Effect of mechanical stress on the stability of flexible InGaZnO thin-film transistors

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ABSTRACT

Demonstrated herein is the effect of mechanical stress on the device performance and stability of amorphous indium–gallium–zinc oxide thin-film transistors (TFTs) on a flexible polyimide substrate. Flexible TFTs were placed on jigs with various bending radii to apply different degrees of mechanical strain on them. When the tensile strain on the TFTs was increased from 0.19% to 0.93%, the threshold voltage shifted after a 10,000 s increase in bias–temperature–stress (BTS), under vacuum conditions. The BTS instability was further exacerbated when the device was exposed to the air ambient at a 0.93% strain. The device reliability deteriorated due to the increase in the subgap density of states as well as the enhanced ambient effects via the strain-induced gas permeation paths.

1. Introduction

Flexible displays have gained much attention due to their thinness, lightness, and durability, along with their adaptability to arbitrarily shaped surfaces compared to the conventional glass substrate-based displays. Flexible displays experience external mechanical stress with a small radius of curvature (R), especially rollable and foldable displays. In addition, various forms of flexible user interface require various bending radii according to the specific user application. Among the many existing flexible substrates, such as plastic films, metal foil, and thin glass [1,2], polyimide (PI) plastic films are commonly used for fabricating flexible displays due to their high glass transition temperature (∼400°C) and low coefficient of thermal expansion (10 < ppm K⁻¹) [3].

Amorphous indium–gallium–zinc oxide (a-IGZO) thin-film transistors (TFTs) have desirable electrical properties, such as high mobility, high $I_{ON}/I_{OFF}$ ratio, and good stability, compared to the conventional amorphous silicon, as well as a low process temperature, good uniformity, and a low fabricating process cost, making it suitable for flexible applications. Several research groups have reported the electrical performance of flexible a-IGZO TFTs under mechanical stress, but no significant change has been observed [4–9]. Moreover, the origin of instability degradation under mechanical stress is still not completely understood.

Reported in this paper are the electrical performance and stability of a-IGZO TFTs on a PI substrate for various degrees of mechanical stress created by changing the bending radius. Harsh mechanical, electrical, and thermal stress conditions were applied until differences in instability characteristics were observed, to investigate the effect of mechanical strain on the device characteristics. Furthermore, the instability was measured in both vacuum and air conditions to study the ambient effect. Also, the subgap density of states (DOS) was extracted to understand the origin of strain-induced instability.

2. Experiment

Top-gate/bottom-contact structure a-IGZO TFTs were fabricated on a PI substrate, as shown in Figure 1(a). First, a 140-nm-thick aluminum oxide ($\text{Al}_2\text{O}_3$) buffer layer was deposited via atomic layer deposition (ALD) at 200°C on a 17-μm-thick PI film. Source and drain electrodes were formed by depositing a 150-nm indium-tin oxide (ITO) layer via RF magnetron sputtering patterned through a wet-etch process using a mixed acid etchant, including HCl, HNO₃, and acetic acid. The active layer was formed...
through the deposition of 30-nm a-IGZO via RF magnetron sputtering, followed by the deposition of a 100-nm Al2O3 gate insulator at 200°C via ALD. The active and gate insulator layers were patterned via wet etching using diluted hydrofluoric acid (H2O:HF = 200:1) and phosphoric acid, respectively. Then a 150-nm ITO gate electrode was formed. Post-annealing was conducted at 250°C for 1 h. Finally, the PI films were detached from the glass substrate.

To apply mechanical stress, the flexible TFT stack was placed and fastened on bending jigs with 10, 5, and 2 mm radii, which correspond to 0.19%, 0.38%, and 0.93% strain ($\varepsilon$), respectively. The electrical properties of the TFTs were evaluated under dark conditions using an HP 4155A semiconductor parameter analyzer.

### 3. Results and discussion

Figure 2(a) shows the transfer curves of the a-IGZO TFTs while attached to the bending jigs with various radii. Figure 2(b), on the other hand, shows the device parameters, such as the saturation field effect mobility ($\mu_{sat}$), threshold voltage ($V_{th}$), and subthreshold swing (SS), at different strains. The devices on a jig with a smaller R had more positive $V_{th}$ values as well as marginally larger SS values. The SS degradation was presumably due to the increased interface trap density.

The $\mu_{sat}$ values were 12.5, 11.3, and 9.9 cm$^2$ V$^{-1}$ s$^{-1}$ at $\varepsilon = 0.19\%$, 0.38\%, and 0.93\%, respectively. The hump-like behavior at $\varepsilon = 0.93\%$ showed an increase in SS as well as a current drop, which can be explained by the creation of acceptor defects near the conduction band edge [10, 11]. The source/drain series resistance ($R_{sd}$) with different strains was extracted through the transmission line method, using the following equation:

$$R_{tot} = R_{sd} + R_{chan} = \frac{V_{DS}}{I_D} = R_{sd} + \frac{L - \Delta L}{\mu_{eff} C_{ox} W (V_{GS} - V_{th})},$$

where $C_{ox}$ is the capacitance per unit area of the gate dielectric (F cm$^{-2}$), $L$ is the physical gate length, and...
ΔL is the difference between L and the electrically effective channel length. The 20, 40, and 80 μm L values were used for R_{tot}-L extrapolation while the channel width (W) was fixed at 40 μm. As the strain increased from 0.19% to 0.38% and 0.93%, the width-normalized series resistance (R_{sd-W}) increased from 19.0 to 29.6 and 43.9 Ω cm, respectively. The higher series resistance at a high mechanical strain could have been due to the contact resistance degradation by the local delamination of the ITO electrodes [12], and/or to the increase in the access resistance due to the defect formation in the active layer [10].

Next, the device reliability was evaluated while the TFTs were under tensile strain. Figure 3(a) shows the evolution of V_{th} with respect to the duration of bias-temperature-stress (BTS). The negative (N) and positive (P) BTS conditions were V_{GS} = ±20 V at 60°C for 10,000 s, respectively. To distinguish the ambient effect, measurements were done in a 10 mTorr vacuum to eliminate the external ambient effects, and in an air environment (relative humidity: 30%). Under the NBTS, the stress-free device (strain: ε = 0) showed a smaller change (−0.38 V) in the threshold voltage (∆V_{th}) in the vacuum condition than in the air ambient condition (∆V_{th shift} = −0.58 V). As the strain increased from 0.19% to 0.93% in the vacuum condition, the ∆V_{th shift} increased from −0.5 to −0.97 V.

Ambient effects are significant in flexible TFTs because PI is known to absorb water due to its high water vapor permeability [13,14]. When measurements are performed in vacuum conditions, less water molecules in the ambient are absorbed in the PI substrate. When measured in air, the BTS instability worsens due to the mechanical stress and is further accelerated by the external ambient effects. In this study, the device with ε = 0.19% showed a −1.35 V ∆V_{th shift} while the device with ε = 0.93% significantly degraded the ∆V_{th shift} (−6.49 V) under the NBTS. After the PBTS, the device with ε = 0.19% showed a 0.65 V ∆V_{th shift} while the device with ε = 0.93% showed a 4.96 V ∆V_{th shift}. This suggests that the BTS instability is degraded under the combined effect of the mechanical stress and the ambient.

To further investigate the origin of the instability of a-IGZO flexible TFTs, the subgap DOS of the TFTs was extracted at different strains. The DOS was extracted through the Meyer–Neldel (MN) rule method, using measurement temperatures ranging from 25°C to 115°C [15]. Figure 4 shows the extracted DOS profile of the TFT devices at different strains. The device with 0.93% strain had one to two orders of magnitude-higher DOS than the two other strain cases over the entire energy range. A large mechanical stress induces higher trap states.

**Figure 4.** Extracted DOS distribution of the flexible a-IGZO TFTs with various strains as a function of energy relative to the conduction band minima.

**Figure 3.** (a) BTS (V_{GS} = ±20 V at 60°C) time evolution of the threshold voltages for the ε = 0.19% (circle) and 0.93% (square) cases in vacuum (Solid/Black) and air ambient (Hollow/Red). (b) V_{th} shift after 10,000 s BTS for different strain and ambient conditions.
that can affect the TFT reliability because the excess electrons at the insulator/semiconductor interface are easily activated by the external thermal and gate bias stress.

Previous reports discovered crack formation inside TFTs through an optical microscope, which resulted in the degradation of the flexible TFT performance under mechanical stress [16]. No cracks were observed in the flexible TFTs, however, under mechanical stress. Two possible degradation mechanisms are thus proposed herein.

First, when TFTs receive external mechanical stress, trap sites or defect states are easily formed at the interface between the two materials with different Young’s modulus values. The Al2O3 dielectric, α-IGZO, and ITO layer have Young’s modulus values of 300, 137, and 190 GPa, respectively [17,18]. When equal strain is applied to each layer, the Al2O3 dielectric layer undergoes larger stress than the other layers, which can then generate structural defects at the interface with the active layer. When more strain is applied, the $V_{th}$ shift is accelerated after BTS. This may be due to the interface defects in vacuum conditions.

Second, microcracks are formed when devices are subject to mechanical stress, although the formed microcracks may not be large enough to be detected optically. Microcracks may provide a permeation path for gas molecules (H2O, O2) from the ambient to reach the α-IGZO channel [19]. Especially, H2O molecules, which are prevalent in the underlying PI, can permeate through the dielectric layers to be adsorbed at the interface and hence donate electrons to the active layer [14,20]. Therefore, the worst-case scenario for BTS degradation occurs under the combined influence of mechanical stress and the air ambient. Hence, to suppress gas permeation paths along strain-induced defects, which are detrimental to the device reliability, implementing barrier and passivation schemes robust against mechanical bending is crucial.

4. Conclusion

In this work, the effect of mechanical stress on the device performance and reliability of flexible α-IGZO TFTs was studied. As the bending radius decreased, the on-current was reduced due to the increased series resistance. Furthermore, as the mechanical stress increased, the device reliability deteriorated due to the increase in the subgap DOS and the enhanced ambient effects. Such dependence on both mechanical strain and the ambient suggests that there is a combinative effect of an increase in the interface defect states and H2O permeation through the microcracks in the dielectric layers induced by mechanical stress. The flexible TFT stacks must be mechanically robust at the target bending radius under ambient conditions to satisfy the reliability requirements for the user-specific application.

Disclosure statement

No potential conflict of interest was reported by the authors.

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