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Dependence of Light-Accelerated Instability on Bias and Environment in Amorphous Indium-Gallium-Zinc-Oxide Thin Film Transistors

Yu-Chun Chen,[a,*] Ting-Chang Chang,[a,b,z] Hung-Wei Li,[c] Wan-Fang Chung,[d] Tien-Yu Hsieh,[a] Yi-Hsien Chen,[a,*] Wu-Wei Tsai,[e] Wen-Jen Chiang,[e] and Jing-Yi Yan[e]

[a]*Department of Physics, National Sun Yat-Sen University, Kaohsiung, Taiwan*
[b]*Advanced Optoelectronics Technology Center, National Cheng Kung University, Taiwan*
[c]*Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan*
[d]*Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan*
[e]*Industrial Technology Research Institute, Hsinchu, 31040, Taiwan*

This study examines the dependence of light-accelerated instability on bias and environment in amorphous indium-gallium-zinc-oxide thin film transistors. When device is in vacuum ambient, the threshold voltage of device after negative gate bias illumination stress (NBIS) showed bias-dependent electrical degradation behavior. However, experimental results show the degradation of electrical characteristic in a-IGZO devices does not only rely on the charge trapping mechanism for NBIS. During NBIS in oxygen, moisture-simulated and atmosphere ambient, the negative shift in electrical characteristic is suppressed when compared to that in vacuum. This implies that the adsorbent gas species in the surrounding environment dominates the electrical characteristic degradation of devices during NBIS, which leading the change of dominant mechanism from photon-created carrier trapping to adsorbed/desorbed gas phenomenon.

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In the last decade, amorphous oxide semiconductors (AOSs) have become popular for the channel layer material in thin film transistors (TFTs) for use in active matrix light emitting diode (AMOLED) and other flexible displays.[1] Because of their large electron mobility (>10 cm^2/V.s) and uniform electrical characteristic over large area deposition at room temperature, AOSs TFTs are expected to act as the driven-TFTs in large area displays (e.g. >55 inches) or displays with a high frame rate (e.g., 240 Hz) and to become integrated into innovative transparent electronics such as AOS-based systems on glass.[2–4] In particular, to satisfy the requirements above, amorphous indium gallium zinc oxide (a-IGZO) has been intensively studied as an active layer for TFTs requiring superior electrical performance.

When used to drive AMOLED pixels, the a-IGZO TFTs are required to be under a high gate bias operation condition, which results in an accelerated degradation in their electrical characteristics.[5] This issue has been intensively studied in recent years.[6–8] However, when used as the switching TFT in the AMOLED pixel circuit, most of the time they remain in the "off" state or experience a negative bias. In particular, light illumination during gate bias operation is inevitable for a-IGZO TFTs in display applications. The reliability of a-IGZO TFTs under negative bias stress with light exposure has been reported to be induced by several mechanisms: photo generation of ionized oxygen vacancies,[9] hole trapping at the channel/insulator interface[10,11] or environmental gas ambient effects.[12–14] For the first mechanism, the photo generation of ionized oxygen vacancies usually accompanies raised off-current owing to increase of electron concentration in a-IGZO. For the latter two mechanisms, however, that there have been few attempts to establish a direct relationship between the influences which combine environmental gases and gate bias and the degradation of a-IGZO TFTs after negative gate bias illumination stress (NBIS). This work investigated the dependence of light-accelerated instability on negative bias and environmental gas ambient in a-IGZO TFTs.

Experimental

TFT fabrication.— The bottom gate and bottom contact structure of the a-IGZO TFTs are fabricated. The DC sputtered Ti/Al/Ti gate and source/drain electrodes with thickness of 50/200/50 nm were deposited and patterned by standard photolithography on a glass substrate, respectively. The 30-nm a-IGZO (In_2O_3 :Ga_2O_3 :ZnO = 1:1:1) was deposited on a 300-nm plasma enhanced chemical vapor deposited SiOx to serve as the channel layer by DC magnetron sputtering system at room temperature in an ambient gas mixture ratio of O_2 /Ar = 6.7% with a working pressure of 5 mTorr. Finally, the TFTs were annealed at 150°C for 30 minutes under atmosphere ambient.

TFT characterization.— All of the current-voltage (I-V) and capacitance-voltage (C-V) characteristic measurements were measured at room temperature by using an Agilent B1500 semiconductor parameter analyzer. The probe station was set in a vacuum chamber with gas flow control and moisture feeding equipment.[12] The threshold voltage (V_T) was determined by using the constant current method as the gate voltage which induced a drain current of L/W × 1 nA of normalized drain current (NI_D), and subthreshold swing (SS) was determined by the equation $SS = dV_{GS}/d(\log I_{DS})$ (V/dec) while the current was between 10^{-10} and 10^{-9} A. The light illumination of 10000 lux intensity in this work was obtained by a halogen lamp whose spectrum is shown in the inset of Fig. 1a.

Experimental Results and Discussion

Before to understand the effect of NBIS on a-IGZO TFTs, the illumination on devices without stress bias in different gas ambience are performed to investigate the impact of photo-induced

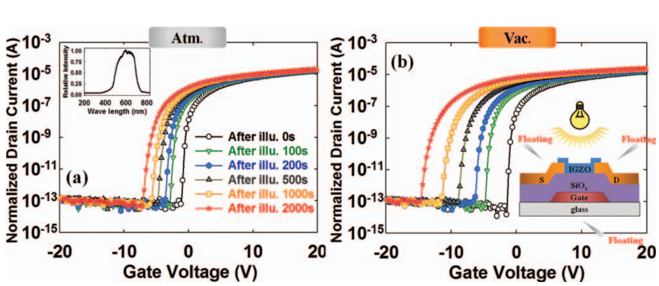

Figure 1. Transfer NI_D -V_G characteristics of a-IGZO TFTs during and after illumination for 2000s (a) in atmospheric ambient. (b) in vacuum ambient. The inset of (a) shows the illumination spectrum of the halogen lamp.

*Electrochemical Society Student Member.
[z]E-mail: tcchang@mail.phys.nsysu.edu.tw

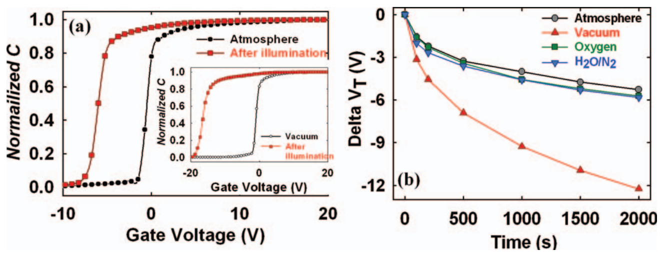

Figure 2. The C-V characteristics of a-IGZO TFTs during and after illumination for 2000s (a) in atmospheric ambient. The inset shows the result in vacuum ambient. (b) Time dependence of delta V_T during and after illumination for 2000s in atmospheric, vacuum, oxygen and moisture-simulated ambient.

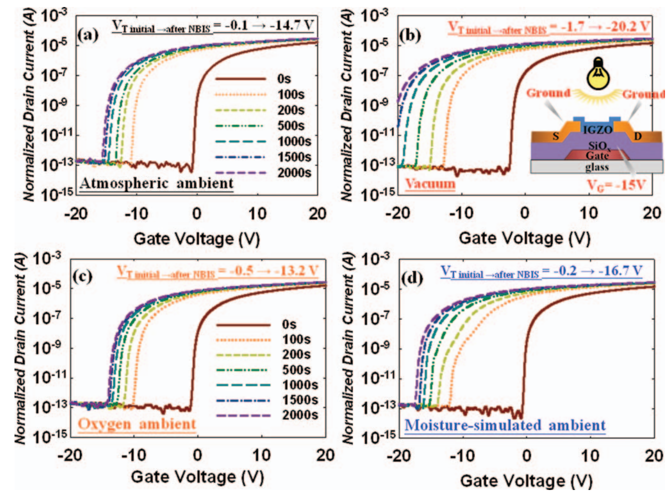

Figure 4. Transfer NI_D -V_G characteristics of a-IGZO TFTs during and after NBIS for 2000s in (a) atmospheric ambient (b) vacuum ambient (c) oxygen ambient (d) moisture-simulated ambient.

instability of a-IGZO TFTs. Figure 1a and 1b show the NI_D-V_G electrical characteristics of a-IGZO TFTs in atmospheric or vacuum ambient, respectively. By comparison, the electrical characteristics of a-IGZO TFTs shift in a more negative direction when the environment varies from atmospheric to vacuum ambient. The suppressed negative shifts of a-IGZO TFTs in atmospheric ambient with only minute variations in SS after illumination can be attributed to two mechanisms. First, the subgap photon excitation occurs from the deep-subgap density of state (DOS) to the conduction band. The photon generation of electron-hole pairs during illumination is generated from subgap photon excitation due to the large deep-subgap DOS in a-IGZO.[13] Then the photon generation of holes discharges the negatively charged adsorbed oxygen ions into the active backchannel as a form of $\mathbf{O_2{}^-{}_{(ads)} + h^+ \rightarrow O_{2\,(solid)}}$, with no change in drain off-current and SS, as shown in Figure 1.[15] The second mechanism is that the surrounding oxygen molecules from the atmospheric ambient can capture electrons from the conduction band and then cause the adsorption of oxygen ions (O^-, O^{2-}) on the active layer, resulting in a depletion layer on the backchannel and an increase in the V_T of AOS-based TFTs.[15–17] Because this second oxygen adsorption mechanism will not occur in vacuum, the negative shift of a-IGZO TFTs in vacuum after illumination is more significant than for in atmospheric ambient. This result reveals the important role of ambient gases, which affect the electrical characteristics in passivation-free devices.

In Figure 2a, the C-V measurement of a-IGZO TFTs in atmospheric or vacuum ambient after illumination of visible light are shown, respectively. That the C-V characteristics of a-IGZO TFTs show results similar to I-V characteristics means that there is no defect creation at the GI/ semiconductor interface under different gas ambient. To investigate more about the influence of gas ambient on the electrical characteristics of a-IGZO TFTs during illumination, the Figure 2b shows the progressive V_T shift of I-V after illumination in atmospheric, in oxygen, in moisture-simulated and in vacuum ambient, respectively. The shift of V_T after illumination in atmospheric and oxygen ambient exhibits the same tendency. This result can be attributed to the fact that both adsorption and desorption of oxygen may occur on the back channel of a-IGZO TFTs during illumination.

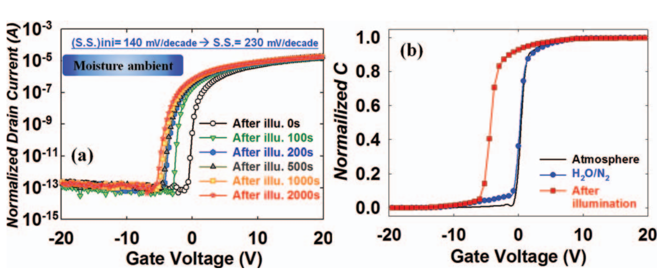

Figure 3. (a) Transfer NI_D -V_G characteristics (b) C-V characteristics of a-IGZO TFTs before illumination in atmospheric ambient, moisture-simulated ambient and after illumination for 2000s in moisture-simulated ambient.

Figure 3a and 3b show the NI_D-V_G electrical characteristics and C-V measurement of a-IGZO TFTs in moisture-simulated ambient after illumination, respectively. The I-V shows a negative shift of V_T and a less SS deterioration after illumination. The increase of SS in electrical characteristics can be attributed to the formation of defects in the a-IGZO. Meanwhile, the created states influence the C-V characteristics before flatband voltage. In literature, the created states can be associated to moisture-induced donor-type states in the a-IGZO.[10] After illumination in moisture-simulated ambient, surprisingly, the V_T of a-IGZO TFTs shows less shift than that in vacuum, as shown in Figure 2b. This implies that there is another mechanism that affects the phenomenon, which will be discussed later.

Next, we investigated the stability of a-IGZO TFTs under NBIS in different environmental gas ambient. Figure 4a–4d show the transfer NI_D-V_G characteristics of a-IGZO TFTs in atmospheric, vacuum, oxygen and moisture-simulated ambient under NBIS for the same negative gate biases of –15 V with grounded drain and source for 2000 seconds. In atmospheric, vacuum and oxygen ambient, parallel shifts in I-V characteristics with a negligible change in SS after NBIS are observed. However, the smaller negative shifts in the TFT I-V characteristics after NBIS in atmospheric or oxygen ambient indicate that the charge trapping model cannot entirely account for this result.

Figure 5 shows the progressive shift of V_T in atmospheric, vacuum, oxygen and moisture-simulated ambient under NBIS of −15 V.

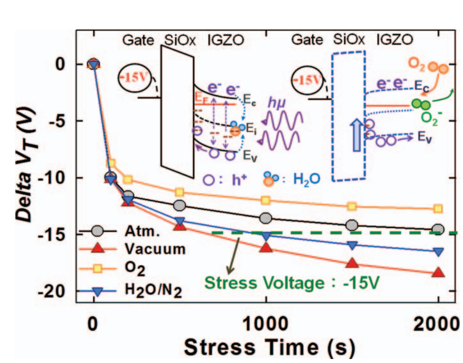

Figure 5. Time dependence of delta V_T during and after NBIS in atmospheric, vacuum, oxygen and moisture-simulated ambient. The inset shows the schematic diagram of instability mechanism under NBIS in different environmental gases and the variation of the bent energy band of a-IGZO as the negative V_T shift reaches stress gate voltage, which lead photo generated holes to drift toward the front channel or back channel of the device.

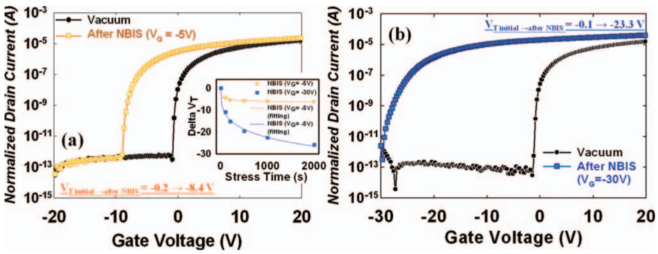

Figure 6. The evolution of I-V characteristics of a-IGZO TFTs after NBIS of (a) −5 V (b) −30 V. The inset shows time dependence of delta V_T during and after NBIS of −5 or −30 V in vacuum, which are well fit to the stretched-exponential equation.

The V_T shift seems to be closely connected to the stress gate bias. In oxygen ambient, the V_T shift after NBIS is smallest. A possible instability mechanism of a−IGZO TFTs under NBIS is depicted in the inset of Figure 5.[18] During NBIS testing, the subgap-excited holes under illumination are attracted to drift toward the channel/insulator interface and trap in the preexisting traps located at the interface or in the gate dielectric. As the negative V_T shift reaches stress gate voltage, the variation of the bent energy band of a-IGZO leads photo generated holes to drift toward the back channel of the device, so no hole trapping phenomenon occurs. Therefore, NBIS changes to become a sort of illuminated *positive* gate bias stress.[19] The V_T variation of devices in oxygen ambient displays a saturated V_T shift of devices near –15 V, which indicates that bias-induced oxygen adsorption will alternate with the hole-trapping phenomenon during NBIS.[16]

In literature, the moisture-related defect state in the a-IGZO acts as a trapping center during NBIS and enhances the hole trapping phenomenon.[12] However, for the V_T shift during NBIS in moisture-simulated ambient, the result shows less negative shift when compared to that in vacuum. Moreover, in the Figure 2b, the negative shift after illumination in moisture-simulated ambient is also suppressed when compared to the results in vacuum. One possible explanation for the findings is that the residual moisture-related defect states in the a-IGZO play the role of recombination centers. When device is under illumination only, the photo-generation of electron-hole pairs during illumination can recombine in residual moisture-related defect states, decreasing the desorption of adsorbed oxygen on the backchannel. In Figure 4d, the hump-like I-V curves can be observed in the early 1000 seconds of NBIS, which indicates that extra moisture-induced states form in the a-IGZO. Therefore, the moisture-induced defect states, i.e., recombination centers, decrease the desorption of adsorbed oxygen and hole trapping phenomenon during NBIS, which results in less negative shift than that in vacuum.

To assess the model above, the dependence of instability on gate bias of NBIS was studied in vacuum ambient. Figure 6a and 6b show the transfer NI_D-V_G characteristics of a-IGZO TFTs in vacuum ambient under NBIS for negative gate biases of −5 and −30 V, respectively. Clearly, the NI_D-V_G curve only shifts in the negative direction with negligible variations in SS and off current. Because of absent adsorption of ambient gas, these results in vacuum have been suggested to be desorption of adsorbed oxygen and photon-generated hole trapping in the preexisting traps located at the insulator/semiconductor interface, with the time dependence of $^{\Delta}V_T$ under stress following a stretched exponential equation, as follows:

$$^{\Delta}V_T = {}^{\Delta}V_{TO}\{1 - \exp[-(t/\tau)^{\beta}]\}$$

where $^{\Delta}V_{T0}$ is the $^{\Delta}V_T$ at infinite time, β is the stretched-exponential exponent, and τ is the constant characteristic trapping time.[16] The inset of Figure 6 shows the experimental data and well fitting curves for the devices under NBIS for negative gate biases of −5 and −30 V, respectively. Thus, the charge trapping mechanism is dominant for the results shown in Figure 6. In the inset of Figure 6, the shift of V_T saturates rapidly near the stress gate voltage for the NBIS with smaller gate bias. Under NBIS with larger gate bias, the delta V_T of a-IGZO TFTs shows a continuous negative shift. This demonstrates that the energy band bending of a-IGZO, which depends on gate bias, leads the different degradation behavior of device under NBIS.

In conclusion, dependence of a-IGZO TFT instability on bias and environment under NBIS operation are addressed in this work. A physical model is presented to demonstrate the transition of dominant mechanisms from photon-generated hole trapping mechanism to the adsorbed/desorbed gas phenomenon. As the influences of environmental gases being excluded, charge trapping becomes the dominant degradation mechanism during NBIS in vacuum ambient. For the oxygen ambient, an additional mechanism of the adsorption/desorption of oxygen on the back channel occurs. When the environmental moisture is present, it exhibits a less negative V_T shift than that of NBIS and illumination stress in the vacuum. This result indicates that the residual moisture-related defect states in the a-IGZO acts as a recombination centers during NBIS and decreases the hole trapping phenomenon and desorption of adsorbed oxygen. This study then contributes to a general understanding of the illuminated and gas ambient-related gate bias instability of a-IGZO TFTs.

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