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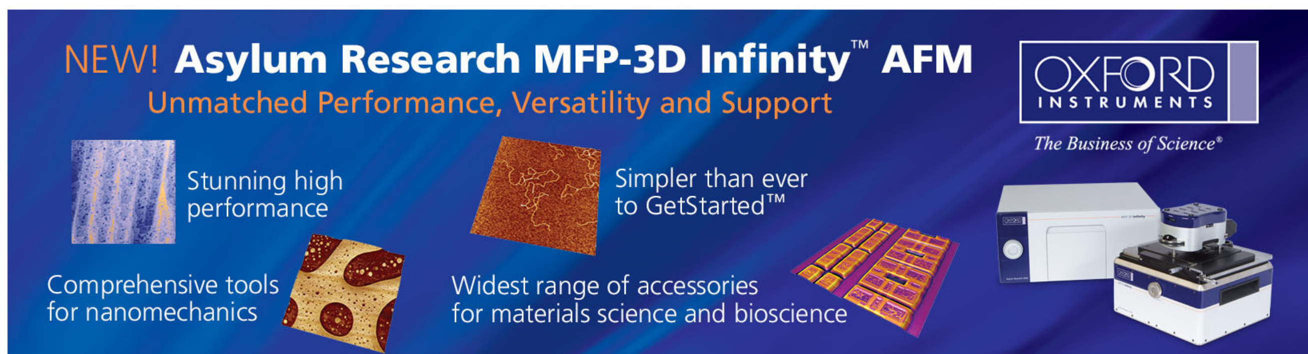

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Investigation of on-current degradation behavior induced by surface hydrolysis effect under negative gate bias stress in amorphous InGaZnO thin-film transistors

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This study investigates the electrical instability under negative gate bias stress (NGBS) induced by surface hydrolysis effect. Electrical characteristics exhibit instability for amorphous InGaZnO (a-IGZO) Thin Film Transistors (TFTs) under NGBS, in which on-current degradation and current crowding phenomenon can be observed. When the negative gate bias is applied on the TFT, hydrogen ions will dissociate from ZnO-H bonds and the dissociated hydrogen ions will cause electrical instability under NGBS. The ISE-Technology Computer Aided Design simulation tool and moisture partial pressure modulation measurement are utilized to clarify the anomalous degradation behavior. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4863682]

Recently, portable electronic products have been applied widely. Especially, the low power consumption IC,[1] non-volatile memory,[2–6] and Thin Film Transistors (TFTs)[7,8] have been used extensively in those portable electronic products. TFTs with active layers of metal oxide semiconductors, such as ZnO and amorphous InGaZnO (a-IGZO), have attracted considerable attention for the application in next generation display industry.[9,10] In particular, a-IGZO thin film transistors have been widely investigated for future large-area electronics owing to its good uniformity, high mobility, excellent transparency to visible light, and feasibility of room temperature fabrication.[10–12] Therefore, it is a very promising alternative to replace amorphous silicon TFT for application in Active Matrix Liquid Crystal Displays (AMLCD) and Organic Light-Emitting Diode Displays (AMOLED) as switching/driving devices. However, there are some difficulties which are necessary to overcome for oxide TFTs to be practical in applications, such as instability under gate bias stress and the surrounding ambiance.[13–17] As Amorphous Oxide Semiconductor (AOS) TFTs used in AM displays must be operated under gate bias, the reliability issue under gate bias stress in ambient gas is of great importance.

This study investigates electrical degradation behaviors and mechanisms under negative gate bias stress (NGBS). On-current degradation and current crowding phenomenon can be observed after NGBS. Mechanisms of degradation are analyzed and clarified using capacitance-voltage measurement, and the ISE-Technology Computer Aided Design (ISE-TCAD) simulation tool is utilized to further confirm the degradation mechanism.

Inverted coplanar structure a-IGZO TFTs were fabricated on glass substrate in this work. The tri-layer Ti/Al/Ti (50/200/50 nm) gate electrodes films were deposited and then patterned via photolithography on glass substrate. A 300-nm-thick SiO_2 gate dielectric film was deposited on the patterned gate electrode by plasma enhanced chemical vapor deposition (PECVD). And Ti/Al/Ti (50/200/50 nm) source/drain electrodes were formed by DC-sputtering. An active layer of 30-nm-thick a-IGZO film was finally deposited by DC magnetron sputtering using a target of In:Ga:Zn = 1:1:1 in atomic ratio at room temperature. The dimension of channel width/length (W/L) was 100 μm/10 μm. After that, the device was annealed in an oven at 330 °C for 2 h under dark environment. Electrical measurements, including transfer characteristics and capacitance-voltage curves, were done by Agilent 4156C semiconductor analyzer and Agilent 4294A precision LCR meter, respectively. And the whole measurements were performed in dark environment with ambient pressure of 10^{-2} Torr.

Figures 1(a) and 1(b) show the normalized I_D-V_G and I_D-V_D curves of a-IGZO TFTs under NGBS, respectively. Under NGBS condition, the gate electrode was fixed at −30 V for 1000 s, while source and drain were grounded. According to the previous report, amorphous IGZO TFT is stable under NGBS because the holes are negligible in the n-type metal-oxide semiconductor valance bands. In addition, holes cannot transport in the p-orbital because of the dislocation of the p-orbital for metal-oxide semiconductor material.[18,19] However, significant on-current degradation is observed from the transfer characteristic in this study, as shown in Figure 1(a). Furthermore, an obvious current crowding phenomenon can be also observed, and the on-current deteriorates 33% after the NGBS for 1000 s (Figure 1(b)). To investigate the anomalous on-current degradation, capacitance-voltage measurement was adopted.

Figures 1(c) and 1(d) show the gate-to-drain capacitance (C_{GD}) and the gate-to-source capacitance (C_{GS}) characteristics.

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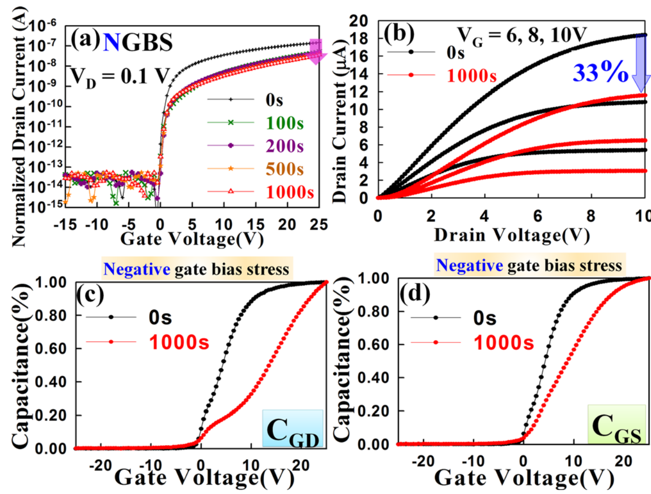

FIG. 1. (a) I_D-V_G transfer characteristic of a-IGZO TFT before and after NGBS. (b) I_D-V_D output characteristic of a-IGZO TFT before and after NGBS. (c) C_{GD}-V_G transfer characteristic of a-IGZO TFT before and after NGBS. (d) C_{GS}-V_G transfer characteristic of a-IGZO TFT before and after NGBS.

In the C_{GD} measurement, the capacitance measurement high (CMH) and capacitance measurement low (CML) were applied on the gate and drain electrode, respectively, with source electrode floating. On the other hand, to the C_{GS} measurement, the gate electrode is still connected to CMH, while the CML is applied on the source electrode with drain electrode floating. Both the C_{GD} and C_{GS} measurements were measured at 1 MHz. After NGBS, an obvious stretch-out phenomenon in C_{GD}-V_G and C_{GS}-V_G curves can be observed between $V_G = 0$ V and 6 V, which is shown in Figures 1(c) and 1(d). The deterioration observed from C_{GD} and C_{GS} measurement indicates that the degradation occurs near the drain/source side after NGBS.

According to the experimental results, a physical model is proposed to clarify the mechanism of device degradation. As the device structure is inverted coplanar without passivation layer, the active layer is exposed to the atmosphere. The moisture in atmosphere will react with the back surface material of a-IGZO film, causing the a-IGZO film hydrolyzed.[20]

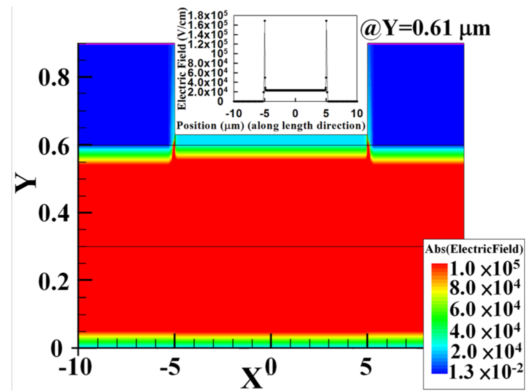

FIG. 3. The electric field distribution under NGBS simulated by ISE-TCAD simulation tool. The inset illustrates the distribution of electric field along the length direction at Y = 0.61 μm, where Y represents the perpendicular distance from the substrate.

Consequently, ZnO-H bonds will form on the back surface of a-IGZO film, as shown in Figure 2(a) together with the reaction equation. When the TFT is operated under NGBS condition, ZnO-H bonds will be broken with hydrogen ions released. Because the TFT is operated at off state ($V_G = -30$ V, source/drain = 0 V), there exists maximum electric field in/around the area between gate and source/drain. As a result, the dissociated hydrogen ions will be attracted toward the interface between a-IGZO film and source/drain terminals. Then the hydrogen ions will be bounded with ZnO InO or GaO to form ZnO-H InO-H or GaO-H bonds near the interface between a-IGZO active layer and the source/drain side. Because of the degradation of the contact between source/drain and a-IGZO active layer, the current crowding phenomenon can be observed after NGBS. Furthermore, owing to the alteration of the atomic structure of the a-IGZO, some strained bonds are generated, as shown in Figure 2(b). In the view of vertical energy band diagram, the generated strained bonds will induce tail states in a-IGZO film near the interface between a-IGZO active layer and source/drain side. When the device is operated at

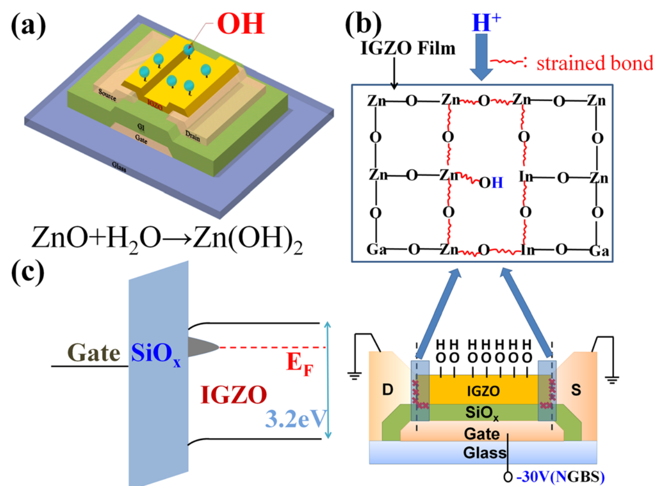

FIG. 2. (a) Schematic diagram of the hydrolysis effect and hydrolysis equation of a-IGZO TFT. (b) Schematic diagram of the degradation mechanism of a-IGZO TFT under NGBS. (c) Vertical band diagram at on-state after NGBS.

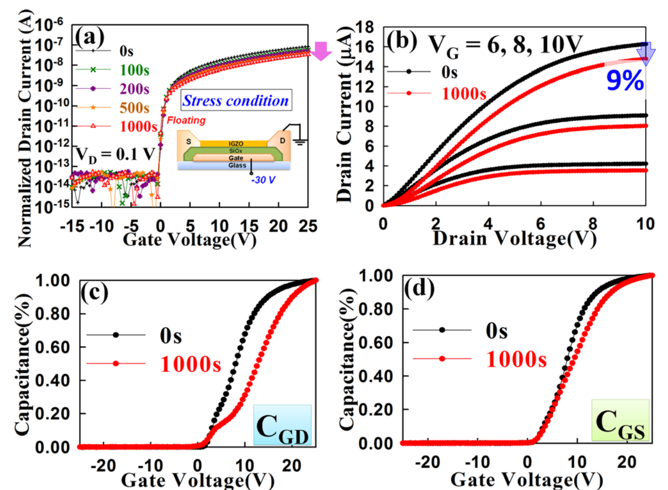

FIG. 4. (a) I_D-V_G transfer characteristic of a-IGZO TFT before and after NGBS with floating source. (b) I_D-V_D output characteristic of a-IGZO TFT before and after NGBS with floating source. (c) C_{GD}-V_G transfer characteristic of a-IGZO TFT before and after NGBS with floating source. (d) C_{GS}-V_G transfer characteristic of a-IGZO TFT before and after NGBS with floating source.

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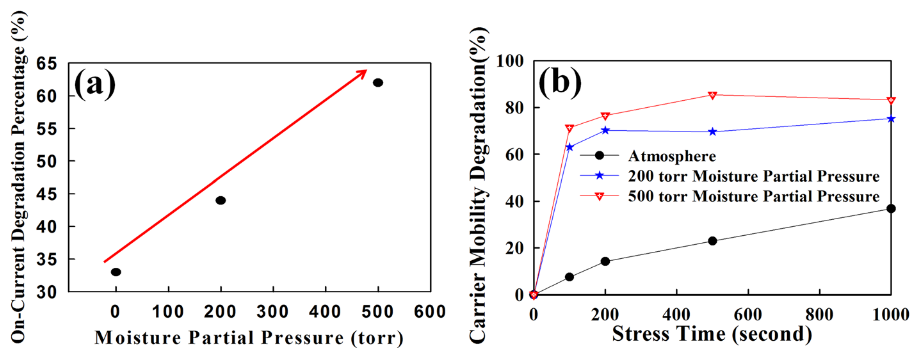

FIG. 5. (a) Illustration of moisture-partial-pressure-dependent on-current degradation after NGBS. (b) Illustration of carrier mobility degradation with stress time under different moisture partial pressure.

on-state, V_G increases with the energy band bending downward. As a result, channel electrons will be captured by those traps, from which obvious on-current degradation can be observed, as shown in Figure 2(c).

Figure 3 shows the distribution of electric field under NGBS simulated by ISE-TCAD simulation tool. The inset of Figure 3 shows the distribution of electric field along the length direction at $Y = 0.61\ \mu$m, where Y represents the perpendicular distance from the substrate. From the result of simulation under NGBS, the maximum electric field is found to locate near the interface between a-IGZO and source/drain terminals. Therefore, the dissociated hydrogen ions are more likely to be attracted toward the interface between a-IGZO film and source/drain terminals.

In order to verify the physical mechanism, NGBS was carried out with source electrode floating. From Figures 4(a) and 4(b), smaller on-current degradation (9%) and more slight current crowding phenomenon can be observed compared with the stress condition of NGBS with source/drain grounded. Since the source terminal is floating under NGBS, the dissociated hydrogen ions will only move toward the drain side. Therefore, only the interface between a-IGZO active layer and the drain side will degrade, while the source side is intact. Besides in the C_{GD} measurement process, an obvious stretch-out phenomenon can be observed between $V_G = 0$ V and 6 V, shown in Figure 4(c). Comparatively, stretch-out phenomenon cannot be observed in C_{GS} measurement within the same voltage range of V_G. Only when V_G exceeds 10 V, stretch-out phenomenon can be observed due to the extension of channel to the drain (Figure 4(d)).

To further confirm the proposed degradation mechanism, TFT is operated under moisture ambiance with various moisture partial pressures. From Figure 5(a), more severe on-current degradation can be observed after NGBS with higher moisture partial pressure. In the moisture ambience, the hydrolysis effect of the back surface of a-IGZO film will become more severe, resulting in more arresting on-current degradation due to the hydrolysis effect. Furthermore, carrier mobility is found to degrade with stress time, and the degree of degradation becomes more severe as moisture partial pressure increases, as shown in Figure 5(b). This further corroborates the proposed model.

In summary, we have investigated the degradation mechanisms of a-IGZO TFT under NGBS. The moisture in the atmosphere can react with the back surface of a-IGZO film, causing the a-IGZO film to be hydrolyzed. During NGBS, the dissociated hydrogen ions are attracted toward the source and drain sides, leading to the degradation between a-IGZO active layer and source/drain side. Hence, an on-current degradation and current crowding phenomenon can be observed. Furthermore, the result of ISE-TCAD simulation and C_{GD}/C_{GS} measurements confirms the degradation occurs near the source/drain side after NGBS. In addition, floating source NGBS of C_{GD} and C_{GS} further corroborates the degradation area, namely, the interface between drain and active layer. Moreover, in the moisture ambience, the on-current degradation becomes more pronounced after NGBS. From the discussion above, it is of great value to investigate the hydrolysis of a-IGZO surface in order to achieve satisfactory device performance.

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