Investigation of Photo-Induced Hysteresis and Off-Current in Amorphous In–Ga–Zn Oxide Thin-Film Transistors Under UV Light Irradiation

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Abstract—We investigated the hysteresis and off-current ($I_{\text{off}}$) of amorphous In–Ga–Zn oxide thin-film transistors illuminated by 400 nm light at various intensities. Both hysteresis and $I_{\text{off}}$ are induced by the ionized oxygen vacancy ($V_{\text{o}}^{2+}$) that forms at the interface between the gate insulator and active layer. In our measurements, $I_{\text{off}}$ was much less than the estimated photocurrent. $I_{\text{off}}$ showed a rapid nonlinear increase with light intensity, while the photocurrent of a conventional crystalline semiconductor is expected to show a linear relationship. Furthermore, a numerical analysis suggested that the response time of $V_{\text{o}}^{2+}$ should be considered when analyzing the hysteresis of these devices.

Index Terms—Amorphous In–Ga–Zn oxide, hysteresis, off-current, thin-film transistors.

I. INTRODUCTION

RECENTLY, amorphous indium-gallium-zinc oxide (IGZO) thin-film transistors (TFTs) have attracted considerable attentions for the various flat panel displays such as active-matrix liquid crystal displays and active-matrix organic light emitting diode displays due to the high field-effect mobility and good uniformity [1]–[3].

IGZO TFTs exhibit rather good electrical characteristics and stability in the dark [4]; however, when illuminated by light under negative gate bias stress, the threshold voltage ($V_{\text{th}}$) is decreased considerably without subthreshold slope (SS) degradation. This occurs even when the light has photon energy smaller than the optical bandgap ($E_{\text{opt}}$) of IGZO (~3.1 eV) [4]–[6]. Two mechanisms have been proposed for the negative shift of $V_{\text{th}}$ under a combination of negative gate bias stress and light illumination: charge trapping of the photo-induced holes [5] and the creation and diffusion of ionized oxygen vacancies ($V_{\text{o}}^{2+}$) [4], [6]. $V_{\text{o}}^{2+}$ is created when oxygen vacancies ($V_{\text{o}}$) capture photo-induce holes [4] or lost two electrons through excitation by light with photon energy lower than $E_{\text{opt}}$ of IGZO [6].

In IGZO TFTs, the transfer characteristic shows hysteresis and increase of off-current ($I_{\text{off}}$) under light illumination without prolonged negative bias stress [7]–[11]. In the double sweep measurement, under illumination by light with photon energy lower than $E_{\text{opt}}$, a decrease of $V_{\text{th}}$ is found and SS increases during the forward sweep. The reverse sweep, however, shows recovery of a typical transfer curve. This hysteresis phenomenon was explained by $V_{\text{o}}^{2+}$ created through photoexcitation at the interface between the gate insulator and channel layers [7], [8]. The transfer curve is immediately recovered in the reverse sweep because $V_{\text{o}}^{2+}$ is neutralized by capture of electrons. An increase of $I_{\text{off}}$ is found, attributed to the photogenerated carriers travelling between the source/drain electrodes [10], [11], or photogenerated carriers inducing an increase of the doping level [9]. For the latter case, $V_{\text{th}}$ also decreases without a change in SS. However, without a passivation layer, IGZO channel may be affected by photodesorption of oxygen molecules [12] and subgap states [13] at IGZO back surface. Because IGZO is affected by both the light illumination and the ambient atmosphere, the mechanism of the photo-induced phenomenon cannot be clearly defined. To understand the effects of light on IGZO, a passivation layer is required to prevent the effect of ambient atmosphere and to reduce the subgap states in IGZO back surface [13].

In this paper, we investigated the effects of 400 nm light intensity on IGZO TFTs employing a SiO$_2$ passivation layer. We have observed hysteresis and increases of $I_{\text{off}}$ in the transfer curve under illumination by light with a wavelength of 400 nm without prolonged gate bias stress. The transfer curve was not altered by light with photon energy less energy than $E_{\text{opt}}$. We could find that changes in $I_{\text{off}}$ in our experimental results did not follow previously reported mechanisms.

II. FABRICATION AND EXPERIMENT

We fabricated IGZO TFTs with inverted-staggered etch stopper structures featuring a SiO$_2$ passivation layer as shown in Fig. 1. The details of the fabrication process have been reported elsewhere [14]. The channel width and length of our device were 50 and 15 μm, respectively, and the active layer thickness was 400 Å. We used monochromatic light with a band-pass filter from a Xenon lamp light source. The transfer curves were measured using double sweep which starts from the forward sweep (from $V_{\text{GS}} = -20$ V to 20 V) to the reverse sweep (from $V_{\text{GS}} = 20$ V to $-20$ V).
We measured the device under the light of various wavelengths, such as 400, 450, 550, and 650 nm. Significant hysteresis and increases of \( I_{\text{off}} \) were observed when illuminated at 400 nm (3.1 eV), while the electrical characteristics were not altered by 450, 550, and 650 nm light (1.91 – 2.76 eV). The transfer characteristics changed when the light had photon energy larger than \( E_{\text{opt}} \). From these results, it was inferred that the passivation layer successfully suppresses the photodesorption of oxygen and subgap states.

### III. RESULTS AND DISCUSSION

Fig. 2(a) shows the transfer characteristics of IGZO TFTs under various light intensities. The output characteristics under light illumination are also shown in Fig. 2(b). Under light illumination, two distinct phenomena were observed: hysteresis and an increase in \( I_{\text{off}} \). For the hysteresis, \( V_{\text{th}} \) decreased and SS increased during the forward sweep, while \( V_{\text{th}} \) and SS hardly changed in the reverse sweep. The degree of hysteresis increased at higher light intensities and \( I_{\text{off}} \) also increased. As shown in Fig. 2(c), \( I_{\text{off}} \) increased linearly with drain bias \( (V_{\text{DS}}) \) with a negative gate bias. When the light was turned off, the device recovered immediately and the transfer curves recovered their initial characteristics before the illumination. In this paper, we will discuss the hysteresis phenomenon before the increase of \( I_{\text{off}} \).

#### A. Photo-Induced Hysteresis

Under illumination, \( V_{\text{th}} \) decreased and SS increased during the forward sweep; however, these values returned to normal during the reverse sweep. During the forward sweep, the devices turned on at more negative gate bias and featured an extended sub-threshold region. Fig. 3 shows the Capacitance-Voltage (C–V) characteristics of forward and reverse sweeps conducted to investigate the interface of the devices. The C–V curves also shifted to negative voltages, extended during the forward sweep and remained unchanged from the dark measurement during the reverse sweep. These results indicate that donor-like states were created at the interface under light illumination. The presence and distribution of these donor-like states \( (D_{\text{GD}}(E)) \) alter the charge at the interface depending on the location of the Fermi level \( (E_F) \), which in turn affects the transfer curve. This can be expressed as

\[
V_{\text{GS}} = -\frac{Q_{\text{IGZO}}}{C_{\text{ox}}} + \frac{Q_{\text{it}}}{C_{\text{ox}}} + \phi_s
\]

where \( C_{\text{ox}}, \phi_s, Q_{\text{it}}, \) and \( E_C \) are the gate insulator capacitance, surface potential, interface charge, and conduction band energy level, respectively. For simplicity, the states above \( E_F \) were considered to be empty and those below \( E_F \) were filled by electrons. Fig. 4 illustrates the energy band diagrams of the device under different gate bias conditions. When a...
negative gate bias was applied, \( E_F \) is shifted such that the separation between \( E_C \) is large and the interface is positively charged. Thus, the turn on voltage shifts negatively under light illumination. When the gate bias increases, the separation between \( E_F \) and \( E_C \) becomes smaller, and the donor-like interface states are filled by the electrons so that the interface states become neutral. This process is observed as a SS change.

Donor-like states may arise from \( \text{Vo}^{2+} \) in IGZO TFTs [6], produced by \( \text{Vo} \) hole capture [4], [7], [8]. In this case, the transfer characteristics were changed when illuminated by light having photon energy greater than \( E_{\text{opt}} \) of IGZO. This suggested that the hysteresis and the increase of \( I_{\text{off}} \) were caused by photoexcited electron-hole pairs. The resulting \( \text{Vo}^{2+} \) created by photo-induced holes caused hysteresis under light illumination. Immediate recovery occurred because IGZO is n-type and has high electron concentration (\( 10^{16} - 10^{17} \) cm\(^{-3} \)) [15]. Depending on the gate bias, the carrier concentration of IGZO is changed; however, when no longer illuminated and no bias exists on the gate and source/drain electrodes, the IGZO active layer will revert to a high electron concentration (\( 10^{16} - 10^{17} \) cm\(^{-3} \)). Then, \( \text{Vo}^{2+} \) recovers to \( \text{Vo} \) with electron capture. This effect explains the temporary nature of the photo-induced hysteresis and off-currents.

During the forward sweep, we observed the effects of the donor-like interface states; however, in the reverse sweep no changes were seen in the subthreshold region even under illumination. This effect may be related to the response time \( \tau \) of the donor-like interface states. When the donor-like interface states cannot respond immediately, \( \tau > 0 \), these empty interface states (\( D_{\text{GD}}^{\text{+}} \)) remain below \( E_F \) during the forward sweep as shown in Fig. 5(b). When \( E_F \) moves toward the valence band (\( E_V \)) during the reverse sweep, electrons will continue to occupy the interface states above \( E_F \) if \( \tau > 0 \) as shown in Fig. 5(b). We investigated the effect of the response time of the donor-like interface state using numerical analysis based on the following theory.

First, we assumed that donor-like states near \( E_C \) were created at the interface with a Gaussian distribution

\[
D_{\text{GD}}(E) = N_{\text{GD}} \exp[-(E - E_{\text{GD}})^2/W_{\text{GD}}^2] \tag{3}
\]

where \( N_{\text{GD}} \) is the peak value of the Gaussian donor-like state, \( E_{\text{GD}} \) is the location below \( E_V \), and \( W_{\text{GD}} \) is the variation. \( E_C - E_F \) vs. \( V_{\text{GS}} \) were determined from an Arrhenius plot (\( \ln(I_{\text{DS}}) \) vs. \( 1/T \)) [16] allowing \( V_{\text{GS}}{\text{shift}} = Q_{\text{it}}/C_{\text{ox}} \) at each \( V_{\text{GS}} \) in the dark to be determined by (2) and (3). When donor-like interface states cannot respond immediately to a change in \( E_F \), the \( D_{\text{GD}}^{\text{+}}(E) \) will be occupied by electrons with the response time, \( \tau_f \), during the forward sweep as

\[
\frac{\partial D_{\text{GD}}^{\text{+}}(E)}{\partial t} = - \frac{D_{\text{GD}}^{\text{+}}(E)}{\tau_f} \tag{4}
\]

and the states will empty again during the reverse sweep with a response time \( \tau_r \) given by

\[
\frac{\partial D_{\text{GD}}^{\text{+}}(E)}{\partial t} = - \frac{D_{\text{GD}}(E) - D_{\text{GD}}^{\text{+}}(E)}{\tau_r} \tag{5}
\]
B. Photo-Induced Off-Current

Considering the hysteresis and \(I_{\text{off}}\) phenomena in Fig. 1(a), \(I_{\text{off}}\) increased linearly with \(V_{\text{GS}}\) as shown in Fig. 2 (c), which suggested that this is attributed to drift current. Furthermore, \(I_{\text{off}}\) increased with light intensity as shown in Fig. 7, where \(I_{\text{off}}\) was measured with \(V_{\text{GS}} = -10\) V and \(V_{\text{DS}} = 10\) V during the reverse sweep. It is well known that \(I_{\text{off}}\) increases under light illumination because of photogenerated charge carriers that are collected by the source/drain electrodes [10], [11]. In IGZO, the photoexcitation increases both the doping level of IGZO and \(I_{\text{off}}\). The increase of \(I_{\text{off}}\) is explained by the photogenerated carriers, \(I_{\text{off}}\), which can be expressed as a drift current

\[
I_{\text{off}} = A q \mu_n \tau_n G V_{\text{DS}}/L \tag{6}
\]

where \(A\) is a cross-sectional area of current flow, \(\tau_n\) is the life time of charge carrier, and \(G\) is the carrier generation rate from the incident light. In a crystalline semiconductor, the photo-current increases linearly with light intensity. As the intensity of light is increased, the photo-induced carrier density also increases, while other factors \(\mu_n\) and \(\tau_n\) remain constant. With a carrier lifetime of \(\sim 10^{-9}\) s [18] and absorption coefficient at 400 nm of \(\sim 1 \times 10^4\) cm\(^{-1}\) [17], the photo-induced carrier density was estimated to be \(10^{12}\) to \(10^{13}\) cm\(^{-3}\). The \(I_{\text{off}}\) was estimated at \(\sim 10^{-9}\) A at 0.84 mW/cm\(^2\), which is much higher than the experimental result, \(\sim 10^{-11}\) A. When both photo-induced holes and electrons are collected by the source/drain electrodes, \(I_{\text{off}}\) is increased. However, IGZO has a wide band gap (\(\approx 3.1\) eV) and a deep bulk state near \(E_V\) [19] and the energy barrier between the source electrode and \(E_V\) of IGZO is large for the photo-induced holes even under at high negative gate bias. Therefore, \(I_{\text{off}}\) is not significantly increased by the photo-induced carriers in IGZO TFTs. In a conventional amorphous semiconductor, the photocurrent cannot increase linearly with light intensity because of the formation of localized states [10], [20]. The localized states behave as recombination centers for the photogenerated carriers, decreasing their lifetime. As light intensity is increased, the carrier generation rate increases linearly; however, the lifetime decreases at the same time. The change in \(I_{\text{off}}\) should therefore be expected to decrease with increasing light intensity. However, our experimental results showed that the change in \(I_{\text{off}}\) increased with increasing light intensity. This result also supports our suggestion that the measured \(I_{\text{off}}\) from our experimental results was not caused by photogenerated carriers. We can also exclude a change in doping level because the photo-induced carrier density was much lower than the IGZO doping level (\(\gg 10^{17}\) cm\(^{-3}\)) and \(V_{ih}\) was barely changed during the reverse sweep.

An increase of \(I_{\text{off}}\) is also observed when the electrons in the IGZO are not completely depleted in the off-region. When a large number of states exist at the interface or bulk, the energy band of IGZO is unchanged because \(E_F\) hardly shifts toward \(E_V\) even under high negative \(V_{\text{GS}}\). Under illumination, \(V_{02}^{2+}\) was created and caused the hysteresis in IGZO TFTs. Depletion of electrons in the IGZO is also prevented by the large amount of interface states \(V_{02}^{2+}\) even...
at high negative $V_{GS}$. $V_{o2}^{2+}$ causes not only the hysteresis, but also the increase of $I_{off}$ under light illumination. To explore the effect of $V_{o2}^{2+}$ on the increase of $I_{off}$, simulations were performed using ATLAS (SILVACO). Parameters for the IGZO transistor models were based on previous reports [9].

An electron affinity of 4.3 eV, doping concentration of $5 \times 10^{16}$ cm$^{-3}$, and band gap of 3.1 eV were used. The acceptor-like tail states at $E_C$ were $3.5 \times 10^{16}$ cm$^{-3}$, the decay energy for the tail distribution was 0.15 eV, and the peak value and variation of acceptor-like Gaussian states were $1.6 \times 10^{16}$ cm$^{-3}$/eV and 0.21 eV, respectively. The peak for acceptor-like Gaussian state was located 1.34 eV below $E_C$. In the donor-like Gaussian states, the peak value and variation were $1 \times 10^{21}$ cm$^{-3}$/eV and 0.3 eV, respectively. The energy location of the peak for donor-like Gaussian states was 0.7 eV above $E_V$. To express the effect of $V_{o2}^{2+}$, donor-like Gaussian states were added at the interface between the active layer and the insulator layer. The total density of donor-like Gaussian interface states was $\sim 10^{13}$ cm$^{-2}$ and the Gaussian distribution peak was located at 2.42 eV above $E_V$ of IGZO. The donor-like interface state density was assumed to increase linearly with the incident photon flux. $I_{off}$ values were calculated at $V_{GS} = -10$ V with various densities of interface states. The results of these simulations are shown in Fig. 7 and $I_{off}$ values followed the same trend as the experimental results. $I_{off}$ increased under illumination because of $E_F$ pinning caused by $V_{o2}^{2+}$ at the interface. For the SiO$_2$, the Gaussian distribution peak was located near the middle of the SiO$_2$ energy gap ($\sim$ eV). There are various types of $V_o$ states in SiO$_2$ [21], and Vo near the $E_V$ of SiO$_2$ may be related to the $V_{th}$ shift under illumination by UV light and negative gate bias stress [4]. However, the changes under illumination by UV light without prolonged gate bias were more likely related to mid gap Vo of SiO$_2$.

IV. CONCLUSION

We investigated photo-induced hysteresis and $I_{off}$ of IGZO TFT under various light intensities. $V_{o2}^{2+}$ was created at the interface through capture of photo-induced holes by Vo. Under a negative gate bias, Vo was recovered from $V_{o2}^{2+}$ by electron capture. The decrease in $V_{th}$ and increases in SS were explained by $V_{o2}^{2+}$ formation at the interface. However, the significant hysteresis could not be explained without considering the response time of $V_{o2}^{2+}$. Because the creation and recovery of $V_{o2}^{2+}$ cannot occur immediately during $V_{GS}$ potential sweep, hysteresis was observed under UV light. When $I_{off}$ was considered as the drift current of the photogenerated carriers, the $I_{off}$ of the experimental results was much lower than the calculated values. Furthermore, $I_{off}$ showed a rapid non-linear increase with light intensity, whereas the photo-current should be expected to increase linearly with light intensity in crystalline semiconductors. In this case, the increase in $I_{off}$ was attributed to formation of $V_{o2}^{2+}$ at the interface. Additionally, midgap Vo of SiO$_2$ could explain the behavior under UV light without prolonged bias.

REFERENCES


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