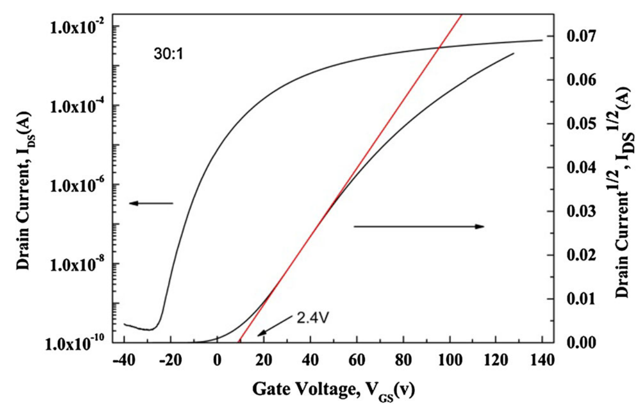

Fig. 3. Transfer characteristics of InZnO:N TFT with V_{DS} = 40 V.

at a drain voltage of 40 V. The field-effect mobility (μ_{SAT}) and the threshold voltage (V_{TH}) were calculated by linearly fitting the square root of the drain current (I_{DS}) versus gate voltage (V_{GS}) curve, according to the expression:

$$I_{DS} = \frac{C_i \mu_{SAT} W}{2L}(V_{GS} - V_{TH})^2, \quad \text{for} \quad V_{DS} \geq V_{GS} - V_{TH} \tag{1}$$

$$C_i = \frac{\varepsilon_0 \varepsilon_{SiO_2}}{t_{SiO_2}}, \tag{2}$$

where C_i is the capacitance per unit area of the gate insulator, W and L are the channel width and length, respectively, ε_0 is the permittivity of free space, ε_{SiO_2} is the relative permittivity of SiO_2, and t_{SiO_2} is the thickness of SiO_2. The I_{OFF} and $I_{ON/OFF}$ ratio are measured to be 3.0×10^{-10} and 1.1×10^7.

From the calculations, we get a V_{TH} of 2.4 V and a μ_{SAT} of 39.3 cm^2/Vs for InZnO:N TFT. That is better than the highest field-effect mobility μ_{SAT} of 17.9 cm^2/Vs InZnO TFT in the earlier report which was fabricated by RF magnetron sputtering.[15] It has been reported that in N-doped ZnO thin films,

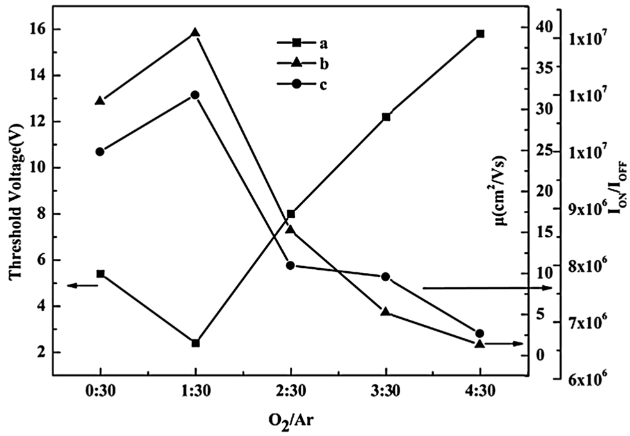

Fig. 4. Evolution of the threshold voltage (a), field-effect mobility (b) and $I_{ON/OFF}$ ratio (*c*) with different O_2/Ar.

the nitrogen atoms could substitute for oxygen as acceptors and then serve as fixed negative charges in the lattice.[16] A similar effect should happen in InZnO:N thin films as well, improving the field-effect mobility of InZnO:N TFTs.

Figure 4 shows the evolution of the threshold voltage (a), field-effect mobilities (b) and $I_{ON/OFF}$ ratio (c) at different O_2/Ar gas flow ratio. When the O_2/Ar gas flow ratio increases from 0/30 to 1/30, the V_{TH} of the TFT decreases from 5.4 V to 2.4 V, the field-effect mobility of the TFT increases from 31.0 cm^2/Vs to 39.3 cm^2/V s, and the $I_{ON}/_{OFF}$ ratio also rises from 1.0×10^7 to 1.1×10^7. When a small quantity of oxygen incorporates into the InZnO:N film, the compositional change of In, Zn and oxygen elements reduce the intrinsic defects in the film, leading to the increase of channel carrier concentration.[17] And then with O_2/Ar gas flow ratio increases from 1/30 to 4/30, the field-effect mobility and the $I_{ON/OFF}$ ratio decreases from 39.3 cm^2/Vs to 1.3 cm^2/Vs and 1.1×10^7 to 6.8×10^6, and the V_{TH} rises form 2.4 V to 15.8 V. These results are presumably related to the dramatic increase of resistivity with increasing of oxygen partial pressure. These results can be explained in that increasing oxygen partial pressure reduces oxygen vacancies to act like donors;[17,18] the research of Carcia has similar results.[19]

CONCLUSION

The preparation and electrical characterization of InZnO:N TFTs employing RF magnetron sputtering were investigated in this paper. Good performance is obtained with the field-effect mobility of 39.3 cm^2/V s, a V_{TH} of 2.4 V and a $I_{ON/OFF}$ ratio of 1.1×10^7 by the O_2/Ar gas flow ratio at 1/30. The effect of the oxygen contents in the preparation of the active layer on the electrical properties of the InZnO:N TFTs was investigated. As the O_2/Ar gas flow ratio increased from 0/30 to 1/30, the field-effect mobility and the $I_{ON/OFF}$ ratio were increased, and the threshold voltage was shifted to the negative direction, due to the increase of carrier concentration in the active layer. When the O_2/Ar gas flow ratio increased from 1/30 to 4/30, the electrical property decreased due to the increase of resistivity in the InZnO:N film.

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REFERENCES

1. E. Fortunato, P. Barquinha, and R. Martins, *Adv. Mater.* 24, 2945 (2012).
2. J.S. Lee, S. Chang, S.M. Koo, and S.Y. Lee, *IEEE Electron Device Lett.* 31, 225 (2010).
3. D.X. Luo, L.F. Lan, M. Xu, H. Xu, M. Li, L. Wang, and J.B. Peng, *J. Electrochem. Soc.* 159, H502 (2012).
4. S.Y. Park, B.J. Kim, K. Kim, M.S. Kang, K.H. Lim, T.I. Lee, J.M. Myoung, H.K. Baik, J.H. Cho, and Y.S. Kim, *Adv. Mater.* 24, 834 (2012).
5. P.I. Reyes, C.J. Ku, Z. Duan, Y. Lu, A. Solanki, and K.B. Lee, *Appl. Phys. Lett.* 98, 173702 (2011).
6. Y.S. Tsai, C.H. Li, I.C. Chiu, H.A. Chin, I.C. Cheng, and J.Z. Chen, *Thin Solid Films* 529, 360 (2013).
7. J. Li, X.W. Ding, J.H. Zhang, H. Zhang, X.Y. Jiang, and Z.L. Zhang, *AIP Adv.* 3, 102132 (2013).
8. K.C. Ok, S.H.K. Park, C.S. Hwang, H. Kim, H.S. Shin, J. Bae, and J.S. Park, *Appl. Phys. Lett.* 104, 063508 (2014).
9. Y.K. Moon, S. Lee, D.Y. Moon, W.S. Kim, B.W. Kang, and J.W. Park, *Surf. Coat. Technol.* 205, S109 (2010).
10. K. Nomura, H. Ohta, A. Takagi, M. Hirano, and H. Hosono, *Nature* 432, 488 (2004).
11. L.P. Peng, L. Fang, X.F. Yang, H.B. Ruan, Y.J. Li, Q.L. Huangand, and C.Y. Kong, *Physica E* 41, 1819 (2009).
12. S.J. Lim, S.J. Kwon, H. Kim, and J.S. Park, *Appl. Phys. Lett.* 91, 183517 (2007).
13. X.A. Zhang, J.W. Zhang, W.F. Zhang, D. Wang, Z. Bi, X.M. Bian, and X. Hou, *Thin Solid Films* 516, 3305 (2008).
14. J.M. Kim, T. Nam, S.J. Lim, Y.G. Seol, N.E. Lee, D. Kim, and H. Kim, *Appl. Phys. Lett.* 98, 142113 (2011).
15. X.W. Ding, H. Ding, C.X. Huang, H. Zhang, W.M. Shi, J.H. Zhang, J. Li, X.Y. Jiang, and Z.L. Zhang, *Superlattice Microstruct.* 74, 11 (2014).
16. Y.R. Sui, B. Yao, J.H. Yang, H.F. Cui, X.M. Huang, T. Yang, L.L. Gao, R. Deng, and D.Z. Shen, *Appl. Surf. Sci.* 256, 2726 (2010).
17. K.-H. Lee, K.-C. Ok, H. Kim, and J.-S. Park, *Ceram. Int.* 40, 3215 (2014).
18. Q.H. Li, Y.X. Liang, Q. Wan, and T.H. Wang, *Appl. Phys. Lett.* 85, 6389 (2004).
19. P.F. Carcia, R.S. Mclean, M.H. Reilly, and G. Nunes, *Appl. Phys. Lett.* 82, 1117 (2003).