Surface & Coatings Technology 231 (2013) 531–534

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Characterization of environment-dependent hysteresis in indium gallium zinc oxide thin film transistors

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ARTICLE INFO

Available online 7 March 2012

Keyword:
Indium gallium zinc oxide
Thin film transistors
Hysteresis

ABSTRACT

This study investigates environmentally dependent electrical performance as a function of hysteresis phenomena for amorphous indium–gallium–zinc-oxide (a-IGZO) thin film transistors (TFTs). Because ambient gas has a great influence on the electrical characteristics of zinc oxide-based TFTs during electrical measurements, the hysteresis for current–voltage and capacitance–voltage measurements are employed in different ambient gases (ambient air, vacuum, oxygen ambient and moisture ambient) to study this issue. Although the hysteresis phenomenon has been explained by the charge trapping and de-trapping model, in order to obtain stable electrical characteristics it is necessary to clarify the original principal mechanism leading to threshold voltage instability under gate bias operations in different environments. Also, the relationship between de-trapping rate and electrical hysteresis is investigated by prolonging the integration time of the semiconductor parameter analyzer. This study may be of importance in explaining the dynamic relationship between the TFT electrical characteristics and ambient gas, as well as providing a better understanding of the environment-dependent hysteresis phenomenon of the IGZO TFTs.

1. Introduction

Recently, amorphous oxide semiconductors (AOSs) have been considered appropriate for application in thin film transistors (TFTs) for use in large-area flexible electronic devices due to the great electrical uniformity and process advantage of being deposited at room temperature [1–4]. Compared to hydrogenated amorphous silicon (a-Si:H), they have excellent electron mobility and a reduced density of band tail state because their conduction band is composed of spherical overlapping orbital [5]. In particular, ZnO-based semiconductors incorporate indium-oxide and gallium-oxide or hafnium-oxide as a carrier mobility enhancer and as a structure suppressor for amorphous phase, respectively, to achieve channel material requirements of high field effect mobility and low leakage current, such as In–Ga–Zn–O and Hf–In–Zn–O [6–8]. Moreover, due to the high carrier mobility of AOSs, transparent and flexible nonvolatile memories can be developed by incorporating AOSs, in order to meet the future goals of system-on-panel applications [9,10]. In previous studies, the ambient gas causes a notable reliability on the electrical characteristic of ZnO-based TFTs under a gate bias stress [11–14]. Although some proper passivation layers to eliminate the influence of ambient gas on the active layer have been studied [15–17], it is advisable to establish the principal ambient-induced mechanism which can be expected to decrease any environment ambient effects without a passivation layer and therefore reduce panel cost. However, very little research has focused on the electrical hysteresis phenomena of a-IGZO TFT under rapid on-state or off-state operation in actual display applications [18].

2. Experiment detail

2.1. TFT fabrication

In this article, we investigate the environmental effect on the electrical hysteresis by current–voltage (I–V) and capacitance–voltage (C–V) measurements. For this purpose, passivation-free bottom gate coplanar a-IGZO TFTs are adopted to examine the electrical hysteresis of a-IGZO TFTs in different ambient gases. First, the patterned Ti/Al/Ti (50/200/50 nm) tri-layer gate electrodes on glass substrate were capped with SiOx (300 nm) film as gate insulator, which was grown

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doi:10.1016/j.surfcoat.2012.02.057

by plasma enhanced chemical vapor deposition (PECVD) at 370 °C. The source/drain electrodes were formed by DC sputtering with Ti/Al/Ti (50/200/50 nm) and then patterned by wet-etching. The active layer, composed of 30 nm thick a-IGZO, was deposited by DC magnetron sputtering system at room temperature, using a target of In:Ga:Zn = 1:1:1 in atomic ratio. The process was performed with a plasma discharge power of 300 W, and in a 5 mTorr (0.6 Pa) working pressure of argon ambiance with oxygen partial pressure ratio of 6.7%. The patterned dimensions of the channel are 10–15 μm in width and 10 μm in length. Finally, all of the devices were annealed in an oven in an ambient air at 330 °C for 2 h in an O_2 gas with the H_2O partial pressure ratio of 19.7%.

2.2. TFT characterization

The I–V and C–V characteristics of a-IGZO TFTs were measured at room temperature by an Agilent B1500 semiconductor parameter analyzer. The probe station is set in a vacuum chamber with gas flow control and moisture feeding equipment [19]. All of the electrical operations under different ambient gas were performed in the dark at room temperature. The V_T was determined by using the constant current method as the gate voltage which induces a drain current of L/W × 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. For the C–V measurement, the V_T was extracted by the gate voltage (V_{GS}) which induced 1/3 of maximum capacitance.

3. Experiment result and discussions

Fig. 1(a) shows the electrical hysteresis of source-to-drain current (I_{DS}) as a function of V_{GS} with the fixed drain voltage (V_{DS}) at 0.1 V in linear regime of a-IGZO TFTs under different environments of ambient air, 1×10^{-4} Torr vacuum, H_2O/N_2 (moisture ambient), and oxygen ambient. The V_{GS} is swept by 0.75 V increments along a forward sweep from a negative voltage to a positive voltage, and along a reverse sweep from positive voltage back to the starting negative voltage (e.g., −30 to 30 to −30 V). Clockwise hysteresis of transfer curves with different V_T between forward sweep and reverse sweep are observed in different ambiences. Recently, a-IGZO TFTs have been shown to be basically n-type devices with a positive bias generating an accumulation layer of electrons in a channel close to the channel/dielectric interface [7]. The electrical hysteresis phenomenon has been explained by the variations of interface state occupancy between the insulator and channel in a-Si:H TFTs [20]. Our experiment results showed clear hysteresis in atmosphere and moisture ambient but minimal hysteresis in vacuum for the same device, indicating that the charge trapping model cannot entirely explain the hysteresis behavior, as shown in Fig. 1(a). Meanwhile, the estimated SS value differences between forward sweep and reverse sweep in atmospheric and moisture ambient are both about 0.2. This indicates that the interface states of a-IGZO TFTs were altered in ambient air and moisture ambient [19,21,22]. Thus, to investigate the various subgap states of the channel layer or the gate insulator (GI)/semiconductor interface characteristics in detail, electrical hysteresis in the C–V measurement at 100 kHz frequency with 0.75 V increment of gate voltage was performed and shown in Fig. 1(b). Compared to the I–V measurement without any apparent change, the C–V measurement is more sensitive to the variation of the interface state of the device. It has been reported that environment effects such as bias-induced oxygen adsorption or metastable gap state induced by moisture could accelerate the instability of a-IGZO TFTs [14,19,24]. These phenomena imply that a complex mechanism causes the electrical hysteresis in ambient air, as will be discussed later.

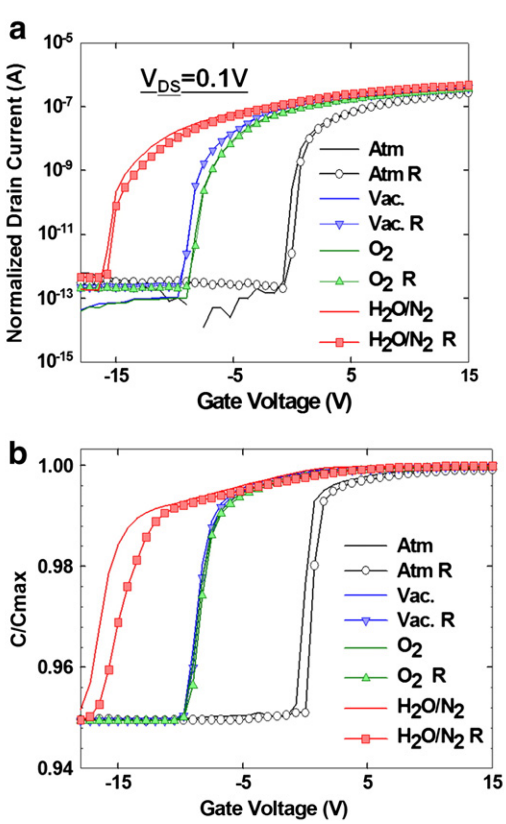

Fig. 1. Electrical hysteresis of (a) I_{Ds}–V_{Gs} characteristics with fixed drain voltage (V_{DS}) at 0.1 V and (b) *C–V* characteristics of a-IGZO TFTs in linear regime for a-IGZO TFTs under ambient air, vacuum, moisture ambient, and oxygen ambient.

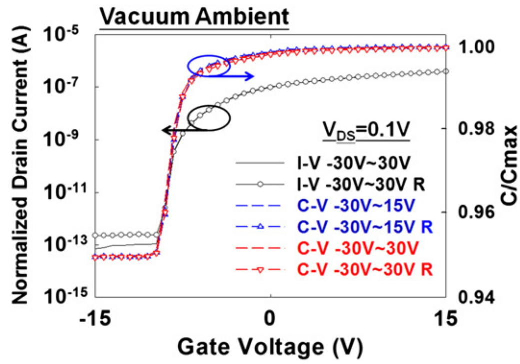

Fig. 2. *I–V* and *C–V* hysteresis characteristics of a-IGZO TFTs measured with different gate sweep ranges in vacuum environment.

Fig. 2 shows the I–V and C–V hysteresis of the a-IGZO TFTs measured in a vacuum environment. Clearly, no abnormality between the forward sweep and reverse sweep both in the I–V and C–V hysteresis measurements can be observed. In general, because of the absence of ambient gas, this result has been suggested to be due to electron trapping in the preexisting traps located at the GI/semiconductor interface. Note that the interface-trapped electron interrupts the subsequent flow of electron in the channel layer. As a result, even the stop sweep V_{GS} was doubled from 15 V to 30 V, and no I–V hysteresis was found, which clarifies that no more electron traps exist at the GI/ a-IGZO interface. Literature has implied that the band tail state generated from structural disorder and defects may be eliminated by incorporating hydrogen into a-IGZO during active layer deposition or thermal annealing at the end of the fabrication process. [5,25]

In Fig. 3(a) and (b), the I–V and C–V hysteresis measurement are shown for a-IGZO TFTs in oxygen ambient pressures of 1 Torr, 10 Torr, 100 Torr and 760 Torr, respectively. The SS of the forward and reverse sweeps are similar, exhibiting no defect creation at the

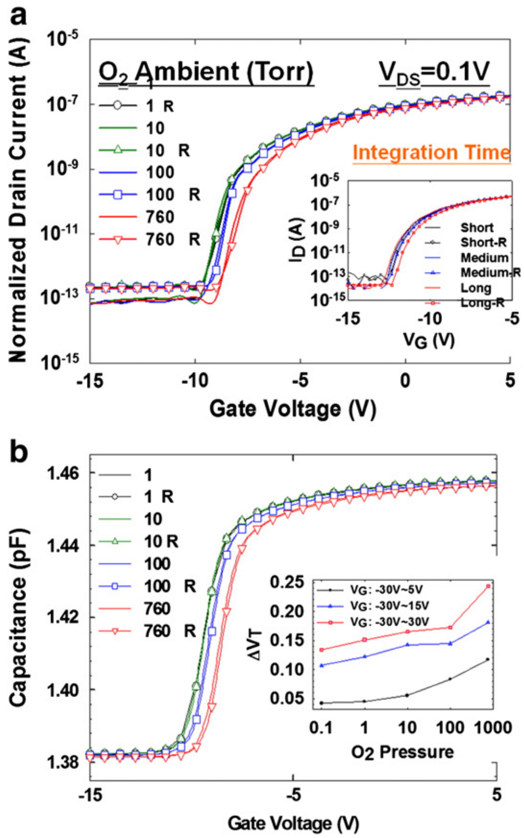

Fig. 3. The evolution of (a) I_{DS}–V_{GS} and (b) *C–V* hysteresis measurement for a-IGZO TFTs in oxygen ambient pressures of 1 Torr, 10 Torr, 100 Torr and 760 Torr. The inset of figure (a) shows the I–V hysteresis measurement with different integration times. The inset of figure (b) shows the delta threshold voltage of *C–V* hysteresis measurement with different V_G sweep ranges in oxygen ambient pressures of 1 Torr, 10 Torr, 100 Torr and 760 Torr.

GI/semiconductor interface under different oxygen partial pressures. In the inset of Fig. 3(a), the estimated delta V_T from I–V hysteresis of a-IGZO TFT increases with increasing oxygen partial pressure. These results indicate that two responsible mechanisms for the delta V_T can be proposed: (1) simple charge trapping phenomenon and (2) environment effects. Moreover, the same tendency of the C–V hysteresis measurement without any distortion was observed in Fig. 3(b). The delta V_T of the C–V hysteresis measurement in oxygen ambient with different ending of positive sweep V_{GS} is depicted in the inset of Fig. 3(b). The experimental results in Fig. 3(b) demonstrate that the more oxygen that surrounds a-IGZO TFTs, the more delta threshold voltage is measured. A previous study suggested that the surrounding oxygen molecules can capture electrons from the conduction band and then adsorb on the device as a form of $O_2 + e^- \rightarrow O_2{}^-{}_{(ads)}$, resulting in a depletion layer in the active back-channel [23]. If the electron trapping/de-trapping mechanism dominates the hysteresis phenomenon of a-IGZO TFTs in oxygen ambient by prolonging the measurement integration time, the de-trapping rate would be enhanced and electrical hysteresis would be reduced [20]. Because the de-trapping rate increases with longer integration time, the electron released from trapping states helps the current flow in the reverse sweep, so a smaller positive shift of reverse sweep curve would be observed.

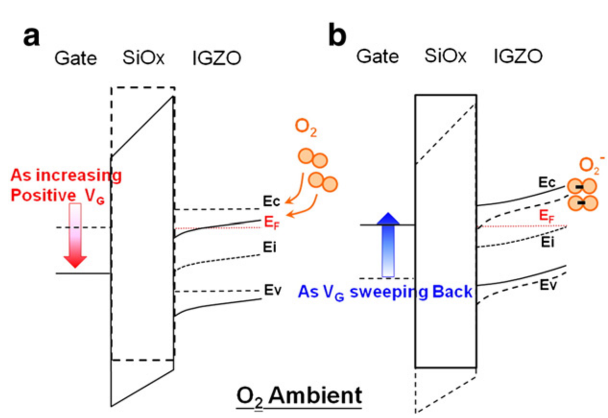

Fig. 4. Schematic band diagram explaining the experiment result, which are (a) chemisorption of oxygen with increasing V_G during the on-state of a-IGZO TFTs (b) chemisorbed oxygen on the back channel of a-IGZO TFTs screen the applied V_G during the reverse sweep.

The inset of Fig. 3(a) represents the I–V hysteresis of a-IGZO TFT with short (20 ms), medium (40 ms) and long (2 s) integration times. For the long time, the reverse sweep shows a clear increase of V_T in the inset of Fig. 3(a), which seems to be different from those found in previous work [20]. Even the oxygen in ambient and the interface trap act in the same role to trap electrons and cause an increase in V_T; nevertheless, the de-trapping time of chemisorbed electrons from oxygen is longer than interface trapped electron. Thus, this phenomenon may be associated with more bias-induced adsorption oxygen on the back channel of a-IGZO TFTs during the on-state period. We assume that during forward measurement, one oxygen molecule in environment can capture an electron from the conduction band during large electrical current flow in the channel layer. A schematic of the possible mechanism during rapid operation in oxygen ambient is depicted in Fig. 4(a). With increasing V_{GS}, the bent energy band of a-IGZO causes the chemisorption of oxygen which lowers the Fermi level. During the reverse sweep, in Fig. 4(b), the oxygen chemisorbed on the back channel of a-IGZO TFTs screens the applied gate voltage, which produces a lower V_{GS} required to turn off the a-IGZO TFTs during reverse sweep. Therefore, the more time during the on state, the more chemisorption of oxygen occurs, as shown in the inset of Fig. 3(b).

Fig. 1(a) and (b) shows about −14 V V_T shift, a 0.5 degradation in SS for the I–V curve and a distorted C–V curve for the device in moisture ambient when compared to atmosphere ambient. This implies that the creation of subgap states in a-IGZO arise from the moisture ambient [21–23]. For the hysteresis C–V measurement in Fig. 1(b), it can be assumed that the creation states in the GI/channel layer interface screen the applied gate voltage in moisture ambient, leading to a C–V measurement that is largely stretched out. It should be noted that the distorted C–V of a pristine device is particularly ranged in a gate voltage regime that corresponds to the off-state in the I–V measurement. In order to investigate the cause of this phenomenon, we measured the hysteresis C–V characteristics by two different gate voltage sweep ranges. One is from off state to close to the on-

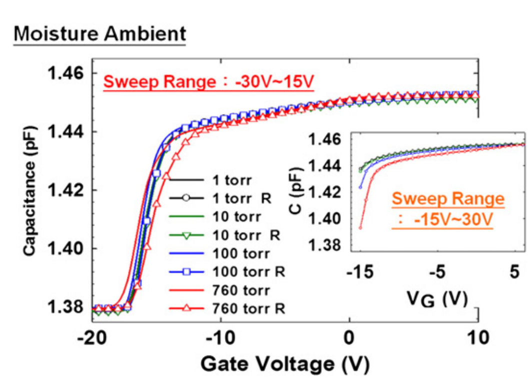

Fig. 5. *C–V* hysteresis measurement with V_G sweep range from −30 V to 15 V and V_G sweep range from −15 V to 30 V (inset) in the moisture ambient of pressures of 1 Torr, 10 Torr, 100 Torr and 760 Torr.

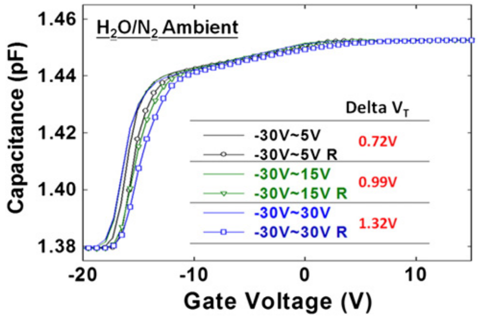

Fig. 6. *C–V* hysteresis measurement with different ending of positive gate voltages. The inset shows the estimated delta V_T from *C–V* hysteresis measurement for different ending of positive gate voltages.

state (−30 V to 15 V), and the other is from subthreshold state to the on-state (−15 V to 30 V). In Fig. 5, C–V curves which sweep range is from off state to on-state are stretched-out toward the negative direction as environmental moisture increases. In literature, the chemisorption of moisture molecules seems to act as a donor-like trap in a-IGZO [26]. Nevertheless, Nomura et al. reported a high density of occupied sub gap states near the valence band maximum in a-IGZO [5]. However, the inset of Fig. 5 demonstrates that the significant on-state degradation in the C–V measurement can be attributed to the generation of acceptor-like traps by the adsorption of moisture on the shallow traps in a-IGZO. The V_T shift by this interface charge increases as the gate voltage sweeps toward the positive direction, indicating that they are negative when traps are occupied by electrons, as acceptor-like states. We assume that the adsorption of moisture is uniform in the channel layer by reaction as a form of $H_2O + M-O-M \rightarrow M-OH + M-OH + V_o^+ + e^-$, where M is the metal cation and V_o^+ is the oxygen vacancy. The O-vacancies of ZnO-based semiconductors are easily hydroxylated due to residual water [27,28]. Hence, in this case, it is possible that the acceptor-like traps and donor-like traps are generated in an a-IGZO channel layer due to the adsorption of moisture molecules. [26]

In Fig. 6, as the sweeping gate voltage becomes more positive, the positive shift of V_T in the reverse C–V measurement occurs, which results in a decreasing magnitude of capacitance for the same applied gate voltage. In general, the total capacitance can be ascribed to the product of the total balance charge and V_{GS}. The balance charge can be expressed as the sum of a-IGZO charge (Q_S) and interface trapping charge (Q_I), while the Q_S is constant under the same V_{GS} in the forward sweep. Thus, the delta capacitance in hysteresis C–V measurement is induced by electron trapping in the defect states created from adsorption of moisture. For a higher positive starting gate voltage in the reverse voltage sweeps, since the Fermi-level is nearer to the conduction band, many acceptor-like traps are filled, resulting in an increasing hysteresis C–V phenomenon.

4. Conclusions

In summary, the electrical hysteresis phenomenon of a-IGZO TFTs is analyzed in different environments by I–V and C–V measurement. In oxygen ambient, the parallel shift between forward sweep and reverse sweep from the I–V or C–V characteristics of a-IGZO TFTs can be thought of as the chemisorption of oxygen for increasing V_G during the on-state. On the contrary, the hydroxylated O-vacancies forming O−H species in a-IGZO are generated from dissociation of H_2O molecules in the environment, which causes more defect states in a-IGZO. Moreover, the created state from moisture increases the hysteresis C–V phenomenon by accelerating the electron trapping rate. These results indicate that the electrical hysteresis phenomenon of a-IGZO TFTs in atmospheric ambient can be regarded as the combination of the hysteresis characteristics in the oxygen ambient and moisture ambient.

Acknowledgment

This work was performed at National Science Council Core Facilities Laboratory for Nano-Science and Nano-Technology in Kaohsiung-Pingtung area. The authors would like to acknowledge the financial support of the National Science Council of the Republic of China under contract no. NSC-100-2120-M-110-003.

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