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Effect of interface states on the instability under temperature stress in amorphous SiInZnO thin film transistor

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The instability of amorphous SiInZnO thin-film transistor with different active layer thickness under temperature stress has been investigated using the density of states extracted directly from capacitance-voltage characteristics. Interestingly, it is found that the instability under temperature stress is inversely proportional to the magnitude of interfacial trap density not the total trap density. This was observed from the decrease of the falling rate of activation energy as increasing interfacial trap density. Therefore, the interfacial trap plays a very important role as a key origin for the negative threshold voltage shift under temperature stress in SiInZnO thin-film transistors.

Mo, as a gate electrode, was deposited on a glass substrate by direct current sputtering method, and then amorphous SIZO ALs with different thickness were prepared by the radio frequency magnetron sputtering method at room temperature on 200 nm thick SiN as a GI. Amorphous SIZO ALs and source/drain (S/D) electrodes were defined by the conventional photo-lithography and wet etching process. Ti/Au (10 nm/50 nm) as source/drain electrodes was prepared by electron beam evaporation and thermal evaporation methods, respectively. The well defined channel length and width of the SIZO-TFTs were 200 μm and 100 μm, respectively. All of SIZO-TFTs were annealed at 150 °C for 1 h in thermal furnace with N2 atmosphere.

There has been growing interest in ZnO-based amorphous oxide semiconductors (AOSs), recently, due to their potential application to thin-film transistors (TFTs) of electronic products such as active matrix organic light emitting diode (AMOLED) and active matrix liquid crystal display (AMLCMD). The TFTs using ZnO-based AOSs fabricated at low process temperature have shown higher field effect mobility (μFE) than that of the conventional TFTs using hydrogenated amorphous silicon (Si) active layer (AL).2,3 Also, the AOS-TFTs have many good advantages, such as high transparency at visible light, abundance in nature, the thermal stability, and the chemical stability.4,5 Especially, the TFTs with InZnO (SIZO) as the AL have exhibited the μFE beyond ~10 cm2/Vs and good stability under various stresses, such as positive/negative bias, illumination, and temperature stress (TS).6,7 However, the process temperature over 300 °C has been required to fabricate the GIZO-TFTs, showing the degradation of the electrical performances in the case of GIZO-TFTs prepared below 300 °C. Recently, Si doped InZnO (SIZO) TFTs with the high μFE of ~21.6 cm2/Vs and comparable stability with that of GIZO-TFTs have been fabricated at the very low process temperature of 150 °C.8 Accordingly, an amorphous SIZO-TFT can be one of the superior candidates that can replace the conventional Si-TFTs. However, to date, the extensive and systematic investigations related to stability of SIZO-TFTs have not been carried out. The study should be necessarily performed to comprehend and improve the performances of SIZO-TFTs. Density of states (DOSs) of SIZO-TFTs were extracted from multi-frequency method (MFM) (Ref. 9) to investigate in detail the relationship between TS induced instability and trap states in SIZO-TFTs, even though carrier concentration and total trap density can be estimated from the analysis of transfer characteristics.

In this paper, the instability of amorphous SIZO-TFTs with different AL thickness under TS has been investigated through the subgap DOSs extracted from MFM technique using capacitance-voltage (C-V) characteristics. The instability under TS was roughly inversely proportional to the interfacial trap density (Nit) rather than the total trap density (NT). This was well agreed with the reduction of the falling rate (FR) of activation energy (Ea) as increasing Nit. Consequently, the gate insulator (GI)/channel interface trap was considered as a key origin of the instability under TS in SIZO-TFTs.

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FIG. 1. (Color online) (a) Transfer curves and (b) the frequency dependent C-V curves of SIZO-TFTs with different AL thickness.

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ambient. Transfer characteristics were carried out by using semiconductor parameter analyzer (HP 4145B) in dark and vacuum state of <2 \times 10^{-2} \text{Torr. The C-V measurements to extract the DOSs in SIZO-TFTs with different AL thickness were performed by using precision LCR meter (Agilent 4284 A).

Figure 1(a) shows the transfer curves of amorphous SIZO-TFTs with different AL thickness. The SIZO AL thickness measured by a-step (AMBIOS, XP-2) was 18, 31, and 40 nm, respectively. Their electrical properties, such as threshold voltage (Vth), \( \mu_{FE} \), subthreshold swing (SS), and on-off current ratio (Ion-off ratio) were summarized in Table I. The \( \mu_{FE} \) values at linear region were extracted from transfer curves measured at drain to source voltage (Vds) of 0.1 V, while other parameters were extracted from transfer curves measured at Vds = 5.1 V. In particular, the Vth of SIZO-TFTs was shifted to negative direction as increasing AL thickness. It can be attributed to the reduction of trap in SIZO-TFT as increasing AL thickness, resulting in the increase of free electron in SIZO-TFT. The C-V curve was negatively shifted at a given f with increasing AL thickness, meaning the increase of free electron in SIZO-TFT. The C-V result is well matched with that of transfer characteristics in terms of the increase of carrier in SIZO-TFT with increasing AL thickness.

To investigate in detail the distribution and density of tail states and deep states within energy band gap in SIZO-TFTs, the DOSs were extracted from MFM (Ref. 9) method even though \( N_T \) can be estimated from analysis of transfer characteristics. Figure 2 shows the subgap DOSs in SIZO-TFTs with different AL thickness. The DOSs only within the energy range from the conduction band (Ec) to 0.2 eV below Ec were decreased as increasing AL thickness. Based on this result, the further negative Vth shift as increasing AL thickness could be also related with acceptor-like (shallow) tail states in SIZO-TFT. Interestingly, the subgap DOSs in SIZO-TFT was reduced by about ten times compared with that in amorphous GIZO-TFT.

Table I. Summarization of electrical properties of SIZO-TFTs with AL thickness.

<table>
<thead>
<tr>
<th>Channel thickness (nm)</th>
<th>Vth (V)</th>
<th>( \mu_{FE} ) (cm²/Vs)</th>
<th>Ion-off ratio</th>
<th>SS (V/decade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>5.6</td>
<td>16.9</td>
<td>6.5 \times 10^7</td>
<td>0.26</td>
</tr>
<tr>
<td>31</td>
<td>4.8</td>
<td>16.9</td>
<td>5.5 \times 10^7</td>
<td>0.39</td>
</tr>
<tr>
<td>40</td>
<td>4.1</td>
<td>16.9</td>
<td>5.8 \times 10^7</td>
<td>0.42</td>
</tr>
</tbody>
</table>

FIG. 2. (Color online) The DOSs of SIZO-TFTs with different AL thickness extracted from MFM technique.

FIG. 3. (Color online) The evolutions of transfer curves of SIZO-TFTs with different AL thickness under TS. (a) \( \Delta V_{th} \approx 4.28 \text{ V} \) for 18 nm thick SIZO-TFT, (b) \( \Delta V_{th} \approx 4.93 \text{ V} \) for 31 nm thick SIZO-TFT, and (c) \( \Delta V_{th} \approx 4.95 \text{ V} \) for 40 nm thick SIZO-TFT, respectively.

\[ N_{it,max} = \frac{SS \log(e)}{kT/q} - 1 \frac{C_{ox}}{q}, \]

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 the absolute temperature. The \( N_{it} \) of SIZO-TFTs with different AL thickness was estimated by using the following equation: \[ (1) \]
temperature. This negative $V_{th}$ shift as increasing temperature can be explained by the thermal activation process of the subthreshold drain current. The subthreshold drain current in ZnO-based AOS-TFTs was well understood by the Arrhenius model.\textsuperscript{14–16} where it was assumed that thermally activated electrons from deep trap sites into the $E_c$ moved to the $D$ electrode due to the $V_{ds}$. The $\Delta V_{th}$ under TS was 4.28 V for 18 nm thick SIZO-TFT, 4.93 V for 31 nm SIZO-TFT, and 4.95 V for 40 nm SIZO-TFT. It seems that the $\Delta V_{th}$ value under TS is not related to $N_T$ extracted from the subgap DOSs with increasing AL thickness. It is interesting to note that the $\Delta V_{th}$ increases as increasing $N_T$ in SIZO-TFTs. It was reported that the rate of change in $E_a$ with respect to $V_{gs}$ ($|\Delta E_a/\Delta V_{gs}|$) defined as FR is inversely proportional to the magnitude of $N_T$ in the case of a TFT with a significantly large trap density ($N_T$) including the DOSs of a semiconductor film and an interfacial trap density of $N_{tr}$. This indicates that the $\Delta V_{th}$ under TS increases and FR decreases with increasing $N_T$.

To determine the dependence of the FR on $N_T$ or $N_{tr}$ in SIZO-TFTs, the logarithm of the $I_{ds}(V_{gs} - V_{th})^{-1}$ versus $(kT)^{-1}$ was plotted using the following equation:\textsuperscript{19}

$$I_{ds} \approx g(V_{gs} - V_{th}) \exp \left( \frac{-E_a(V_{gs})}{kT} \right),$$

(2)

where $I_{ds}$ is the drain current in subthreshold region, $E_a$ is the activation energy, $k$ is the Boltzmann constant, and $g$ is a constant which does not depend on the temperature and the drain current. Next, the $E_a (= E_c - E_f)$ of the subthreshold drain current as a function of gate voltage ($V_{gs}$) was plotted as shown in Fig. 4. The estimated FR values were 0.32, 0.21, and 0.20 eV (V)$^{-1}$ for 18 nm, 31 nm, and 40 nm SIZO-TFTs, respectively. As increasing AL thickness or $N_T$, the FR value is reduced, showing the clear relationship between FR and $N_T$. However, it is found that there is no correlation between the FR and $N_T$ under our experiment. As a result, the faster FR of 18 nm thick SIZO-TFT, compared to that of other SIZO-TFTs, means that the $N_T$ is reduced. The inset in Fig. 4 shows clear relation between the FR and AL thickness.

Figure 5 shows the summarization of our investigation. As increasing AL thickness, the $N_T$ and $\Delta V_{th}$ increased. Also, the FR value is decreased with increasing $N_T$ as shown in the inset in Fig. 5, indicating that the $\Delta V_{th}$ under TS increases and FR decreases with increasing $N_T$, not $N_T$.

In summary, it is found that the stability of amorphous SIZO-TFT under TS was roughly inversely proportional to the magnitude of $N_T$, not $N_T$ or trapping may not play a significant role for the stability of these SiInZnO TFTs. It is also supported by the fact that the FR is closely related with the change of $V_{th}$. Therefore, it is important to note that trapping of electrons to $E_c$ at the GI/channel interface traps is a key origin for the $\Delta V_{th}$ under TS in SIZO-TFTs.

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