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The Time Response of the On-Current for the Amorphous In-Ga-Zn-O Thin Film Transistor to the Illumination Pulse

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In this study, the time response behavior of the amorphous indium gallium zinc oxide (a-IGZO) thin film transistors (TFTs) to the illumination pulse is analyzed. The mechanism is proposed to correlate the oxygen vacancy reacting with the light-induced electron-hole pairs. The temperature effect on the time response to the illumination pulse is also studied. The higher excitation level, either from light or temperature, results in the similar excited and recovering behaviors. The formulas for the time response are proposed to be possibly used in the simulation for the circuit performance in real situation of illumination, which is important in the development of transparent electronics using a-IGZO TFT.

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Nowadays, amorphous-silicon (a-Si) thin film transistor (TFTs) have been used widely in flat-panel displays (FPD) in production, with the growing need for large area displays for home entertainment and the full adoption of digital broadcasting. Even with the success, there are still some drawbacks for the TFTs. For example, the low mobility leads to low open area in a pixel because of designing the large size to achieve the high current. For the state-of-art process rule with definite gate length, adopting TFTs with higher mobility is one possible solution to achieve high aperture ratio in a small pixel area without sacrificing the display performance. Therefore, new TFTs with high mobility are needed to replace a-Si TFTs. Among those newly proposed TFTs with high mobility, poly-crystalline silicon (poly-Si) TFTs and amorphous indium-gallium-zinc-oxide (a-IGZO) TFTs attract the most attention.

Although poly-Si TFT has μ_{eff} close to 100 cm^2/V s, it requires additional re-crystallization steps such as excimer-laser annealing, metal seeding or solid phase crystallization. These add more complexity and costs to the process. The substrate size used by poly-Si TFT technology is about 4 generations behind what a-Si TFTs can achieve today, while a-IGZO device encounters no special issue when it comes to the glass size. A-IGZO TFTs have many advantages like low temperature process (below 300°C) and high on/off ratio ($\sim 10^6$).[1] In addition, it is highly transparent in visible light with transmittance over 90% as illustrated due to wide bandgap (~3 eV).

These properties open up to new applications such as transparent electronics, flexible electronics, and photo sensor.[2,3] Even though a-IGZO TFTs exhibit good electrical characteristics and stability in the dark state, the significant electrical instability is observed when they are illuminated. Many article reported threshold voltage (V_{TH}) shift and mobility change after illumination at different light intensities, and those changes can recover in time.[4,5] In the applications of transparent electronics and photo sensor, the a-IGZO TFTs are expected to operate in the transmission of ambient light with frequently varying intensity. In addition, most of the reports studied the change in the devices under for long-time illumination,[6–8] but the response to the illumination in short time may also induce the false operation in transparent electronics and should be carefully studied. Therefore, the time response of a-IGZO TFTs to the ambience and the induced instability needs to be investigated. In this paper, we analyze the response of the a-IGZO TFTs to the light changing in time, propose the descriptive model, and explain the mechanism.

Experimental

The a-IGZO TFTs in this work are based on the bottom-gate TFT devices with symmetrical source/drain (S/D) fabricated on the glass substrate. The shaped Ti/Al/Ti (50/200/50 nm) gate electrodes were capped with 400-nm-thick SiNx gate dielectric, which was deposited by plasma enhanced chemical vapor deposition (PECVD) at 370°C. The active layer of 60-nm-thick a-IGZO film was deposited by DC magnetron sputtering system using a target of In:Ga:Zn = 1:1:1 in atomic ratio with the O_2/Ar ratio about 6%. For the S/D metals, Ti/Al/Ti of 50/200/50 nm in thickness was prepared by DC sputtering at room temperature. Then, the devices are capped with passivation at 280°C as protection layer to avoid the disturbance of outside surrounding. We used the very same TFT sample with width of 20 μm and length of 5 μm for each light-stress condition to avoid the difference from device to device.

The TFT was biased at the fixed gate voltage (V_G) of 10 V and drain voltage (V_D) of 10 V during the illumination. After the experiment of illumination, the TFT was put in dark environment for at least 1 hr for the better recovery to the relatively stable performance. The illumination is done by white light of LED in the intensities of light of 7616 lux, 12648 lux, and 17272 lux. Furthermore, the measurements are conducted at different temperatures of 318 K, 333 K and 348 K with fixed illumination. The electrical properties of transistor were measured in sweeping voltage or sampling mode by Keithley 4200 semiconductor parametric analyzer.

Response to the Pulse Illumination

Monitoring threshold voltage shift.— Before the study of time response, we need to verify that the change in the drain current (ΔI_D) can reflect the change in the threshold voltage (ΔV_{TH}), which is previously reported.[9] Fig. 1 shows the I_D-V_G curves under steady light illuminations. The inset of Fig. 1 shows the parallel shift of curves in the on region. This parallel shift fairly indicates that the slope of the I_D-V_G curve does not change by the illumination. We can correlate ΔV_{TH} and ΔI_D by the transformation equation:

$$\Delta V_{TH} = \Delta I_D/(dI_D/dV_G) \quad [1]$$

where the slope dI_D/dV_G of the I_D-V_G curves keeps constant during the experiment of response time. Accordingly, by monitoring the change of I_D before, during and after the illumination pulse, the time response of ΔV_{TH} can be calculated by Eq. 1.

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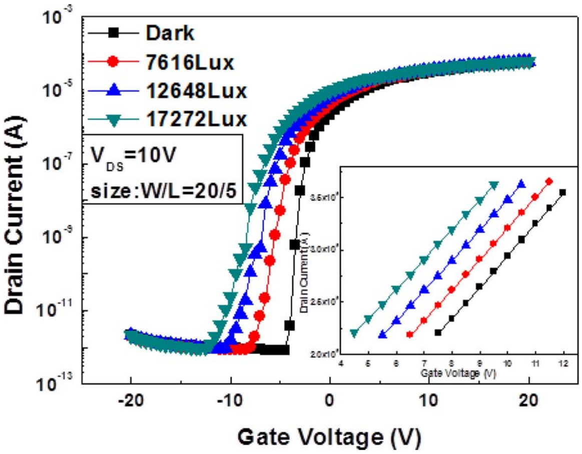


Figure 1. Drain current versus gate voltage under illumination of different light intensities.

Positive bias stress induced instability.— Fig. 2a shows the time responses of ΔI_D shined with the light pulse at different intensities and duration, where ΔI_D is the difference between the sampled I_D (t) and its initial value I_D $(t = 0$ s). It was initially dark and then the light was turned on for about 20 seconds and then turned off to be dark again.

It is firstly noticed that the ΔI_D decays even before the illumination. Many articles reported the slow decrease of the drain current in the dark,[10,11] which is attributed to the mechanism of positive bias stress (PBS) induced instability. It is further observed that the behavior of decay is like exponential decay with time. Therefore, as a first order approximation, we propose an equation to formulate the PBS instability, and the PBS instability can be expressed by

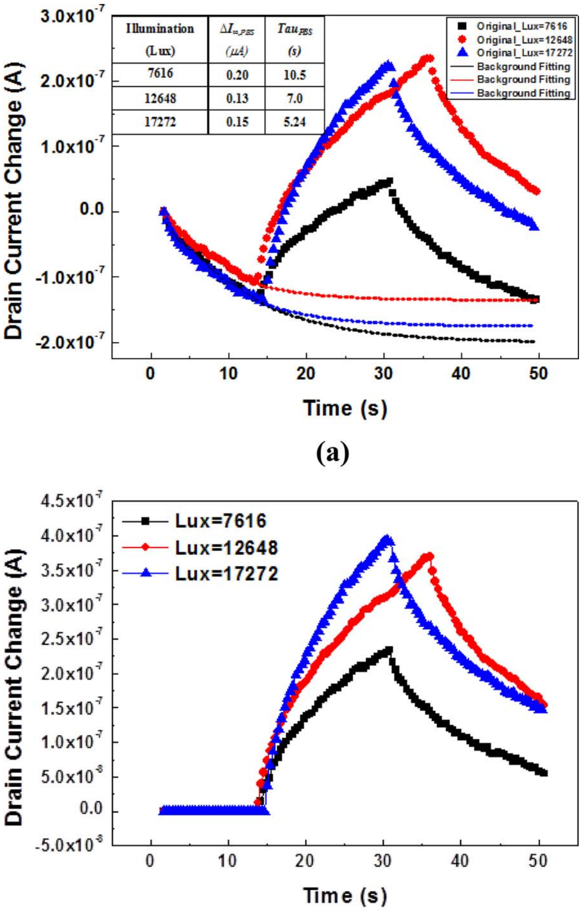
$$\Delta I_{D,PBS}(t) = \Delta I_{\infty,PBS} - [\Delta I_{\infty,PBS} - \Delta I_{0,PBS}]e^{-t/Tau_{PBS}}, \qquad [2]$$

where $\Delta I_{0,\ PBS}$ and $\Delta I_{\infty,\ PBS}$ are the initial and the expected saturation value of the current change owing to PBS, respectively, and Tau_{PBS} is the fitting parameter for the time constant.[12,13] In this study, we assume that this effect of PBS instability follows Eq. 2 even under the illumination. Thus, we fit the data in the region before illumination to Eq. 2 and extrapolate the curves to the light responded region, as shown by in the dotted curves in Fig. 2a. The fitting parameters of these background PBS curves are listed in inset table in Fig. 2a. In such a way, we take the extrapolated components of ΔI_D as the PBS background and we simply deduct them from to total response in this study.

After deducting the fitted extrapolation part of the PBS components, the curves after deduction are redrawn in Fig. 2b. The trend for the excited response of ΔI_D is induced by light, and that for the recovering behavior corresponds to the period after the light is shut off. According to the previous report,[14] the excitation and recovery behaviors are well described with a unified stretched exponential function based on the photo-induced charge trapping model, which supports the mechanism of photo induced carrier trapping.

Excited behavior.—In Fig. 3, we replot the rising parts in Fig. 2b, which correspond to the current increase ΔI_D excited by the illumination. The excited response of ΔI_D can be fitted by

$$\Delta I_{D,Excited} = \Delta I_{\infty,Excited}[1 - e^{-t/Tau_{Excite}}], \qquad [3]$$

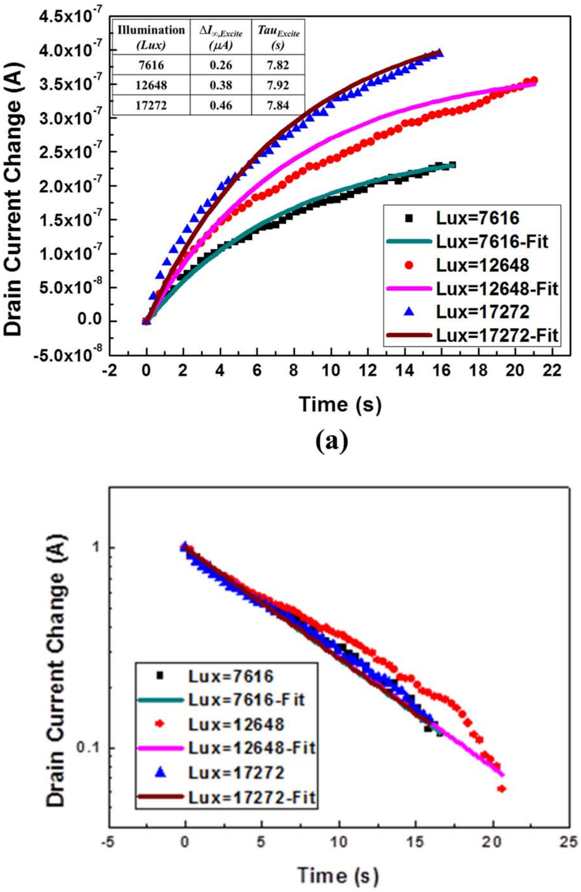


Illumination (Lux)	$\Delta I_{\infty,PBS}$ (μA)	Tau_{PBS} (s)
7616	0.20	10.5
12648	0.13	7.0
17272	0.15	5.24

(a)

(b)

Figure 2. Time responses of ΔI_D to the light pulse at different intensities (a) before and (b) after deducting the PBS components.



Illumination (Lux)	$\Delta I_{\infty,Excite}$ (μA)	Tau_{Excite} (s)
7616	0.26	7.82
12648	0.38	7.92
17272	0.46	7.84

(a)

(b)

Figure 3. (a) ΔI_D and (b) $\log(1 - \Delta I_D/\Delta I_{\infty,\ Excite})$ versus time for the excited response in the illumination period at different light intensities.

where $\Delta I_{\infty,\,Excite}$ is the expected saturation value of $\Delta I_{D,\,Excite}$, Tau_{Excite} is the fitting parameter, and their values are subject to change with the illumination intensity. The inset table in Fig. 3 lists the parameters of fitting formula for the different illumination.

The mechanism of excited behavior is correlated to the electrons generated in the conduction band via the ionization of neutral oxygen vacancy,[15,16] which is expressed by

$$V_O \rightarrow {V_O}^{2+} + 2e^-, \qquad [4]$$

where V_O and ${V_O}^{2+}$ are the numbers of neutral and ionized oxygen vacancy, respectively. The continuous illumination at fixed light intensity keeps the process of ionizing the neutral oxygen vacancy. Here we assume ${V_O}^{2+}$ is generated at a constant rate R_{Gen}.

On the other hand, in the reverse reaction, the created ionized oxygen vacancy ${V_O}^{2+}$ can recapture the electrons and diminish. From the view point of chemical reaction, the rate of the reverse reaction should be proportional to the number of ${V_O}^{2+}$ and it can be written as

$$R_{{V_O}^{2+} \rightarrow V_O} = {V_O}^{2+}/\tau, \qquad [5]$$

where τ reflects the reaction rate. Therefore, the net increase rate R_{Net} of ${V_O}^{2+}$ can be expressed as:

$$R_{Net} = d({V_O}^{2+})/dt = R_{Gen} - R_{{V_O}^{2+} \rightarrow V_O} = R_{Gen} - ({V_O}^{2+}/\tau). \qquad [6]$$

We further assume that ${V_O}^{2+}$ is negligible before the illumination, i.e., ${V_O}^{2+}$ $(t = 0) = 0$. According to the previous report,[17] ${V_O}^{2+}$ is proportional to the released trap charge, which leads to the decrease of ΔV_{TH} and the increase of ΔI_D according to Eq. 1, as shown in Eq. 7:

$${V_O}^{2+} \propto C_{OX}(\Delta V_{TH}/q) \propto \Delta I_D, \qquad [7]$$

where C_{OX} is the gate insulator capacitance and q is elementary electron charge. Since ${V_O}^{2+}$ and ΔI_D are in proportion as shown in Eq. 7, we can rewrite the differential Eq. 6 into:

$$\frac{d[\Delta I_D(t)]}{dt} = C - \frac{\Delta I_D(t)}{Tau_{Excite}}, \qquad [8]$$

where constant C and Tau_{Excite} are in the same proportion to R_{Gen} and τ in Eq. 5 accordingly. The solution of Eq. 7 is consistent with Eq. 3, which is the fitting formula we used, if only

$$\Delta I_D(\infty) = C\,Tau_{Excite}. \qquad [9]$$

This consistency suggests that the mechanism of the excited behavior of drain current is strongly related to the ionization of neutral oxygen vacancy induced by the illumination. Therefore, we propose that ΔI_D increase shown in Fig. 3 can reflect the ${V_O}^{2+}$ increase.

Moreover, we discuss the parameters for fitting formula of excited behavior with respect to the light intensity. Since the initial value of $\Delta I_{0,\,Excite}$ is set to 0 A, only Tau_{Excite} and $\Delta I_{D,\,Excite}$ need to be discussed. Firstly, as shows in Fig. 4, it is observed that the Tau_{Excite} is almost independent of the light intensity. As mentioned in Eq. 5, the recapture rate $R_{{V_O}^{2+} \rightarrow V_O}$ represents the reverse reaction rate that ${V_O}^{2+}$ recaptures the electrons back to become V_O again. This is consistent with the result that the recapture of the electrons is not affected by the light illumination.

As for $\Delta I_{\infty,\,Excite}$, it can be seen in Fig. 4 that $\Delta I_{\infty,\,Excite}$ is roughly in proportion to the light intensity. Since Tau_{Excite} is constant to the light intensity, according to Eq. 9, $\Delta I_{\infty,\,Excite}$ is linear to C, which is in ratio to the generation rate R_{Gen}. The higher light intensity means more electrons in V_O can be released by the more incident photons. Therefore, the linear light dependence of R_{Gen} is reflected in $\Delta I_{\infty,\,Excite}$, too.

Fitting Formula for Recovering Behavior.— In Fig. 5, we enlarge the falling parts in Fig. 2b, which correspond to the recovering behavior after the light is shut off. For the recovering behavior, since the light is shut off, only the reverse reaction in Eq. 3 retains. It implies the exponential decay of ${V_O}^{2+}$ is in the trend of

$${V_O}^{2+}(t) = {V_O}^{2+}(t = \infty) - \left[{V_O}^{2+}(t = \infty) - {V_O}^{2+}(t = 0)\right]e^{-t/\tau'}, \qquad [10]$$

where τ′ reflects the rate of reverse reaction. The curves in Fig. 6 can be fitted in the form of

$$\Delta I_{D,Rec}(t) = \Delta I_{\infty,Rec} - [\Delta I_{\infty,Rec} - \Delta I_{0,Rec}]e^{-t/Tau_{Rec}} \qquad [11]$$

where $\Delta I_{0,\,Rec}$ and $\Delta I_{\infty,\,Rec}$ is the initial and expected saturation value of $\Delta I_{D,\,Rec}$, respectively, and Tau_{Rec} is the fitting parameter. The inset table in Fig. 5 lists the parameters of fitting formula for the different illumination.

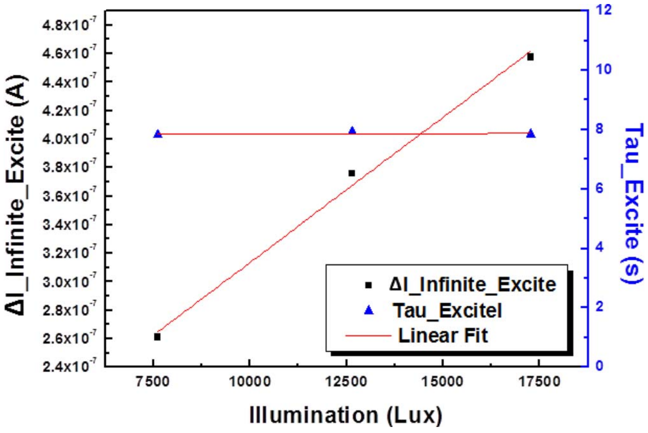
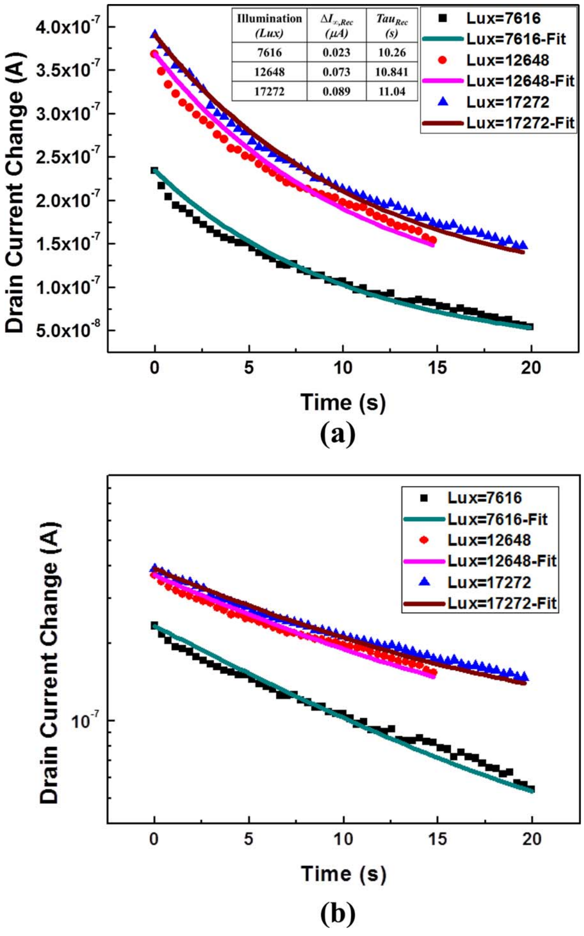


Figure 4. The parameter Tau_{Excite} and $\Delta I_{\infty,\,Excite}$ versus light intensity.



Illumination (Lux)	$\Delta I_{\infty,Rec}$ (μA)	Tau_{Rec} (s)
7616	0.023	10.26
12648	0.073	10.841
17272	0.089	11.04

Figure 5. ΔI_D versus time for the recovering behavior after the light of different intensity is shut off with y-axis in (a) linear and (b) logarithmic scale.

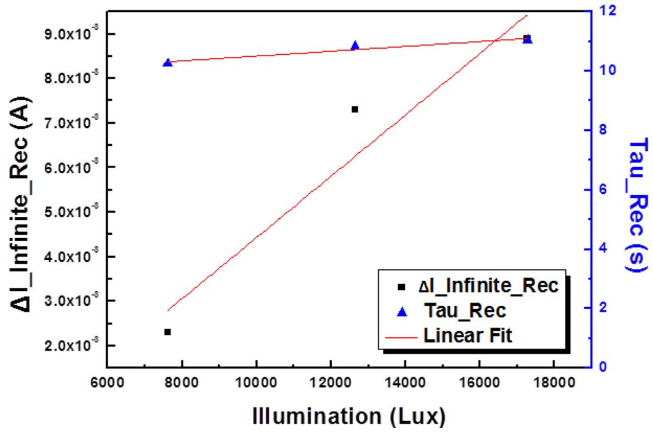


Figure 6. The Tau_{Rec} and $\Delta I_{\infty,\ Rec}$ versus light intensity.

The consistency of the form for ΔI_D and $V_O{}^{2+}$ in Eqs. 8 and 9 as well as that in Eqs. 2 and 6 suggest that the mechanism of both the excited and recovering behaviors of drain current is strongly related to oxygen vacancy. More specifically, it is related to the ionization of neutral oxygen vacancy V_O induced by the illumination and the recapture of the electrons by the ionized oxygen vacancy $V_O{}^{2+}$.

In the analysis of recovering behavior, we do not need to discuss parameter for fitting formula with the light intensity, because the light is turned off during this time. Considering only the reverse reaction of Eq. 4, we instead discuss the recovering parameters with respect to the initial value of $\Delta I_{0,\ Rec}$.

Fig. 6 plots Tau_{Rec} and $\Delta I_{\infty,\ Rec}$ versus the light intensity. It can be seen that Tau_{Rec} is nearly a constant for different cases, like Tau_{Excite} is. This also exhibits the independence of the electron reception on the light illumination. In Fig. 6, it is also observed that $\Delta I_{\infty,\ Rec}$ increases with the light intensity. The non-zero value of $\Delta I_{\infty,\ Rec}$ depicts that not all but only a portion of $V_O{}^{2+}$ can recapture the electrons. Some ionized oxygen vacancies change in states after the illumination, which can be long term compared to the measurement period. It is suspected that those vacancies become slow trapping states during the illumination, and thus the $\Delta I_{\infty,\ Rec}$ gets higher.

Temperature effect.— The experiment of light pulse response is conducted at different temperatures. In other words, the device is firstly raised to the higher temperature. At the raised temperature, the pulse illumination with a light intensity of 17272 lux is shined on the device. In the meantime, the drain current is measured in sampling mode with fixed gate and drain voltages. Fig. 7a shows the drain current change and the fitted PBS background under different temperatures at 318 K, 333 K, and 348 K, while the intensity of light is fixed at 17272 lux. At different temperatures, the slope dI_D/dV_G of the $I_D - V_G$ curves is no more constant. Thus, we also convert ΔI_D to ΔV_{TH} using Eq. 1 and plot them together in Fig. 7a and Fig. 7b.

At the first look, the trend of ΔV_{TH} corresponding to the illumination pulse at raised temperature acts like the way ΔI_D does to the higher light intensity. We can use the same formula to fit the behavior of time response at different temperatures. By the same procedures of fitting and deduction for the PBS background, we extract the fitting parameters and plot them in Figs. 8 and 9.

For the excited behavior, the dependences of Tau_{Rec}, $\Delta I_{D\infty,\ Excite}$, and $\Delta V_{TH\ \infty,\ Excite}$ on the temperature are plotted in Fig. 8. It is observed that the $\Delta V_{TH\ \infty,\ Excite}$ increases with temperature, which can reflect the increase in $V_O{}^{2+}$. Many papers reported that the instability mechanism in a-IGZO TFTs under PBITS conditions can be explained by the models of charge injection and defect creation. The temperature causes the $V_O{}^{2+}$ increase in the IGZO.[18,19] The more $V_O{}^{2+}$ created by temperature and light result in the increase of $\Delta V_{TH\ \infty,\ Excite}$. On the other hand, Tau_{Excite} is almost independent of the temperature, which is just like the case of illumination.

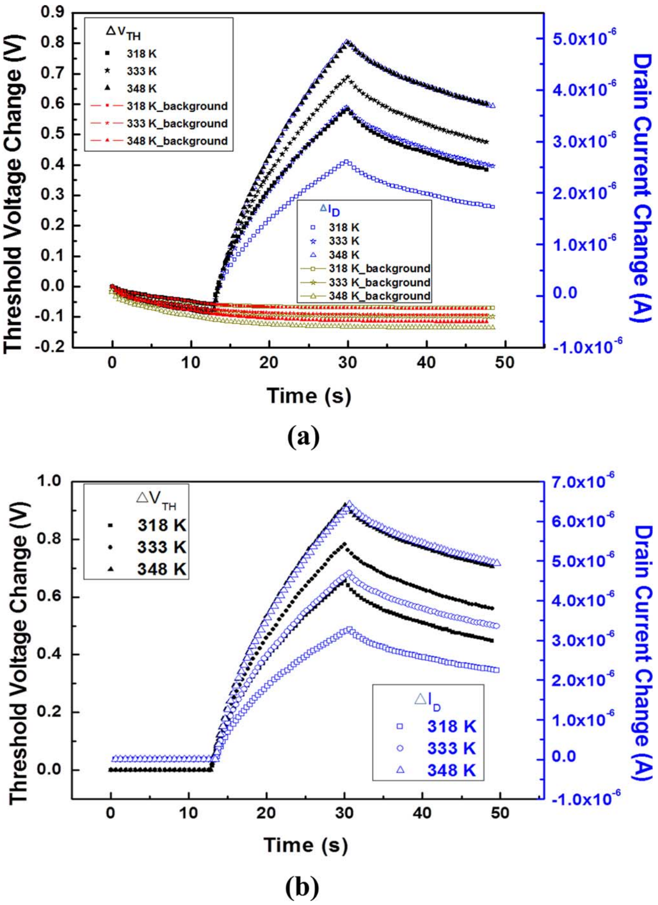


Figure 7. Time responses of the changes in drain current and threshold voltage to the light pulse at different temperatures (a) before and (b) after deducting the PBS components.

As for the recovering behavior, Fig. 9 shows that the Tau_{Rec}, $\Delta I_{D\ \infty,\ Rec}$, and $\Delta V_{TH\ \ \infty,\ Rec}$ versus temperature. It can be seen that Tau_{Rec} does not change much by the temperature. It is also noticed that $\Delta V_{TH\ \infty,\ Rec}$ increases with the temperature. The behaviors of the both parameters at higher temperature exhibit similar responses to those with higher illumination intensity.

In summary, the excitations from temperature have the similar effects on the change in the drain current or threshold voltage to the illumination with higher intensity. After removing the excitation, the trend of restoring to its initial state is alike, too. The role of oxygen

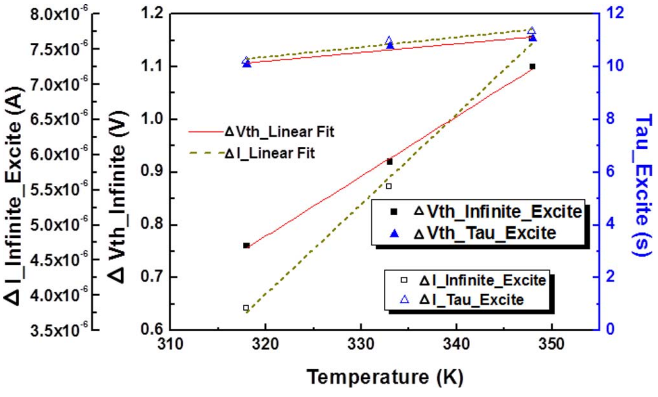


Figure 8. The parameters $\Delta I_{D\ \infty,\ Excite}$, $\Delta V_{TH\ \infty,\ Excite}$, and Tau_{Excite} as a function of temperature.

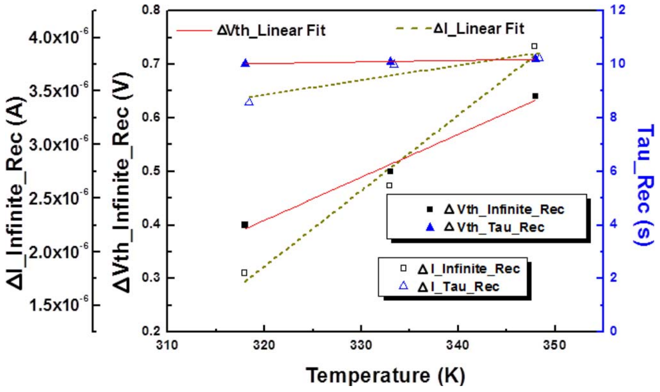


Figure 9. The parameters $\Delta I_{D\,\infty,\,Rec}$, $\Delta V_{TH\,\infty,\,Rec}$, and Tau_{Rec} as a function of temperature.

vacancy is believed to be important in the behavior of the time response to the light pulse.

Conclusions

In this paper, the time response of a-IGZO TFTs to the illumination pulse and the temperature effect are studied. We characterize the time response by sampling the drain current change, which reflects the voltage shift. By deducting the component of PBS instability, we develop two fitting formulas to depict the behavior of rise and fall of the drain current change in time upon the illumination pulse, respectively. The mechanisms are strongly related to the ionization of neutral oxygen vacancy and the recapture of the electrons by the ionized oxygen vacancy. The developed formulas can be helpful to describe the drain current change in time responded to the more complex illumination or temperature conditions.

Acknowledgments

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