Highly Robust Bendable a-IGZO TFTs on Polyimide Substrate with New Structure

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Abstract

A new flexible TFT backplane structure with improved mechanical reliability is proposed. Amorphous indium-gallium-zinc-oxide (a-IGZO) thin film transistors based on this structure have been fabricated on a polyimide substrate, and the resultant mechanical durability has been evaluated in a cyclic bending test. The panel can withstand 10,000 bending cycles at a bending radius of 5 mm without any noticeable TFT degradation. After 10K bending cycles, the change of threshold voltage, mobility, sub-threshold slope, and gate leakage current were only -0.22V, -0.13cm^2/V-s, -0.05V/decade, and -3.05×10^{-13}A, respectively.

1. Introduction

Recently, active matrix organic light-emitting diodes (AMOLEDs) have received considerable attention because they have many attractive features including self-emission, low power consumption, wide viewing angle, wide color gamut, and fast response time [1,2]. To realize a flexible or rollable AMOLED display, a new device structure for small critical bending radius needs to be developed.

Many groups have been examining the strain effect on amorphous silicon thin film transistors (TFTs) performance from the late 1990s [3,4]. Suo *et al.* reported a theoretical analysis of mechanical strain in a thin coating deposited on a flexible substrate and the concept of the neutral surface with no strain applied [3,4]. In order to achieve a device with a small bending radius, materials with a small Young's modulus are required. Metals and dielectric materials commonly used in TFTs such as ITO, Mo, MoW, SiO_xN_y, SiO, and SiN have a high modulus and are brittle [4,5]. Therefore, it is very difficult to achieve a small (in the range of a few mm) bending radius for an inorganic TFT without any mechanical damage to inorganic layers. For example, critical bending radii of 7mm and 9mm were reported for SiO_xN_y and ITO, respectively, on 125µm and 180µm thick PET plastic substrates [6,7].

In this paper, mechanical failure conditions and the cause of performance degradation in indium-gallium-zinc oxide (a-IGZO) TFTs are evaluated. Based on these results, a new approach is suggested for strain-release of thin-film electron devices on flexible substrates, such as flexible AMOLED displays. The new structure can withstand a small bending radius, thereby enabling flexible and rollable displays.

2. Experiments

N-channel a-IGZO TFTs with an inverted staggered structure were fabricated on 10~50µm thick polyimide substrates. In order to prevent permeation of oxygen and water through the back side of the polyimide substrate, a barrier multilayer consisting of SiO_2 and SiN_x was deposited on the polyimide (PI) substrate. For gate metal, 2000Å-thick Mo was deposited and patterned using conventional sputter and photo-lithography. A 1000Å-thick SiN_x gate insulator was grown using plasma enhanced chemical vapor deposition (PECVD). A-IGZO semiconductor with 500Å-thickness was sputter-deposited and patterned following etch stop layer (ESL) deposition. After making contact holes, Mo (300nm) was sputter-deposited and patterned for source-drain metal. Finally, the planarization layer, pixel electrode, and pixel defining layer (PDL) were formed on the ESL.

The OLED device structure consisted of a hole injection layer (HIL), hole transport layer (HTL), RGB emitting layer (EML), hole blocking layer (HBL), electron transfer layer (ETL), electron injection layer (EIL), and transparent cathode. A multilayer thin film structure composed of inorganic and organic layers was used for flexible encapsulation.

For bending experiments, the TFT backplane on PI substrate was laminated on protective film (adhesive-coated polymer film) or sandwiched between two protective films.

3. Results and discussion

When a TFT on substrate is bent, the top surface of the TFT (ε_{top}) experiences a tensile strain and the bottom surface of the substrate has a compressive strain as shown in Fig.1(a). When we do not take the difference of modulus and thickness of the substrate and TFT into consideration, a neutral surface (no strain applied, $\Delta L=0$) is formed exactly in the middle of total stack. Then, the strain can be calculated as in equation (1) [3,4]:

$$\varepsilon_{top} = \frac{\Delta L}{L} = \frac{(r + d/2)\,\theta - r\theta}{r\theta} = d/2r \quad (1)$$

However, when the difference of modulus and thickness of TFT and substrate are considered to make a more accurate estimate, the strain of the top surface of TFT (ε_{top}) can be calculated according to equation (2) [3,4]:

$$\varepsilon_{top} = \left(\frac{d}{2r}\right) A = \left(\frac{d}{2r}\right) \frac{\left(1 + 2\eta + \chi\eta^2\right)}{(1+\eta)(1+\chi\eta)} \qquad (2)$$

where A is the correction factor, $d=d_f+d_s$, $\eta=d_f/d_s$, and $\chi=Y_f/Y_s$. For a thin coating of TFT (1.5μm, 8.5GPa) on sufficiently thick substrate including a protective film (103μm, 200GPa), $\eta=0.015$ and $\chi=23.5$, the correction factor (A) is estimated to be ~0.8, similar to 1 which is the value calculated based on the assumption that there is no difference between the modulus of TFT and substrate and the neutral plane exists just in the middle of the total thickness. Therefore, we may assume that the neutral plane exists approximately in the middle of total thickness for a thin TFT on significantly thick substrate.

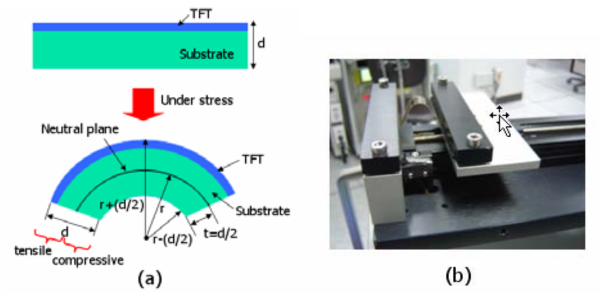

Fig. 1. (a) Position of neutral surface under bending and (b) cyclic bending test equipment.

For one-time bending, the TFT sample was bent for 1 min at each radius, going from R=50mm to 3mm. After bending to each curvature, the TFT I-V characteristics were measured in the flat state. Total sample thickness including PI film, protective film and TFT backplane was about 100μm. Protective film was attached to the back side of the TFT/PI sample i.e. the film was facing the PI substrate. The evolution of TFT ON-current (I_{ON}), OFF-state current (I_{OFF}) and gate leakage current (I_G) with bending radius is shown in Fig. 2(a) for inward and outward bending. For outward bending, an increase in I_G current and I_{OFF} current was observed at R=10mm followed by electrical failure (typically a short circuit between source-drain and the gate). Simultaneously, a microscope inspection revealed cracks that propagated through inorganic layers (Fig 2b).

The calculated failure strain for outward bending was estimated to be about 0.5%. Similar estimates for inward bending indicated that critical compressive strain must exceed at least about 1% (no failure at R=5 mm). These values are similar to those in a-Si TFTs where the failure strains were reported to be in the range of 0.3%-0.5% and ~2% under tensile stress and compressive stress, respectively [4,8,9]. The microscopic picture and FIB-SEM (focused ion beam scanning electron microscope) picture showed that wherever cracks happened, they propagated through all of the deposited layers. It is non-trival to determine the point from which the cracks originate.

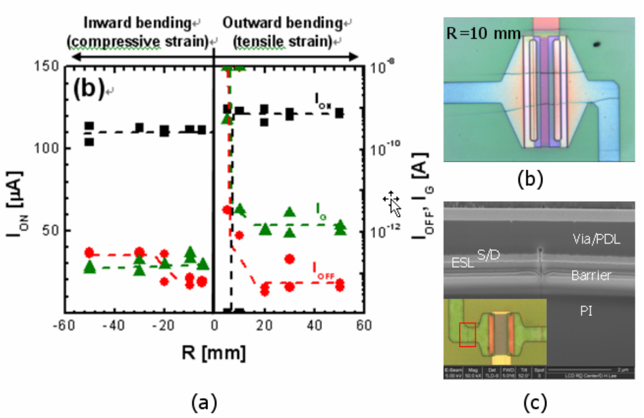

Fig. 2. (a) Change of TFT of I_{ON}, I_{OFF}, and I_G with bending curvature. Left and right sides correspond to inward and outward bending, respectively; sample thickness ~100μm, (b) microscopic picture of the crack occurring at R=10 mm in outward bending, and (c) FIB-SEM picture showing cross-section of the crack.

In order to reduce strain on the TFT layers and to enable reduction of the critical bending radius, a new structure is suggested. Here, the TFT backplane on a thin PI substrate is sandwiched between two protective films (Fig. 3).

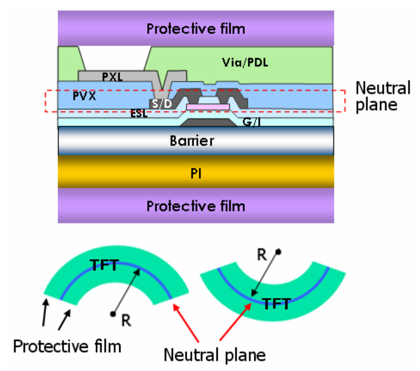

Fig.3. Cross-section of new structure which reduces strain on the TFT.

The strain on the TFT structure under both inward and outward bending is reduced by establishing a neutral plane for the TFT layers. For a total thickness of protective films and TFT/PI backplane of ~200 um, the sample showed no layer cracking under outward bending to R=5mm. This value is half that of the critical radius of the previous structure.

To evaluate mechanical durability of a flexible a-IGZO TFT backplane, a cyclic bending test was also performed. The substrate was bent with TFTs facing inwards. The curvature radius during the bending cycle was fixed at either 10 or 5 mm. TFT transfer characteristics were measured before the cyclic test and after 200, 500, 1000, 2000, 5000, and 10,000 bending cycles. The change of TFT characteristics and performance parameters according to the number of bending cycles is shown in Fig, 4(a-f). No visible change in TFT transfer characteristics was observed after 10,000 bending cycles at R=5 mm were applied to the new structure.

The changes in threshold voltage, mobility (μ_{FE}), subthreshold slope (S) and gate leakage current were small and were extracted to be -0.22V, -0.13 cm^2/V-s, -0.05 V/decade, and ~3.05×10^{-13}A respectively. Small, insignificant variations in I_{ON}/I_{OFF}-ratio were believed to be due to instrumentation leakage and noise when measuring low off-state currents.

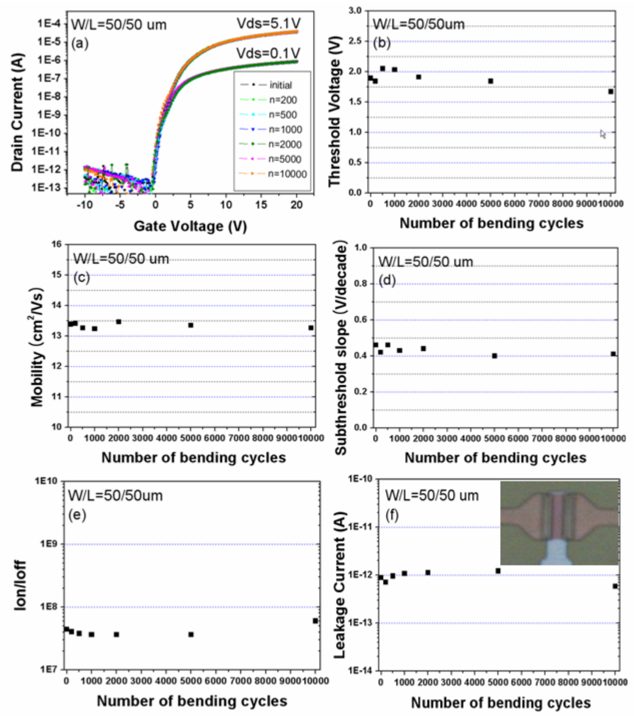

Fig. 4. Electrical properties of a-IGZO TFTs on polyimide substrate vs. number of bending cycles: (a) transfer curve, (b) threshold voltage, (c) mobility, (d)subthreshold voltage, (e) I_{ON}/I_{OFF} ratio, and (f) gate leakage current; inset shows microscopic picture of a-TFT subjected to compressive deformation with bending radius of R=5mm.

The fact that there is no substantial change of subthreshold slope (S), mobility (μ_{FE}), and threshold voltage (V_{th}) shows that there is no considerable increase in deep states or tail states in the a-IGZO semiconductor or its interface with the gate dielectric. After-test microscopic inspection also revealed that there was no layer cracking or any other mechanical damage to the test samples as shown in the Fig. 4(f) inset.

Thus the proposed TFT backplane structure can withstand prolonged cyclic bending to a small radius of curvature without any degradation of TFT characteristics. We believe that small bending radius and good mechanical durability can be achieved because the neutral, strain-free, surface is established in close proximity to TFT layers. As a result, bending-induced strain in brittle TFT inorganic layers (gate dielectric, ESL, metal layers, etc.) has been reduced and the mechanical robustness of the TFT backplane has been improved.

Figure 5 shows the photograph of the world largest 6.5-inch flexible full color top emission AMOLED display on a PI substrate. Here, the flexible panel is bent to a radius of approximately 2cm. The panel has a pixel resolution of 160×RGB×272 (WQVGA, 85ppi resolution), 256 gray colors, and an aperture ratio of 53%. The overall thickness of the AMOLED display was <0.1mm. The displayed image was observed without any visible distortion even when the display was bent to a curvature of approximately 2cm.

Fig. 5. Display images of the 6.5-inch flexible full-color top emission AMOLED on PI substrate.

4. Summary

A new improved flexible backplane structure has been proposed to effectively reduce mechanical strain in TFT layers under bending deformation by establishing the TFT layers close to the neutral plane. This new structure can be bent to a 5 mm curvature radius without any device degradation. Moreover, no TFT degradation and no mechanical damage were observed after 10,000 bending cycles at a bending curvature of 5mm. The new strain-release structure enables the manufacture of electronic devices with significant mechanical flexibility and robustness using conventional brittle inorganic films. By combining our new strain-release structure with an a-IGZO TFT backplane using top-emitting OLEDs and thin-film encapsulation on a polyimide substrate, we have been able to construct and demonstrate a 6.5-inch full color light-weight and highly-flexible AMOLED display.

5. References

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