Stability Improvement of Nitrogen Doping on IGO TFTs under Positive Gate Bias Stress and Hysteresis Test

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Thin-film transistors (TFTs) using indium-gallium-oxide (IGO) semiconductor materials as channel layers were fabricated. In this study, nitrogen was introduced in the process of channel deposition to investigate its effect on device performance. The experimental results showed that moderate nitrogen doping can significantly reduce the device stability under positive gate bias stressowing to the reduction of oxygen vacancies. Furthermore, for the purpose of understanding the influence of different doping levels, the nitrogen doping ratio was modulated in an ascending order from 0 sccm to 5 sccm. Among the fabricated c-IGO TFTs, the one with 2 sccm nitrogen doping exhibited the least threshold voltage shift. In addition, the hysteresis measurement further confirmed that the interface traps between the channel and the dielectric were significantly passivated in nitrogen-doped TFT. In this regard, the method of in situ nitrogen doping was certified to serve an efficient way of fabricating a passivation-free TFT and improve the device stability simultaneously.

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Recently, transparent oxide semiconductors (TOSs) have been the object of extensive research in various connected fields. Owing to the advantages of high mobility, good transparency and ideal uniformity, TOSs are more suitable for the application of thin-film transistors (TFTs) than conventional Si TFTs.1,2

In addition, the features of low-temperature process and their compatibility with flexible electronic enable TOSs to become the mainstream channel materials in next generation flat panel displays, such as active-matrix liquid crystal displays (AMLCDs)3 and active-matrix (RF) magnetron sputtering using the IGO target (In2O3:Ga2O3)10 sccm nitrogen doping exhibited the least threshold voltage shift. In addition, the hysteresis measurement further confirmed that the interface traps between the channel and the dielectric were significantly passivated in nitrogen-doped TFT. In this regard, the method of in situ nitrogen doping was certified to serve an efficient way of fabricating a passivation-free TFT and improve the device stability simultaneously.

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Experimental

Figure 1 demonstrates the structure of inverted-staggered IGO TFTs. The devices with slightly nitrogen-doped active layers were prepared on quartz substrates in this study. In the beginning, the bottom gate electrode of 80-nm-thick aluminum (Al) was deposited by E-beam evaporation through the shadow mask and capped with a 200-nm-thick SiO2 gate dielectric by plasma-enhanced chemical vapor deposition (PECVD) at 300°C subsequently. The active layers of 10-nm-thick IGO films with different nitrogen doping ratios were sputtered on the dielectric by radio frequency (RF) magnetron sputtering using the IGO target to 20-10:5 wt% at room temperature. In the process of channel deposition, the fluxes of argon (Ar) and oxygen gas (O2) were fixed at 40 and 10 sccm, respectively. In order to investigate the influence of nitrogen doping in varying degrees on device performance, the nitrogen gas (N2) with five different nitrogen doping fluxes (0, 1, 2, 3 and 5 sccm) was introduced into the chamber. The exact gas ratio of Ar:N2 was fixed at 40:10:0, 40:10:1, 40:10:2, 40:10:3 and 40:10:5 sccm. The total working pressure was kept at 5 mTorr with an RF discharge power of 80 W. Finally, 80-nm-thick Al films were evaporated onto the IGO channel, serving as source/drain (S/D) electrodes, via an E-beam evaporation. Both the IGO channel and S/D electrodes were also patterned by specific shadow masks, where the channel length (L) and width (W) of the fabricated TFTs were 10 and 100 μm, individually.

Figure 1. The schematic of fabricated inverted-staggered IGO TFT.
Results and Discussion

Figure 2 shows the XRD spectra of the IGO films with different nitrogen doping ratios to observe their crystallinity states. Apart from the broad halo peak of quartz substrate around 2θ = 23°, a crystalline peak, located approximately at 31°, was found, primarily due to the crystalline phase of In_{2}O_{3}, based on the standard X-ray diffraction patterns of JCPDS. The fabricated IGO films had a specific orientation swing (SS), threshold voltage (VTH), on-off current ratio (ION/IOFF), and a fixed drain voltage (VDS) of 8 V. The corresponding calculated electrical parameters such as field effect mobility (\(\mu_{FE}\)), subthreshold swing (SS), threshold voltage (VTH), on-off current ratio (ION/IOFF), and density of trap states (NSS) of these TFTs were summarized in Table I. The threshold voltage was characterized through the constant current method, where VTH was defined as the gate voltage when the drain current reached the level of 10^{-6} A. 

Figure 4 shows that the transfer curves of the IGO TFTs shifted to the right with the doping flow increasing from 0 to 5 sccm, where the threshold voltage also increased from −1.18 V to −1.10 V. Additionally, as shown in Table I, the on-current (ION), which was defined as the drain current (IDS) was a function of the gate voltage (VGS), with the drain current (IDS) was a function of the gate voltage (VGS), with a fixed drain voltage (VDS) of 8 V . The corresponding calculated electrical parameters such as field effect mobility (\(\mu_{FE}\)), subthreshold swing (SS), threshold voltage (VTH), on-off current ratio (ION/IOFF), and density of trap states (NSS) of these TFTs were summarized in Table I. The threshold voltage was characterized through the constant current method, where VTH was defined as the gate voltage when the drain current reached the level of 10^{-6} A. 

Moreover, the subthreshold swing (SS), which represents the existence of defects in bulk channel and/or at the interface between channel and gate dielectric, degraded from 0.23 to 1.80 V/dec. The degradation of SS was driven by the elevation of the number of undesirable traps originating from nitrogen doping process. Hoffman et al. discovered that the deep defects in metal oxide materials, including undercoordinated oxygen atoms and dangling bonds, etc., could affect subthreshold swing extremely. Siddiqui et al. also reported defect creation is the fundamental cause for the degradation of mobility and subthreshold swing of ZnO TFTs under NBTS. With regard to the strong correlation between subthreshold swing and deep trap states, the trap density (\(N_{SS}\)) was calculated using the following equation:

\[
N_{SS} = \left[ \frac{SS \log(e)}{kT/q} - 1 \right] \frac{C_i}{q},
\]

where k is Boltzmann constant, T is absolute temperature, q is electron charge and Ci is the capacitance of gate dielectric per unit area.

Table I. Extracted electrical parameters of IGO TFTs doped with various ratios for nitrogen.

| sccm | ION (A) | IOFF (A) | ION/IOFF | \(\mu_{FE}\) (cm²V⁻¹s⁻¹) | SS (V/dec) | NSS (cm⁻²) | VTH (V) |
|------|---------|----------|----------|-----------------|------------|-----------|----------|
| 0    | 6.1 × 10⁻⁵ | 1.0 × 10⁻¹² | 6.1 × 10⁷ | 9.91 | 0.27 | 4.10 × 10¹³ | −0.69 |
| 1    | 3.2 × 10⁻⁵ | 1.1 × 10⁻¹¹ | 2.8 × 10⁶ | 5.33 | 0.64 | 1.14 × 10¹² | 0.21 |
| 2    | 1.7 × 10⁻⁵ | 4.4 × 10⁻¹¹ | 3.9 × 10⁵ | 3.75 | 1.42 | 2.53 × 10¹² | 0.91 |
| 3    | 1.5 × 10⁻⁵ | 1.5 × 10⁻¹² | 9.8 × 10⁶ | 2.46 | 1.51 | 2.69 × 10¹² | 1.34 |
| 5    | 3.8 × 10⁻⁶ | 2.6 × 10⁻¹¹ | 1.5 × 10⁵ | 1.69 | 1.80 | 3.21 × 10¹² | 2.33 |
It increased from $4.10 \times 10^{11}$ to $3.21 \times 10^{12}$ cm$^{-2}$ with the nitrogen doping up to 5 sccm. From a certain perspective, excessive nitrogen atoms, which were considered as doping impurities, not only induced the strained bonds but disturbed the electron transportation.$^{21}$ However, the incorporation of nitrogen had advantageous effect on device stability. The time evolution of the transfer curves under positive gate bias stress (PBS) are shown in Figs. 4a–4e, where the positive gate bias stress was performed with the gate bias fixed at +20 V, and with the source/drain electrodes grounded for a stress time of 1000 seconds. The positive $V_{TH}$ shifts of the IGO TFTs with nitrogen doping of 0, 1, 2, 3 and 5 sccm were 7.89 V, 7.56 V, 4.39 V, 7.04 V, and 7.30 V, respectively. The nitrogen doping hereby contributed to a significant reduction in $\Delta V_{TH}$. Fig. 4f clearly reveals that 2 sccm nitrogen-doped IGO TFT possessed the optimized stability in the PBS test among all the fabricated devices, where its $\Delta V_{TH}$ was 4.39 V. Normally, the bias-stress-induced $\Delta V_{TH}$ was mainly concerned with the generation of defects in the bulk channel and/or at the interface between channel and dielectric.$^{22}$ By means of nitrogen doping process, the oxygen vacancy related defects could be effectively diminished, and restrained the threshold voltage shift. Another advantage is that some researchers confirmed that, from the aspect of bonding energy, the metal-nitrogen bonding strengthened the lattice structure and was more stable as compared with the metal-oxygen bonding.$^{23,24}$

However, with increasing the nitrogen doping concentration, the IGO TFT with 3 and 5 sccm doping exhibited inferior PBS stability than the one doped with 2 sccm. This tendency, where the $V_{TH}$ shift declined at first but became larger after the doping ratio rose over 2 sccm, was the result of too much intrinsic deep traps induced by excessive nitrogen doping in the bulk channel, and it also led to the degradation of subthreshold swing. Figure 5 indicates that the application of positive bias stress degraded the subthreshold swing, which meant the increment of interface trap and/or defect trap creation after the bias stress, as further shown in Table II. Additionally, the similar situation also occurred in Fig. 6, making the carrier mobility...
Table II. Extracted electrical parameters of IGO TFTs doped with various ratios for nitrogen after positive bias stress.

| N2 Doping  | $I_{ON}$ (A) | $I_{OFF}$ (A) | $I_{ON}/I_{OFF}$ | $\mu_{FE}$ (cm$^2$V$^{-1}$s$^{-1}$) | SS (V/dec) | $N_{SS}$ (cm$^{-2}$) | $V_{TH}$ (V) |
|------------|--------------|---------------|------------------|-----------------------------------|------------|---------------------|-------------|
| 0 sccm     | $2.7 \times 10^{-5}$ | $1.3 \times 10^{-12}$ | 2.2 $\times 10^7$ | 8.58                              | 0.23       | 4.81 $\times 10^{11}$ | 7.20        |
| 1 sccm     | $1.3 \times 10^{-5}$ | $1.4 \times 10^{-13}$ | 9.3 $\times 10^7$ | 5.04                              | 0.67       | 1.43 $\times 10^{12}$ | 7.77        |
| 2 sccm     | $1.2 \times 10^{-5}$ | $2.2 \times 10^{-11}$ | 5.4 $\times 10^5$ | 3.68                              | 1.44       | 2.64 $\times 10^{12}$ | 5.30        |
| 3 sccm     | $4.4 \times 10^{-6}$ | $5.2 \times 10^{-13}$ | 8.4 $\times 10^6$ | 1.21                              | 1.52       | 2.94 $\times 10^{12}$ | 8.38        |
| 5 sccm     | $1.7 \times 10^{-6}$ | $3.0 \times 10^{-13}$ | 5.6 $\times 10^6$ | 0.91                              | 1.79       | 3.17 $\times 10^{12}$ | 9.63        |

Decrease. These results showed that the degradation for 2 sccm device was least severe, implying only moderate nitrogen doping showed the best electrical stability.

To further clarify the associated mechanism, XPS measurement was conducted to characterize the chemical bonding states of the channel layer with varied nitrogen doping ratio. The deconvolution of XPS spectrum of OIs were analyzed in Figs. 7a–7e, with the three sub-peaks fitted by Gaussian fitting method. The OIs could be fitted by three principal component peaks: O$_1$ was centered at 530.1 ± 0.2 eV, O$_2$ was centered at 531.5 ± 0.2 eV and O$_{III}$ was centered at 532.5 ± 0.2 eV. The three major sub-peaks, which are O$_1$, O$_2$, and O$_{III}$, represent the oxygen ions combined with metal ions without oxygen deficiencies, the oxygen ions in the oxygen-deficient region, and the adsorbed oxygen from the environment, involving absorbed O$_2$−CO$_3$, or −OH, respectively. With the raise of nitrogen doping ratio, the proportional areas of sub-peaks were affected clearly, and therefore the O$_{III}$/O$_{total}$ increased with nitrogen doping, shown in above-mentioned XRD results. We can reasonably presume that the smaller grain size suggested that more grain boundaries existed in the bulk channel and retained more defect traps. These defect traps interfered the carrier transport and brought about the worse carrier mobility, as agreed with the previous research.

To realize whether the method of nitrogen doping decreased the trap density, the IGO TFTs with the five N-doping ratios were prepared for the I-V hysteresis to estimate the number of defect traps. The application of hysteresis measurement further helped differentiate the interface traps between channel and dielectric from deep traps in bulk channel. The gate voltage here was first swept by a forward sweep (F) from −15 V to +20 V and followed by a reverse sweep (R) from +20 V to −15 V subsequently. The clockwise hysteresis in transfer curves from 0 to 5 sccm nitrogen-doped TFTs are displayed in Figs. 9a–9c, separately. It is worth mentioning that the hysteresis window, encircled by both the forward sweep and the reverse sweep, was able to deduce the amount of interface traps between the dielectric and the channel layer. As shown in Fig. 9a, the undoped IGO TFT exhibited an obviously wider window with slight degradation in subthreshold swing, presenting an inferior hysteresis behavior. This was attributed to the phenomenon of charge trapping happening at the interface. On the contrary, the transfer curve of the IGO TFT with 2 sccm nitrogen doping in Fig. 9e was shifted only slightly, and no subthreshold swing decay was measured, which directly accounted for the fact that no defect creation took place at the dielectric/channel interface after I-V hysteresis. It showed that the nitrogen atoms repaired the dangling bonds and avoided a worse $V_{TH}$ shift during the positive gate bias stress. It should be noticed that the hysteresis window decreased after the PBS, showing that the accumulation of electron under positive gate bias reduced the interface traps between the channel layer and dielectric layer, as was confirmed in the previous literature. Um et al. confirmed that PBS contributed to the neutralization of ionized oxygen vacancies and decreased existing shallow trap states.

Moreover, nitrogen doping serves an effective way of keeping back-channel from further interaction with surrounding oxygen and in the case of higher doping concentration. It was also reflected in above-mentioned XRD results. We can reasonably presume that the smaller grain size suggested that more grain boundaries existed in the bulk channel and retained more defect traps. These defect traps interfered the carrier transport and brought about the worse carrier mobility, as agreed with the previous research.
Figure 7. O1s XPS spectra of IGO films with nitrogen doping of (a) 0, (b) 1, (c) 2, (d) 3 and (e) 5 sccm, and (f) the area percentages of three oxygen bonding states (OI, OII and OIII) in the IGO films.

Conclusions

In summary, the electrical characteristics of IGO TFTs with nitrogen doping at different levels were investigated. Though the introduction of excessive nitrogen imposed serious impact on both mobility and subthreshold swing, this study proved that moderate nitrogen doping not only lowered the number of oxygen vacancy related defects, but also passivated the interface trap states effectively. Owning to the reduction of oxygen vacancy related defects, IGO TFT with 2 sccm nitrogen doping exhibited superior positive bias stress stability relative to that of undoped TFT. Moreover, the application of I-V hysteresis confirmed the interface trap states were reduced by nitrogen doping as well. For these reasons, it can be seen that the in-situ nitro-
gen doping process achieved the effect of improving device stability, and it served as channel passivation from environmental impact at the same time.

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**Figure 9.** I-V hysteresis transfer characteristics measured from IGO TFTs with nitrogen ratio of (a) 0, (b) 1, (c) 2, (d) 3 and (e) 5 sccm.
References
1. M. Kim, J. H. Jeong, H. J. Lee, T. K. Ahn, H. S. Shin, J.-S. Park, J. K. Jeong, Y.-G. Mo, and H. D. Kim, “High mobility bottom gate InGaZnO thin film transistors with SiOx etch stopper,” Appl. Phys. Lett., 90(21), 212114 (2007).
2. K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hiranr, and H. Hosono, “Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors,” Nature, 432(7016), 488 (2004).
3. J. Lee, D. Kim, D. Yang, S. Hong, K. Yoon, P. Hong, C. Jeong, H. Park, S. Y. Kim, S. K. Lim, S. S. Kim, K. Son, T. Kim, J. Kwon, and S. Lee, “42.2: World’s Largest (15-inch) XGA AMLCD Panel Using IGZO Oxide TFT,” SID Symp. Dig. Tech. Pap., 39(4), 625 (2008).
4. I. Raja, K. Jang, N. Balaji, W. Choi, T. Thuy Trinh, and J. Yi, “Negative gate-bias temperature stability of N-doped InGaZnO active-layer thin-film transistors,” Appl. Phys. Lett., 102(8), 1 (2013).
5. H. Xie, G. Liu, L. Zhang, Y. Zhou, and C. Dong, “Amorphous Oxide Thin Film Transistors with Nitrogen-Doped Hetero-Structure Channel Layers,” Appl. Sci., 7(12), 1099 (2017).
6. X.-A. Zhang, J.-W. Zhang, W.-F. Zhang, Z. Bi, X.-M. Bian, and X. Hou, “Enhancement-mode thin film transistor with nitrogen-doped ZnO channel layer deposited by laser molecular beam epitaxy,” Thin Solid Films, 516(10), 3305 (2008).
7. S. J. Lim, S. Kwon, H. Kim, and J.-S. Park, “High performance thin film transistor with low temperature atomic layer deposition nitrogen-doped ZnO,” Appl. Phys. Lett., 91(14), 183517 (2007).
8. J. Sun, D. A. Mourey, D. Zhao, S. K. Park, S. F. Nelson, D. H. Levy, D. Freeman, P. Cowdery-Corvan, L. Tutt, and T. N. Jackson, “ZnO Thin-Film Transistor Ring Oscillators with 31-n Propagation Delay,” IEEE Electron Device Lett., 29(7), 721 (2008).
9. P. T. Liu, Y.-T. Chou, L.-F. Li, and H.-P. Shieh, “Nitrogenated amorphous InGaZnO thin film transistor,” Appl. Phys. Lett., 98(5), 052102 (2011).
10. J. Yang, Y. Han, R. Fu, and Q. Zhang, “Effects of Nitrogen Doping on Performance of Amorphous SnO/Thin Film Transistor,” J. Disp. Technol., 12(12), 1560 (2016).
11. C. Eun Kim and I. Yun, “Effects of nitrogen doping on device characteristics of InSnO thin film transistor,” Appl. Phys. Lett., 100(1), 013501 (2012).
12. Y. S. Rim, H. W. Choi, K. H. Kim, and H. J. Kim, “Effects of structural modification via high-pressure annealing on solution-processed InGaO films and thin-film transistors,” J. Phys. D: Appl. Phys., 49(7), 075112 (2016).
13. Y. C. Chen, T. C. Chang, W. H. Li, H. S. Chen, W. F. Chung, Y. H. Chen, Y. H. Tai, T. Y. Tseng, and F. S. Yeh, “Surface states related the bias stability of amorphous InGa-Zn-O thin film transistors under different ambient gases,” Thin Solid Films, 529(5), 1432 (2011).
14. A. Abliz, Q. Gao, D. Wan, X. Liu, L. Xu, C. Jiang, X. Li, H. Chen, T. Guo, J. Li, and L. Liao, “Effects of Nitrogen and Hydrogen Codoping on the Electrical Performance and Reliability of InGaZnO Thin-Film Transistors,” ACS Appl. Mater. Interfaces, 9(12), 10798 (2017).
15. H. Xie, Q. Wu, L. Xu, L. Zhang, G. Liu, and C. Dong, “Nitrogen-doped amorphous oxide semiconductor thin film transistors with double-stacked channel layers,” Appl. Surf. Sci., 387, 237 (2016).
16. J. K. Jeong, J. H. Jeong, H. W. Yang, J.-S. Park, Y.-G. Mo, and H. D. Kim, “High performance thin film transistors with co-sputtered amorphous indium gallium zinc oxide channel,” Appl. Phys. Lett., 91(11), 113505 (2007).
17. R. L. Hoffman, “ZnO-channel thin-film transistors: Channel mobility,” J. Appl. Phys., 95(10), 5813 (2004).
18. T. Kamiya, K. Nomura, and H. Hosono, “Present status of amorphous In–Ga–Zn–O thin-film transistors,” Sci. Technol. Adv. Mater., 11(4), 044305 (2010).