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Amorphous boron–indium–zinc-oxide active channel layers for thin-film transistor fabrication
Amorphous boron–indium–zinc-oxide active channel layers for thin-film transistor fabrication†

Shanmugam Parthiban and Jang-Yeon Kwon*

We investigate thin-film transistor (TFT) fabrication, using a novel amorphous boron–indium–zinc-oxide (a-BIZO) thin-film as an active channel layer and a radio-frequency sputtering technique. The structural, surface, and optical properties of the a-BIZO thin-film were studied. X-ray diffraction (XRD) patterns and high-resolution transmission electron microscopy (HR-TEM) analysis confirmed the amorphous nature of the a-BIZO thin-film. Atomic force microscopy revealed a smooth a-BIZO thin-film surface with a uniform and root mean square roughness of 0.45 nm. The transparency of a-BIZO thin-films was shown to be more than 80% in the wavelength range between 400 and 800 nm, which confirmed a good transparency. The a-BIZO TFT post-annealed at 250 °C under nitrogen atmospheric conditions showed a saturation field-effect mobility of 9.6 cm² V⁻¹ s⁻¹, a threshold voltage of 5.3 V, and a subthreshold swing of 0.77 V per dec with an I_ON/I_OFF current ratio of 2.5 × 10⁷. The small amount of boron dopant acts as a strong carrier suppressor via the formation of oxygen vacancies in the a-IZO matrix.

Introduction

Amorphous oxide semiconductors (AOS) are a key material for next generation electronic devices because of their high mobility, excellent uniformity, low temperature deposition and transparency.¹⁻⁶ Most of the research and development has focused on amorphous indium–gallium–zinc-oxide (a-IGZO) thin-film transistor (TFT) fabrication as alternatives to amorphous/poly-crystalline silicon (Si) TFTs.⁷–⁹ However, AOS TFTs require enhanced mobility and stability for next generation displays such as ultra-high-resolution and high-frame-rate-displays.⁷ a-IZO TFTs can suppress oxygen vacancies (Vₒ) by adding Ga and reducing the instability of the device.¹⁰ However, for high performance applications, Hf, Zr, Ti, La, Sc, Mg, Ta, W, B, Si, La, Gd, etc. have been incorporated as carrier suppressors instead of Ga.¹⁰⁻²¹ Among the carrier suppressors incorporated into the AOS TFT, the Si incorporation has shown enhanced mobility and stability because of the strong binding dissociation energy of silicon–oxygen (799.6 kJ mol⁻¹) thus suppressing carrier concentration formation via oxygen vacancies.¹¹,¹³,¹⁶,²² For enhanced stability, the strong binding dissociation energy between the carrier suppressor and oxide is believed to be a significant property.¹¹,¹³,¹⁴ However, for enhanced mobility, a clear mechanism has yet to be suggested.

Based on the high Lewis acid strength (L) of dopants, transparent conducting oxide (TCO) thin-films have been reported with high mobility and visible to near infrared transparency.²³ According to Wen et al., high L dopants polarize the electronic charge away from the oxygen 2p valance band more strongly than low L, resulting in screening of the charge and weakening of the activity as a scattering center, hence increasing the mobility.²⁴ The scattering center is a significant parameter to determine the mobility; if the scattering center is low high mobility can be expected.²⁵,²⁶ The high L elements are suppressed scattering centers that result in high mobility. Based on the high L and strong metal–oxygen bonding dissociation energy, the boron (B) dopant was chosen which retains a unique metal and oxygen bonding dissociation energy,²² Moreover, B retained a stable state (3⁺), high L (10.7) and strong metal–oxygen bonding dissociation energy (~808.0 kJ mol⁻¹), therefore we believe that boron could be a strong carrier suppressor in AOS thin-films.²²,²⁷ In this work, 2.2 mol% B₂O₃ was chosen in order to avoid the deterioration of TFT performance.²⁸⁻³⁰ Table 1 summarizes the typical elements that have high L and strong metal–oxygen bonding dissociation energy. Among the elements, B has a high L and strong metal–oxygen bonding strength.

Experimental section

For the a-BIZO, IZO (~35 nm) thin-films were deposited on a SiO₂ (100 nm)/Si-p-type substrate using a radio-frequency sputtering technique with the BIZO (22.5/75.4/2.03 mol% of In₂O₃/ZnO/B₂O₃) and IZO (25.0/75.0 mol% of In₂O₃/ZnO) (LTS Chemicals, Orangeburg, NY, USA) targets at room temperature. To avoid the sublimation of B₂O₃ powder while preparing the sputtering target B₂O₃, In₂O₃ and ZnO were mixed; powder was...
filled in a graphite mold, and then subjected to cold pressing and cold isostatic pressing to perform a green compact. Finally, the graphite mold with the performed green compact was put into a furnace and sintered at 800°C for 20 hours. The 4 inch circular target was placed at a distance of 10 cm from the substrate. The sputtering power was fixed at 100 W and the chamber pressure was set at 5 mTorr. The oxygen/argon (O₂/Ar) flow ratio varied from 0–9%. The sputtered a-BIZO thin-films were post-annealed at 250°C for one hour under nitrogen (N₂) atmospheric conditions. The transfer characteristics of the TFTs were measured at room temperature under dark conditions using a semiconductor parameter analyzer (Keithley SCS 4200).

Results and discussion

Fig. 1(a) shows the XRD patterns of 100 nm thick a-BIZO films deposited on Corning glass substrates as a function of the O₂/Ar ratio and post-annealed at 250°C under N₂ atmospheric conditions for one hour. Diffraction peaks were not observed in the crystalline phase in the XRD spectra. The spectra indicate that the amorphous nature of the films remained after post-annealing at 250°C for 1 hour. Although these films are nearly three times thicker than the film used for the active channel in the TFTs, it has been reported that thinner films are expected to be even more amorphous in nature. The FFT showed a diffused diffraction pattern that indicates the amorphous nature of the a-BIZO thin-film. Additionally, the FFT pattern clearly indicated that the a-BIZO film grew uniformly and displayed an amorphous phase. Fig. 1(c) shows the surface of an atomic force microscopy image of the a-BIZO thin film revealing uniform and smooth morphology, which indicates no crystalline structure. A root mean square roughness of ~0.45 nm was observed. The BIZO sputter target and post-annealed thin-film were analyzed by XPS measurements.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Lewis acid strength</th>
<th>Metal–oxygen bond dissociation energy (kJ mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La³⁺</td>
<td>0.852</td>
<td>799</td>
</tr>
<tr>
<td>Ga³⁺</td>
<td>1.167</td>
<td>353</td>
</tr>
<tr>
<td>Hf⁴⁺</td>
<td>1.462</td>
<td>801</td>
</tr>
<tr>
<td>Ta⁵⁺</td>
<td>1.734</td>
<td>799</td>
</tr>
<tr>
<td>Zr⁶⁺</td>
<td>2.043</td>
<td>776</td>
</tr>
<tr>
<td>Ti⁴⁺</td>
<td>3.064</td>
<td>672</td>
</tr>
<tr>
<td>W⁶⁺</td>
<td>3.158</td>
<td>672</td>
</tr>
<tr>
<td>Si⁴⁺</td>
<td>8.096</td>
<td>799</td>
</tr>
<tr>
<td>B³⁺</td>
<td>10.709</td>
<td>808</td>
</tr>
</tbody>
</table>

Fig. 2 (a) Transmittance spectra and (b) band gap of a-BIZO thin-films with respect to various O₂/Ar.
which confirmed the B/In/Zn compositions of 2.4/14.5/17.7 and 3.5/14.3/17.5, respectively.

Fig. 2(a) shows the transmittance spectra of the a-BIZO (35 nm) thin-film coated on a Corning glass substrate with respect to various O2/Ar ratios. All a-BIZO thin-films were optically transparent and showed an average transmittance exceeding 80% at wavelengths ranging between 400 and 800 nm. In contrast, the optical band gap (Eg) varied with respect to the O2/Ar ratio. The values of Eg were obtained by extrapolating the plot of (a(hv))2 versus hv to the intercept (at α = 0) for a-BIZO thin-films with respect to the O2/Ar ratio as shown in Fig. 2(b).33,34 As the O2/Ar ratio increased from 1 to 9%, the values of Eg increased by 3.3–3.6 eV. The variation of Eg increased mainly due to the increased O2/Ar ratios.35

Fig. 3(a) shows the schematic device structure of the bottom gate inverted staggered a-BIZO TFT and Fig. 3(b) shows an optical microscopy image of the top-view of the a-BIZO TFT fabrication. The W and L channels were tightly patterned to avoid the fringing effect and over-estimated the mobility.36

Fig. 4(a) shows the transfer curves of an a-BIZO TFT with respect to various O2/Ar ratios. The 3% O2/Ar ratio a-IZO (without boron doping) TFT was fabricated under the same deposition conditions of 3% O2/Ar a-BIZO. The 3% O2/Ar ratio a-IZO was shown to have a more conductive nature, possibly due to the excess carrier concentration. The O2/Ar was varied from 0 to 9% to determine the optimum condition. The O2/Ar of 0% and 1% of a-BIZO TFT were shown to have a conductive nature, while 3%, 5%, 7%, and 9% O2/Ar TFTs were shown to exhibit a good transfer curve. Fig. 4(a) shows the field-effect mobility (μsat) and subthreshold swing (SS) as a function of O2/Ar, whereas Vth shifted to a positive direction which can be explained by the reduction of oxygen vacancies in the a-BIZO films.37

Table 2  TFT properties of a-BIZO devices

<table>
<thead>
<tr>
<th>O2/Ar (%)</th>
<th>Vth (V)</th>
<th>Ion/Ioff</th>
<th>μsat (cm² V⁻¹ s⁻¹)</th>
<th>SS (V per dec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>5.3</td>
<td>2.5 × 10⁷</td>
<td>9.6</td>
<td>0.77</td>
</tr>
<tr>
<td>5</td>
<td>7.5</td>
<td>2.2 × 10⁷</td>
<td>8.6</td>
<td>0.60</td>
</tr>
<tr>
<td>7</td>
<td>9.9</td>
<td>1.4 × 10⁷</td>
<td>7.7</td>
<td>0.55</td>
</tr>
<tr>
<td>9</td>
<td>6.8</td>
<td>3.5 × 10⁵</td>
<td>4.6</td>
<td>0.78</td>
</tr>
</tbody>
</table>

where: 
μsat = \( \frac{\partial \sqrt{I_D}}{\partial V_{GS}} \frac{2L}{W} \frac{1}{C_G} \),

SS = \( \frac{\partial \log_{10} I_D}{\partial V_{GS}} \)⁻¹.

The field-effect mobility (μsat) and subthreshold swing (SS) of the TFTs were estimated in the saturation regime of the transfer curve using the following equations.
unit area of the gate dielectric. The extracted TFT properties are reported in Table 2. The 3% O$_2$/Ar ratio a-BIZO TFT exhibited good transfer characteristics at $V_{DS} = 30$ V, such as a $\mu_{sat}$ of 9.7 cm$^2$V$^{-1}$s$^{-1}$, a $V_{th}$ of 5.3 V, an SS of 0.77 V per decade, and an $I_{ON}/I_{OFF}$ ratio of $2.5 \times 10^5$. In addition, the forward and reverse sweeps of the TFT hysteresis are negligible. The transfer ($I_{DS} - V_{DS}$) and output characteristics obtained from the 3% O$_2$/Ar ratio of the a-BIZO TFT are shown in Fig. 4(b) and (c). The drain current $I_D$ in the outer curve increased linearly at a low-drain-source voltage ($V_{DS}$), indicating that the ohmic contact was consistently made between the a-BZIO and Mo electrodes and showed clear saturation behavior at high $V_{DS}$. In addition, no signs were observed of the current crowding phenomenon in the low-drain voltage regime.\textsuperscript{38}

Conclusions

In summary, we investigated the a-BIZO thin-film as an active channel layer material for oxide TFT fabrication. The a-BIZO thin-films with various O$_2$/Ar ratios were deposited using sputtering. The structural properties of the a-BIZO thin-films were analyzed using XRD and TEM. The amorphous nature of the a-BIZO thin-films was confirmed by XRD and TEM. The average transmittance of the a-BIZO thin-films was shown to be over 80% in the wavelength range between 400 and 800 nm. The 3% O$_2$/Ar a-BIZO TFT exhibited a saturation field effect mobility of 9.7 cm$^2$V$^{-1}$s$^{-1}$, a subthreshold swing of 0.77 V per dec, and an $I_{ON}/I_{OFF}$ ratio of $2.5 \times 10^5$. However, the same deposition conditions of undoped a-IZO TFTs showed a conductive nature. These results indicated that the B$_2$O$_3$ dopant strongly suppressed the concentration. B acts as a strong carrier suppressor, due to the high boron–oxygen bond-dissociation energy and the high Lewis acid strength of B ions, resulting in high performance of a-BIZO TFTs. The high mobility amorphous oxide TFT can be achieved by varying the B doping percentage and various deposition conditions. The results of the present study aid in the design of high performance novel amorphous oxide TFT fabrication.

Acknowledgements

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References