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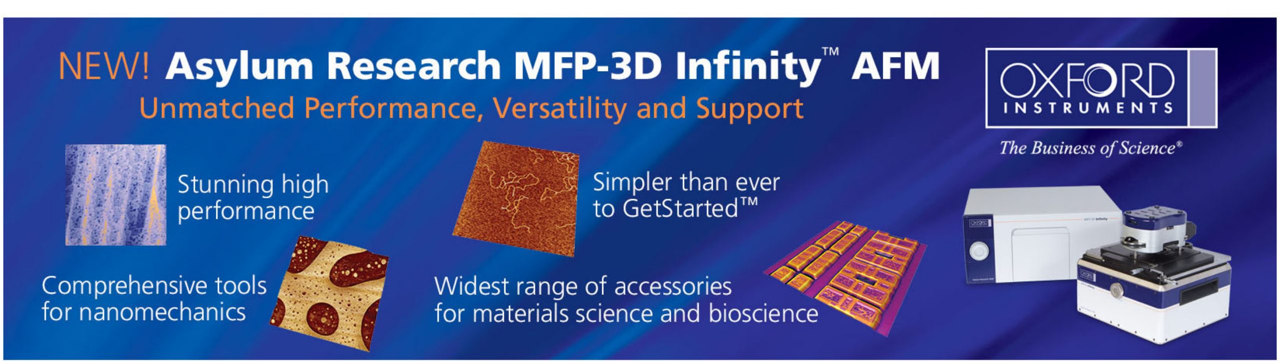

Environment-dependent metastability of passivation-free indium zinc oxide thin film transistor after gate bias stress

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We investigated the effects of bias stress on a passivation-free InZnO thin-film transistors (a-IZO TFTs) exposed to either the atmosphere or a vacuum. The magnitude of threshold voltage shift increased with the application duration of bias stress, to an extent that was much larger in the atmosphere than in the vacuum. The threshold voltage recovered slowly to its nearly initial value when the gate bias stress was removed. The electrical metastability was attributed to the interaction between the exposed a-IZO backchannel and oxygen/moisture from the atmosphere, and a dynamic equilibrium was finally achieved, regardless of the polarity of stress voltage. © *2009 American Institute of Physics*. [doi:10.1063/1.3272016]

Amorphous transparent conducting oxides (TCOs) have been attracting substantial attention in recent years as candidate materials for the use in thin film transistors (TFTs) in photoelectric devices.[1,2] Such amorphous TCOs as indium zinc oxide (a-IZO) not only have great potential to form a uniform amorphous phase but also include highly conducting carriers and exhibit high field-effect carrier mobility characteristics.[3–5] For the sake of electrical operation, electrical reliability of amorphous TCO-based material, such as indium gallium zinc oxide (IGZO) has been studied in a device structure with a passivation layer on the amorphous IGZO film to avoid the interference from environment.[6,7] However, it has been observed that the process for depositing passivation layer easily affected device characteristics.[8–10] This leaded the variation of intrinsic a-IZO characteristics not to be virtually presented out during electrical assessment. On the other hand, previous documents also have reported the impact of gate bias stress on the TCO-based TFT, but lacking of the studies on the relationship between gate bias-induced metastability and environmental factors, especially not for a-IZO TFT. Also, an electrical recovery behavior has been observed after removing gate bias stress, but has never been widely discussed yet.[11] The studies on the effect of bias stress polarity are practically important when the a-IZO TFT device is used as a switching device. In this work, the passivation-free a-IZO TFT devices in the ambient air and in a vacuum are adopted to study the effect of the polarity of gate bias stress and explore its relation to ambient environments.

Inverted coplanar TFT devices were fabricated with a MoW gate electrode (100 nm) below a 300 nm thick silicon nitride gate insulator. Then, a 100 nm thick indium tin oxide layer was sputter deposited and patterned to form source/drain electrodes. 50 nm thick a-IZO film was formed by a rf magnetron sputtering, and then defined by microlithography and wet etching. The film deposition conditions and device manufacture processes were the same as those reported previously.[12] The channel length and channel width of the a-IZO TFT were 40 and 12 μm, respectively. Electrical characteristics were measured in ambient air at 760 torr and in a vacuum at 2×10^{-5} torr, respectively, by using a Keithley 4200 semiconductor parameter analyzer. Voltages of ±30 V were applied separately to the gate electrodes of the a-IZO TFT devices at room temperature for 3 h in the dark, to study the effect of bias stress.

In the beginning, we have previously confirmed the a-IZO TFT device without any gate bias stress stayed in a vacuum environment for 18 h kept nearly the same electrical characteristics as the initial state. Figures 1(a) and 1(b) present transfer characteristics of a-IZO TFTs with +30 V gate bias stress for 3 h in the atmosphere and in a vacuum, respectively. The characteristic curves in both the atmosphere and the vacuum shifted initially in the direction of positive voltages; the shift was greater in the atmosphere than in a vacuum. As the electrical characteristics returned to an another long-run equilibrium after the gate bias stress was removed, the transfer curves shifted negatively until they were close to the curves in the initial dark state, which

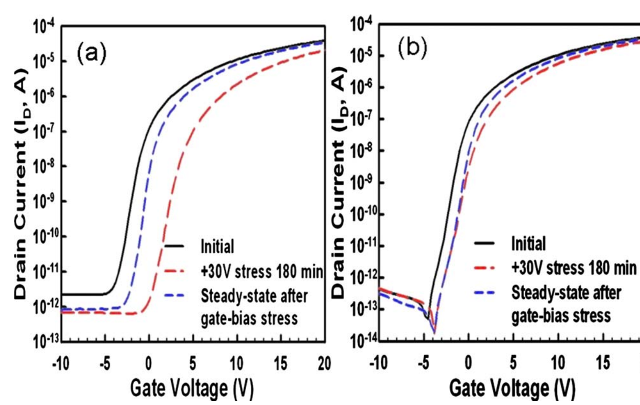

FIG. 1. (Color online) Transfer characteristics of a-IZO TFT device at drain voltage (V_D) V_D=11 V, with +30 V gate bias stress for 180 min in ambient atmosphere [Fig. 1(a)] and in a vacuum [Fig. 1(b)]. The gate bias stress was removed, and the new long-run equilibrium (referred to as steady state) characteristics of the bias-stressed a-IZO TFT left to stand in the atmosphere and a vacuum are shown. In this work, a steady state was reached in 810 min in the ambient atmosphere, and in 840 min in a vacuum.

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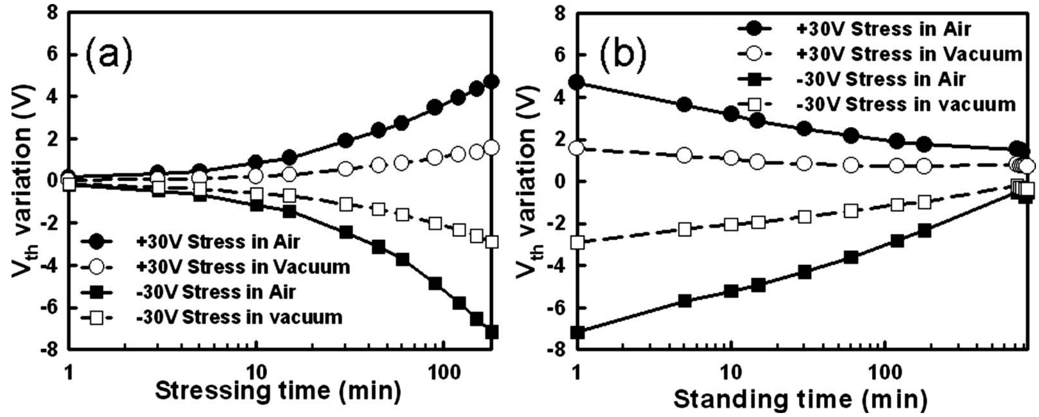

FIG. 2. (a) Variation in V_{th} (ΔV_{th}) of a-IZO TFTs to which ± 30 V gate bias stress was applied for various durations, as measured in air (solid symbol and solid line) and a vacuum (empty symbol and dashed line). The variation in V_{th} is defined as the difference between the threshold voltages with and without the application of a gate bias stress to the a-IZO TFT device. (b) Variation in V_{th} of ± 30 V gate-bias stressed a-IZO TFTs as function of standing period in air (solid symbol and solid line) and a vacuum (empty symbol and dashed line), after the source of gate bias stress had been removed. Variation in V_{th} is defined as difference between the threshold voltages of gate-bias stressed a-IZO TFT device and such a device without gate bias stress (i.e., initial device).

are the steady state in Figs. 1(a) and 1(b). In this work, the steady state of the a-IZO TFT in ambient air was reached in 810 min, but in a vacuum was reached in 840 min. Figure 2(a) plots the corresponding V_{th} variations (ΔV_{th}) of the a-IZO TFTs to which were applied a gate bias stress of ± 30 V in the atmosphere and in a vacuum for various periods. The magnitude of ΔV_{th} increased with the duration of the application of bias stress, to an extent that was much larger in the atmosphere than in the vacuum. Additionally, after the source of the gate bias stress was removed, the ΔV_{th} of the gate-bias stressed a-IZO TFTs was found to be a function of the standing periods, as presented in Fig. 2(b). The magnitude of the variation of V_{th} gradually declined as the standing period increased until it finally reached a steady-state value. Figure 3(a) schematically displays the proposed mechanism of the +30 V bias-stress-induced metastability in a-IZO TFT. When the +30 V gate bias stress was applied in the atmosphere, the positive gate voltage increased the number of excess electrons that accumulated in the a-IZO channel region. The oxygen species absorbed from the ambient atmosphere can capture electrons in the conducting channel, to generate the negatively charged species ($O^-_{2(s)}$), as described by the following chemical reaction:

$$O_{2(g)} + e^- \leftrightarrow O^-_{2(s)}, \qquad (1)$$

where e^- denotes electrons. $O_{2(g)}$ and $O^-_{2(s)}$ represent the neutral and charged oxygen molecules in the backchannel of a-IZO TFT.[6] As the concentration of the electrons increased,

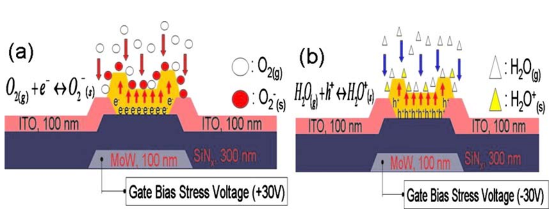

FIG. 3. (Color online) (a) Schematic of adsorption of oxygen molecules on a-IZO TFT backchannel under application of +30 V gate bias stress. Oxygen species absorbed from ambient air and a-IZO film can capture electrons in conducting channel, forming the negatively charged species [$O^-_{2(s)}$], positively shifting V_{th}. (b) Schematic reaction of water molecules on a-IZO TFT backchannel under -30 V gate bias stress. Resultant buildup of positive space charges [$H_2O^+_{(s)}$] negatively shifts V_{th}.

the equilibrium of reaction Eq. (1) was disturbed, and the reaction moved toward the right side of the reaction equation. The resultant buildup of negative space charges $O^-_{2(s)}$ easily repelled conduction electrons in the a-IZO TFT channel, positively shifting V_{th} and enlarging the magnitude of ΔV_{th}, as increasing the duration of the positive gate bias stress.[13] Furthermore, the surrounding air constantly supplied $O_{2(g)}$ to the bias-stressed a-IZO TFT in the air. In a vacuum, however, the only source of $O_{2(g)}$ was those species that were originally adsorbed on the passivation-free a-IZO backchannel layer. The supply of sufficient $O_{2(g)}$ in the air further promoted the reaction toward the right side of Eq. (1). Accordingly, the magnitude of the variation of V_{th} of the a-IZO TFT in the atmosphere exceeded that of the TFT in the vacuum during the positive gate bias. As applying negative gate bias stress, the insufficient $O_{2(g)}$ and depletion of electrons in a vacuum should cause more obvious negative shifts of V_{th} than that in the ambient air with sufficient $O_{2(g)}$, if the chemical reaction on a-IZO film only follows Eq. (1). However, this inference solely from Eq. (1) is opposite to the fact that the negative shift of V_{th} is more evident in the air than in a vacuum during negative gate bias stress, shown in Fig. 2(a). This suggests the sole Eq. (1) could not dominate the chemical reaction on the a-IZO TFT during the negative gate bias stress. In contrast, with the consideration of water molecules, the negative gate bias stress (-30 V) increased the number of holes in the a-IZO channel region, and caused the adsorbed moisture ($H_2O_{(g)}$) from the atmosphere to form positively charged species ($H_2O^+_{(s)}$), as depicted schematically in Fig. 3(b). The reaction process is proposed as follows:

$$H_2O_{(g)} + h^+ \leftrightarrow H_2O^+_{(s)}, \qquad (2)$$

where h^+ is a hole. $H_2O_{(g)}$ and $H_2O^+_{(s)}$ represent the neutral and positively charged water molecules, respectively. The proposed Eq. (2) is reasonably supported by previous work, which stated water molecule from the atmosphere typically acts as an electron donor and undergoes a charge exchange process different from $O_{2(g)}$ on the TCO-based film.[7] As the stress duration is increased, the increase in the hole concentration moved the reaction direction toward the right-hand side of the reaction equation. The resultant buildup of positive space charges $H_2O^+_{(s)}$ easily induce conduction electrons in the a-IZO TFT channel, negatively shifting V_{th} and increasing the magnitude of ΔV_{th}. In addition, the supply of sufficient $H_2O_{(g)}$ in the air further enhanced the reaction toward the right side of Eq. (2). This can resultantly lead to a more obvious shift of negative V_{th} occurred in the air than in the vacuum during negative gate bias stress. After the source of the gate bias stress was removed, an another steady state was achieved, according to the dynamic equilibrium given by Eqs. (1) and (2) and moved toward the left-hand side of the reaction equation. The slow recovery of electrical characteristics was thus observed, and the magnitude of the variation in V_{th} decreased as the standing period increased, as plotted in Fig. 2(b). In this work, a weak charge trapping effect in the gate insulator of a-IZO TFT could arise because of the long period, 180 min, of the application of stress, such that the transfer curves before and after gate bias stress did not matched each other exactly. In this study, however, the electrical characteristics of the gate-bias stressed a-IZO TFT were not seriously degraded, since the subthreshold swing and carrier mobility were almost equal (not shown here).

In summary, the environment-dependent metastability of intrinsic a-IZO TFT after gate bias stress has been studied in a vacuum to exclude the potential impact from passivation layer deposition process. The adsorption/desorption reaction of ambient oxygen and water molecules, on the back-channel affects the electrical characteristics of a-IZO TFTs. The magnitude of the variation of V_{th} was increased with the duration of application of the gate bias stress, but decreased to a low value after the gate bias stress was removed. Moreover, the variation in V_{th} of the a-IZO TFT device bias-stressed in the ambient atmosphere markedly exceeded that of the device stressed in a vacuum, because more $O_{2(g)}$ and $H_2O_{(g)}$ was supplied from the atmosphere than the vacuum. The effect of stress voltage polarity on the a-IZO TFT device was expounded by the dynamic reaction equilibrium of oxygen and water in the ambient atmosphere.

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