Improving the Negative Bias Illumination Stress-Induced Instability of High Mobility Oxide Thin-film Transistors

Yun Yu, Yuan Chen, Pu Wang, Chenghao Bu, Kyoungsoo Lee, Jinjin Yang, Bonggeum Lee

Tianma Microelectronics Co., Ltd, Wuhan, China

Abstract

The degradation mechanism of Negative Bias Illumination Stress (NBIS) in high mobility oxide thin-film transistors has been systematically investigated and elaborated in this paper. The optimization scheme of fabrication process is also proposed according to our theory. The top gate self-align IGZTO TFT was fabricated with different process conditions and the stability with Positive Bias Temperature Stress (PBTS) of 0.44V and NBIS of -1.12V are achieved by optimizing the oxide annealing and ILD deposition process. At the same time, the device shows the excellent basic electrical properties with V_{th} of 0.29V and Mobility of 20.88 cm^2/V s.

Author Keywords

IGZTO; High Mobility Oxide TFTs; Negative Bias Illumination Stress

1. Introduction

Owing to its large area uniformity, ultra-low leakage and uncomplicated process, amorphous Indium-Gallium-Zinc Oxide (a-IGZO) thin film transistors (TFTs) are widely used as the backplane for OLED display in recent years. However, the relatively low field effect mobility (μ_{FE}) of IGZO TFTs (<10 cm^2/V s) still hinders their application in high resolution and high fresh rate display. In order to satisfy the requirements of driving circuit in high quality display panel, further improving the μ_{FE} of oxide based TFTs will be of great importance [1].

There have been many approaches to achieving high mobility oxide TFTs, including crystallization technique such as polycrystalline IGO, or adding metal elements such as In and Sn that can increase the concentration of carriers, and reducing the percentage content of carrier inhibitor element Ga [2-4]. The change of material composition leads to the decrease of optical band gap width (E_g) of oxide films. Generally, the E_g of IGZO film is approximately 3.1eV, while the E_g of high mobility oxide film is less than IGZO [5], which will cause poor light reliability.

In combination with the actual circuits working conditions of OLED display panel, the switching TFTs are almost always in the off state, that is, the devices are under the negative bias voltage stress for a long time, the stability of NBS (Negative Bias Stress) is generally better due to the scarce holes in the channel of oxide TFTs. While considering the illumination of panel self-emitting and the influence of external illumination, the instability of high mobility oxide TFTs devices incurred by NBIS, which can cause the abnormal working state of driving circuit, is the more serious problem to be resolved. Nowadays, many studies have been reported in an effort to clarifying the failure mechanism of NBIS in IGZO devices [6-8], but the intensive research on improving the stability of NBIS in high mobility oxide TFTs is still scarce. At the meantime, the balance of high mobility and excellent device reliability is the crucial challenge to the commercial application of oxide TFTs.

In this work, we systematically analyzed electrical characteristics instability of self-align top gate IGZTO TFTs under NBIS. Using TCAD (Technology Computer-Aided Design) simulation, we proposed that the excessive doubly charged oxygen vacancies (Vo^{2+}) generated by synergic effect of negative bias and light illumination are the failure mechanism of NBIS in IGZTO devices. According to the above theory, the fabrication process of IGZTO device was optimized, and a high field effect mobility of 20.88 cm^2/V s, a threshold voltage 0.29V with excellent uniformity were achieved. Moreover, the remarkable stability of NBIS ($|\Delta V_{th}|$<1.20V) reveals the promising prospect for mass production of high mobility oxide TFTs.

2. Experiment

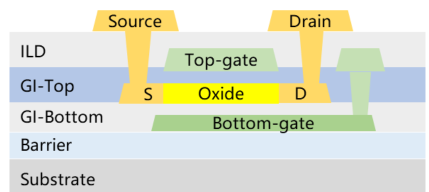


Figure 1. The structure of top gate self-align oxide TFT.

Figure 1 shows the oxide TFT structure diagram used in this work. The device adopted the top-gate self-align structure, bottom gate contacts with top gate, which could increase the driving current. Firstly, a SiO_2 barrier layer was deposited by PECVD to block ion pollution from substrate. Secondly, a Mo metal layer was deposited by PVD and patterned as the bottom gate in the TFT region. Then the SiNx/SiOx double inorganic layers were stacked as the bottom GI layer. IGZTO film was deposited as the active channel layer by PVD, oxygen partial pressure was set to O_2/O_2+Ar=80%. Next, a SiOx layer was deposited as the top GI layer, and in order to obtain good electrical uniformity and high mobility, a high temperature annealing process in air atmosphere was carried out after top GI deposition, so as to prevent the channel shorting, and ensure its semiconductor properties. Similarly, a Mo/Ti metal layer was deposited and patterned as the top gate, then the source and drain region was defined by self-align ion implantation technique. Finally, a SiOx or SiOx/SiNx layer was deposited as (Interlayer Deposition) ILD, S/D contact hole was realized by dry etch, Ti/Al/Ti layers were deposited as the source/drain (S/D) electrodes. The electrical performance and stability of our fabricated TFTs were measured by a semiconductor parameter analyzer (Keysight B1500). The PBTS stability test was applied at Vgs of +30V and Vds of 0V for 3600s, the temperature was fixed at 60°C. The stability of NBIS test was applied at Vgs of -20V and Vds of 0V for 3600s. The illumination from bottom of the device was executed with brightness of (1000 cd/m^2), simultaneously.

3. Results & Discussion

The transfer characteristic and stability of the double gate IGZTO TFT device were evaluated. The device exhibits the mean V_{th} of 0.37V, a mobility of 18.88 cm^2/V s, a S.S. of 0.10 V/decade at W/L=4μm/6μm. The mobility is calculated veritably by the total Cox of top and bottom GI. The V_{th} distribution range of G4.5 glass is 0.34V (equally distributed points are calculated).

Figure 2(a) and 2(b) show the evolution of transfer curves as a function of the applied PBTS and NBIS time, respectively. The variation of V_{th} is 0.47V when the gate voltage stress of +30V was applied for 3600s at 60℃. The positive shift of the V_{th} after PBTS is attributed to the charge trapping of accumulated electrons at the interface between GI and oxide active layer. For the NBIS test, a quite negative V_{th} shift of -3.01V was observed after the gate voltage stress of -20V was applied for 3600s under illumination, this large negative V_{th} shift phenomenon is unexpected.

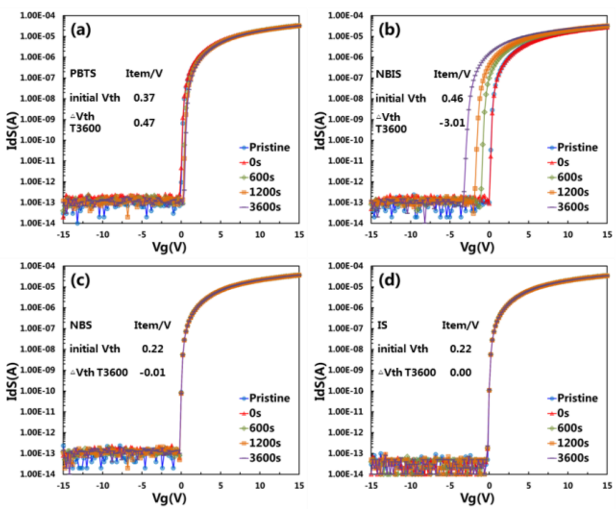
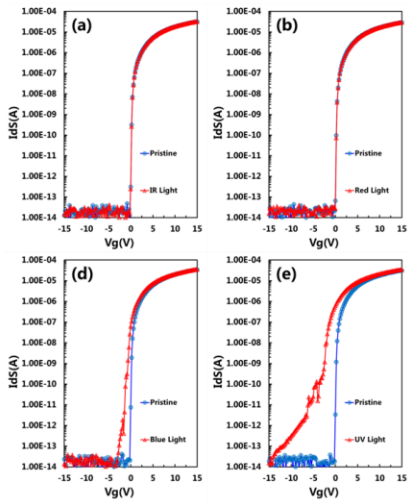


Figure 2. Transfer curves evolution of IGZTO TFTs under different stress conditions: (a) PBTS, Vgs=+30V, 60℃, (b) NBIS, Vgs=-20V, 1000cd/m^2 white light bottom illumination, (c) NBS, Vgs=-20V, (d) Illumination stress (IS), 1000cd/m^2 white light bottom illumination.

To clarify this rigid V_{th} shift by the NBIS, the device electrical property behavior has been investigated under the individual illumination and individual negative voltage stress, and the results are shown in Figure 2(c) and 2(d). The device did not suffer any V_{th} shift either under NBS in the dark or under the same illumination stress without negative bias voltage. Owing to the intrinsic material property of oxide semiconductor, the hole carriers are scarce in channel, imperceptible V_{th} change under the NBS indicates the superior interface characteristic between GI and semiconductor of the IGZTO TFT. Even so, the resulting negative shift by NBS under visible light illumination is quite large. Thus, we supposed that the synergistic effect of incident photon and negative bias voltage would change the property of oxide semiconductor or oxide/GI interface.

To further study the effect of photon, five monochromatic lights with different wavelength including IR light (λ=850nm, E_{ph}=1.53eV), Red light (λ=627nm, E_{ph}=2.08eV), Green light (λ=528nm, E_{ph}=2.47eV), Blue light (λ=457nm, E_{ph}=2.85eV), UV light (λ=384nm, E_{ph}=3.40eV) were employed in the individual illumination measurements. As shown in Figure 3, the shift of the transfer curves was wavelength dependent. For IR [Figure 3(a)], red [Figure 3(b)] and green light [Figure 3(c)], the changes in V_{th}, S.S and I_{off} are negligible. For Blue [Figure 3(d)] and UV [Figure 3(e)] light, the changes in V_{th}, S.S and I_{off} become increasingly apparent with decreasing wavelength. Among them, the shift of V_{th} under Blue and UV light are -0.16V and -2.57V, respectively. Meanwhile, the significant hump phenomenon is observed in the transfer curves under UV light illumination.



Item	Photon energy/eV	△Vth/V
IR	1.53	0.00
Red	2.08	0.00
Green	2.47	0.00
Blue	2.85	-0.16
UV	3.40	-2.57

Figure 3. Transfer curves before and after illumination with different wavelengths，the corresponding wavelength of IR/ Red/ Green/ Blue/ UV are 850/ 627/ 528/ 457/ 384nm.

In the semiconducting oxide materials such as a-IGZO, IZTO, etc., the defect induced subgap states are frequently related to oxygen vacancies (Vo) [7,9,10]. Generally, neutral oxygen vacancies (fully occupied states) locate above the valence band maximum (VBM) in high density. Furthermore, Vo can be created from centers with weak or broken bonds at the higher photon energy level, due to the released energy from electron-hole recombination. According to the previous report, the light instability originates from the following two processes: i) transition and recombination of photo-excited electron-hole pairs, ii) the photoionization of existing and newly created V_O to V_O^{2+} states, a process which donates two electrons to conduction band (CB) [8-11].

As the band gap of IGZTO is approximately 2.9 eV, the electron excitation from valence band (VB) to the CB under IR, Red, Green and Blue light illumination is difficult, in other words, the first process mentioned above would not occur when the photon energy are less than 2.9 eV. Thus transfer curves dosen't exhibit any deviation under IR, Red and Green light reasonably. And the 0.16V negative shift of V_{th} under the Blue light can explained by the second physical process mentioned above, after irradiated by the Blue light, the transition from Vo to Vo^{2+}, with excess electron carriers hopping to the CB leads to the negative shift of transfer curve. Due to higher photon energy of UV light, both physical process mentioned above would occur, a large amount of extra electron carriers formed by photo-excited electron and photoionization of V_O will cause the larger negative

V_{th} shift in transfer curve and the significant degradation of S.S. When the Vgs is applied in the off states region, a large number of photo-generated holes are accumulated on the channel surface by the applied negative gate voltage, then drift from drain to source to form a high off state leakage current.

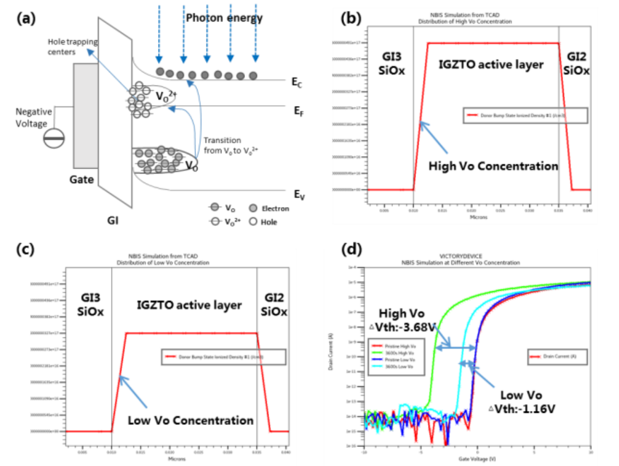


Figure 4. (a) Schematic diagram of IGZTO TFT degradation mechanism under NBIS. TCAD simulation result of IGZTO TFTs with High (b) and low (c) Vo concentration distribution at VBM, (d) the TCAD simulated transfer curves evolution of IGZTO TFTs with high and low Vo after 3600s NBIS

Combined with the study of different wavelength light illumination characteristics and the change of transfer curves under NBS test with visible light illumination, we illustrated the degradation mechanism of NBIS in Figure 4(a). Electrons in valence band can't obtain sufficient activation energy to generate the electron-hole pairs by band to band transition under the visible light irradiation. However, the Vo near above the VBM would be photoexcited to Vo^{2+} with two electrons production by the effect of photon energy [11].When a large negative bias is applied to gate electrode, the photo-generated V_O^{2+} states were attracted to the oxide/GI interface, acting as the positive fixed charge effectively to screen the gate bias in the Id-Vg measurement and result the negative shift of transfer curve. Moreover, the V_O^{2+} also act as hole trapping centers, preventing the electrons generated by oxygen vacancy photoionization from recombining with excess holes. Thus, the photo excitation of V_O to stable V_O^{2+} states could yield excess free electron carriers in conduction band continuously, which aggravate the negative shift of transfer curve of IGZTO TFT. Meanwhile, because the photo energy is insufficient to generate the electron hole pairs, there is almost no hole accumulated in the channel to form leakage current under the turn-off voltage. Hence, the noticeable change in V_{th} instead of increased I_{off} is observed in the NBIS evaluation of IGZTO TFT.

TCAD simulation is illustrated in Figure 4(b), 4(c) & 4(d), we defined two devices with the high and low Vo concentration near the VBM and the Vo concentration distribution are shown in Figure 4b and 4c respectively. The NBIS process model was used in Id-Vg simulation. The V_{th} shift of device with high Vo is larger than that of device with low Vo (Figure 4d). It is consistent with the proposed degradation mechanism.

In this work, the key process of device fabrication has been optimized to improve the NBIS stability of IGZTO TFTs. The main strategy is decreasing the oxygen assocaited defect states in oxide active layer and oxide/GI interface by adjusting oxide annealing position and the parameters of ILD deposition process. As shown in Figure 5(a) and Figure 5(b) and Table 1, the DOE1 device and DOE2 device exhibit the V_{th} shift of -0.98V and -1.12V respectively after 3600s NBIS test. Both of which are much less than the reference device (-3.01V). However, DOE1 device has a significant deterioration in the V_{th} shift (+2.77V) after 3600s PBTS test, while the V_{th} shift of DOE2 device (+0.44V) is equivalent to the level of reference device. The optimized devices fabricated by DOE2 conditions exhibits the mean V_{th} of 0.29V, the mobility of 20.88 $cm^2/V\,s$, the Ion of 25.60μA and the S.S. of 0.10 V/decade. The V_{th} distribution range of G4.5 glass is 0.26V, as shown in Figure 5(c) and Figure 5(d), the V_{th} presents a normal distribution and the convergent performance of the Id-Vg curves is excellent.

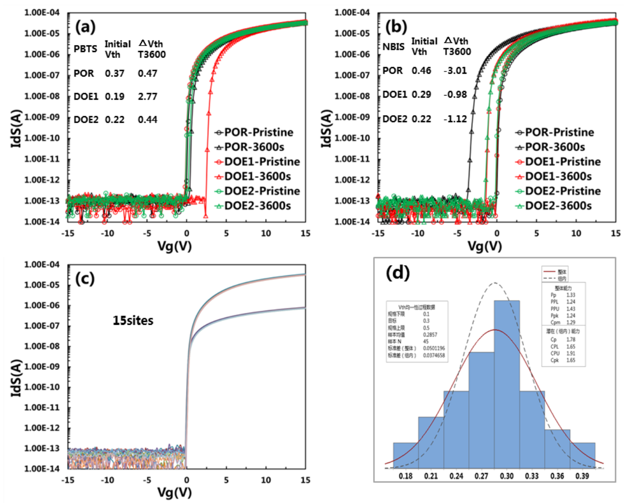


Figure 5. The transfer curves of IGZTO TFTs with different fabrication process before and after 3600s: (a) PBTS test, (b) NBIS test. The basic electrical properties of optimized IGZTO TFTs (DOE2): (c) the transfer curves on the G4.5-sized glass, (d) The V_{th} Process Capability of DOE2 devices

Table 1. Key parameters of IGZTO TFT electrical property

Item	Reference	DOE1	DOE2
V_{th} (V)	0.37	0.21	0.29
V_{th} range (V)	0.34	0.24	0.26
S.S (V/decade)	0.10	0.10	0.10
Mobility ($cm^2/V\,s$)	18.88	21.07	20.88
I_{on} (μA)	23.40	27.80	25.60
PBTS ΔV_{th} (V)	0.47	2.77	0.44
NBIS ΔV_{th} (V)	-3.01	-0.98	-1.12

Compared with the fabrication process of the reference device，the post-annealing position of oxide layer in DOE1 device was adjusted from film deposition to wet etch. The distribution of oxygen atoms in oxide channel layer is undesirable after IGZTO film deposition, and there are a large amount of oxygen vacancies related defect states. When the annealing was executed after the IGZTO film deposition, the oxygen vacancies could not be fully passivated by oxygen atoms due to its unidirectional diffusion (as illustrated in Figure 6a). As a contrast, shown in Figure 6b, the oxygen vacancies related defects (especially on the taper side wall of the channel following covered by GI film) could be fully passivated by vertical and lateral diffused oxygen atoms , when the annealing process was executed after wet etch. It is speculated that the quantity of Vo are dramatically reduced after the annealing position and temperature was optimized, and the NBIS stability is greatly improved with the shift of V_{th} from -3.01V to -0.98V.

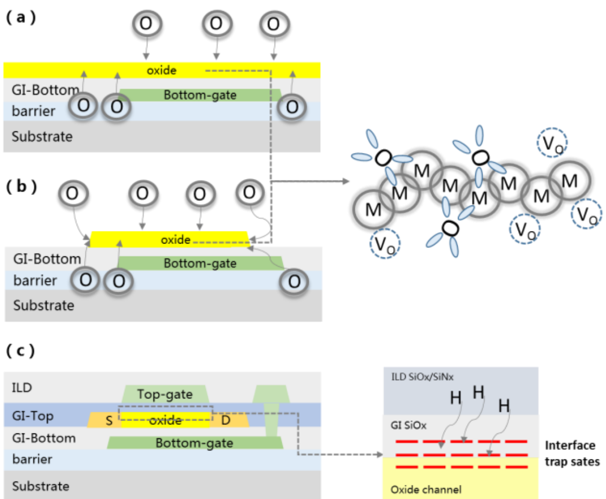


Figure 6. Schematic diagram of NBIS improvement mechanism by optimizing key fabrication process: annealing in air atmosphere (a) oxygen atoms diffusion process after IGZTO film deposition, (b) oxygen atoms diffusion process after IGZTO film wet etch, (c) interface trap states passivation by H diffused from ILD SiNx (PBTS stability maintaining)

However, the trap states at the interface of oxide/GI may increase with the interface excess oxygen (O_{ex}) induced by annealing. By capturing an electron, the metastable O_{ex}- could transfer to O^{2-}, which result the degradation of PBTS stability (DOE1:ΔV_{th}=2.77V). Referring to Figure 6(c), we have adjusted the ILD film deposition process parameters to obtain moderate H concentration and the best diffusion effect, the diffused H could participate the reaction of $Si\text{-}O_{ex}^{-}+H \rightarrow$ Si-OH and eliminate the interfacial excess oxygen defects [12]. Finally, the better PBTS stability (DOE2:ΔV_{th}=0.44V) has also been achieved.

4. Conclusion

In summary, the electrical stability of a-IGZTO TFTs is systematically investigated under PBTS and NBIS. It is found that the NBIS degradation mechanism of high mobility oxide device is significantly related to the Vo photoionization. By adjusting oxide annealing position and deposition process parameters of ILD, we obtained a device with excellent electrical properties with a mean V_{th} of 0.29V, a saturation mobility of 20.88 cm^2/V s and a Ion of 25.60μA. Compared with the reference device, the optimized IGZTO TFT exhibits the remarkably improved NBIS stability (ΔV_{th} decreased from −3.01V to −1.12V after 3600 s) and the superior PBTS stability (ΔV_{th} decreased from 0.47V to 0.44V after 3600 s). The electrical stability improvement of the IGZTO TFTs can be attributed to the suppression of Vo-related defects in oxide and oxide/GI interface by optimized fabrication process. This study discloses that the control of oxygen vacancies is crucial for fabricating the high mobility oxide TFT devices with excellent stability.

5. References

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