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Research Paper

Effects of oxygen plasma treatment on the on/off current ratio and stability of ZnO thin film transistors

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ABSTRACT

Thin-film transistors (TFTs) using ZnO as the active semi-conductor and SiO_2 as the dielectric were fabricated on Si substrates. Oxygen plasma treatment was applied on ZnO or SiO_2 surface to investigate its effects on the electrical performance of TFTs. As compared to the TFT device with oxygen plasma applied on the ZnO surface, the TFT device subject to oxygen plasma treatment on the SiO_2 surface exhibits a reduced off current and improved on/off current ratio. X-ray photoelectron spectroscopy analysis revealed that more complete Zn-O bondings in the ZnO film nearby the dielectric should contribute to the reduced off current and enhance on/off current ratio of the O_2 plasma treated SiO_2 TFT device. The relation between electrical bias stress stability and plasma treatment is further discussed in this work.

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INTRODUCTION

Thin film transistors (TFTs) based on hydrogenated amorphous silicon (α-Si: H) are the fundamental driving circuits for flat panel displays (Wehrspohn et al., 2003; Yamauchi and Reif, 1994). But it is rather difficult to apply α-Si: H TFTs to large-size and high-resolution active matrix liquid crystal displays (AMLCDs) because of the high sensitivity to light, low carrier mobility (about 0.5 cm^2 /Vs) and poor TFT characteristics against electrical stress.

ZnO-based TFTs are one of the candidates for overcoming these problems (Gogoi et al., 2015; Jiang et al., 2015; Kang et al., 2014; Chang et al., 2015). However, for ZnO TFTs, the major problem of the device are the high off current and low on/off current ratio (Kang et al., 2007; Liu and Huang, 2006; Carcia et al., 2006). In general, the n-type conductivity of ZnO is due to deviations from stoichiometry, such as oxygen vacancies or zinc interstitial, which will increase the electron concentration. When ZnO is used as an active layer of TFT, the defect-induced background electron concentration must be reduced in order to decrease the off current. Doping and post-deposition annealing are methods used to reduce the defects in ZnO films. However, the introduction of transition metal ions or rare earth ions into the ZnO leads to an additional complexity to the fabrication process. On the other hand, considering the use of glass substrate in display industry, the annealing process is also restricted.

Plasma treatments can be referred to as a kind of pretreatment of surface, which are used to clean and modify the surfaces of materials before any coating, printing or adhesion. The advantages of plasma treatments are short reaction time and inherently environmentally friendly. In addition, plasmas can be employed to modify surface properties of a material without affecting the material characteristics. The effect of plasma on a given material is determined by the chemistry of the reactions between the surface and the reactive species present in the plasma. At the low exposure energies typically used for surface treatment, the plasma surface interactions only change the surface of the material; the effects are confined to a region only several molecular layers deep. The resulting surface changes depend on the composition of the surface and the gas used (Milker, 1991).

Therefore, plasma treatment is a suitable method to overcome the problem of ZnO, since it is consistent with

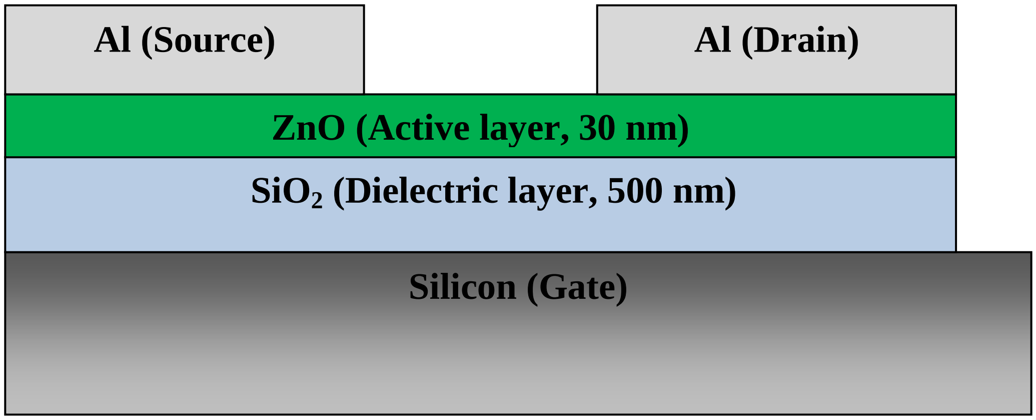

Figure 1: Schematic cross-sectional device structure of the ZnO-based thin film transistor.

device fabrication process and proceeds at low temperature. Some researchers reported that plasma treatment can improve the device characteristics of TFT (Remashan et al., 2008; Park et al., 2007; Kim et al., 1994; Park et al., 2009). The report of Remashan et al. (2008) stated that N_2O plasma treatment on ZnO surface can decrease the oxygen vacancies in ZnO and thereby reduce the effective carrier concentration.

The investigation of Park et al. (2009) also indicated that N_2O plasma treatment on the surface of TiO_x active layer increased the sheet resistance of active layer at off state and reduced the off current of device. However, it was mentioned that the condition of plasma treatment must be taken carefully because it may reduce the on current simultaneously or damage the film. In another work done by Kim et al. (1994) when a bottom gate TFTs structure was subject to N_2 plasma treatment on the dielectric layer, some nitrogen atoms would adhere to the dielectric layer and then diffused into the active layer during the sequential deposition of active layer. This process thus can improve the quality of the interface between active layer and dielectric layer and lower the off current.

Therefore, in this study, the effects of O_2 plasma treatment on the surface of ZnO active semi-conductor layer or on the SiO_2 dielectric layer of ZnO-based TFTs are investigated. The relation to electrical stress stability is also studied. The merit and drawback of plasma treatment on either ZnO or SiO_2 surface was also discussed.

MATERIALS AND METHODS

Figure 1 shows the schematic cross-sectional structure of the bottom-gate-electrode ZnO-based TFTs and the devices were fabricated as follows: A 500 nm SiO_2 dielectric layer was first grown by thermal oxidation on Si wafer. Thereafter, a 30 nm ZnO active layer was sputtered with a ZnO target (99.995% purity) at RF (radio frequency, 13.5 MHz) power of 50 W. The sputtering ambient was pure Ar and the working pressure 10 mTorr. The substrate was neither biased nor heated. An O_2 plasma treatment at RF power of 100 W for 1 min before or after ZnO deposition was carried out in a capacitively-coupled parallel-plate apparatus.

In other words, the O_2 plasma treatment was done on SiO_2 or ZnO surface. Subsequently, 300 nm-thick Al was deposited by electron beam evaporation as the source/drain electrodes. The active layer and source/drain electrode regions were defined by shadow masks. The channel width and length of the TFTs are 2000 and 100 μm, respectively. Finally, SiO_2 at one edge of the sample was scraped off to expose the underneath Si substrate as the gate electrode. Grazing incident angle X-ray diffraction (GIAXRD, Rigaku TTRAX III) measurements were performed at room temperature to investigate the crystallinity of ZnO films. Electrical characteristics of TFTs were measured using a semi-conductor parameter analyzer (Agilent 4156 C). X-ray Photoelectron Spectroscopy (XPS, VG ESCA Scientific Theta Probe) analysis was employed to confirm the chemical bonding states of ZnO films.

RESULTS AND DISCUSSION

The crystallinity of ZnO films is identified by using GIAXRD at an incident angle of 2° with Cu Kα radiation. Figure 2 shows the GIAXRD patterns of samples without or with O_2 plasma treatment on ZnO surface or SiO_2 surface. For all samples, a strong ZnO (002) peak at $2\theta \sim 34.12°$ was observed, revealing that the films are crystalline with a hexagonal structure (ICDD-PDF 36-1451). The results indicated that plasma treatment on ZnO or SiO_2 surface will not dramatically change the crystallinity of ZnO films. The average crystallite size was calculated to be around 14±1 nm using the Scherrer equation (Cullity and Stock, 2001).

Figure 3 shows the transfer characteristics of ZnO TFTs with and without plasma treatment. For the non-treated TFT, the off current was close to 10^{-8} A with an on/off

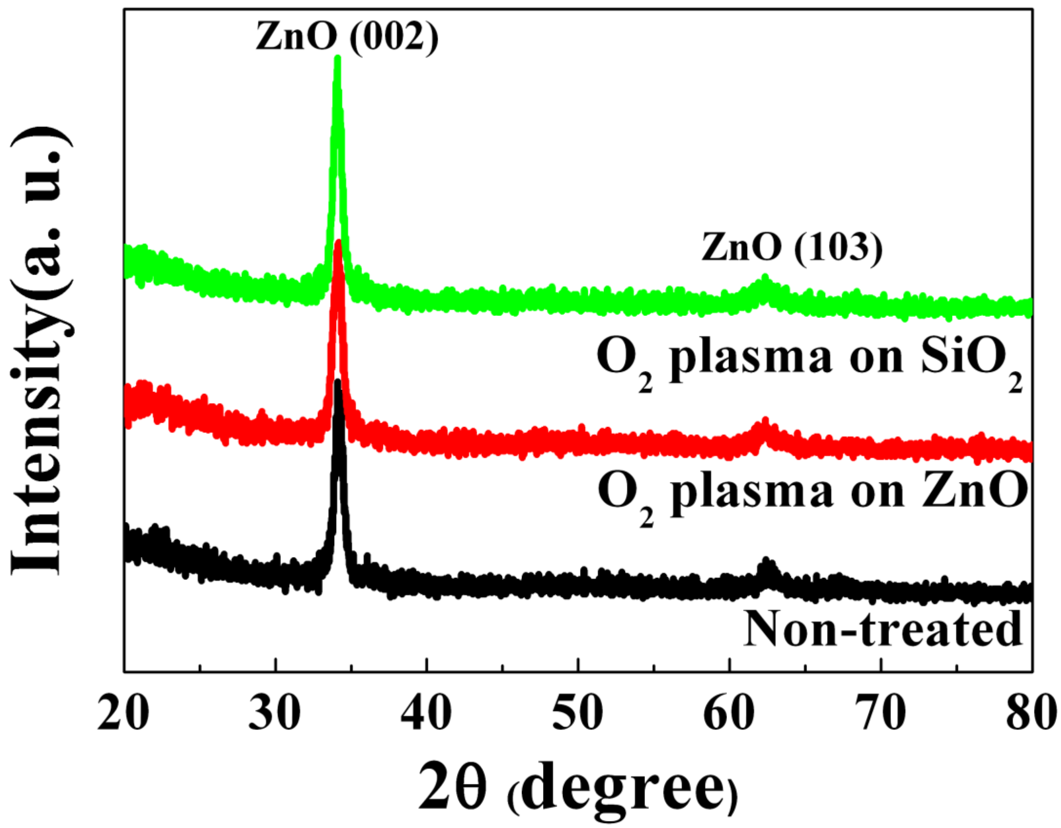

Figure 2: GIAXRD patterns of ZnO films deposited on SiO_2/Si substrate, without plasma treatment, and with O_2 plasma treatment on ZnO surface or on SiO_2 surface.

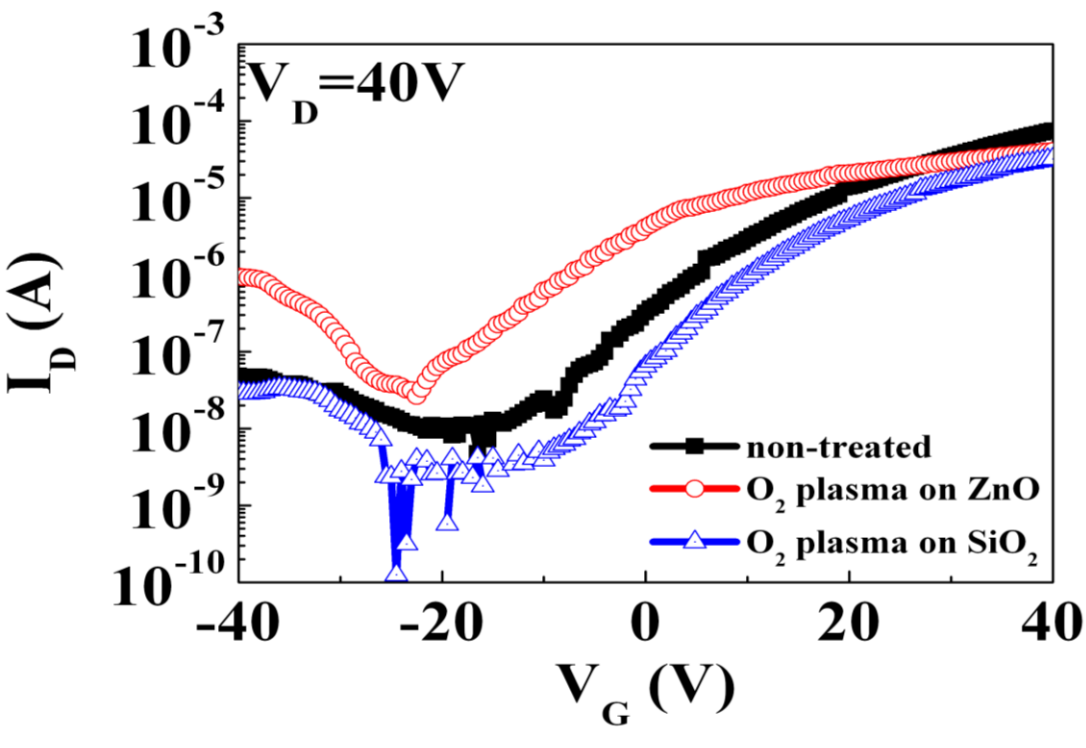

Figure 3: Transfer characteristics of ZnO-based TFTs without and with O_2 plasma treatment on ZnO or SiO_2 surface.

Table 1: On/off current ratio, field effect mobility (μ) and threshold voltage (V_{TH}) of the TFT devices without and with O_2 plasma applied on ZnO or SiO_2 surface.

Sample	On/Off ratio	μ (cm^2/Vs)	V_{TH} (V)
Non-treated	7.5×10^3	0.81	7.7
O_2 plasma treated on ZnO	1.5×10^3	0.17	-17.7
O_2 plasma treated on SiO_2	1.8×10^4	0.34	6.6

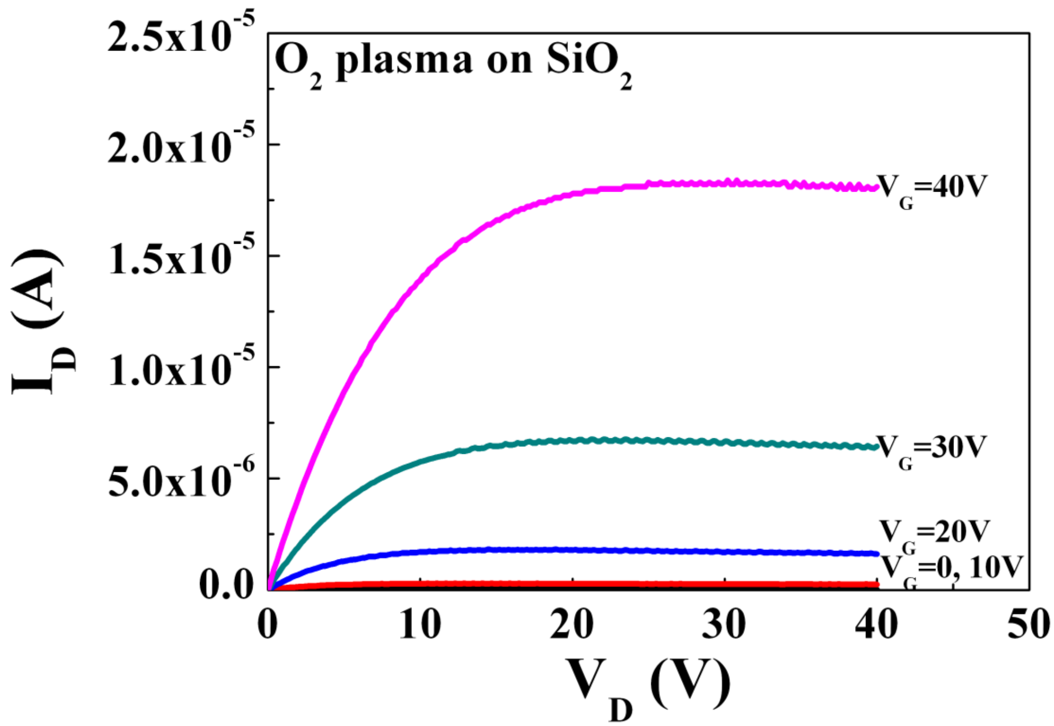

Figure 4: Output characteristics of ZnO-based TFT with O_2 plasma treatment on SiO_2 surface.

current ratio of 7.5×10^3. With O_2 plasma applied on the ZnO surface, the device exhibits an off current of about 10^{-8} A and an on/off current ratio of 1.5×10^3. On the other hand, when the O_2 plasma treatment was applied on the SiO_2 surface, the off current decreased to 10^{-9} A. With a slightly reduction of the on current, the on/off current ratio can reach 1.8×10^4, which is an order higher than that of the device with O_2 plasma treated on ZnO surface.

Table 1 lists the main TFT parameters of the ZnO-based devices with and without O_2 plasma treatment. When the O_2 plasma is applied on ZnO surface, the device exhibits a negative threshold voltage, indicating that a negative gate bias is needed to deplete the carriers and turn off the device. Since the ZnO TFT without plasma treatment exhibits a positive threshold voltage, the fact suggests that the O_2 plasma treatment on ZnO surface will damage ZnO film, generate defects and increase the carrier concentration.

Therefore, the high off current of the device treated with O_2 plasma on ZnO surface shall be in connection with the large effective carrier concentration in ZnO active layer. In contrast, for the device treated with O_2 plasma on SiO_2 surface, the threshold voltage (6.6 V) stays positive and the field effect mobility (0.34 cm^2/Vs) is higher than that of the ZnO-surface-treated sample. Figure 4 shows the output characteristics of ZnO-based TFT with O_2 plasma treatment on SiO_2 surface. The device exhibits a well saturation I_D-V_D characteristics and an n-channel enhancement mode behavior.

To understand the origin of the reduced off current and enhanced on/off current ratio obtained from the device with O_2 plasma treatment on SiO_2 surface, XPS analysis was carried out. The samples for XPS analysis have the same layered structure as those of TFT devices. Figure 5 shows Zn $2p_{3/2}$ core level XPS spectra of ZnO and SiO_2-surface-treated samples, with the signals emanating from the surface of ZnO film (Figure 5a) and from the interface between SiO_2 and ZnO (Figure 5b). On the surface of ZnO, Zn $2p_{3/2}$ peaks of two samples were located at the similar binding energy (1021.5 eV), but at the interface between

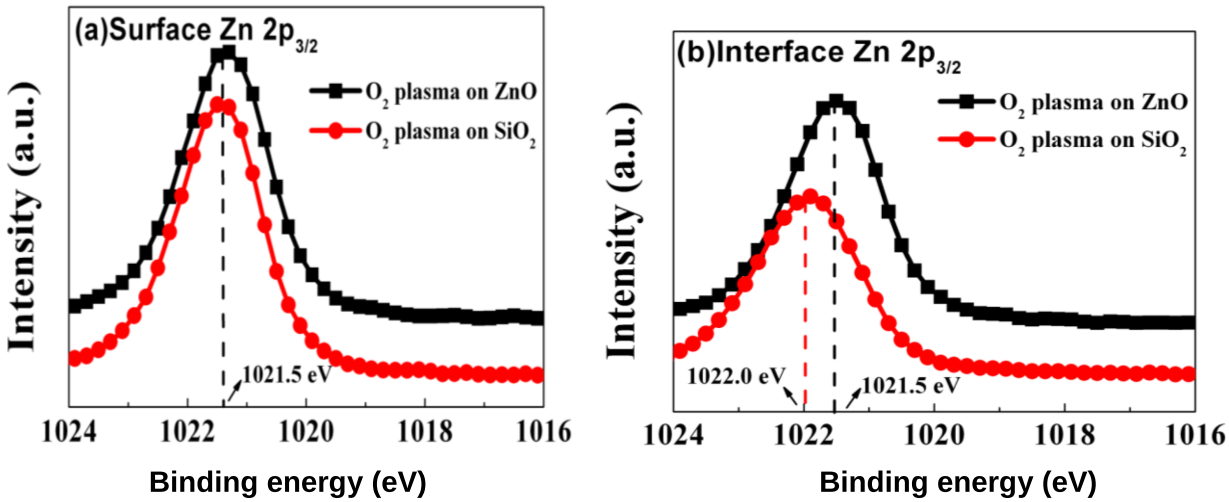

Figure 5: XPS spectra of Zn $2p_{3/2}$ core level (a) at the ZnO surface and (b) at the interface between SiO_2 and ZnO for the samples with O_2 plasma treatment on either ZnO or SiO_2 surface.

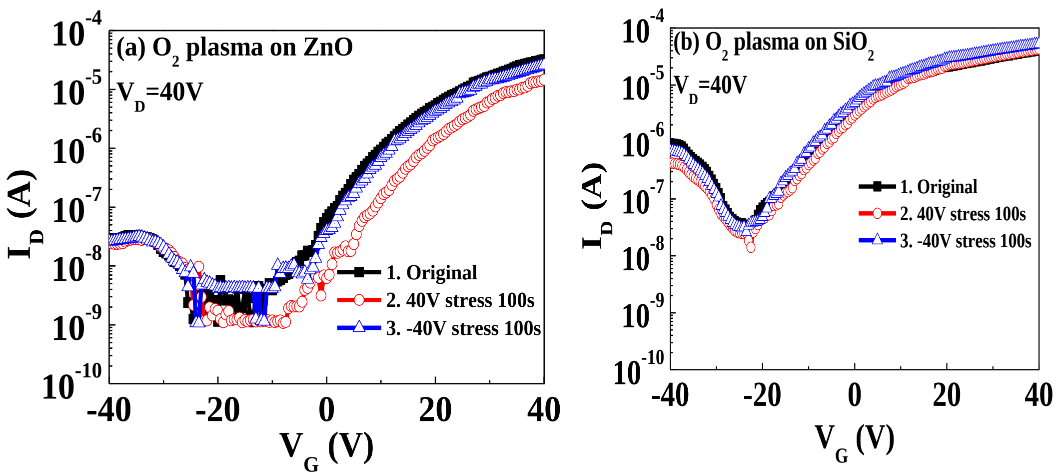

Figure 6: Transfer characteristics of ZnO-based TFTs before (original) and after bias test for 100 sec. at 40V or -40V. (a) Device with O_2 plasma treatment on ZnO surface and (b) device with O_2 plasma treatment on SiO_2 surface.

SiO_2 and ZnO, the Zn $2p_{3/2}$ peak of the sample with O_2 plasma treatment on SiO_2 surface shifts to a higher binding energy, indicative of more complete Zn-O bondings in the ZnO film.

According to previous research by Kim et al. (1994), energetic ions may incorporate into dielectric layer or adhere to the dielectric surface through plasma treatment. During the sequential deposition of active layer, these ions will release and then combine with the atoms of active layer. In this experiment, the oxygen ions may adhere to the SiO_2 surface upon O_2 plasma treatment. Then, during deposition of ZnO, these oxygen ions will bond with Zn and passivate the defects in ZnO. For this reason, the O_2 plasma treatment on SiO_2 reduces the effective carrier concentration and thereby lowers the off current and enhances the on/off current ratio of TFTs.

The relation between electrical stress stability and plasma treatment is also investigated in this work. Before giving the bias stress, an I_D-V_G curve of TFTs was measured at V_D=40 V and referred as the "original". Afterwards, a positive 40 V of bias stress was applied on the gate for 100 s with source and drain both grounded. After releasing the bias, the second I_D-V_G curve was measured at V_D=40 V. This curve is referred as the "40 V stress 100 s". Following, a negative -40 V of DC bias stress was applied on the gate for 100 s with source and drain both grounded. The third I_D-V_G curve was measured again at V_D=40 V after releasing the -40 V bias. This curve is referred as the "-40 V stress 100 s". Figure 6 shows the transfer characteristics of ZnO-surface-treated and SiO_2-surface-treated TFTs of three states:

Table 2: The change of field effect mobility and threshold voltage of ZnO-based TFTs after bias stress test (at 40V or -40V for 100 s).

Sample	O_2 plasma on ZnO		O_2 plasma on SiO_2	
	$\Delta\mu$ (cm^2/Vs)	ΔV_{TH} (V)	$\Delta\mu$ (cm^2/Vs)	ΔV_{TH} (V)
40 V stress	-0.12	5.47	0.005	0.7
-40 V stress	-0.08	-0.74	0.058	0

original, after 40 V stress and after -40 V stress.

Figure 6a shows that the ZnO-surface-treated TFTs exhibit an apparent positive shift of I_D-V_G curve after the +40 V bias stress. The positive shift is attributed to the existence of defects in ZnO arisen from the plasma treatment. The defects will trap electrons and consequently shift the I_D-V_G curve to the positive voltage regime (Powell, 1983; Navamathavan et al., 2006). The electrons trapped in ZnO shall come from the accumulated electrons in ZnO during the application of the positive gate bias (+40 V) stress. However, the curve can be shifted back after giving a negative gate bias stress. On the contrary, the device with O_2 plasma treatment on SiO_2 exhibits stable I_D-V_G characteristics before and after bias stress (Figure 6b), which is due to the lower oxygen vacancy concentration at the ZnO channel layer/ SiO_2 interface for SiO_2-surface-treated TFTs.

Table 2 lists the change of mobility and threshold voltage for the O_2 plasma treated devices after bias stress test. The ΔV_T for the device with O_2 plasma treatment on ZnO surface after positive bias stress and subsequent negative bias stress are 5.47 and -0.74 V, respectively. It revealed that the device with plasma treatment on ZnO exhibits instability against bias stress, but the offset can be recovered by applying a negative gate bias. The ΔV_T for the device with O_2 plasma treatment on SiO_2 surface after positive bias stress and subsequent negative bias stress are 0.7 and 0 V, respectively indicating that the device performance is quite stable. Therefore, oxygen plasma treatment on the SiO_2 dielectric is still a suitable means to enhance the on/off current ratio of ZnO-based TFTs.

Conclusions

In conclusion, with oxygen plasma treatment on the ZnO surface, the bottom-gate-electrode ZnO-based TFT turns to operate in depletion mode and degrades the on/off current ratio. However, with plasma treatment on the SiO_2 surface, more complete Zn-O bondings are developed in the ZnO film. Therefore, the TFT revealed a reduced off current and the on/off current ratio is enhanced.

In addition, the TFT performance for device with plasma treatment on SiO_2 surface is more stable than that for device with O_2 plasma treatment on ZnO surface. As a result, for a bottom gate TFT structure, plasma treatment on the dielectric layer is a suitable approach to reduce the off current and improve the on/off current ratio, as compared to plasma treatment on the active layer.

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