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Light Response of Top Gate InGaZnO Thin Film Transistor

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The light stability of top gate indium gallium zinc oxide (IGZO) thin film transistor (TFT) has been investigated under gate bias and constant current stress to explore the possibility of active matrix display applications. While the halogen lamp irradiation onto the device under positive gate bias stress caused just −0.18 V of threshold voltage shift (ΔV_{th}), it resulted in −15.1 V shift under negative gate bias stress. When the white light extracted from the halogen lamp of 100 μW/cm^2 power illuminated the device under constant current stress, operation voltage shifted just −0.05 V for 21 h. The result shows good promise for the application of highly stable IGZO TFT to active matrix organic light emitting diodes (AMOLEDs).

1. Introduction

Dramatic improvements have been made in the oxide thin film transistor (TFT) technology after the release of reports on an amorphous InGaZnO TFT by Hosono *et al.*[1] and a polycrystalline ZnO TFT by Wager.[2] This technology has attracted an astonishing amount of attention thanks to their diverse applications in displays, memory devices, and other electronics such as ring oscillators.[3–6]

Oxide TFTs, which can be fabricated uniformly on large substrates, have both high mobility and good stability. The main interest in the area of displays has natually been focused on replacing the currently dominant TFTs technology based on amorphous silicon and low temperature polysilicon for the next generation backplanes of active matrix organic light emitting diodes (AMOLEDs),[7] thin film transistor-liquid crystal displays (TFT-LCDs),[8] flexible displays including electronic papers,[9] and transparent displays.[10] Recently, several factors affecting the bias stability of oxide TFTs have been intensively investigated and electrically stable oxide TFTs could be obtained.[11,12] Now, the remaining issue for the mass application of oxide TFTs appears to be the light stability.

There are several concerns about the light stability of oxide TFTs for the application to display backplanes. The first is the stability under ambient light. Most of ultraviolet (UV) can be filtered using the proper UV absorbing layer, but TFTs cannot be shielded completely from the visible light. The second issue is the negative bias enhanced light instability. In the case of TFT-LCD, the switching TFTs keep off-state much longer time under negative bias than on-state under positive bias with the backlight illumination. Thirdly, the threshold voltage (V_{th}) shift under constant current stress with the self emitted light is of importance for the application to AMOLED.

Here, we report the light response of highly stable transparent top gate IGZO TFT and discuss the origin of the light/bias stress instability of oxide TFT.

2. Experimental Methods

We fabricated the top gate structured IGZO TFT as shown in Fig. 1. Indium tin oxide (ITO) was deposited as a source/drain (S/D) in 150 nm thickness. After the patterning of ITO (S/D), the 25 nm thick IGZO semiconductor film was deposited by sputtering. After the 9 nm thick alumina, which plays a role of the active protection layer (PL) as well as the first gate insulator, was deposited by atomic layer deposition (ALD), the active layer and PL were patterned by wet etching, followed by annealing at 250 °C for 2 h at oxygen atmosphere. The alumina for the second gate insulator was deposited with the thickness of 176 nm at the temperature of 150 °C by ALD, followed by the S/D pad opening by the wet etching of alumina. The sputtered ITO layer with the thickness of 150 nm was annealed at 200 °C at vacuum for 2 h and patterned to be used as the gate electrode. For the light stress test at room temperature, we used a halogen lamp with the light intensity of 100 μW/cm^2. The light was irradiated onto the gate electrode side and the channel dimension for the measurement was 40 μm/20 μm. For the constant current stress at room temperature, we connected the gate electrode with the drain electrode, and kept the current between the source and the drain to be 10 μA. We monitored the voltage change between the gate and the source, and call the voltage V_{op}.

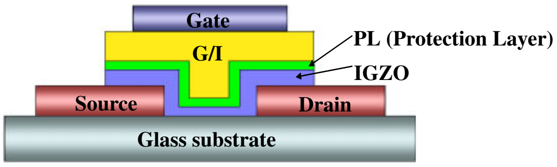

Fig. 1. (Color online) Schematic diagram of top gate IGZO TFT.

3. Results and Discussion

Although oxide semiconductor has wide band gap, it has been well known that oxide TFTs show instability even to the visible light without mentioning the UV light.[13] Most of light response of oxide TFT has been attributed to the defect creation and new carrier generation in the channel, and the positive charge trapping in the dielectric.[14–16] To investigate the origin of light effect carefully, it is very important to suppress the ambient effect on the oxide TFT and to minimize the effect of the electron trapping at the interface. For example, UV light illumination induced oxygen desorption from the surface of oxide film, which resulted in the increase of electron density on the surface[17] to cause

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the negative shift of V_{th} and the reverse reaction would occur immediately when the light is turned off. Therefore, passivation of oxide TFT would be very important to clarify light effect itself. Furthermore, Lee *et al.* suggested that environmental water generates metastable gap states, leading to the increase of hole carriers followed by the negative V_{th} shift due to the hole trap in the gate insulator.[16] Secondly, electrically unstable device may show ostensibly better performance under light stress by trapping electrons at the interface and/or in the gate insulator. With considering these factors, we tried to fabricate the IGZO TFT which is electrically and environmentally stable under the gate bias stress and the current stress. Adopting ultra-thin PL on IGZO film enables TFT to behave well by protecting the channel from a photoresist (PR) stripper which increases the carrier amount in the channel and contaminates the channel.[12] Transparent top gate IGZO TFT has no concern of passivation thanks to highly dense film of gate insulator and showed high stability under bias stress by minimizing charge trapping sites in the gate and/or interface. Top gate IGZO TFT has field effect mobility of 12.2 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ and subthreshold swing (SS) of 0.21 V per decade.

Before exploring light stability, we investigated electrical stability of our device. Figure 2 shows the gate bias stability of top gate IGZO TFT. Under the positive bias stress (gate voltage V_g) of 20 V for 10,000 s, threshold voltage shifted from 1.73 to 2.01 V without change in mobility and SS, while the ΔV_{th} under the negative bias of -20 V during the same time was almost negligible. Under the constant current stress of 10 µA for 40 h, the V_{op} change was less than $+0.09$ V.

Although the ambient light instability of oxide TFT is reported by several groups,[15,18] 100 µW/cm^2 power of halogen lamp irradiation onto our oxide TFT without gate bias did not cause the increase of off- and on-current in our measuring system. When the halogen lamp irradiation was made under the gate bias stress of 20 V for 10,000 s, a small ΔV_{th} of -0.18 V was observed, as seen in Fig. 3, with no change of mobility and SS. In our case of highly stable TFT, the electrons and positive charges newly generated by light illumination under the positive gate bias seem to recombine very quickly under high drain-source current to result in less V_{th} shift.

However, when the negative bias stress was applied under the same light illumination, the situation changed dramatically as shown in Fig. 4. The ΔV_{th} under the illumination with halogen lamp was -15.1 V with no change of SS. The huge negative shift of V_{th} under the negative bias stress with the light illumination has been reported by several groups.[14,16,19] The negative shift of V_{th} of oxide TFT can be described by the generation of new positively charged state, the hole trapping, and/or positively charged state trapping in the gate insulator.[20] Oxygen vacancy in the amorphous oxide semiconductor is known to play both as a deep donor and a shallow donor.[21] When the halogen lamp was irradiated onto TFT, several transitions can occur. First is electrons transition from valence band to conduction band to generate holes and electrons. The other possibility is electron transition from oxygen vacancy to the conduction band to generate the positive charged oxygen vacancy and electrons. Here, we exclude the transition from valence band to the

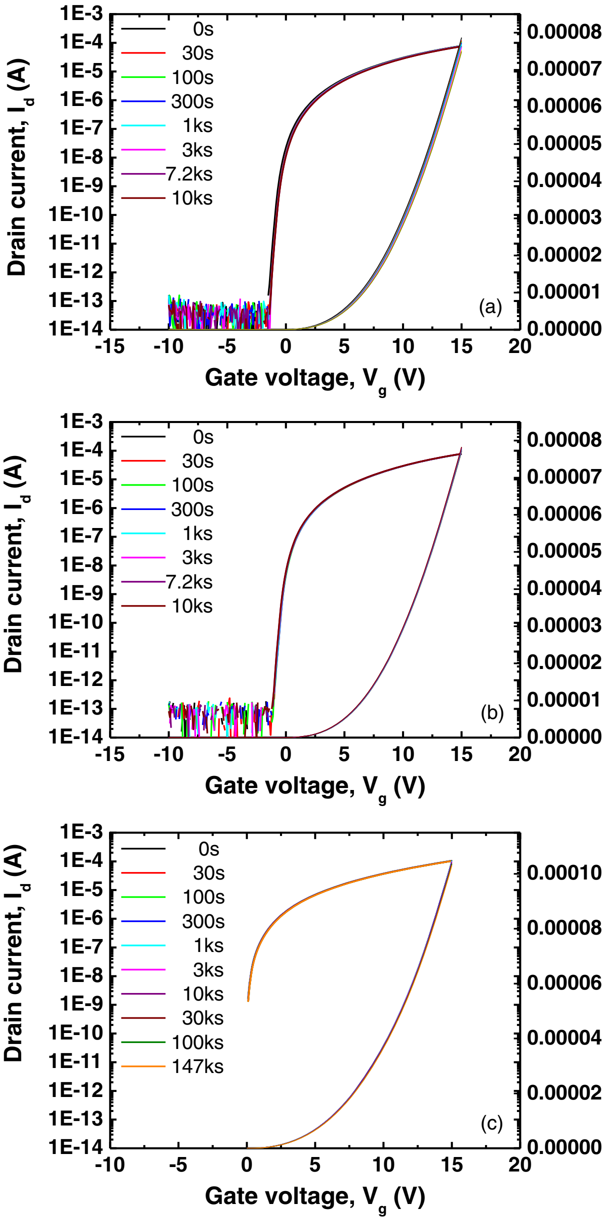

Fig. 2. (Color online) Gate bias stability data of top gate IGZO TFT under dark V_g = (a) 20 V, (b) = -20 V, (c) constant current stress of 10 µA for $W/L = 40/20$ µm.

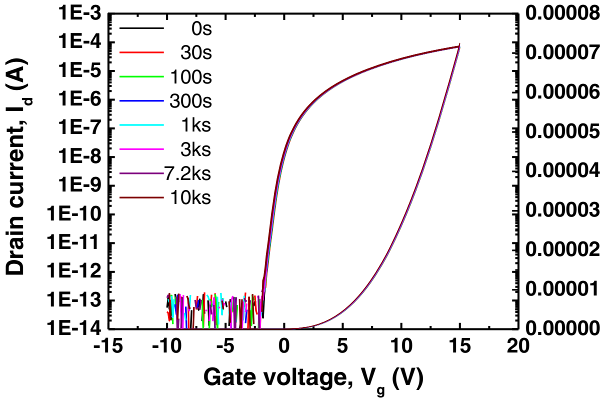

Fig. 3. (Color online) Light stability of top gate IGZO TFT under $V_g = 20$ V with halogen lamp illumination for $W/L = 40/20$ µm.

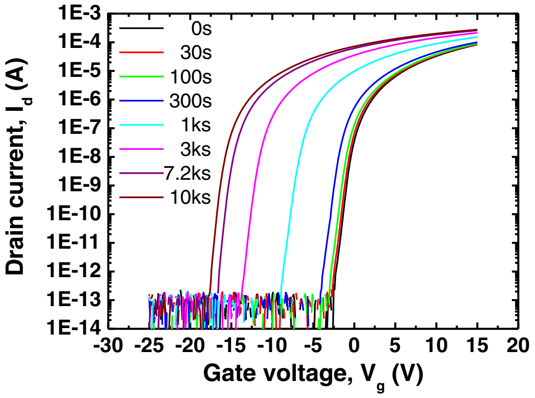

Fig. 4. (Color online) Light stability of top gate IGZO TFT under $V_g = -20\,V$ with halogen lamp illumination for $W/L = 40/20\,\mu m$.

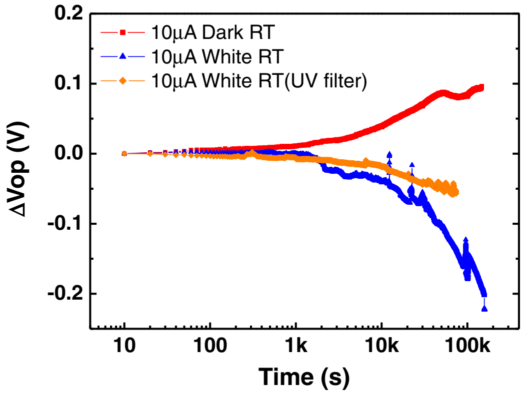

Fig. 5. (Color online) Light stability of top gate IGZO TFT under constant current stress of $10\,\mu A$ for $W/L = 40/20\,\mu m$ with visible white light illumination extracted from the halogen lamp.

state since top gate IGZO showed good electrical stability under positive and negative bias stress. We can confirm this possibility by illumination of longer wavelength light of green onto the TFT under negative bias stress to result in negative V_{th} shift. (The result is not shown here.) Contrary to the case of positive bias stress inducing lots of electrons in the channel, the application of negative gate bias instead depletes the electrons in the channel to minimize electron-hole recombination and increase holes in the valence band. These holes can be captured by oxygen vacancy and it induces the transformation of a deep donor oxygen vacancy into positive charged oxygen vacancy. It was reported that the oxygen vacancy are related to the persistent photo current of oxide film.[22,23] Increased positive charged oxygen vacancy states obtained by hole capture in the channel and trapping of these states at the interface or/and insulator can cause negative V_{th} shift. In addition, considering the light enhanced V_{th} shift dependency on the gate insulator material, we cannot exclude the possibility of direct hole trapping in the gate insulator. We are now under investigating the effect of gate insulator on the negative bias enhanced light instability.

While the constant bias stress stability with and without the light illumination has been intensively investigated, the constant current stress (CCS) stability with and without the light illumination has been rarely reported. Contrary to the TFT for TFT-LCD which needs to endure harsh negative bias under bright backlight illumination, the situation is much more forgiving for AMOLED: the light intensity to which the TFT for AMOLED is exposed is not intense and UV comes just from the outdoor daylight which can be cut off by the proper design of device structure. Therefore, major concern would be the V_{th} shift due to the self emission of AMOLED. Thus, we cut off UV to extract just visible white light and investigated the light/current stress stability. The V_{op} change of IGZO TFT stressed by the white light under CCS of $10\,\mu A$ was $-0.05\,V$ for 21 h as shown in Fig. 5. The relatively small shift of V_{op} under CCS can also be ascribed to the rapid recapture of electron by positively charged oxygen vacancy or by holes under high electron density in the channel. Although the top gate oxide TFT shows the negative shift of V_{op}, its value is small enough to ensure that highly stable IGZO TFT can be used to drive AMOLEDs successfully.

4. Conclusions

In summary, we have investigated the light response of top gate IGZO TFT. Since the light response is affected by the electrical stability, we tried to fabricate highly stable oxide TFT under dark condition to examine pure light effect under bias stress. The application of the positive gate bias stress of 20 V and the negative bias stress of $-20\,V$ to the device resulted in ΔV_{th} of 0.28 V and no change, respectively, after 10,000 s stress without the change of mobility and SS. While the halogen lamp irradiation onto the device with the positive bias stress caused just $-0.18\,V$ of ΔV_{th}, it resulted in $-15.1\,V$ shift with the negative bias stress. This huge negative bias stress enhanced light instability at room temperature might be attributed to the generation of positive charged states originated from the oxygen vacancy or/and the hole trapping in the gate insulator. For the application of oxide TFT to AMOLED, we investigated the light effect under constant current stress of $10\,\mu A$. Contrary to the light effect on TFT-LCD, the light irradiation in the AMOLED driving condition induced relatively small change of TFT characteristics. With the current stress and the illumination of white light extracted from the halogen lamp of 100 $\mu W/cm^2$, operation voltage shifted just $-0.05\,V$ for 21 h, which shows good promise of the application of highly stable IGZO TFT to AMOLED.

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