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Origin of instability by positive bias stress in amorphous Si-In-Zn-O thin film transistor

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The origin of instability under positive bias stress (PBS) in amorphous Si-In-Zn-O (SIZO) thin film transistor (TFT) with different Si concentration has been investigated by x-ray photoelectron spectroscopy (XPS) and density of states (DOSs) analysis. It is found that stability of SIZO-TFT with 3 wt. % Si under PBS became more deteriorated than that of 1 wt. % Si incorporated SIZO-TFT due to the increased oxygen related trap distributed in energy range from conduction band to ~0.3 eV below the conduction band. The origin of instability under PBS was discussed in terms of oxygen related trap derived from DOSs and XPS analysis. © 2011 American Institute of Physics. [doi:10.1063/1.3657511]

Amorphous oxide semiconductor based thin-film transistors (TFTs) have the significant potential for practical applications in active matrix organic light emitting diode due to their high field effect mobility ($\mu_{FE}$) and additional strong points.1–5 Especially, many groups reported that amorphous Ga-In-Zn-O (GIZO) has high $\mu_{FE}$ and good stability under various stress conditions.6,7 Recently, Lee et al.8 reported that amorphous Si-In-Zn-O (SIZO) TFT with high $\mu_{FE}$ and good stability compared with that of GIZO-TFT was fabricated at 150 °C, thereby facilitating the realization of high performance flexible electronics.

In this paper, the origin of the instability under positive bias stress (PBS) in SIZO-TFTs with different Si concentration has been investigated by analyzing the x-ray photoelectron spectroscopy (XPS) and density of states (DOSs) extracted from multi-frequency method (MFM) technique.9

Mo, as a gate electrode, was deposited on glass substrate by direct current sputtering method, and then amorphous SIZO active layer was grown by the radio frequency magnetron sputtering method at room temperature on 200 nm thick SiNx as gate insulator (GI). More details of device fabrication were described in our previous work.10 All of SIZO-TFTs were annealed at 150 °C for 1 h in N2 ambient. Transfer characteristics were obtained by using semiconductor parameter analyzer (HP 4145B) in dark and vacuum state of <2 × 10−2 Torr. The gate capacitance measurements (C-V) to extract the DOSs in SIZO-TFT with different Si concentration were performed by using precision LCR meter (Agilent 4284A).

Figure 1 illustrates transfer curves of amorphous SIZO-TFTs with 1 wt. % (1SIZO) and 3 wt. % Si concentration (3SIZO), respectively. Thickness of all SIZO active layers was kept at 55 nm. Their electrical properties, such as the threshold voltage ($V_{th}$), $\mu_{FE}$, subthreshold swing (SS), and on-off current ratio ($I_{on-off}$ ratio), are summarized in Table I. The $\mu_{FE}$ for 3SIZO-TFT was deteriorated compared with that for 1SIZO-TFT. This implies that 3SIZO-TFT has larger trap states below the conduction band edge ($E_{c}$) than those of 1SIZO-TFT.11,12 To compare interface trap density ($N_{it}$) of the SIZO-TFTs with different Si concentration, the following equation was used:13

$$N_{iT}^{max} = \frac{SS \log(e)}{kT/q} \left( \frac{e}{C_{ox}} \right) \left( \frac{1}{q} \right) \left( \frac{C_{ox}}{q} \right), \hspace{1cm} (1)$$

where $k$ is the Boltzmann constant, $q$ is the electron charge, $e$ is the base of natural logarithm, $C_{ox}$ is the capacitance per unit area of GI, and $T$ is absolute temperature. The $N_{it}$ of 1SIZO- and 3SIZO-TFT derived from SS values showed about $3.4 \times 10^{12}$ cm−2 and $2.3 \times 10^{12}$ cm−2, respectively. Particularly, the $V_{th}$ of 3SIZO-TFT was shifted to further positive direction compared with that of 1SIZO-TFT. This can be attributed to the decrease of oxygen vacancies as shallow donor states due to the increase of strong Si-O bonds or the increase of total trap density in 3SIZO-TFT, which

![](image)

FIG. 1. (Color online) Transfer curves of SIZO-TFTs with different Si concentrations.

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induces the reduction of free electron by charge trapping in SIZO channel layer.10

To investigate the origin of the further positive $V_{th}$ shift in the 3SIZO-TFT as shown in Fig. 1, the DOSs in SIZO-TFTs were extracted from MFM technique using frequency dependent C-V measurement. Figure 2 shows the subgap DOSs of SIZO-TFTs with different Si concentration. Interestingly, the DOS for 3SIZO-TFT was larger than that for 1SIZO-TFT, especially in energy range from $E_c$ to $0.3 \text{ eV}$ below the $E_c$. It was reported that the acceptor-like DOS extracted from MFM technique was originated from the channel/GI interface trap and the bulk trap in the channel layer. Therefore, in terms of the DOSs in SIZO-TFTs, the decrease in $l_{FE}$ and the further positive $V_{th}$ shift of 3SIZO-TFT than those of 1SIZO-TFT can be explained by the increase of total trap density, which is within energy range from $E_c$ to 0.3 eV below $E_c$, rather than the decrease of oxygen vacancies. It was reported that 1 wt. % Si incorporated in IZO system plays an important role as carrier suppressor and stabilizer. However, in this study, it was found that 3 wt. % Si deteriorates $\mu_{FE}$ and increases DOS within energy band gap, implying that Si concentration in IZO system should be optimized for high performances. As one of possible reasons for the difference in DOSs, the structural deformation due to the difference in atomic volume of Si and other cations can be generated when the empty sites of cations are replaced with Si ions. The 3SIZO-TFT can be significantly deformable, resulting in the generation of much more traps than those of 1SIZO-TFT as shown in Fig. 2.

In order to investigate the relationship between the electrical performances and the chemical properties in SIZO-TFTs, the O 1s XPS spectra in SIZO-TFTs have been analyzed. Gaussian fitting was used to de-convolute these O 1s peaks. As shown in Fig. 4, the Zn 2p$_{3/2}$ peak from Zn-O bonds and In 3d$_{5/2}$ peak from In-O bonds in 3SIZO-TFT was shifted to higher binding energy than in 1SIZO-TFT. Interestingly, the In 3d$_{5/2}$ XPS peak in the 3SIZO-TFT showed a remarkable shift in binding energy compared with that of Zn 2p$_{3/2}$ peak. Juan et al. reported that Zr 3d peak in CeZrO$_4$ thin film was shifted to higher binding energy as decreasing oxygen flow rate. Therefore, the peak shift for metal ions in an oxide system to higher binding energy indicates the increase of oxygen related traps due to formation of oxygen deficient state. Based on these results, oxygen related traps in SIZO-TFT result primarily from In-O bonds rather than Zn-O bonds. Hsieh et al. reported that the continuous tail states extending from $E_c$ originate from variation of In-O metal bonding angles, since the $E_c$ of amorphous GIZO is mainly composed of In 5s orbitals. This report supports our observations in which larger DOS originated from In-O bonds of 3SIZO-TFT is mainly found in energy range from $E_c$ to

<table>
<thead>
<tr>
<th>Wt. % of Si in SIZO</th>
<th>$V_{th}$ (V)</th>
<th>$\mu_{FE}$ (cm$^2$/Vs)</th>
<th>$l_{on-off}$ ratio</th>
<th>Subthreshold swing (V/decade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SIZO 0.75</td>
<td>8.52</td>
<td>$1.72 \times 10^7$</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>3SIZO 5.80</td>
<td>4.69</td>
<td>$3.47 \times 10^7$</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

TABLE I. Summarization of electrical properties of SIZO-TFTs with different Si concentrations.

![FIG. 2. (Color online) The DOSs of SIZO-TFTs extracted from MFM technique.](image)

![FIG. 3. (Color online) O 1s XPS spectra of (a) 1SIZO and (b) 3SIZO films.](image)
0.3 eV below $E_c$. Therefore, it is suggested that the 3SIZO-TFT has larger oxygen related traps originated mainly from In-O bonds than those of 1SIZO-TFT.

Figure 5 shows the $V_{th}$ instability under PBS in SIZO-TFTs with different Si concentration. The bias stress was applied at $V_{GS} = V_{th} = 20$ V and drain to source voltage ($V_{DS}$) of 10.1 V during 3600 s in vacuum and dark state. As a result, the $V_{th}$ shift ($\Delta V_{th}$) of 1SIZO- and 3SIZO-TFT under PBS was 1.0 V and 5.2 V, respectively. Si contents of 3 wt. % in SIZO-TFT can degrade the stability under PBS and $\mu_{FE}$ due to the increased oxygen related traps, which was confirmed by consistency of DOS and XPS analysis. Under our investigations, the origin for the deteriorated $V_{th}$ shift of 3SIZO-TFT under PBS conditions can be oxygen related traps in the channel bulk and at the GI/channel interface. Especially, it is believed that the oxygen related traps originate from In-O bonds in SIZO-TFT.

In summary, it is found that the stability of SIZO-TFT with 3 wt. % Si concentration under PBS was degraded compared with that of 1SIZO-TFT due to the increased oxygen related traps. Also, it is suggested that the oxygen related traps originate primarily from In-O bonds in SIZO-TFT. Consequently, the stability in SIZO-TFT under PBS conditions was very susceptible to variation of Si concentration. Therefore, it is needed to fabricate the SIZO-TFT with optimized Si concentration for its practical usage in terms of the stability.

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