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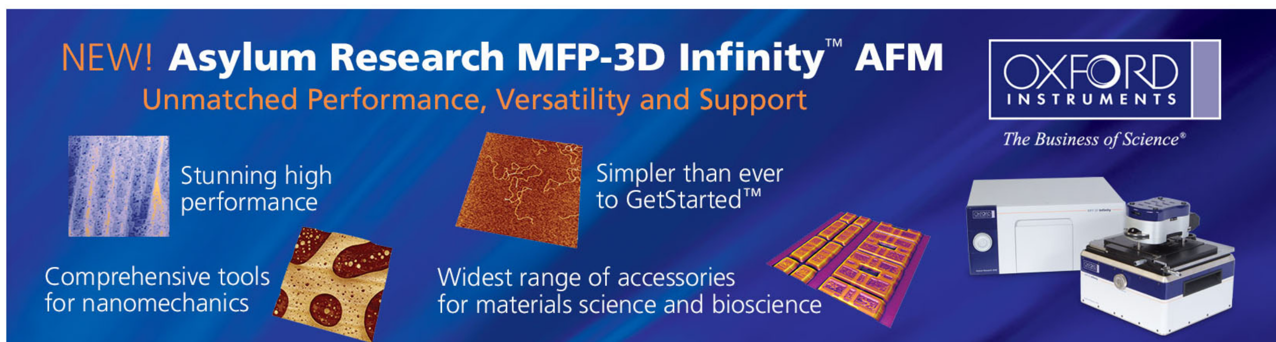


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# Charge pumping method for photosensor application by using amorphous indium-zinc oxide thin film transistors

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The study investigated the photoreaction behavior of amorphous indium-zinc oxide thin film transistor ($a$-IZO TFT), which was thought to be insensitive to visible light. The obvious threshold voltage shift was observed after light illumination, and it exhibited slow recovery while returning to initial status. The photoreaction mechanism is well explained by the dynamic equilibrium of charge exchange reaction between $O_{2(g)}$ and $O_2^-$ in $a$-IZO layer. A charge pumping technique is used to confirm the mechanism and accelerate recoverability. Using knowledge of photoreaction behavior, an operation scheme of photosensing elements consist of $a$-IZO TFT is also demonstrated in this work. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3155507]

Transparent-conducting-oxide (TCO) thin film transistors (TFTs) have attracted great attention because of transparence and high carrier-mobility characteristics.[1,2] However, the commonly used TCO, such as zinc oxide (ZnO), is usually polycrystalline in nature and is dependent on the quantity of defects in itself.[3,4] Therefore, a sputtered amorphous $In_2O_3$ doped zinc ($a$-IZO) capable of forming a uniform amorphous phase has been investigated extensively in recent years. $a$-IZO film with an energy band gap of about 3.8–3.9 eV exhibited high mobility and highly transparent properties.[5–7] Nevertheless, visible light sensitivity was still found in the $a$-IZO TFT.[8,9] Few researchers have addressed the physical mechanism responsible for the photoreaction behavior. The present work proposes a reasonable physical mechanism to describe the photoreaction behavior of the $a$-IZO TFT device. Using knowledge of the photoreaction mechanism, potential applications for photosensor devices are depicted in this study.

Bottom-gate TFT devices in a coplanar structure were fabricated on a glass substrate. First, a 100-nm-thick MoW layer was formed, which served as a gate electrode in a dc sputtering system. A layer of 300-nm-thick silicon nitride ($SiN_x$) was subsequently deposited on the patterned MoW layer using a plasma-enhanced chemical vapor deposition. Then, a 100-nm-thick indium tin oxide (ITO) layer was sputter deposited and patterned to form source/drain electrodes. It was followed that an active channel layer of 50-nm-thick $a$-IZO was formed by a rf magnetron sputtering with a power of 100 W at room temperature. This was defined by microlithography and wet etching processes. The target for the $a$-IZO film deposition was an IZO pellet with a component ratio of 1:1 ($In_2O_3$:ZnO). The sputtering process was done in an argon/oxygen mixture with a ratio of $Ar/O_2=2/1$ under a total pressure of about $3\times10^{-3}$ torr. Diluted HCl-based solution was used as a chemical etchant of $a$-IZO film and the etch rate was about 10A/s. Finally, these samples were thermally annealed at 350 °C in nitrogen ambience for 1 h. While studying photoreaction, the light source was a halogen optic lamp from OSRAM Inc. at 150 W generating light intensity about 63315 lx. The charge pumping procedure and electrical measurements were carried out using electrical analyzer Keithley 4200. Samples were kept in a black box to prevent interference from the ambient environment.

Figure 1(a) depicts the transfer characteristics of the $a$-IZO TFT biased at different drain voltages ($V_D$). The threshold voltage ($V_{th}$), subthreshold swing, and effective field mobility extracted at $V_D=1$ V are 0.75 V, 750 mV/decade, and 44.68 $cm^2/V\,s$, respectively. The inset plot shows the transmittance of $a$-IZO film deposited on the glass substrate and indicates the sensitivity of an $a$-IZO film in light illumination of around 550 nm in the visible light region. A sequence of electrical characteristics were recorded and studied at different measurement stages, including the initial dark state (referred to as Initial), the instant light turn-on (referred to as Instant light on), the 10 min light illumination (referred to as the L10) as well as samples which stayed in the dark for various durations from 0 to 720 min (referred to as D0 and D720) following the 10 min light illumination. The $a$-IZO TFT transfer curves were ob-

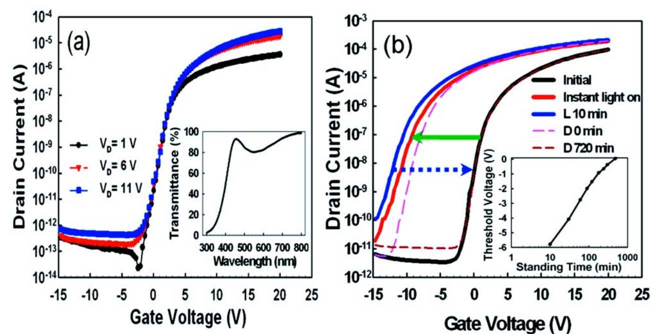


FIG. 1. (Color online) (a) Transfer characteristics of $a$-IZO TFTs in the dark state and (the inset) the transmittance of $a$-IZO film on a glass substrate. (b) The $I_D$-$V_G$ characteristics of the $a$-IZO TFT device measured at a sequence of measuring stages, such as the initial dark state (referred to as Initial), instant light turn-on, light illumination lasting for 10 min (referred to as L10) and then kept in dark for 720 min, referred to as D720. (b) The evolution of threshold voltage of the light-illuminated $a$-IZO TFT as a function of time in the dark, recorded from measuring stage D0 to D720.

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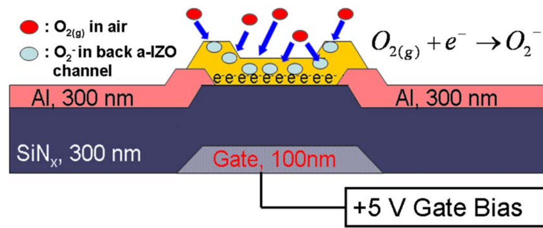


FIG. 2. (Color online) The schematic setup of charge pumping measurement. A constant gate-to-source voltage of 5 V was applied to accumulate electrons in the *a*-IZO channel and shifted the reaction equation of the photoreaction process toward the right side.

served shifting in the direction of negative voltage as a result of exposure to visible light. The value of $V_{th}$ measured at $V_D = 11$ V changes from an initial 0.22 to −11.89 V following visible light illumination for 10 min. After removing the light source, the transfer curves of the *a*-IZO TFT shifted in the direction of positive voltage to a limited extent ($V_{th}$ being −9.1 V) and did not return to the initial dark state immediately. After 720 min period of time, the transfer curve recovered its initial dark state, as shown in the D720 curve of Fig. 1(b). The inset of Fig. 1(b) summarizes the evolution of $V_{th}$ as a function of duration in the dark.

Previous studies on TCO films reported that physical and chemical absorption of oxygen species from ambient air generally occurs in ITO-based film and the reaction is slow. Equations (1) and (2) describe the reactions[9,10]

$$O_{2(\mathrm{gas})} + e^- = O_{2(\mathrm{solid})}^-, \tag{1}$$

$$O_{2(\mathrm{gas})} = O_{2(\mathrm{solid})}^- + h^+, \tag{2}$$

where $e^-$ denotes electrons and $h^+$ denotes holes. In this experiment, $O_{2(\mathrm{gas})}$ was present in the ambient air and was easily negatively charged ($O_{2(\mathrm{solid})}^-$) by capturing free electrons. An *a*-IZO TFT is a *n*-type semiconductor with many electrons. Chemical reactions will also be equilibrated dynamically in the ambient. This suggests that the reaction equilibrium is disturbed and the net reaction direction moves toward the right side of the reaction equation. Conducting electrons are trapped by $O_{2(g)}$ to form $O_2^-$. The resultant buildup of negative space charges ($O_2^-$) easily repels conduction electrons in the *a*-IZO TFT channel, leading to a decreased on current and thereby positively shifting $V_{th}$.[11] In contrast, the $V_{th}$ will negatively shift while the chemical reaction moves toward the left. Generally, excess electron-hole pairs are generated and contribute to photoleakage current in electronic devices while a typical semiconductor exposes to light illumination. In a *n*-type *a*-IZO film, the percentage change of minority-carrier (hole) concentration originating from light illumination becomes more significant than that of majority-carrier (electron) in *a*-IZO film. The hole quantity variation disturbs initial chemical equilibrium and reacts Eq. (2) shift left while Eq. (1) remains itself, causing the net reaction transferring toward the left. As a result, after light illumination to the *a*-IZO TFT, the $V_{th}$ shifts in the direction of negative voltages[12,13] as indicated in the curve of L10 of Fig. 1(b).

To confirm the validity of the proposed mechanism responsible for the photoreaction behavior, a charge pumping procedure was conducted to disturb the equilibrium of Eqs. (1) and (2) by increasing the electrons in the *a*-IZO film.

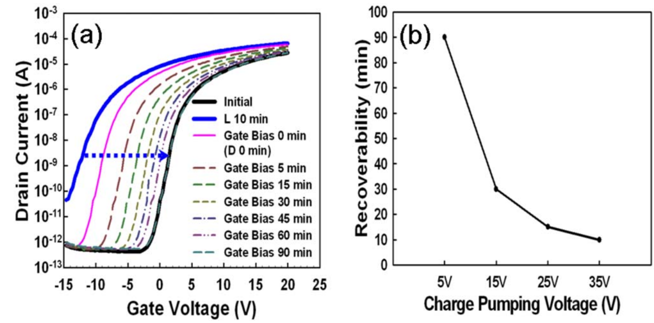


FIG. 3. (Color online) (a) Transfer characteristics of the 10 min light-illuminated *a*-IZO TFT, which was gate biased at a dc voltage of 5 V for 5, 15, 30, 45, 60, and 90 min, respectively. The recovery speed of electrical characteristics increased to 90 min to return the electrical characteristic to the same status as the initial dark state. (b) Charge pumping voltages vs recoverability of threshold voltage (minutes). As the pumping voltage increases up to 35 V, a rapid recovery of the threshold voltage can be achieved within a period of 10 min.

Figure 2 schematically sketches the proposed charge pumping method and the accumulation of electrons in the *a*-IZO channel. The charge pumping was acted by a 5 V constant voltage on the gate electrode. The applied gate voltage of 5 V was verified in advance so as not to degrade electrical characteristics of the *a*-IZO TFT. A period of 90 min was required to return the electrical characteristics of the light-illuminated *a*-IZO TFT to the initial dark state, as shown in Fig. 3(a). Comparing this result to no gate bias, 720 min was required as shown in Fig. 1(b). Speedy electrical characteristic recovery was attributed to excess electrons accumulated in the *a*-IZO layer. These electrons were responsible for shifting Eq. (1) toward right. Consequently, the resultant increase of $O_2^-$ speed up the $V_{th}$ of the light-illuminated *a*-IZO TFT positively shifts and return to the initial dark state, as discussed above. The nearly matching transfer curve between the *a*-IZO TFT with and the *a*-IZO TFT without 5 V gate bias also confirms electrical degradation not to occur during the charge pumping process. The relationship between charge pumping voltages versus the recovery periods of threshold voltage is shown in Fig. 3(b). It is found that a rapid recovery of the threshold voltage is achieved within a period of 10 min, as the gate pumping voltage increases to 35 V. The recovery property results of high pumping voltage with short time period potentially create the application for photosensor devices, also proposed in this work.

Figure 4 illustrates the schematic circuit of the light sensing element. A constant gate-to-source voltage ($V_{GS}$) can be used to detect the ON/OFF state of *a*-IZO TFT with an obvious $V_{th}$ shift, before and after light exposure. In our

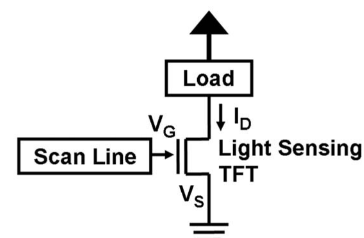


FIG. 4. A proposed light sensing element circuit consisted of *a*-IZO TFT for a low-power sensor array application using $V_{GS} = -2$ V as a reference voltage. $V_{DD}$ is the power supply voltage, $V_{out}$ the output voltage, $V_G$ the gate voltage, and $V_S$ the source voltage.

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case, the $V_{GS}$ can be set at $-2$ V. While in the dark ($V_{th}$ $=0.25$ V), the applied $V_{GS}$ of $-2$ V maintains the *a*-IZO TFT cutoff, resulting in an output voltage equal to the power supply voltage ($V_{DD}$). The output power ($P_{output}$) is equal to $I_D \times V_{DS}=0$. In the other hand, after light exposure, the $V_{th}$ negatively shift, causing the applied $V_{GS}$ of $-2$ V to turn the *a*-IZO TFT on and pull the output voltage close to zero. This indicates light sensing element power consumption will be low and will potentially realize an array circuit form for sensor technology. The proposed charge pumping method can be applied to rapidly refresh the sensing element which consists of an *a*-IZO TFT to repeat the cycle.

In summary, experimental results have shown the $V_{th}$ shift occurred on the *a*-IZO TFT after visible light illumination. The mechanism responsible for photoreaction behavior can be explained by the dynamic equilibrium between $O_{2(g)}$ and $O_2^-$ in the *a*-IZO layer. Under visible light irradiation, the minority-carrier variation forces the reaction equation to fluctuate left and lead to the $V_{th}$ shift negatively. The recoverability of electrical characteristics to the initial state is rather slow. With a charge pumping method, the recoverability of electrical characteristic is speeded up remarkably. The knowledge of physical mechanisms for the photoreaction behavior of *a*-IZO TFT will be potentially beneficial for photosensor technology applications.

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