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Effect of Hydrogen on Long-Term Reliability of InZnO TFTs Characterized by Low-Frequency Noise

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ABSTRACT The long-term reliability of InZnO (IZO) thin film transistors (TFTs) under a hydrogen-containing environment is researched. Hydrogen incorporation induces hydroxyl groups and oxygen vacancies, leading to the generation of electrons and extra random trap/emission processes in the IZO films. Consequently, the electrical properties and low frequency noise characteristics of IZO TFTs are deteriorated under the long-term hydrogen treatment. Additionally, the recovery characteristics of IZO TFTs after the hydrogen treatment demonstrate that the hydrogen induced hydroxyl groups and oxygen vacancies remain stable at room temperature. The oxygen vacancies can be eliminated, while the hydroxyl groups may still exist at a high temperature. These results may provide useful guidelines in the design and application of IZO TFTs.

INDEX TERMS InZnO, defect, thin film transistors (TFTs), hydrogen.

I. INTRODUCTION

Amorphous indium zinc oxide (IZO) thin-film transistors (TFTs) are considered to be one of promising devices for applying in the flat panel display and flexible integrated circuits due to their high electron mobility, large switching ratio, good uniformity, and electrical stability [1]. In particular, IZO TFTs are expected to be applied in sealed environments such as spacecraft, high-energy particle accelerators and medical detectors [2], [3]. However, these devices will suffer from a long-term hydrogen incorporation in such conditions.

It is reported that the hydrogen incorporation is one of the main defect types in the active layer of metal-oxide TFTs [4]. This process often happens during deposition with annealing under certain conditions, or by the diffusion from the gate dielectric and etch stopper/passivation layer [4], [5]. However, as the devices are hermetically encapsulated to work in sealed environments, hydrogen in packaging materials could be released and permeate into devices. Thus, hydrogen incorporation also occurs and affect the electrical characteristics eventually, resulting in a long-term failure of devices [6], [7]. Currently, some groups have discussed the hydrogen doping effect during the manufacturing process of metal-oxide TFTs, yet few researchers has investigated the reliability under a long-term hydrogen incorporation stress of IZO TFTs. Such studies on IZO TFTs are urgently required before they can be used in special conditions.

Low frequency noise (LFN) can sensitively reflect the potential defects of semiconductor materials and device [8], [9]. Based on the LFN of devices, the energy and spatial distribution of traps at the interface and the gate dielectric can be analyzed. Therefore, the degradation mechanism of IZO TFTs under long-term hydrogen stress can be characterized by LFN measurement results.

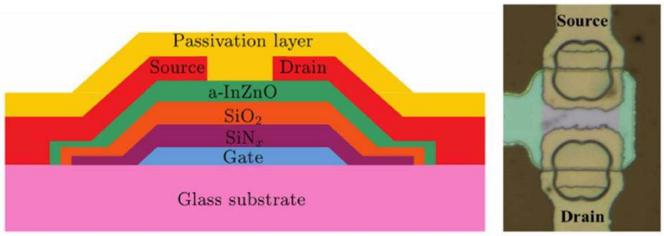

FIGURE 1. (a) Cross-sectional view and (b) micrograph of IZO TFTs.

In this letter, the long-term reliability of IZO TFTs under a hydrogen-containing environment is studied. The electrical properties and the low frequency noise of the fabricated TFTs were measured before and after hydrogen treatment. In addition, the recovery characteristics after hydrogen stress were also observed. Finally, the corresponding failure mechanism of IZO TFTs under the hydrogen stress was analyzed and discussed.

II. EXPERIMENT

The IZO TFTs with bottom-gate structure is shown in Fig. 1. The gate of the device is beneath the gate oxide and not shown in Fig. 1(b). A 300 nm Al gate layer was sputtered on a glass substrate and patterned by wet etching. A gate dielectric layer composed of 50 nm SiO_2 and 250 nm SiNx was deposited by plasma-enhanced chemical vapor deposition (PECVD) at 310°C. A 30 nm IZO layer was deposited as the active layer by radio frequency magnetron sputtering. Then, a stacked structure of Mo/Al/Mo (25 nm/100 nm/25nm) was deposited and patterned as source and drain electrodes, which controlled the channel length and width of devices. All devices were passivized by a 300-nm-thick SiO_2 layer grown by PECVD. To apply the long-term hydrogen incorporation stress, the chamber was vacuumed firstly and then filled with hydrogen to the atmospheric pressure. The percent of the hydrogen content under the hydrogen stress is considered to be 100%. The fresh devices were placed in a chamber full of hydrogen for one week at 100°C to promote the hydrogen diffusion into IZO films, and the I-V and LFN properties were measured at the room temperature every other day. Additionally, the recovery characteristics of IZO TFTs were investigated by annealing at the room temperature (27°C) and 127°C for a long time. The variation of the transfer curves before and after the recovery process were also measured at the room temperature. Electrical performance of our devices were measured by an Agilent B1500, while LFN characteristics were obtained by SR785 dynamic signal analyzer in a dark condition.

III. RESULTS AND DISCUSSION

The electrical properties of IZO TFTs measured at different hydrogen stress time are shown in Fig. 2. It is obvious that the transfer curves shift negatively with an increasing treatment time. The electrical parameters during the hydrogen stress were extracted, as shown in Fig. 3 (a)-(c).

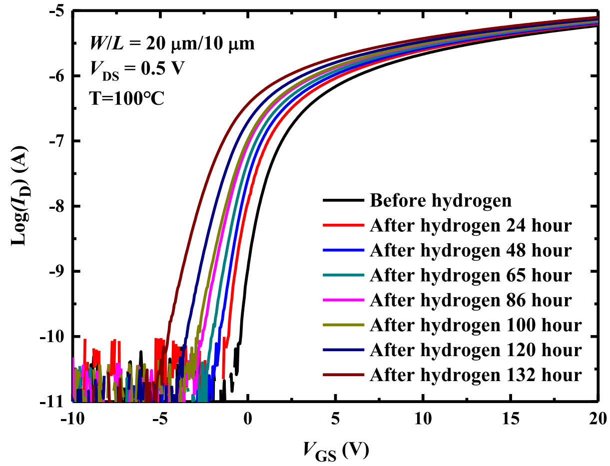

FIGURE 2. Transfer characteristics of IZO TFTs measured at different hydrogen stress time.

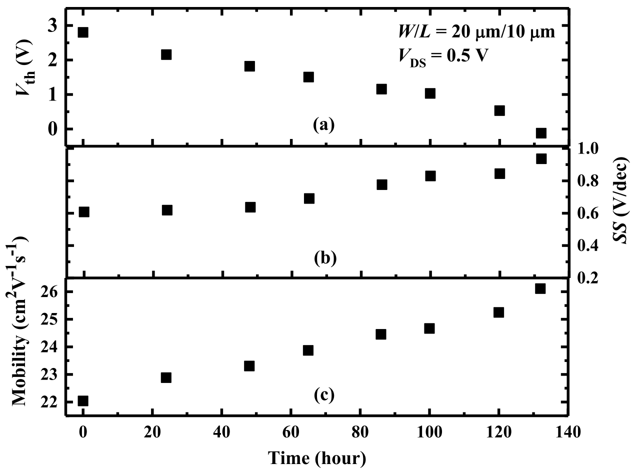

FIGURE 3. Hydrogen stress time dependence of electrical parameters: (a) V_{th}; (b) SS; (c) μ_{FE}.

The threshold voltage (V_{th}) of IZO TFTs is extracted by the extrapolation in the linear region method [10]. It consists of finding the gate-voltage axis intercept of the linear extrapolation of the I_D-V_{GS} curve at its maximum first derivative (slope) point [10]. In addition, the field effect mobility (μ_{FE}) of the samples can be extracted by [11]:

$$I_D = \frac{W}{L}\mu_{FE}C_{ox}\left(V_{GS} - V_{th} - \frac{V_{DS}}{2}\right)V_{DS} \quad (1)$$

where I_d is the drain current, W is the channel width, L is the channel length, C_{ox} is the capacitance per unit area of the gate insulator and V_{th} is the threshold voltage. The value of V_{DS} was set to 0.5V, while the value of V_{GS} was determined by $V_{GS} - V_{th} = 10V$.

According to Fig. 3, the threshold voltage (V_{th}) exhibits a negative shift under a long-term hydrogen stress. As hydrogen diffuses into the IZO films, the hydrogen atoms (H^0) will combine with oxygen ions (O^{2-}) in the IZO film to form hydroxyl groups (OH^-) and release an electron [12]. The process can be expressed as $H^0 + O^{2-} \rightarrow OH^- + e^-$ [12]. Meanwhile, the hydrogen incorporation may induce the oxygen vacancies (V_O) due to the elimination of O^{2-}. The extracted V_{th} is closely related to the density of the ionized oxygen vacancy (V_O^{2+}) and OH^-. The generated V_O^{2+} may act as positive fixed charges near the IZO/SiO_2 interface, which effectively screens the gate bias and then results in the negative shifts [13]. At the same time, the OH^- will be bound to metal atoms or be freed in the IZO film, which may be also attribute to the negative shift of V_{th}.

The subthreshold swing (SS) presents a negligibly variation with a stress time less than 48 hours, which indicates the density of the localized states are not changed in the channel. This phenomenon suggests that hydrogen atoms tend to bind with oxygen and act as a donor defect with a low electron concentration. When a high electron concentration is achieved ($>1.65\times10^{20}$ e/cm^3), hydrogen atoms start to bind with metal atoms. In this process, the hydrogen atoms trap electrons to form H^-, which can occupy oxygen vacancies and bond with the surrounding metal ions, leading to the formation of the metal-hydrogen (M-H) bonding ($H^0 + e^- + V_O \rightarrow H^- + V_O \rightarrow H_O$, where H_O is the hydrogen atom occupying oxygen vacancies). As reported [14], the M-H bonding shows contributions to the density of states (DOS) at the valence band top. Thus, the increment of SS above 48 hours may be induced by the M-H defects.

The field effect mobilities (μ_{FE}) were extracted at $V_{GS} - V_{th} = 10$V, and $V_{DS} = 0.5$V, as shown in Fig. 3 (c). The μ_{FE} ascends with increasing hydrogen stress time. According to the previous analysis, the doped hydrogen is contributed to the formation of V_O and OH^-. Based on [12], electrons are generated during the formation of OH^- groups. Besides, the oxygen vacancies can also produce additional free electrons by $V_O = V_O^{2+} + 2e^-$ [15], [16]. Thence, the carrier concentration in the channel of IZO TFTs is increased, resulting in the growth of μ_{FE}.

The LFN properties can electrically characterize the trap-assisted conduction process in channels and gate dielectrics in TFTs [17]. To investigate the affect of the hydrogen stress on the LFN characteristics of devices, the normalized drain current noise (S_{ID}/I_D^2) versus drain current (I_D) was obtained before and after the hydrogen stress. The drain voltage (V_{DS}) was set to 0.5V. The gate voltage (V_{GS}) in the subthreshold region increases from V_{ON} to $V_{GS} - V_{th} > V_{DS}$ with a step of 0.3V, and then increased with lager steps of 1V, 2V, 3V and 4V in the linear region.

In metal-oxide TFTs, the carrier number fluctuation (ΔN) model [18] is applied to analysis the LFN characteristics, from which the S_{ID}/I_D^2 of IZO TFTs can be expressed by [18]:

$$S_{ID}/I_D^2 = \left(\frac{g_m}{I_D}\right)^2 S_{Vfb} = \left(\frac{g_m}{I_D}\right)^2 \left(\frac{q^2 KT\lambda N_t}{WLC_{ox}^2 f}\right) \quad (2)$$

where g_m is the device transconductance, S_{Vfb} is the flat-band voltage power spectral density, N_t is the trap concentration at the interface between the gate dielectric and the channel,

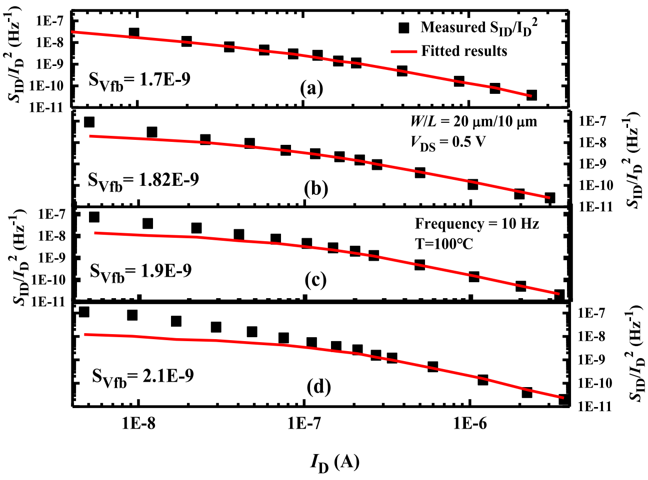

FIGURE 4. Normalized drain current noise versus drain current (a) Before hydrogen; (b) After 65 hours; (c) After 100 hours; (d) After 132 hours.

λ is the tunneling attenuation coefficient, which is ~0.1 nm for SiO_2 [19].

Based on Eq. (1), N_t at the IZO/SiO_2 interface in our devices can be extracted by:

$$N_t = S_{Vfb}\frac{WLC_{ox}^2 f}{q^2 KT\lambda} \quad (3)$$

Fig. 4 plots the measured and fitted results of the S_{ID}/I_D^2 at a frequency of 10Hz. It demonstrates that the LFN properties in IZO TFTs were well fitted by the ΔN model at a high drain current, while a difference between the fitting and measured results is seen in the low drain current. This phenomena is related to carriers fluctuations due to trapping at the grain boundary in amorphous IZO TFTs [20]. In low drain currents, the channel depth is large and grain boundary traps play significant role in carrier number fluctuation. In this conditions, the LFN is affected by the fluctuations of carriers trapping in grain boundary and oxide traps. As the drain current increases, the gate-induced electrons are located closer to the gate/oxide interface and the oxide traps affect mainly the drain current noise. Thus the LFN can be well modeled by the ΔN model.

According to Eq. (2) and Eq. (3), N_t was calculated as 1.016×10^{18} cm^{-3} eV^{-1} before the hydrogen stress and 1.255×10^{18} cm^{-3} eV^{-1} after the hydrogen stress, respectively. This result confirms the generation of new defects in the IZO layer in a hydrogen atmosphere. The hydrogen atoms diffuse into the IZO films as substitutional defects or in OH^- groups, introducing more defects in the active layer. Consequently, the increasing randomness of the trapping/emission processes enlarges the low frequency noise of the devices.

In order to investigate the qualitative spatial distribution of trapped charges in the gate dielectric, the spatial distribution of the trap density can be expressed as [18]:

$$1/2\pi f = \tau_0 \exp(\alpha_t x) \quad (4)$$

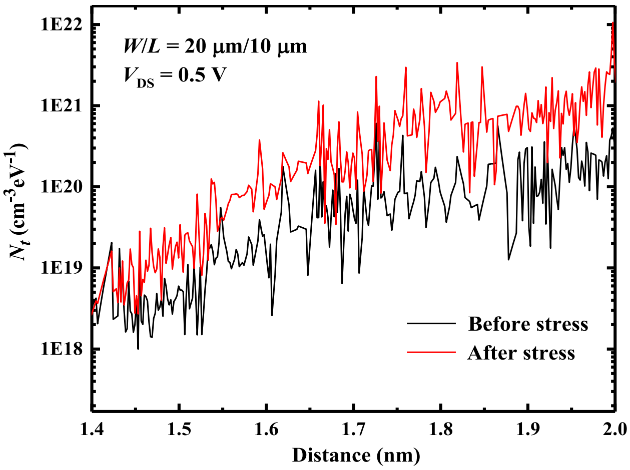

FIGURE 5. Spatial distribution of trapped charges density in the gate dielectric.

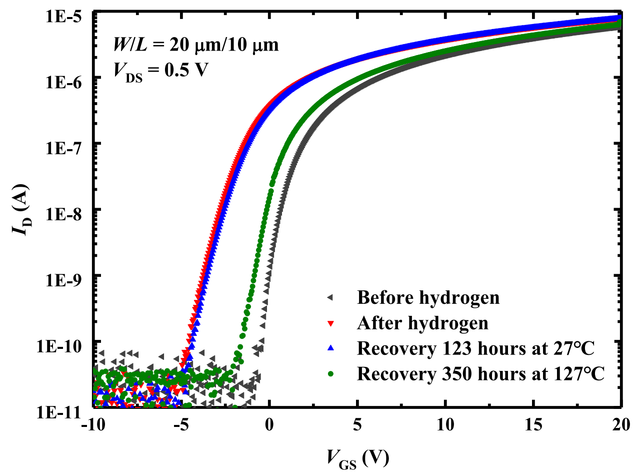

FIGURE 6. Recovery characteristics of IZO TFTs under different annealing temperatures.

where τ_0 is the time constant at the IZO/SiO_2 interface, x is the distance from the interface to the gate dielectric, α_t is the tunneling attenuation coefficient (for SiO_2 is about 10^8 cm^{-1}). The value of τ_0 is equaled to 10^{-10} s for traps distributed near the interface [18], and the frequency f ranged from 1∼1000Hz in this work. Based on Eq. (4), the value of x can be converted to the corresponding frequency f. Additionally, the value of N_t can be determined by the value of S_{ID}, as shown in Eq. (2). For the dependence of S_{ID} on frequency f can be measured by SR785, the correspondence between N_t and f can also be obtained from Eq. (2). As a consequence, the dependence of N_t on x can be extracted according to Eq. (2) and Eq. (4). The extracted density distributions of trapped charges before and after the stress are shown in Fig. 5. In this case, the value of N_t was extracted from the original S_{ID} measurement results, which qualitatively exhibits the tendency of N_t under the hydrogen stress. Obviously shifts of defect space distribution were observed, which also proves the increase of defects after the long-term hydrogen stress.

The recovery characteristics of IZO TFTs after the hydrogen stress are illustrated in Fig. 6. After leaving at the room temperature (27°C) for 123 hours, the changes in the transfer characteristics were almost negligible. It indicates that the V_O^{2+} and OH^- may remain stable at the room temperature. The V_O^{2+} may be formed due to the outward relaxation and metal atoms moving to positions far away from their initial positions [13]. When the devices were annealed at 127°C for 350 h, a certain degree of recovery was seen at first, which suggests that V_O^{2+} was recovered after obtaining enough external energy. The recovery of the transfer curves was saturated with a longer heating time. Such saturation of recovery may be induced by the stability of OH- in IZO films. As reported [21], the OH- in IGZO thin films can only be eliminated at the crystallization proceeds with a relatively high temperature of ∼600°C. Therefore, the OH- in IZO thin films still exists at a low temperature of 127°C. The part of unrecoverable threshold voltage is considered to be caused by the existing OH-.

IV. CONCLUSION

In conclusion, the long-term reliability of IZO TFTs in the hydrogen atmosphere was studied. The degradation of electrical parameters under the hydrogen stress was investigated. The V_{th} of our devices exhibited a negative shift with the increment both of μ_{FE} and SS. The mechanism of such deterioration can be explained by the hydrogen diffusion into the IZO films, which induces V_O and OH^- groups and then generates more electrons in the channel of IZO TFTs. Hence the carrier concentration in IZO TFTs ascended, leading to the degradation of the electrical characteristics. In addition, the LFN characteristics of devices were investigated before and after the hydrogen stress. Based on the LFN results, the trap concentration N_t at the IZO/SiO_2 interface raised from 1.016×10^{18} cm^{-3} eV^{-1} to 1.255×10^{18} cm^{-3} eV^{-1}, proving the generation of new defects near the IZO/SiO_2 interface. Additionally, the recovery characteristics of IZO TFTs after the hydrogen stress demonstrate that the hydrogen induced oxygen vacancies and OH^- groups are almost unchanged at the room temperature. When the devices were annealed at a high temperature of 127°C, the oxygen vacancies reduced while the OH^- groups remained stable. The results of this study may provide useful guidelines in the design and application of IZO TFTs to work in sealed environments.

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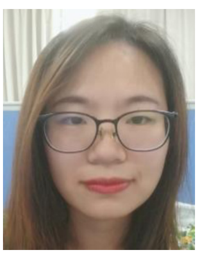

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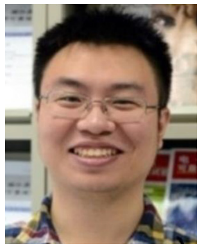

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