Flexible Transparent InGaZnO Thin-Film Transistors on Muscovite Mica

Wenxing Huo, Zengxia Mei, Yanxin Sui, Zuyin Han, Tao Wang, Huili Liang, and Xiaolong Du

Abstract—In this paper, we report the fabrication of flexible and transparent InGaZnO thin-film transistors on muscovite mica substrates. The mica substrate is compatible with four-step photolithographic processes as well as high-temperature processes. The field-effect mobility, subthreshold swing, OFF ratio, threshold voltage, and hysteresis in voltage are improved after annealing both at 300°C and 400°C in nitrogen. The device demonstrates more stable performance under positive gate bias stress when annealed at 400°C than at 300°C. The electrical performances are stable when exposed to tensile bending cycles up to 10,000 times. The mica with devices shows small optical loss in the visible region, where the average transmittance is as high as 86.75%.

Index Terms—InGaZnO (IGZO), Flexible electronics, mica substrate, thin-film transistors (TFTs).

I. INTRODUCTION

SINCE 2004 [1], amorphous oxide semiconductors-based flexible thin-film transistors (TFTs) are attracting significant attention because they are considered as the most promising candidate for next-generation flexible display systems [2]–[4] and many non-display applications [5]. However, the requisite processing temperature, which is essential to eliminate the defects [6]–[8], decreases the contact resistance between the channel and the source/drain electrodes [9], and gives rise to better device performance and stabilities, is generally too high for many common polymer substrates. Susceptibility to gas permeation and large thermal expansion coefficient are the other drawbacks of polymers [10]. Thin metal foils are compatible with high-temperature processes, but their comparatively rough surface requires extra pretreatments, either polishing or planarization for instance [11]–[13]. An insulating layer is necessary for insulation between the electrodes and substrates as well as preventing oxidation of the metal substrates [13]. In addition, they are completely nontransparent.

Mica is a well-known layered silicate compound which has been suggested as an alternative flexible substrate [14]–[16] due to its outstanding features: high melting point (700°C–1100°C) compatible with modern thin-film processes, 2-D structure with atomically flat surface, highly transparent in the ultraviolet-visible-infrared spectra, elastic, flexible, electrically insulating, chemically inert, nontoxic, inexpensive and abundant, lightweight, biocompatibility, and compatible with all deposition techniques [17]. Therefore, mica would be an excellent flexible substrate for TFTs. Despite the challenges in large-area production at present, functional materials and devices have been developed on mica, including flexible heaters based on transparent conducting oxides (TCOs) of indium tin oxide (ITO) [18] and Al-doped zinc oxides [19], spintronics material of Fe3O4 [20], flexible ferroelectric capacitors and piezoelectric energy harvester based on PbZr0.52Ti0.48O3 [21], [22], nonvolatile memories based on BaTi0.95Co0.05O3 [23] and Ba3.25La0.75Ti3O12 [24], and topological insulator of Bi2Se3 [14]. Note that the fabrication procedure of all these devices only contains at most one-step photolithographic process [14]. However, the practical application of mica substrates in the optoelectronic and microelectronic industries requires scaling down of device sizes and integration of various kinds of devices, where multistep photolithography is unavoidable in most cases.

In this paper, we fabricate the regular inverted-staggered InGaZnO (IGZO) TFTs on muscovite mica substrates following conventional fabrication processes [25]–[27] to verify the feasibility of multistep photolithography toward mica. The effect of thermal annealing on the improvement of device performance was investigated, combined with the flexibility of IGZO TFTs.

II. EXPERIMENT

The muscovite mica substrates (15 mm × 15 mm × 0.15 mm, grade V-4, SPI Supplies) were exfoliated by
Annealed at 400 °C IGZO TFT on mica, where the scale bar represents 100 μm.

etching (HCl:HNO₃:H₂O) and patterned by the first-step UV-lithography and wet etching (hot dilute AZ 300MIF developer). A 25-nm-thick IGZO channel layer is deposited by RF-magnetron sputtering at 100 °C with Ar/O₂ = 10:1, then patterned by the third-step UV-lithography and wet etching (dilute hydrochloric acid). Finally, a 100-nm-thick ITO source/drain electrode is deposited by RF-magnetron sputtering and patterned by a lift-off method with the fourth-step UV-lithography. The completed TFTs undergo thermal annealing at 300 °C (denoted by 300AN) and 400 °C (denoted by 400AN) for 1 h in nitrogen, respectively. Then, the mica substrates are further exfoliated from the back side to 15 by 400 μm. The four-layer unpatterned films are also sequentially deposited on mica for transmittance measurement.

Transmittance spectra are measured with an ultraviolet spectrophotometer (UV-3600Plus, Shimadzu). Current–voltage (I–V) characteristics in dark are obtained by using a Keithley 4200 system. More details about the fabrication processes and device characterizations can be found elsewhere [13], [25]–[27].

III. RESULTS AND DISCUSSION

A circular TFT structure is employed to favor the bending direction independence and improve the stability of IGZO TFTs under tensile bending strain [28]. The inner cycle is the source and the outer ring is the drain, which is shown in the inset of Fig. 1(c). The channel length (L) is 16 μm and the effective channel width (W) is 1633 μm [13]. The field-effect mobility (μFE) and subthreshold swing (SS) are derived from the forward sweep of transfer characteristics with a drain voltage (V_DS) of 0.1 V using the following equations [4]:

$$\mu_{FE} = \frac{L}{W \cdot C_{ox} \cdot V_{DS}} \cdot \frac{dI_{DS}}{dV_{GS}}$$

$$SS = \left( \frac{dV_{GS}}{d\log_{10}(I_{DS})} \right)_{\text{max}}$$

where C_ox is the specific capacitance of the gate dielectric per unit area, I_DS the drain current, and V_GS the gate voltage. The threshold voltage (V_th) is defined as the value of V_GS when I_DS = W/L*1 nA in the linear region. The hysteresis voltage (V_H) is defined as the difference in V_th extracted from V_GS sweeps between OFF-to-ON and ON-to-OFF.

First, we characterized the transmittance spectrum of IGZO TFTs on mica, as well as that of bare mica and mica with four-layer unpatterned films, as shown in Fig. 1(a). The inset shows that the flexible and transparent IGZO TFTs were wrapped around a pencil, marked with a dotted square in red. The average transmittance in the visible region (400–760 nm) is 90.62%, 86.75%, and 78.25% for bare mica, mica with TFTs, and mica with unpatterned films, respectively. The optical loss is mainly caused by the ITO films with a total thickness of 200 nm, which can be further reduced by replacing ITO with sandwiched TCO films [29].

Fig. 1(b) shows the transfer characteristics for the as-fabricated and annealed IGZO TFTs measured at V_DS = 0.1 V. The remarkable clockwise hysteresis behavior observed in the as-fabricated device is diminished after thermal annealing, where 400AN suppressed to a greater extent than 300AN. The electrons driven by the forward V_GS sweep accumulate at the channel–dielectrics interface and contribute to the clockwise hysteresis [30]. The extracted electrical parameters from the transfer characteristics are summarized in Table I. The μFE and ON/OFF ratio increase with elevated annealing temperature, while SS, V_th, and V_H decrease, indicating a better device performance after annealing. The improvement could be attributed to the reduction in trap states in IGZO channel, Al₂O₃ dielectric, and their interface [8], [31]. The transfer and output characteristics for the IGZO TFTs annealed at 400 °C are shown in Fig. 1(c) and (d), respectively. The gate current I_GS is in the order of 10⁻¹³ A. The output curves show a good ohmic contact between the IGZO channel and ITO electrodes and no current crowding phenomena.

Fig. 2 presents the positive gate bias stress (PBS) characteristics of 300AN and 400AN IGZO TFTs. The transfer characteristics were measured at V_DS = 0.1 V under a gate bias stress of V_GS = 20 V at set intervals. The PBS results in

### Table I

**Summary of TFT Parameters of As-Fabricated and Annealed IGZO TFTs**

<table>
<thead>
<tr>
<th>Samples</th>
<th>μ_FE (cm²/V·s)</th>
<th>SS (V/dec)</th>
<th>ON/OFF ratio</th>
<th>V_th (V)</th>
<th>V_H (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-fabricated</td>
<td>0.20</td>
<td>0.81</td>
<td>10^6</td>
<td>8.5</td>
<td>10.0</td>
</tr>
<tr>
<td>300AN</td>
<td>0.62</td>
<td>0.66</td>
<td>10^7</td>
<td>6.4</td>
<td>2.4</td>
</tr>
<tr>
<td>400AN</td>
<td>3.03</td>
<td>0.65</td>
<td>10^8</td>
<td>3.6</td>
<td>0.45</td>
</tr>
</tbody>
</table>
ranges from 14 to 10 mm. Since the TFT structure is circular, there is no bending direction dependence [28]. The measurement method is similar to [13], with a different $V_{DS}$ of 0.1 V. The evolution of the transfer curves is shown in Fig. 3(a). $I_D$ and $I_{DS}$ in the OFF state are in the order of $10^{-13}$ A, indicating the absence of cracking-induced gate leakage. The variations in $\mu_{FE}$ and $V_{th}$ as a function of the bending radius are shown in Fig. 3(c). $V_{th}$ shifts in the positive direction for all radii and does not get recovered immediately after the refatten. The change in $\mu_{FE}$ can be ignored. The positive $V_{th}$ shifts are supposed as the result of the built-in strain in the device layer which is larger than the bending induced strain [4], [35]. The fatigue test of the flexible IGZO TFTs is further performed with a self-assembled slide table system, as shown in the inset of Fig. 3(d). The device is stable after undergoing 10 000 bending cycles with $r = 10$ mm, as shown in Fig. 3(b). Repetitive tensile bending stress also exhibits a positive shift in $V_{th}$ and negligible change in $\mu_{FE}$, as shown in Fig. 3(d). The variations are close to the values measured by one-time bending test in Fig. 3(c).

IV. CONCLUSION

In summary, flexible and transparent IGZO TFTs have been successfully fabricated on the mica substrate, indicating that mica is compatible with multistep photolithographic processes. The average transmittance of the device in the visible region is as high as 86.75%. The device performance and stabilities are improved after annealing at 400°C. The electrical performances are stable under tensile bending cycles up to 10 000 with a radius of 10 mm. These results highlight the potential applications of mica substrates in flexible and transparent optoelectronics and other electronic devices.

REFERENCES


