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High stability of amorphous hafnium-indium-zinc-oxide thin film transistor

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Time dependence of the threshold voltage (V_{th}) shift in amorphous hafnium-indium-zinc oxide (a-HIZO) thin film transistor has been reported under on-current bias temperature stress measured at 60 °C. X-ray photoelectron spectroscopy results show the decrease in oxygen vacancies by Hf metal cations in a-HIZO systems after annealing process. High stability of a-HIZO systems has been observed due to low charge injection from the channel layer. Hf metal cations have been effectively incorporated into the IZO thin films as a suppressor against both the oxygen deficiencies and the carrier generation. © 2010 American Institute of Physics. [doi:10.1063/1.3387819]

Zn-based amorphous oxide semiconductors (AOSs) are of great interests for the applications in electronics, optoelectronics, and future displays. On the contrary, polycrystalline oxide materials are suffered by the deterioration of the performance and the stability mainly due to carrier scattering at grain boundaries and defects.[1,2] The main advantages of Zn-based AOS thin film transistors (TFTs) are scalability, uniformity, and availability of low temperature process. Also, they have a large process window in the choice of gate insulators. There have been many reports on Zn-based oxide TFTs. Amorphous Ga-In-ZnO (a-GIZO) is one of the most promising materials for channel layers. One of the properties of Zn-based oxide materials is to adsorb oxygen trapping electrons, which is usually used as gas sensors.[3,4] In other words, the characteristics of Zn-based oxide materials are changed by the surrounding environments, the time, and even the on-current bias stress (BS). Therefore, the long-term stability of Zn-based AOS-TFTs by on-current BS has drawn a lot of attention for future devices.[1–3,5] In the case of the driving transistor used in the flat panel displays, the positive shift in the threshold voltage (V_{th}) leads to the reduction in the luminance and causes the image sticking troubles.[5] Additionally, the properties of as-deposited channel layers are easily influenced by various environment conditions even in passivation processes. The group IV elements, such as Ge, Ti, Zr, Sn, and Hf were used in Zn-based AOS system as electrically nonactive and amphoteric impurities. So, these group IV elements are considered to play important roles in suppressing charge carrier generation and in improving the stability of TFTs by binding with oxygen.[6] Hf and Zr are well combined with Zn-based oxides without any impurities. As a result, the abnormal discharge and nodule formation may be prevented.[7] In this work, high stability in a-Hf-In-ZnO (HIZO) TFTs without passivation treatment has been investigated by the stability tests in both conditions of constant on-current BS and bias temperature stress (BTS). In addition, the role of Hf to achieve high stability in a-HIZO channel layers has been analyzed.

The HIZO films were deposited in argon ambient with different oxygen ratios ranging from 0% to 5% by rf-magnetron sputtering method at room temperature. The

working pressure and the radio frequency power density were 0.56 Pa and 2 W/cm², respectively. The HIZO-TFT with top electrodes were fabricated on SiO_2(200 nm)/p-Si substrate using the conventional photolithography processes. The thickness of the active channel layer was fixed at 30 nm. The channel width and length were 250 μm and 50 μm, respectively. The carrier concentration of the HIZO film was 4.95×10^{14} cm^{-3} measured by Hall measurements system (HMS-3000). The stoichiometry of as-deposited HIZO film was measured by energy dispersive x-ray spectroscopy. The ratio of Hf/In/Zn was measured to be about 21/50/29 wt %, respectively. All electrical measurements were carried out by a semiconductor parameter analyzer (ETCP-1000).

Figure 1 shows XRD spectra of a-HIZO films as-deposited and postannealed. The postannealing process was performed at 350 °C in N_2 environment for 2 h. XRD result clearly indicate amorphous phase of all HIZO films, which is well agreed with the result reported before.[8–10]

Figure 2 shows XPS spectra of a-HIZO films as-deposited and postannealed. Only Hf, In, Zn, and O elements are observed in XPS, which indicates that the films have the
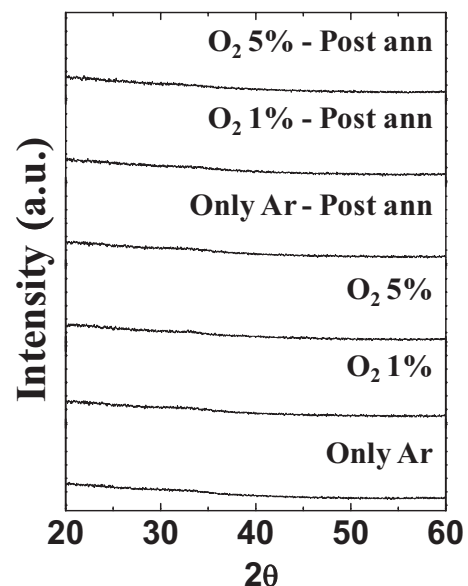

FIG. 1. XRD spectra of a-HIZO films as-deposited and annealed depending on oxygen ratios.
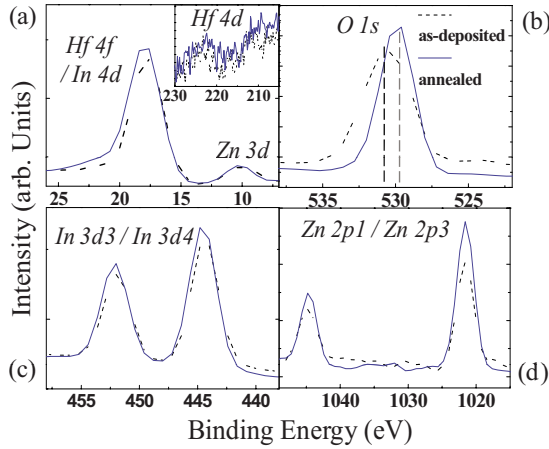
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FIG. 2. (Color online) XPS results of a-HIZO film after thermal annealing. The data shows the peak position of (a) Hf $4f$ and Hf $4d$, (b) O $1s$, (c) In $3d$, and (d) Zn $2p$.

same stoichiometry as that of the target. The binding energy level of pure Hf $4f$ core level, consisting of $4f_{7/2}$ of 16.6 eV and $4f_{5/2}$ of 18.1 eV (Ref. [11]) is overlapped with that of In $4d$ of 17.5 eV.[12] Therefore, the observed peak shows only one broad peak as shown in Fig. 2(a). However, Hf $4d$ peak is observed as shown in the inset of Fig. 2(a), which shows the existence of Hf in a-HIZO system. The binding energy of Hf $4f$ shifted to a higher energy level after annealing, indicating the increase in binding energy with oxygen. Also, the peak intensity of O $1s$ is increased and the position is shifted to lower binding energy level from 531 to 529.5 eV after thermal annealing, which is well agreed with the decrease in oxygen vacancy due to Hf metal cations as shown in Fig. 2(b). The O $1s$ core level of the annealed films is at 529.5 eV that corresponds to O$_2$-state.[13] This value is considerably lower than that of the as-deposited a-HIZO films observed at 531 eV and that of annealed a-GIZO (atomic ratio, Ga:In:Zn$\sim$2:2:1) films at 530.7 eV.[14] This means that oxygen vacancies are reduced by adopting Hf metal cations during the postannealing process. Hf^{4+} can easily capture the mobile electrons because Hf^{4+} forms a positive charge center when Hf is incorporated in the Zn-based oxide film.[8] Thus, the electron concentration in Zn-based oxide TFTs can be easily obtained below 10^{17} cm^{-3} due to the incorporated Hf ions.

The transfer characteristics were measured before and after applying the on-current stresses. The V_{th} was extracted by extrapolation of the square root of drain current (I_D) versus gate voltage (V_G) curve plot in the saturation region and was determined at V_{DS} of 10 V. The plot can be defined as

$$I_D = \left(\frac{C_i \mu_{sat} W}{2L} \right)(V_G - V_{th})^2 \quad \text{for} \quad V_D > V_G - V_{th}, \quad (1)$$

where, C_i is the capacitance per unit area of the gate insulator, and W and L are the channel width and length, respectively. The transfer characteristics of the a-HIZO TFTs after annealing at 350 °C for 1 h in N$_2$ environment and after BS test for 60 h are compared in Fig. 3. Figure 3(a) shows the transfer curves for a-HIZO TFT as a function of on-current BS. The V_{th}, on-current (I_{on}), and on/off ratio of the a-HIZO TFT are measured to be about 13.5 V, $>2\times10^6$ A, and $\sim5\times10^5$, respectively. We have performed BS test under on-current state at V_G of 24 V and V_{DS} of 10 V for 60 h. The
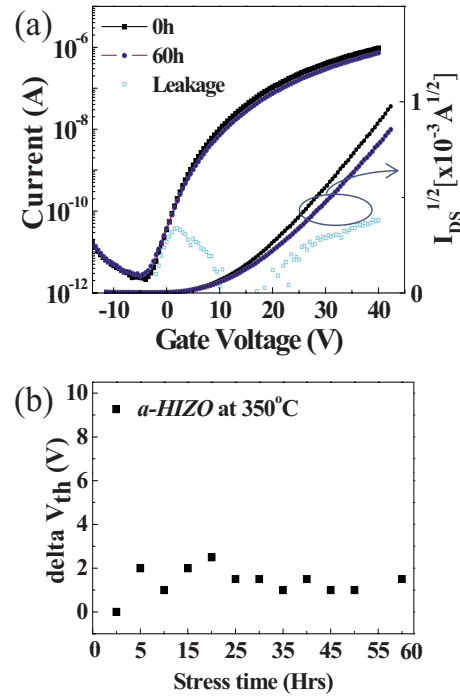

FIG. 3. (Color online) (a) Transfer curves of postannealed a-HIZO TFTs before and after BS for 60 h. (b) Time dependence of variation in V_{th} for postannealed a-HIZO TFT due to applied on-current BS for 60 h.

variation in V_{th} for a-HIZO TFT caused by on-current BS is shown in Fig. 3(b). The bias stability for a-HIZO TFT is particularly important for the applications of the luminance of display devices. It has been reported that the positive V_{th} shift in the Zn-based oxide TFTs is resulted from the charge trapping at the interface between the channel and gate dielectric.[14] The passivated a-GIZO TFTs showed a large positive shift of about 3.4 V in V_{th} after applying on-current BS for 60 h.[5] However, a-HIZO TFTs exhibited less positive V_{th} shift of about 1.5 V as shown in Fig. 3. For comparison, it is reported that the V_{th} was markedly shifted by ~5 V after BS test for 3 h in the case of amorphous indium-zinc oxide (a-IZO) TFTs.[15] Figure 4 shows BTS test result of a-HIZO TFT measured at V_G of 20 V, V_{DS} of 10 V, and temperature of 60 °C for 18 h. It is interesting to note that the V_{th} was positively shifted only by 0.7 V from 19.8 to 20.5 V after BTS test. Compared with a-GIZO and a-IZO TFTs, high stability of a-HIZO TFT was achieved by adding Hf in the IZO system. Because Hf has been verified as a strong suppressor, it improves the stability of oxide TFTs under BS
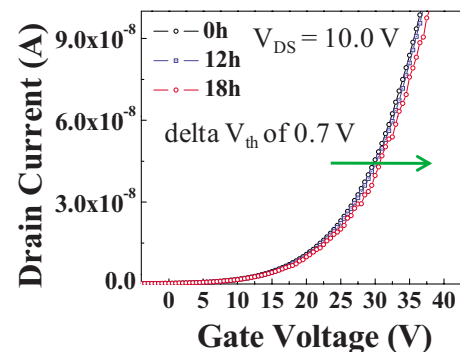

FIG. 4. (Color online) Shift in V_{th} for annealed a-HIZO TFT after BTS test for 18 h.

and BTS test in the air due to its high electron negativity (Hf=1.3).

In conclusion, we have investigated the role of the Hf in the a-HIZO TFT fabricated by the rf-magnetron sputtering process at room temperature without any passivation treatment. The shift in V_{th} has been observed by about 0.7 V after the BTS test for 18 h and by about 1.5 V after the BS test for 60 h. So, it is clear that the use of Hf in a-IZO TFTs results in high stability with improved V_{th} shift under long-term BS and BTS test in the air.

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