



Article Influence of Passivation Layers on Positive Gate Bias-Stress Stability of Amorphous InGaZnO Thin-Film Transistors

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Abstract: Passivation (PV) layers could effectively improve the positive gate bias-stress (PGBS) stability of amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs), whereas the related physical mechanism remains unclear. In this study, SiO₂ or Al₂O₃ films with different thicknesses were used to passivate the a-IGZO TFTs, making the devices more stable during PGBS tests. With the increase in PV layer thickness, the PGBS stability of a-IGZO TFTs improved due to the stronger barrier effect of the PV layers. When the PV layer thickness was larger than the characteristic length, nearly no threshold voltage shift occurred, indicating that the ambient atmosphere effect rather than the charge trapping dominated the PGBS instability of a-IGZO TFTs in this study. The SiO₂ PV layers showed a better improvement effect than the Al₂O₃ because the former had a smaller characteristic length (~5 nm) than that of the Al₂O₃ PV layers (~10 nm).

Keywords: amorphous InGaZnO (a-IGZO); thin-film transistor (TFT); positive gate bias stress (PGBS); passivation layer; characteristic length

1. Introduction

Amorphous InGaZnO thin-film transistors (a-IGZO TFTs) have considerable potential for applications in next-generation flexible, transparent, and large-size flat panel displays (FPDs) because of their superior electrical characteristics, such as large field-effect mobility (~10 cm²/V·s), low subthreshold swing (~0.2 V/decade), small leakage current (<10⁻¹³ A), and so on [1,2]. However, the reliability issues, e.g., threshold voltage (V_{th}) shift under positive gate bias stress (PGBS), remain to be solved. Both charge trapping [3-6] and ambient atmosphere effect [7-14] have been reported to be responsible for Vth shifts in a-IGZO TFTs during PGBS tests. Meanwhile, some research groups have demonstrated that the bulk trapping effect [15,16] and plasma damage [17,18] could also lead to V_{th} shifts under PGBS. Evidently, this V_{th} instability is not preferred. In fact, PGBS instability may seriously hinder the actual applications of a-IGZO TFTs in FPDs because it may directly impact the brightness uniformity and stability of display panels. Therefore, some measures must be taken to make the devices more stable during PGBS tests. Passivation (PV) layers, such as SiO₂, Si₃N₄, etc., have been reported to exhibit a good resistance to ambient atmosphere, and thus improve the PGBS stability of a-IGZO TFTs [19–24]. However, the exact physical mechanism for how PV layers make devices more stable remains unclear. In this paper, we sputtered SiO_2 (or Al_2O_3) with different thicknesses to passivate a-IGZO TFTs, observing the variation of their PGBS instability. Both SiO_2 and Al_2O_3 were chosen for the PV layers because of their good compatibility in TFT process integration. It was found that the V_{th} shift was reduced by increasing the PV layer thickness and the SiO₂ improved the PGBS stability of a-IGZO TFTs more significantly than the Al₂O₃. The related physical mechanism was classified based on the experimental observations.

2. Materials and Methods

Inverted staggered a-IGZO TFTs were fabricated, the schematic cross-section of which is shown in Figure 1. P-type silicon wafers (gate electrodes) with a 200 nm-thick thermal SiO₂ (gate insulators) were used as substrates. After thorough cleaning, 50 nm-thick a-IGZO films (In:Ga:Zn = 1:1:1 in mol ratio) as the channel layers were prepared on the substrates using radio frequency (RF) magnetron sputtering at room temperature (RT) with a power of 60 W, a pressure of 5 mTorr, and an Ar flow rate of 30 sccm. Then, Indium Tin Oxide (ITO) films with a thickness of 200 nm were deposited as source/drain (S/D) electrodes using direct current (DC) magnetron sputtering at RT, where the power was 100 W, the pressure was 5 mTorr, and the Ar flow rate was 30 sccm. For the passivated devices, SiO₂ (or Al₂O₃) films with different thicknesses were deposited using RF sputtering at RT with ta power of 50 W, a pressure of 5 mTorr, and an Ar flow rate of 30 sccm. The channel layers, S/D electrodes, and PV layers were patterned using shadow masks during their depositions, leading to a channel width/length (W/L) of 1000/275 μ m. Finally, the devices were annealed at 400 °C for 1 h.

The electrical characteristics of the TFTs were measured using a 2636 A parameter analyzer (Keithley Instruments, Inc., Beaverton, OR, USA) in an unsealed chamber, which maintained the atmospheric pressure and little gas circulation. The moisture content in the chamber was controlled by feeding the water molecules with the flow of N₂. All the devices were measured at RT in darkness. For the transfer curve measurements, V_{DS} of 10 V was employed. In this study, V_{th} is defined as the gate voltage of the normalized drain current ($I_{DS}/(W/L)$) reaching 100 nA.



Figure 1. Schematic cross-section of the inverted staggered amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs).

3. Results and Discussion

Figure 2a,c shows the time evolution of the transfer characteristics of the unpassivated a-IGZO TFTs under PGBS as well as the relative humidity (RH) of 10%, 50%, and 90%, respectively. During the PGBS tests, direct voltage of +20 V was applied to the gate electrodes for a period and then the transfer curves were instantly measured. With the increase in the stress time, the transfer curve positively shifted, which was apparently influenced by RH. In order to quantitatively describe the stable properties of a-IGZO TFTs under PGBS, we defined a useful term ΔV_{th} , the difference between the V_{th} under stress and its initial value. The ΔV_{th} values under various RH were extracted and listed in Figure 2d. After 4500 s of PGBS test, the positive V_{th} shifts of 5 V, 11.5 V, and 4.5 V were observed under RH = 10%, 50%, and 90%, respectively. It is worth noting that the largest ΔV_{th} occurred at RH = 50% (as shown in Figure 2d), which is consistent with our previous report [22].

The positive V_{th} shift of a-IGZO TFTs under PGBS was attributed to charge trapping at the dielectric/channel interface (front-channel effect) [3–6], ambient atmosphere effects at the back surface (back-channel effect) [7–14], or bulk trapping in the IGZO bulk (bulk effect) [15,16]. According to our previous work [22], The biggest V_{th} shift at RH = 50% is mainly attributed to the competition of oxygen (or moisture) adsorption/desorption at the IGZO back surface during PGBS tests. This result indicates that RH = 50% is the severest condition to characterize the bias-stress stability of a-IGZO TFTs.

In addition, we measured the negative gate bias-stress (NGBS) instability of a-IGZO TFTs at RH = 50%, as shown in Figure 3. During the NGBS tests, a direct voltage of -20 V was applied to

the gate electrodes for a period and then the transfer curves were instantly measured. After 4500 s of NGBS test, nearly no V_{th} shift was observed. When a negative voltage was applied to the gate electrode of a-IGZO TFTs, the oxygen atoms in a-IGZO tended to be repelled into the ambience, leading to negative shifts of V_{th} [25]. However, this process might have been effectively prohibited by the moisture-assisted oxygen adsorption [11,12,22], especially when the ambient RH was high. Therefore, no evident V_{th} shifts were exhibited during the NGBS tests in this study.

In this study, we deliberately adopted the severest measurement condition (RH = 50%) to examine the influence of PV layers on the bias-stress stability of a-IGZO TFTs. Since the devices were rather stable during the NGBS tests, only PGBS stabilities were characterized for the following studies.



Figure 2. Transfer characteristics of the unpassivated a-IGZO TFTs as a function of the positive gate bias-stress (PGBS) time under relative humidity (RH) of (**a**) 10%, (**b**) 50%, and (**c**) 90%, respectively; (**d**) variations of the ΔV_{th} with PGBS time for the a-IGZO TFT devices.



Figure 3. Transfer characteristics of the unpassivated a-IGZO TFTs as a function of the negative gate bias-stress (NGBS) time under RH = 50%.

It is well-known that PV layers can effectively improve the stability of TFT devices, whereas the exact physical mechanism involved is still not very clear. However, we may phenomenally describe the dependence of V_{th} shift (ΔV_{th}) during PGBS tests on PV layer thickness (d) as follows [19],

$$\Delta V_{\rm th} = \alpha \cdot e^{\rm d}_{\tau} + \beta \tag{1}$$

where β is the V_{th} shift affected by charge trapping, bulk trapping, and plasma damage, α is a constant relating to the V_{th} shift affected by ambient atmosphere, and ε is the characteristic length related to the gas diffusion. When d is larger than ε , the ambient gases hardly influence the PGBS stability of a-IGZO TFTs. In other words, the characteristic length ε is the critical dimension for the ambient atmosphere effect during PGBS tests. From an application perspective, a small ε is usually preferred.

To further investigate the ambient effects during PGBS tests, the a-IGZO TFTs were applied using PV layers with different thicknesses. SiO₂, one of the most popular dielectric materials in TFT fabrications, was used to passivate the devices here. For comparison purposes, Al₂O₃, another dense material [23], was also adopted as PV layers for the a-IGZO TFTs in this study. The water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) are reported to be inversely proportional to the PV layer thickness [24]. To analyze the influence of PV layers on PGBS stability of a-IGZO TFTs in depth, SiO₂ and Al₂O₃ films with different thicknesses (0–30 nm) were deposited to passivate the devices.

Figure 4a,e shows the PGBS time evolution of the transfer characteristics of the a-IGZO TFTs with a SiO₂ PV layer thickness of 0 nm, 5 nm, 10 nm, 20 nm, and 30 nm, respectively. We noticed that the passivated a-IGZO TFTs exhibited a similar tendency to that of the unpassivated device, i.e., with the increase in the stress time, the transfer curve gradually shifted in the positive direction. However, the a-IGZO TFTs with SiO_2 PV showed more stable properties during the PGBS tests. To describe this tendency more clearly, we extracted the Vth shifts and listed them in Figure 4f. When the PV layer thickness increased from 0 nm to 30 nm, the ΔV_{th} decreased evidently from 12 V to nearly 0.1 V after 4500 s of bias stress test. This can be attributed to the PV layer barrier effect, i.e., preventing the exchange of O_2/H_2O molecules between the channel layers and the ambient atmosphere. When the PV layer thickness was larger than 5 nm, the V_{th} of the a-IGZO TFTs barely changed. This can be understood by considering the concept of characteristic length (see (1)) in PV layers, which was about 5 nm here. When the SiO₂ PV layer thickness was smaller than the characteristic length, the O_2 molecules easily diffused from the atmosphere into a-IGZO (the H₂O diffused inversely) under PGBS, resulting in positive V_{th} shifts of the a-IGZO TFTs. As the PV layer thickness was larger than ε , the diffusion of O_2/H_2O molecules through the PV layers became rather difficult. This is why the device with a thicker PV layer showed less degradation of its electrical behavior. Since a sufficiently thick PV could nearly eliminate the V_{th} shifts (as shown in Figure 4f), we can assume that the ambient atmosphere effect, rather than charge trapping, dominated the instability of a-IGZO TFTs during the PGBS tests in this study.

For comparison purposes, we also measured the PGBS stability of the a-IGZO TFTs passivated by Al₂O₃ PV layers with a thickness of 0 nm, 5 nm, 10 nm, 20 nm, and 30 nm, respectively, as shown in Figure 5a–e. We may observe that a fairly similar tendency to the case of SiO₂-passivated devices was obtained here, i.e., the a-IGZO TFTs under PGBS became increasingly stable with the increase in the Al₂O₃ PV layer thickness. Meanwhile, for both Al₂O₃ and SiO₂ PVs, the transfer curve positively shifted as the PV layer thickness increased, which can be attributed to the extra interface states generated during the PV depositions [26,27]. However, the Al₂O₃ PV layer also exhibited something different. As shown in Figure 5e, for the device with a thick PV layer (\geq 20 nm), its leakage current gradually rose with the increase in the stress time. This phenomenon was probably due to the plasma bombardment on the surface. Since the deposition rate of Al₂O₃ (0.7 nm/min) was smaller than that of SiO₂ (1.5 nm/min), more sputtering time was needed for the deposition of the Al₂O₃ PV layers, leading to more serious plasma damage at the back channels. What is more, the ion bombardment of the plasma can result in a positive V_{th} shift [17,18], which explains why the leakage current of the devices with thick Al_2O_3 PV layers increased during the PGBS tests.



Figure 4. Stress-time dependence of the transfer characteristics of the a-IGZO TFTs with a SiO₂ PV layer thickness of (**a**) 0 nm, (**b**) 5 nm, (**c**) 10 nm, (**d**) 20 nm, and (**e**) 30 nm, respectively; (**f**) experimental data and fitting curves of the ΔV_{th} under PGBS as a function of PV layer thickness of the a-IGZO TFTs.

To precisely denote the influence of the Al_2O_3 PV layer on the PGBS stability of a-IGZO TFTs, the V_{th} shifts were extracted and listed in Figure 5f. Compared with the data shown in Figure 4f, we may note that the Al_2O_3 PV layers had an inferior barrier function to SiO₂. When the Al_2O_3 PV layer thickness was larger than 10 nm, the V_{th} shift of the devices changed slightly, indicating that the characteristic length of the Al_2O_3 PV layer was around 10 nm. When the PV layer thickness reached 30 nm, the ΔV_{th} became much smaller (~1 V), again confirming that the ambient atmosphere effect dominated during the PGBS tests in this study.

So far, we have obtained two important experimental results: (1) the PGBS stability of a-IGZO TFTs gradually improved with the increase in PV layer thickness; (2) the SiO₂ PV layer exhibited a better improvement effect on the PGBS stability than Al_2O_3 . In order to discuss the theoretical origin of these results, we extracted the critical parameters in (1) of the PV layers. We fit the measurement

data of SiO₂ PV and Al_2O_3 PV with (1), as shown in Figures 4 and 5, respectively. One may observe that the fitting curves agreed well with the measurement data, from which the fitting parameters were obtained and summarized in Table 1.



Figure 5. Stress-time dependence of the transfer characteristics of the a-IGZO TFTs with an Al₂O₃ PV layer thickness of (**a**) 0 nm, (**b**) 5 nm, (**c**) 10 nm, (**d**) 20 nm, and (**e**) 30 nm, respectively; (**f**) experimental data and fitting curves of the ΔV_{th} under PGBS as a function of the PV layer thickness of the a-IGZO TFTs.

Materials	Stress Time (s)	α (V)	β (V)	ε (nm)
SiO ₂	900	6.47	0.06	5.93
	1800	8.46	0.07	5.22
	2700	10	0.04	5.03
	3600	10.86	0.14	4.86
	4500	11.45	0.06	5.13
Al ₂ O ₃	900	6.07	1.39	9.24
	1800	7.95	1.09	9.53
	2700	9.31	0.84	10.21
	3600	10.46	0.30	11.23
	4500	11.07	0.25	11.06

Table 1. Fitting parameters of the PV layers used for a-IGZO TFTs.

As shown in Table 1, the α values of both PV layers were much larger than the β values for the same stress time, indicating that the ambient atmosphere effect instead of charge trapping dominated during the PGBS tests in this study. Therefore, with the increase in PV layer thickness, the ambient atmosphere effect was more strongly prevented, resulting in better PGBS stability of a-IGZO TFTs. The α value

increased with the increase in the bias time, whereas the ε remained nearly unchanged. The increase in α resulted from more O_2/H_2O exchange between the device back channels and the ambience, leading to a larger V_{th} shift. Most importantly, SiO₂ and Al₂O₃ exhibited quite different characteristic length (ε) values, as shown in Table 1. The characteristic length of the SiO₂ PV layers (~5 nm) was far smaller than that of Al₂O₃ (~10 nm), leading to better improvement of the PGBS stability of a-IGZO TFTs by SiO₂ PV layers than Al₂O₃. Therefore, based on our results, the sputtered SiO₂, rather than the sputtered Al₂O₃, should be preferred to passivate a-IGZO TFTs in applications of FPDs.

4. Conclusions

The transfer curve of a-IGZO TFTs shifted positively during the PGBS tests, which could effectively be improved by applying PV layers. In this work, both SiO₂ and Al₂O₃ films with different thicknesses were used to passivate the a-IGZO TFTs, indicating that the ambient atmosphere effect rather than charge trapping dominated the V_{th} shifts during the PGBS tests. A simple model was used to theoretically discuss the related physical mechanism. With the increase in PV layer thickness, the devices became increasingly stable, as a result of the stronger prevention of the ambient atmosphere effect. When the PV layer thickness reached the characteristic length, the variation in V_{th} became quite small. The SiO₂ PV layer showed a better improvement effect than the Al₂O₃ PV layer because the former had a smaller characteristic length.

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Conflicts of Interest: The authors declare no conflict of interest.

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