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We investigated effects of chemical stoichiometry of ZnO channel, controlled by oxygen partial pressure during deposition, on bias instability for ZnO thin-film transistors. Parallel threshold voltage shifts were mainly enhanced under gate bias stresses due to charge trapping when O-rich ZnO was used for channel layer. On the contrary, negative threshold voltage shifts were observed under both gate and drain bias stresses when Zn-rich ZnO was used for channel layer. This degradation was enhanced regardless of the bias polarity and the direction, attributing to electrically activated trap generations. © *2011 American Institute of Physics*. [doi:10.1063/1.3557066]

Recently, technological progresses on oxide-based thin-film transistors (TFTs) are increasingly demanded by rapid evolution of large area electronics such as active-matrix flat panel displays and organic-light emitting diode displays.[1–3] Oxide-based TFTs have superior advantages because of their high field-effect mobility,[4] excellent uniformity, low-processing temperature,[5] and transparency in the visible light.[6] Film properties of oxide materials are drastically influenced by deposition methods and conditions. Especially, it is well known that oxygen pressure during oxide film deposition influences the formation of subgap density of states which play an important role in the TFT performance.[7] However, there is still much unknown physics of the density of states in oxide-based TFTs such as its effect on the device characteristics and bias stability, the defect physics, and so on. We have reported that a ZnO deposited under a low oxygen partial pressure included lots of donor-like traps near the conduction energy and these traps deteriorated the subthreshold characteristics of ZnO TFTs.[8]

In this paper, we report the effects of chemical stoichiometry in ZnO channel on bias stability of ZnO TFTs. The chemical stoichiometry was controlled by changing the oxygen partial pressure during deposition of ZnO via radio frequency (rf) magnetron sputtering that is commonly-used in large area electronics manufacturing.

Bottom-gate ZnO TFTs were fabricated on alkali-free glass substrates. First, a 50 nm thick chromium gate electrode was formed via dc magnetron sputtering and a gate insulator consisted of SiO_x/SiN_x stacked layer was deposited at 350 °C via conventional plasma-enhanced chemical vapor deposition. Then, a 40 nm thick ZnO active layer was deposited at 150 °C via rf magnetron sputtering. An oxygen partial pressure $O_2/(O_2+Ar)$ during the ZnO deposition was set at 0.33 or 0.75 Pa, whose value was optimized to obtain

Zn-rich ZnO or O-rich ZnO, in order to compare the effects of chemical stoichiometry in the ZnO layers. After the ZnO deposition, the ZnO was covered with a SiN_x layer deposited at 250 °C and separated to an individual channel area of a TFT via photolithography and dry etching. A 200 nm thick SiN_x film was subsequently deposited onto the patterned SiN_x/ZnO bilayers, forming contact holes for source and drain contacts. Then, a 50 nm thick ITO was deposited and patterned for source and drain electrodes. Finally, a 200 nm thick SiN_x film was deposited for a passivation layer. The channel width and length of the fabricated TFTs were 50 μm and 20 μm, respectively. The ZnO TFTs with ZnO channel deposited under the oxygen partial pressure of 0.33 Pa or 0.75 Pa were thermally annealed at 360 °C or 375 °C for 3 h in nitrogen atmosphere, respectively, ensuring that it was easy to make comparison for almost the same on-state characteristics.

Figures 1(a) and 1(b) show the thermal desorption spectroscopy (TDS) spectra of zinc and oxygen, respectively, obtained from the ZnO films deposited under the oxygen partial pressure of 0.33 and 0.75 Pa. It is found that the desorption characteristics are strongly influenced by the oxygen partial pressure during the deposition. Zn is mainly desorbed from the ZnO film deposited under the lower oxygen partial pressure (Zn-rich mode). On the contrary, the ZnO films deposited under the higher oxygen partial pressure (O-rich mode) show only oxygen desorption.

Figure 2(a) shows the transfer characteristics of the ZnO TFTs with the inset of the TFT structure. The transfer characteristics of the TFTs with ZnO deposited under oxygen partial pressure of 0.17 (Zn-rich mode) and 0.50 Pa (O-rich mode) are simultaneously shown for comparison. It clearly shows a dependence of the subthreshold characteristics on the oxygen partial pressure during the ZnO deposition. Although the on-state currents for all ZnO TFTs are almost the same, the hump characteristic is only observed in the subthreshold region of the Zn-rich ZnO TFT. This hump is at-

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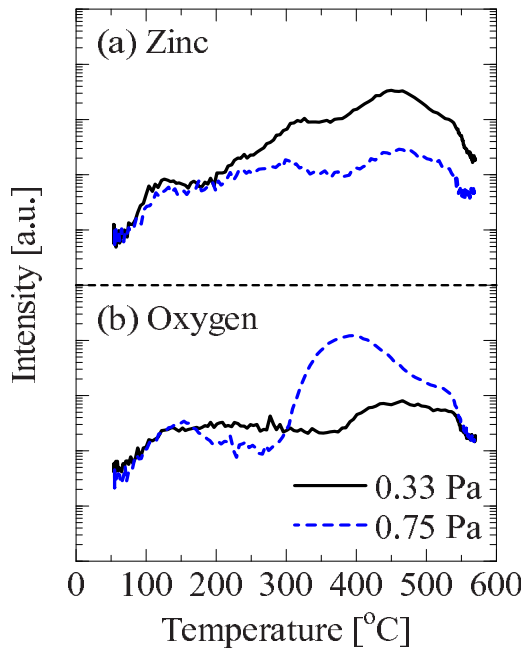
FIG. 1. (Color online) TDS spectra of (a) zinc and (b) oxygen from the ZnO films deposited under oxygen partial pressures of 0.33 and 0.75 Pa.

tributed to the increase in donor-like traps near the conduction band edge (E_c).[8]

Figure 2(b) shows the trap densities in the ZnO channel layers as a functions of the energy (E) from the E_c extracted from low-frequency capacitance-voltage measurements. The details of the characterization methods were reported in a previous paper.[9] The TFT with Zn-rich ZnO includes a larger trap density near the conduction band of ZnO. As a result, the subthreshold characteristic is deteriorated as the appear-
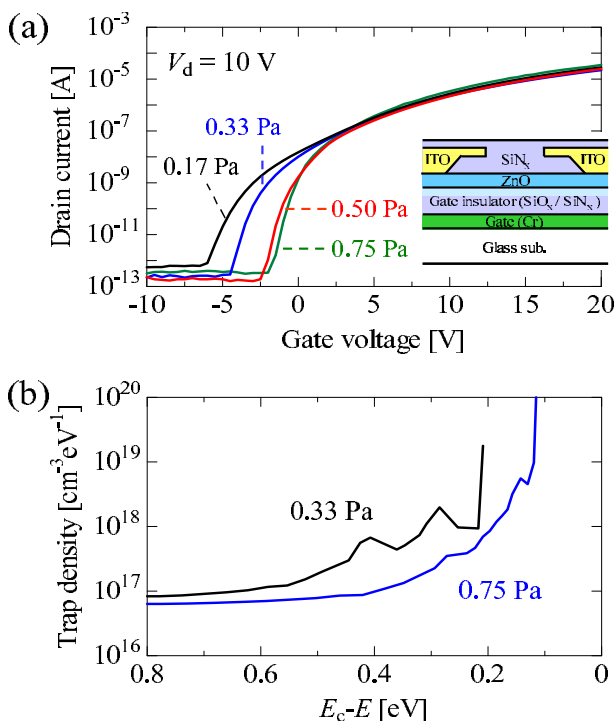

FIG. 2. (Color online) (a) Transfer characteristics of the ZnO TFTs when the ZnO channels were deposited under oxygen partial pressure from 0.17 to 0.75 Pa. The inset is device structure, and (b) trap densities in the ZnO channel layers as a functions of the energy from the conduction band.
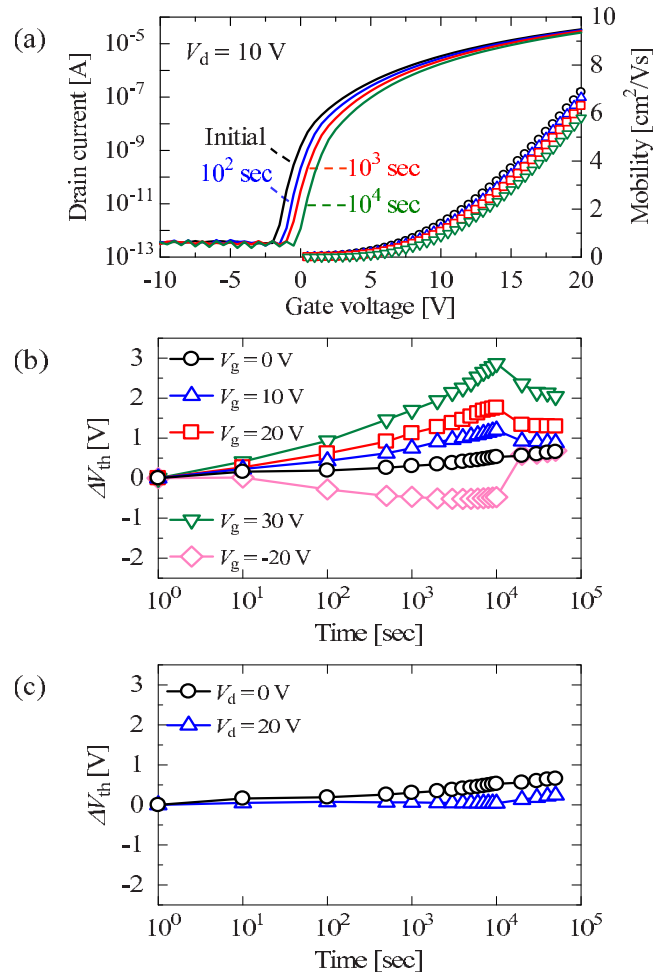

FIG. 3. (Color online) Bias instability results for the TFT with O-rich ZnO. (a) The change in transfer characteristics under a gate bias stress of 20 V and a drain bias stress of 0 V. The change in linear mobility is also indicated with ○: initial, △: 10^2 s, □: 10^3 s, and ▽: 10^4 s, respectively, (b) the variation in V_{th} from the initial value under various gate bias stresses without drain bias stress, and (c) the variation in V_{th} from the initial value under various drain bias stresses without gate bias stress.

ance of undesirable hump characteristic because the traps near the conduction band cause degradation of potential modulation against the gate voltage sweep. The origin of the larger number of traps in Zn-rich ZnO, shown in Fig. 1(b), is attributed to the effects of excess Zn.[10–12]

Stress-tests under various bias conditions were carried out for the TFTs with O-rich or Zn-rich ZnO. The mechanism of bias instability was elucidated by measuring the transfer characteristics when a gate bias stress between −20 and 30 V or a drain bias stress between 0 and 20 V was applied. The stress duration was 10^4 s and the recovery properties after the stress were also measured till 5×10^4 s. Figure 3 shows the experimental results for the TFT with O-rich ZnO in which (a) the change in transfer characteristics under a gate bias stress of 20 V and a drain bias stress of 0 V, (b) the variation in threshold voltage (V_{th}) from the initial value under various gate bias stresses without drain bias stress, and (c) the variation in V_{th} from the initial value under various drain bias stresses without gate bias stress. Here, we defined V_{th} as a gate voltage when a drain current of 1 nA could flow at a drain voltage of 10 V. The transfer characteristics positively shifted as the stress time is increased under positive gate bias and the gate-voltage-
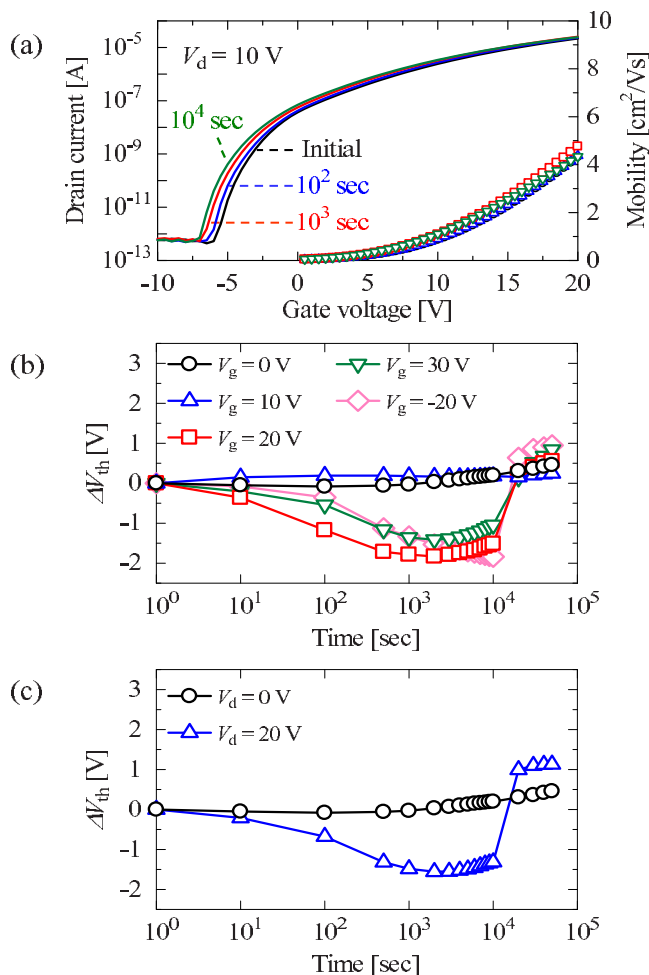
FIG. 4. (Color online) Bias instability results for the TFT with Zn-rich ZnO. (a) The change in transfer characteristics under a gate bias stress of 20 V and a drain bias stress of 0 V. The change in linear mobility is also indicated with ○: initial, △: 10^2 s, □: 10^3 s, and ▽: 10^4 s, respectively, (b) the variation in V_{th} from the initial value under various gate bias stresses without drain bias stress, and (c) the variation in V_{th} from the initial value under various drain bias stresses without gate bias stress.

Additionally, the drain bias stresses also enhance the negative V_{th} shift. The negative shifts in the transfer characteristics are obviously due to a mechanism that is different from the charge trapping. The origin is thought to be that more inactivated Zn-related defect states are present in the Zn-rich ZnO and these defects are electrically activated and/or new defects are generated by the bias stress. As a result, the V_{th} is negatively shifted due to the enhancement in the hump characteristics. The negative V_{th} shift enhanced by electrically active traps seems to appear dominantly though the charge trapping also occurred in the Zn-rich ZnO TFTs.

In conclusion, mechanisms of bias instability in the ZnO TFTs with Zn-rich or O-rich film compositions were investigated by changing the oxygen partial pressure during the ZnO deposition. Positive V_{th} shift mainly occurred under positive gate bias for the TFTs with the ZnO channel layer deposited under O-rich conditions due to negative charge trapping. On the contrary, negative V_{th} shift was enhanced for the TFTs with the ZnO channel layer deposited under Zn-rich conditions due to electrically activated trap generations. These results suggest that slight excess chemical elements in a ZnO channel layer influence the main origin of bias instability. Therefore, precise control of chemical compositions in the ZnO channel layer is crucial for realizing high stability against bias stresses in oxide TFTs.

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dependent linear mobility was changed. This phenomenon is similar to the transfer characteristics shift as shown in Fig. 3(a). To the contrary, it is found that the transfer characteristics are negatively shifted under a negative gate bias stress as shown in Fig. 3(b). A linear relationship between the V_{th} shift and the logarithmic stress time without significant changes in the subthreshold swing and field-effect mobility after the stress suggests that the bias instability may be attributed to the negative charge trapping in the gate insulator and/or the channel/dielectric interface as reported in the literatures.[13–15] Therefore, the V_{th} shift is nearly independent of the drain bias stresses as shown in Fig. 3(c) since the stress along the lateral direction induced by the drain bias do not enhance charge trapping into the gate insulator. The slow recovery time extending to more than 10^4 s can be explained by the slow detrapping properties from the gate insulator. On the contrary, quite different results are obtained for the TFTs with the Zn-rich ZnO as shown in Fig. 4. The transfer characteristics are negatively shifted regardless of the polarities of the gate bias stresses as shown in Figs. 4(a) and 4(b).