Role of Schottky barrier height at source/drain contact for electrical improvement in high carrier concentration amorphous InGaZnO thin film transistors

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A B S T R A C T

We report the fabrication of bottom-gate thin film transistors (TFTs) at various carrier concentrations of an amorphous InGaZnO (a-IGZO) active layer from $\sim 10^{16}$ to $\sim 10^{19}$ cm$^{-3}$, which exceeds the limit of the concentration range for a conventional active layer in a TFT. Using the Schottky TFTs configuration yielded high TFT performance with saturation mobility ($\mu_{sat}$), threshold voltage ($V_{TH}$), and on off current ratio ($I_{ON}/I_{OFF}$) of 16.1 cm$^2$/V s, $-1.22$ V, and $1.3 \times 10^8$, respectively, at the highest carrier concentration active layer of $10^{19}$ cm$^{-3}$. Other carrier concentrations ($< 10^{19}$ cm$^{-3}$) of IGZO resulted in a decrease of its work function and increase in activation energy, which changes the source/drain (S/D) contact with the active layer behavior from Schottky to quasi Ohmic, resulting in achieving conventional TFT. Hence, we successfully manipulate the barrier height between the active layer and the S/D contact by changing the carrier concentration of the active layer. Since the performance of this Schottky type TFT yielded favorable results, it is feasible to explore other high carrier concentration ternary and quaternary materials as active layers.

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1. Introduction

Amorphous oxide semiconductors (AOS), especially amorphous InGaZnO (a-IGZO) thin film transistors (TFTs), are now receiving more attention in the electronic industries due to their superior electrical performance compared with conventional amorphous silicon and polycrystalline silicon TFTs [1,2]. For good TFT performance, the carrier concentration of amorphous semiconductors, as an active channel, must be controlled to less than $10^{15}$ cm$^{-3}$, with good stability and reproducibility to control device characteristics such as threshold voltage ($V_{TH}$) and to suppress the off-current [1]. Unfortunately, many oxide semiconductors have uncontrollable high carrier concentrations, larger than $10^{17}$ cm$^{-3}$, since oxygen vacancies are easily formed and generate excess free electrons [3], causing difficulty for device reliability. For practical application, it is important for AOS devices to exhibit fine reliability, since they suffer from stability phenomena such as gate bias stress and visible light illumination [4]. However, the higher carrier concentration will upgrade the intrinsic mobility of a-IGZO [5], ultimately leading to the expansion of the field-effect mobility of IGZO-TFT.

TFTs using a Schottky barrier (SB) at S/D electrodes were introduced to suppress the leakage current in silicon and amorphous oxide semiconductors TFTs [6–8]. Lee et al. [9] focused on the performance of a high concentration IGZO active layer ($\sim 10^{17}$ cm$^{-3}$) TFT device with Schottky
contact using a Metal–Semiconductor–Metal structure. The non-ideal behavior in the linear regime of the output characteristics due to the formation of an SB between the electrodes and active films [10] led to large contact resistance [11], resulting in significant on-current degradation [12]. However, the use of a high conductivity active layer material can solve these problems. Our group previously proposed the use of a Schottky type contact between S/D and a high carrier concentration IGZO active layer in TFT [13] and non volatile memory (NVM) device [14]. This SB at the interface is the key factor for the TFT operation, since the on/off switching properties do not rely on the accumulation process under gate bias sweeping, but are due to the SB height control. The SB height in this case is affected by the work function and activation energy of the IGZO layer as well as the work function of the S/D metal materials. The carrier concentration of the IGZO active layer not only affects the variation in the intrinsic mobility but also its work function, which changes the S/D-active contact properties. However, a detailed connection between the carrier concentration and the SB height on controlling the TFT operation remains unresolved, and this is therefore the aim of this study. The influences of the IGZO active layer carrier concentration on the SB TFT behavior, corresponding to the variation in the S/D contact origin, were examined in detail.

2. Experimental

Fig. 1 shows a schematic cross-section view of the fabricated IGZO-TFT, which is a p-type silicon wafer with very low resistivity ($\rho \sim 0.001 \Omega \text{cm}$) was used as the gate electrode and a 100 nm wet oxidation SiO$_2$ gate insulator used as the insulator. These substrates were then cleaned with acetone, iso-propyl-alcohol, and de-ionized water in an ultrasonic bath to remove surface organic contamination. a-IGZO thin film of 100 nm was deposited as an active layer using dc magnetron sputtering (Yoonsung company, Korea) at room temperature. The initial vacuum level was less than $5 \times 10^{-5}$ Torr and the dc power density was maintained at 0.446 W cm$^{-2}$ during sputtering. Pre-sputtering was performed for 10 min prior to the active layer deposition to remove any contamination on the target surface. The working pressure was varied to control the carrier concentration of the IGZO films from $10^{16}$ to $10^{19}$ cm$^{-3}$. The post-annealing process was performed in air using rapid thermal annealing equipment at 350 °C. 150 nm of Ag as an S/D electrode was then deposited by thermal evaporation at a base pressure of $5 \times 10^{-5}$ Torr. Finally, the S/D and active regions were patterned using the photolithography method with two mask patterning processes. The TFT channel width by length ratio (W/L) was fixed at 40 μm/12 μm in this investigation.

The carrier concentrations of the IGZO thin films were measured using the Hall measurement system (Ecopia HMS-3000) and the electrical performance of the TFT devices was characterized using an EL 420C semiconductor parameter analyzer. The chemical bonding concentration of the IGZO thin films was identified using the X-ray photoelectron spectroscopy (XPS) technique (Al-Ka source). Hall measurements were conducted to obtain the electrical properties of films using the van der Pauw configuration (HMS-3000).

3. Results and discussion

A systematic investigation of the influence of sputter deposition conditions on the electrical properties of IGZO thin films was carried out and reported. Fig. 2 shows the resistivity, Hall mobility, and carrier concentrations of films deposited at various working pressures. It can be seen that the carrier concentration decreases linearly when the working pressure increases from 1 to 20 mTorr. The carrier concentration falls from $1.8 \times 10^{19}$ to $9.6 \times 10^{16}$ cm$^{-3}$, while the Hall mobility reaches the highest value of 13.49 cm$^2$V$^{-1}$s$^{-1}$ at 10 mTorr and then decreases with further increases in the working pressure. The resistivity of films therefore increases from $10^{-2}$ to $10^2$ Ω cm. The change in electrical properties (in terms of carrier concentration and resistivity), as has also been observed elsewhere [15], can be attributed to the poor morphology of the films caused by the change in sputtered pressure during deposition. When the working pressure increases, the mean free path of the energetic sputtered atoms emanating from the target reduces. In the process, the sputtered atoms and argon ions in the chamber collide more frequently, which results in the reduction of the kinetic energy of the sputtered atoms. Hence, the atoms arriving at the substrate with less energy causes a reduction of the densification of the a-IGZO film and expansion of the gaps and voids; this likely leads to a decrease in the electronic properties through the high bulk defects of the a-IGZO channel [16]. Our group also identified the opposite changing trends in the packed density and surface roughness of the
IGZO films [17] as a function of deposition parameters. Yasuno et al. [18] observed the decrease in the IGZO film density and increase in surface roughness using X-ray reflectivity (XRR) measurement when changing the sputtered pressure from 1 to 10 mTorr, resulting in shrinkage of the electrical properties, which is also consistent with our results. The variation in the surface roughness and surface morphology of the IGZO films may affect the contact quality of the IGZO/metal as well as TFT performances when using these types of films as an active layer.

The variation in resistivity, as well as the carrier concentration of the IGZO films as a function of sputter pressure, can also be analyzed based on the chemical compositions of the films, which were extracted from XPS data. Since point defect including oxygen vacancies, metal interstitial, and antisites contributed to the electrical behavior of the IGZO thin film, O1s peaks and other metal related peaks were analyzed in detail. The O1s peak can be congruously deconvoluted into three peaks, centered at 529.96 ± 0.1 (O1), 531.55 ± 0.1 (O2), and 532.7 ± 0.1 eV (O3) [19]. The O1 is attributed to the O2– ions, surrounded by Zn, Ga, and In [20,21], which represent the number of oxygen atoms in a fully oxidized stoichiometric surrounding. The O2 is associated with the O2– ions in the oxygen deficient regions within the IGZO matrix [22], which each supply two free-electron carriers in the IGZO film, resulting in the increase of electron concentration. The O3 is attributed to the chemisorbed or dissociated oxygen or OH– groups on the surface of the IGZO thin film [22]. Fig. 3(i) shows the detailed three fitting spectra extracted from the O1s core level and Fig. 3(ii) shows a magnified view of the shift in the peaks of O1 and O2 at various IGZO carrier concentrations. The increase in intensity of the O2 peaks as shown in Fig. 3(ii) with decreasing working pressure was attributed to the enhancement of oxygen vacancies in the films. When the working pressure is decreased, the carrier concentration increases, and the O1 and O2 peaks shift to a higher binding energy with shifting values of 0.5 eV and 0.6 eV, respectively (Fig. 3(ii)). The O1s peak also shifts to a higher binding energy from 529.78 eV to 530.16 eV (Fig. 3(i)). Generally, the shift in the peak is related to the variation of chemical bonding states; it can thus be inferred that the chemical bonds between the oxygen and metal ions change with deposition pressure. The shift in the binding energy to a higher level can also be due to the increase of oxygen vacancies in the IGZO film that should be ionized. In general, an ionized oxygen vacancy in the ZnO-based film donates two electrons to the conduction band. The increased electron density due to the ionized oxygen vacancies moves the Fermi level up closer to the conduction band, which results in the decrease of work function, leading to the O1s peak being shifted toward the higher binding energy side in the XPS spectrum [23]. The ratio of the oxygen vacancy peak O2 to total peaks (O2/(O1+O2+O3)) is calculated and shown in Fig. 4(iii), which shows the increase in the ratio of O2 peak with increasing carrier concentration, which is consistent with other reports [24]. This again demonstrates the correlation between the carrier concentration and oxygen vacancies of the IGZO material.

Fig. 4(i)–(iii) shows the percentage of metal–oxygen bonding (M–O), the atomic percentage of all metal compositions, and the ratio of oxygen vacancies over the total percent of oxygen bonding, respectively, as a function of IGZO carrier concentrations. The In–O, Ga–O, and Zn–O bonding percentage was calculated using In 3d5/2 (444.4 eV), Ga 3p3/2 (1116.6 eV), and Zn 2p3/2 (1020.8 eV) peaks [24]. The In, Ga, and Zn components increase from 21.617%, 14.369%, and 5.358% to 27.242%, 23.293%, and 9.414% with increasing carrier concentration, while the number of metal bonds with oxygen decreases from 21.671%, 14.969%, and 5.958% to 14.311%, 10.99%, and 4.615% for In–O, Ga–O, and Zn–O bonding, respectively. As shown in Fig. 4, all metal–oxygen bonding percentages decrease, while the number of metal bonds in the films increases with increasing carrier concentration, implying that there are amount of non bonding metal contributes to the conductivity of the IGZO films. The In component increases with increasing carrier concentration at the lowest working pressure (Fig. 2), which may be because In2O3, with relatively less binding energy, can be preferentially sputtered due to the higher energetic Ar+ in plasma from the a-IGZO target. It is known that the In3+ cations in the a-IGZO primarily form an extended conduction band maximum (CBM) due to the percolation of the In 5s orbitals [25]. Therefore, the improvement in mobility is consistent with the increasing indium content and the consequent increase in carrier density.

The transfer characteristics of IGZO TFTs at the saturation regime (fixed at VD = 10 V) with different carrier concentrations are shown in Fig. 5. A significant increase occurs in the on-current (ION) with increasing film carrier concentrations. ION at above the threshold region increases from $1 \times 10^{-6}$,
1.49 \times 10^{-5}, and 4.56 \times 10^{-5} to 1.25 \times 10^{-4} \text{ A} with increasing active layer carrier concentration from \( \sim 10^{16} \) to \( 10^{19} \text{ cm}^{-3} \), implying that \( I_{ON} \) can enhance up to 2 orders of magnitude by controlling the conductivity of active materials. However, the content of the oxygen vacancies that control the IGZO films' properties from the conductor to the insulator causes a difficulty in devices reliability. This matter needs further investigation to improve the SB-TFT devices' performances. The improvement in the TFT characteristics can be attributed to the bulk conduction as well as the surface morphology quality of the IGZO film. As discussed earlier, the surface morphology (and surface roughness) of the IGZO active layer was affected by the pressure parameter, which then may change the contact properties between the IGZO and S/D metals. The correlation between surface roughness and contact properties has also been reported by [26] for a ZnO based TFT device. Other studies also reported a relationship between IGZO bulk defects and deposition total pressure [16], stating that the density of IGZO thin films plays an important role in the reduction of their bulk traps and also in an improvement of the IGZO TFTs' reliability [27]. Therefore, dense IGZO thin films are desirable for highly reliable a-IGZO TFTs owing to fewer bulk traps in the IGZO films.

For easy observation, Fig. 6 also shows the correlation between key parameters and the carrier concentration of the active layers of TFTs. As seen in the figure, the increase...
in carrier concentrations only affects the increase of the TFTs’ on-current, while the off-current and turn-on voltage did not change significantly (Fig. 6(ii)), which dramatically differs from other reports [28,29]. The saturation mobility extracted from the transfer curves shows (Fig. 6(iii)) an enhancement from 0.11 to 16.1 cm² V⁻¹ s⁻¹ with increase in the carrier concentrations, which is consistent with the Hall mobility obtained for thin film as observed from Fig. 2. Most core TFTs parameters (shown in Table 1) were observed to achieve the best value for the device fabricated at a high carrier concentration active layer of 1.8 × 10¹⁹ cm⁻³. The subthreshold swing (SS), V TH, and µ sat etc. The subthreshold swing of the TFT devices was taken as the minimum value of the inverse slope of the log(I D) versus V G characteristics. The V TH in the saturation region (high V D = 10 V) was calculated by fitting a straight line to the plot of I D/V TH versus V G according to the expression for a field-effect transistor [30]

\[ I_{D}^{1/2} = \sqrt{\frac{W}{2 \pi L}} (V_G - V_{TH}) \]  

(1)

where C i is the capacitance per unit area of the gate insulator.

The subthreshold swing behavior was also noticeably degraded for the devices when decreasing the IGZO carrier concentration, which has a value ranging from 0.38 V dec⁻¹ to 1.51 V dec⁻¹ at 9.6 × 10¹⁸ cm⁻³. Generally, the SS value is an indicator of the total trap density including the bulk trap and interface trap densities. In detail, the improvement in SS when decreasing the sputter pressure has been studied [16], in which it was proposed that the SS can be affected by the bulk trap density in the active layer rather than the interface trap density at the low range of sputter pressure from 1 to 5 mTorr. The increase in the bulk trap density is likely due to the generation of dangling bonds in the a-IGZO film with decreased mean free path during the pressure variation. In this report, the effect of reduced sputtering pressure effectively increases the sputtered ion/atom energy distribution, which the authors attributed to the increase in the a-IGZO density and the decrease in the bulk trap density. In our results, the decrease in the sputter pressure led to an increase in the metal composition as well as an increase in the bonding between In, Ga, and Zn with Oxygen in the IGZO bulks. This reduces the dangling bond of the unsaturated links on the surface, resulting in the improvement of SS. At higher sputter pressure values (ranging from 5 to 20 mTorr), the SS behavior is mainly affected by the interface quality between the active layer and the insulator since the morphology of IGZO degrades with high pressure deposition.

As shown in Table 1, the V TH values are dependent on the carrier concentration. As mentioned above, the threshold voltage decreases when decreasing the working pressure, eventually becoming negative when the carrier concentration is very high. This is a quite reasonable result, because in the case of the a-IGZO TFTs with lower carrier concentration, the device requires a higher positive gate voltage to form an electron channel in the a-IGZO. The µ sat values are dramatically reduced with sputter pressure from 16.1 to 0.11 cm² V⁻¹ s⁻¹ for 1 mTorr to 20 mTorr devices, corresponding to the carrier concentration variation from 1.8 × 10¹⁹ to 9.6 × 10¹⁶ cm⁻³. Unlike other reports [31–33], an explicit increase in the off-current with increasing IGZO carrier concentration was not detected. The transfer characteristics only present the increase in the on-current, which is attributed to the increase in carrier concentration of the active layer [23]. This has been analyzed based on the exits of SB at the interface of the IGZO active layer and S/D materials [13]. Fig. 7 shows the dark I–V characteristics of a-IGZO films at different conductivity levels at a voltage sweep from – 1 V to 1 V. As shown in the figure, the current at the same applied voltage increases with increasing IGZO carrier concentration. The increase in the current value of about 2 orders of magnitude from 10⁻⁹ to 10⁻⁷ A corresponds to the increase in concentration from 10¹⁷ to 10¹⁹ cm⁻³. The contact behaviors change from Schottky to quasi Ohmic when IGZO carrier concentration decreased (as shown in the inset of Fig. 7). Schottky barrier heights of the samples at different concentrations were estimated using the reverse bias region, following the Nord method [34]

\[ I = A \alpha T^2 \exp \left( -\frac{q}{kT \Phi_{bm}} \right) \]  

(2)

where \( \alpha \) is the Richardson constant, T is temperature, and \( \Phi_{bm} \) is the Schottky barrier height. Schottky diodes were fabricated to estimate the barrier height using an asymmetric configuration with 2 different electrode materials of Al and Ag. The dark conductivity of IGZO as a function of temperature was measured to estimate the

![Fig. 7. Dark I–V characteristics of IGZO thin film as a function of the carrier concentrations of the active layers. The inset denotes the I–V characteristics at a longer bias sweep of – 5 V–5 V at a linear scale.](image)

**Table 1**

<table>
<thead>
<tr>
<th>TFT parameters</th>
<th>1.8 × 10¹⁹ cm⁻³</th>
<th>2.0 × 10¹⁸ cm⁻³</th>
<th>4.9 × 10¹⁷ cm⁻³</th>
<th>9.6 × 10¹⁶ cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ sat (cm² V⁻¹ s⁻¹)</td>
<td>16.1</td>
<td>7.47</td>
<td>2.58</td>
<td>0.11</td>
</tr>
<tr>
<td>V TH (V)</td>
<td>– 1.2</td>
<td>0.67</td>
<td>1.27</td>
<td>2.18</td>
</tr>
<tr>
<td>SS (V dec⁻¹)</td>
<td>0.38</td>
<td>0.5</td>
<td>0.77</td>
<td>1.51</td>
</tr>
<tr>
<td>I ON/I OFF</td>
<td>1.3 × 10⁸</td>
<td>4.4 × 10⁷</td>
<td>2.7 × 10⁷</td>
<td>2 × 10⁶</td>
</tr>
</tbody>
</table>
activation energy following the Arrhenius equation \[9\], which is found to be around 0.2–0.85 eV with varying the carrier concentration from \(10^{17}\) to \(10^{19}\) cm\(^{-3}\). The previously proposed [13] Schottky TFT (SB-TFT) operation can be used to explain the operation of these types of devices. The basic operating principles of SB-TFT devices with a finite Schottky barrier (SB) for electron movement through the channel is shown in Fig. 8. In detail, when a negative \(V_G\) is applied with any \(V_D\) (Fig. 8(ii)), the electron concentration in the channel decreases causing a higher band structure. This increases the barrier height at the S/D contacts. The higher potential barrier at the two contacts prevented the electrons from moving from the metal electrode to the IGZO layer. In contrast, when a positive \(V_G\) is applied without a \(V_D\) (Fig. 8(iii)), the electrons accumulate in the channel, which leads to the lowering of the band structure. Hence, the barrier heights at the two contacts are reduced. Once a comparable positive \(V_G\) is applied with a positive \(V_D\), as shown in Fig. 8(iv), electrons will flow from the S to the D electrodes through the a-IGZO channel, creating a drain current. Whenever a sufficient high gate voltage is applied, the drain current, \(I_D\), will be driven by a drain voltage. From the explained mechanism, the SB at the S/D contacts controlled by \(V_G\) is the key point for the TFT operation. The switch on and off properties of the SB-TFTs is determined by Schottky barrier height control.

Decreasing the IGZO carrier concentrations leads to an increase in the activation energies, which then changes the contact behavior between the IGZO–S/D metals. As shown in Fig. 9, the samples with a high carrier concentration IGZO layer have Schottky contact at the S/D interfaces. This barrier height was controlled by gate voltage \(V_G\) in order to ensure the electron moves from S to D through the IGZO channel layer, leading to the operation of the devices. The on/off switching property of the high carrier concentration TFTs is determined by Schottky barrier height control. Besides, with low carrier concentration active layers, the devices operate as conventional TFTs; this means that the electrons accumulate along the interface between the insulator and the IGZO active layer under the applied gate voltage. The contact at the active layer and electrodes does not prevent the movement of the electron.

4. Conclusion

In this study, the influence of the carrier concentration of IGZO active layers on the TFT performances was studied and we were able to achieve good on/off ratio performance of the TFT device using Schottky contact, in which the off-current is almost unaffected by the IGZO concentration. The sputter pressure parameter causes a change in the chemical composition percentage and the quantity of M–O bonding, as well as the oxygen vacancies level, resulting in the variation of resistivity and carrier concentration. The TFT performances show better characteristics for the sample fabricated at low working pressure with a high on/off ratio, high mobility, and
good SS. The results demonstrate that we can accomplish excellent TFT performance with high $\mu_{sat}$ of 16.1 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$, small $V_{TH}$ of $-1.22$ V, and ideal SS of 0.38 V dec$^{-1}$ using high carrier concentration IGZO of about $1.8 \times 10^{19} \text{cm}^{-3}$, fabricated at low sputter pressure deposition. The low pressure deposition is more favorable for obtaining better TFT characteristics due to the superior surface morphology as well as the density quality of the IGZO active layers. The use of the Schottky barrier at the S/D contact for the high carrier density quality of the IGZO active layer TFT can provide a very simple Schottky barrier at the S/D contact for the high carrier density quality of the IGZO active layers. The use of the Schottky barrier at the S/D contact for the high carrier concentration active layer TFT can improve the electrical properties of TFT devices. The applied gate voltage $V_G$ controls the SB height at the S/D contact in the same way as that of the forward and reverse voltage in the conventional Schottky diode. The success in fabrication and introduction of the operating mechanism of high-conductivity IGZO TFT will increase the number of materials available for active layer application in the TFT field. Further investigation on contact quality, treatment condition, and S/D metal, etc., should be performed to improve TFT properties in the future.

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