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Analysis of Electrical Characteristics and Reliability Change of Zinc-Tin-Oxide Thin-Film Transistors by Photo-Thermal Treatment

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This study investigates the influence of a photo-thermal treatment on the electrical characteristics and bias-induced instability of amorphous Zn-Sn-O thin film transistors. Sequences of measurements made in both vacuum and oxygen ambient reveal the most pronounced threshold voltage (V_T) shift, i.e., the highest sensitivity of oxygen, occurs in a device with photo-thermal-treatment. After gate-bias stress in vacuum, the treated device shows less V_T shift than that untreated, which can be attributed to residual adsorbed gas molecules on the backchannel. Thus, the proposed photo-thermal-treatment should be conducted before depositing a passivation layer to increase the reliability of devices after stress.
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Amorphous metal oxide-based semiconductors (AOSs) have demonstrated their benefits in applications such as thin film transistors (TFTs) in next generation displays due to their superior electrical performance, transparency to visible light and tunable carrier concentrations even when deposited at room temperature.[1,2] Recently, zinc oxide (ZnO)-based materials, such as zinc tin oxide (ZTO), and indium gallium zinc oxide, have been intensively studied for adoption as the channel material in TFTs to replace amorphous silicon, especially for flexible and transparent display applications.[3,4] The ZnO-based TFTs can offer enough field effect mobility and low off-state current, which fit the high frame rate and low power consumption requirements for the future displays.

Although ZnO-based TFTs have demonstrated excellent performance, there are still some reliability issues in these devices.[5–8] The electrical degradation of devices under gate bias stress has been mainly attributed to the charge trapping model and the influence of the ambient atmosphere due to electric field-induced oxygen adsorption.[9] Even though suitable passivation layers to eliminate the influence of ambient gas on the devices have been studied,[10,11] certain pre-treatments can be conducted on the active layer in order to obtain stable electrical characteristics. The mechanisms and effects of these pre-treatments on bias-induced electrical instability require further examination.

In this study, a pre-treatment based on chemical reaction theory is proposed, and the principal mechanism of electrical instability is presented to demonstrate the pre-treatment's effect on the subsequent passivation process.

Experimental

Bottom-gate bottom-contact configured sol-gel derived a-ZTO TFTs are used in this study, and shown in the inset of Figure 1. The detailed fabrication procedure of a-ZTO TFTs has been previously reported.[9] The TFTs were run through a sequence of stages, each of which consists of alternating from vacuum to oxygen ambient atmospheres. Stages 1 and 2 were performed identically, and measurements were made under vacuum and different oxygen partial pressures of 1 torr, 10 torr, 100 torr and 760 torr oxygen ambient. The treatment is performed after Stage 2, where TFTs were subjected to either a photo-only, thermal-only, or photo-thermal treatment. After treatment, subsequent measurements were preformed under vacuum and different oxygen partial pressures in Stage 3. All current-voltage characteristics were measured at room temperature and in a vacuum chamber with gas-flow system and probe station using an Agilent B1500 precision semiconductor parameter analyzer. The threshold voltage (V_T) was determined as the gate-to-source voltage (V_G) which induced a drain current (I_D) of 1 nA and subthreshold swing (SS) is determined by the equation $SS = dV_{GS}/d(\log I_{DS})$ (V/dec) while the current is between 10^{-10} and 10^{-9} A.[8,12] The light illumination of 10000 lux in intensity in this work was obtained by a halogen lamp whose spectrum is shown in the inset of Figure 2.

Experimental Results and Discussion

Figure 1a shows the I_D-V_G electrical characteristics of a-ZTO TFTs at V_D of 1 V in vacuum (1×10^{-4} torr, 1.3×10^{-2} pascal), and increasing oxygen ambient pressures of 1 torr (133 pascal), 10 torr (1333 pascal), 100 torr (1.3×10^4 pascal) and 760 torr (1.013×10^5 pascal) (Stage 1). Clearly, the V_T variation of a-ZTO TFTs is

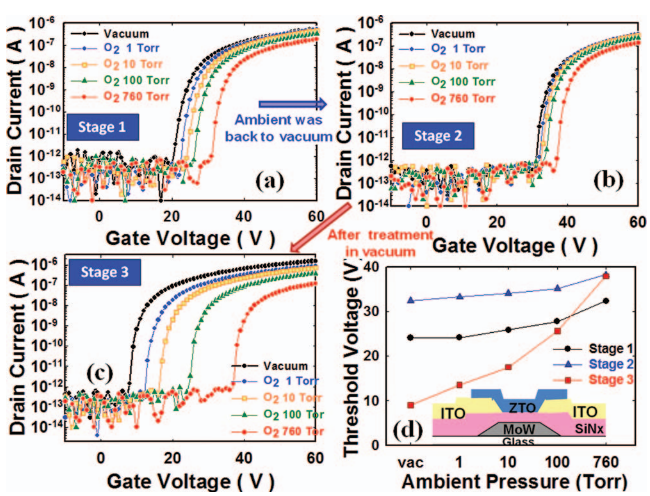

Figure 1. Transfer I_D -V_G characteristics of a-ZTO TFTs in vacuum (1×10^{-4} torr, 1.3×10^{-2} pascal), and increasing oxygen ambient pressures of 1 torr (133 pascal), 10 torr (1333 pascal), 100 torr (1.3×10^4 pascal) and 760 torr (1.013×10^5 pascal) during (a) Stage 1 and (b) Stage 2, both before photo-thermal treatment. (c) Stage 3, after photo-thermal treatment in vacuum (1×10^{-4} torr, 1.3×10^{-2} pascal). (d) Delta V_T of device at Stages 1-3. The inset shows the schematic cross-sectional view of a fabricated bottom-gate a-ZTO TFT.

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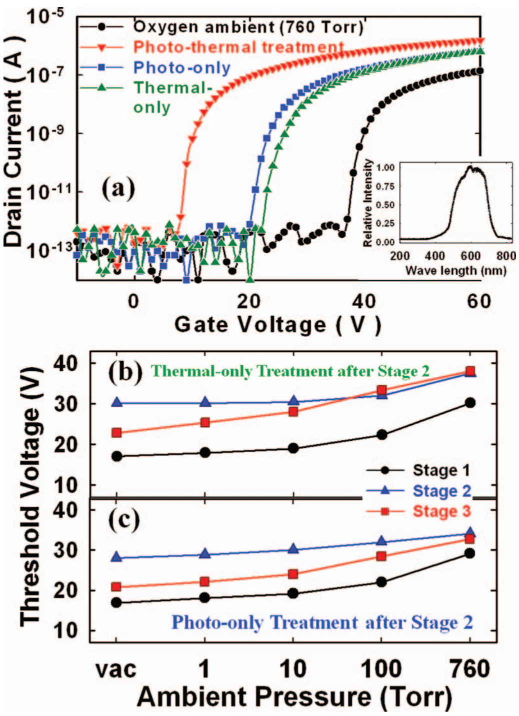

Figure 2. (a) Comparison between I_D-V_G characteristics of devices after different treatments in vacuum ambient and without treatment in oxygen ambient. The inset shows the illumination spectrum of the halogen lamp. Delta V_T of device for (b) with thermal-only treatment and (c) with photo-only treatment for Stages 1-3.

closely correlated with the amount of surrounding oxygen molecules. The SS of the I_D-V_G in different environment of vacuum and oxygen ambient are similar, exhibiting no defect creation at the gate insulator/semiconductor interface under oxygen ambient. In general, literature has described the behavior of surrounding oxygen molecules as capturing electrons from the conduction band and causing the adsorption of oxygen ions (O^-, O^{2-}) on the active layer, resulting in a depletion layer in the backchannel and an increase of V_T in the ZTO TFTs.[13,14] Subsequently, in our experiment, the chamber was pumped down to 1×10^{-4} torr without breaking the vacuum and oxygen was fed into the chamber again (Stage 2). Figure 1b shows the I_D-V_G of the device at the same oxygen partial pressures as in Stage 1. A comparison of Figures 1b and 1a shows that the positive V_T shift of the device in Stage 2 decreases, demonstrating that the degree of V_T shift, i.e., the sensitivity to oxygen, decreases. Based on the results in Figure 1b, this implies that the adsorbed oxygen is not in fact removed by the vacuum process, and the oxygen tends to form chemisorption bonds. This paper suggests a photo-thermal treatment process to effectively remove the chemisorbed gases.

In the photo-thermal treatment process, light illumination is applied at 110 °C in a vacuum environment for 30 minutes. After applying the treatment to the device, the electrical characteristic is again measured in different oxygen partial pressures (Stage 3), as shown in Figure 1c, which indicates that the sensitivity to oxygen is notably increased. It exhibits a V_T shift about 30 V with rare variations in SS between the I_D-V_G after treatment and in oxygen ambient. This proposed method is based on the phenomenon that photo-generated holes can easily migrate to the chemisorbed gas sites due to the built-in electric field and transform the chemisorbed state into a physisorbed state. It is known that the adsorbing force of the physical adsorption is mainly by Van der Waals force. The physisorbed gases can then be desorbed by substrate heating (baking), a process that can also be used to remove the residual moisture existing in the ZTO film. In addition, during the treatment process, the environment should be kept in vacuum to ensure effective evacuation of oxygen from the chamber. In order to prevent electron re-capture by the physically adsorbed gases on the channel layer, the illumination, heating and vacuum system should be applied at the same time.

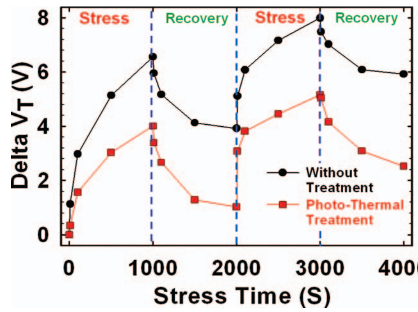

Figure 3. Time evolution of the ΔV_T of devices with/without photo-thermal treatment after dynamic stress in vacuum ambient for 4000 seconds.

To further verify the assumption above, illumination-only (photo-only) and baking-only (thermal-only) treatments are applied on the devices in vacuum ambient. Figure 2a shows the electrical characteristics of the device before and after different treatments. It indicates obviously that the device after photo-thermal treatment exhibits the most negative V_T shift when compared to that in oxygen ambient. In addition, Figures 2b and 2c show that the variations of V_T in the devices with photo-only and thermal-only treatment during Stages 1-3, with Stages 1 and 2 representing devices that have not yet been treated. From the results of Figures 1d, 2b and 2c, the variation of V_T during the first to second run shows a similar behavior. However, the degree of V_T shift, i.e., the sensitivity of oxygen, is highest for the device with photo-thermal treatment. Thus, both the illumination and baking in vacuum ambient are essential to desorb the chemisorbed gases on the backchannel.

To examine the influence of the treatment on the electrical stability of ZTO TFTs, gate bias stress and recovery phases (dynamic stress) were applied on the devices both with and without photo-thermal treatment in vacuum ambient.[15] The gate bias stress was carried out with the gate bias kept at $V_T + 10$ V and grounded source and drain (stress phase). After the stress, the gate bias was sequentially switched to ground to observe the recovery behavior (recovery phase). Figure 3 shows the progressive shift of V_T for devices with and without photo-thermal treatment during dynamic stresses in vacuum ambient. The device without photo-thermal treatment exhibited a more severe threshold voltage shift during the stress phase, but less recovery during the recovery phase. In general, the positive V_T shift during stress has been suggested to be due to electron trapping in the preexisting traps located at the interface or in the gate dielectric. However, this result indicates that the charge trapping model is not sufficient to account for the dynamic stress behavior. Thus, the degradation of the device without treatment can be associated with residual chemisorption of oxygen from the result in Figure 1.

To address this issue, the influence of the residual chemisorption of oxygen on ΔV_T in the stress and recovery phases is examined by fitting the stretched-exponential equation from the charge trapping mechanism.[9,15] The stretched-exponential equation is defined as $\Delta V_T = \Delta V_{TO}\{1 - \exp[-(t/\tau)^{\beta}]\}$ where ΔV_{T0} is the ΔV_T at infinite time, β is the stretched-exponential exponent, and τ is the constant characteristic trapping time for stress phase or de-trapping time for recovery phase. Figures 4a and 4b show the experimental data and fitting curves for the stress and recovery phases. Clearly, the experimental results are in good agreement with the stretched-exponential equation.

Compared to the treated device, the characteristic trapping time constant of the device without treatment decreases from 2677 to 790 seconds during stress, while β remains approximately constant ($\sim$0.58), as shown in Figure 4a. Even in vacuum, the electrical field-induced chemisorption of oxygen on the active backchannel may still occur during the stress phase. This result indicates that electrical field-induced chemisorption of oxygen on the backchannel of active layer

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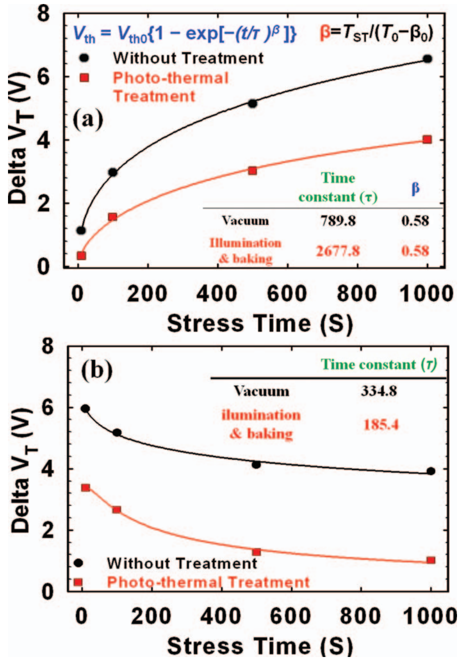

Figure 4. Time dependence of ΔV_T of devices with/without treatment during (a) stress phase and (b) recovery phase in vacuum ambient. The measured data are well fit to the stretched-exponential equation.

as well as trapping of electrons in the interface or bulk dielectric both occur in the device without pre-treatment during the stress phase. The effects of the electrical field which can induce chemisorption of oxygen on the ZnO-based thin film has been described in a previous study.[16] Nevertheless, as shown in Figures 4a and 4b, the more residual oxygen during dynamic stress, the less trapping time and the more de-trapping time exhibited. Accordingly, the photo-thermal treatments for removing the adsorbed gas species of the ZnO-based TFTs are indeed helpful to improve the device bias stability.

Although the effect of oxygen on ZnO-based TFTs has previously been studied, this work investigates the influence of a gas-desorption treatment process on the electrical characteristic and electrical stability of devices. The device with treatment shows better electrical stability than the device without treatment, even in vacuum ambient. Thus, in order to obtain more stable electrical characteristics, the photo-thermal treatment proposed in this work should be conducted to improve device electrical stability.

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