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Effects of mechanical stresses on the reliability of low-temperature polycrystalline silicon thin film transistors for foldable displays

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ABSTRACT

This paper investigates the mechanical reliability of low temperature polycrystalline silicon (LTPS) thin film transistors (TFTs) for foldable display. Both compressive and tensile directions of mechanical stresses were applied for different types of mechanical stresses, such as dynamic and static mechanical stresses. The electrical characteristics of tested n-channel TFTs under mechanical stress conditions were analyzed based on several key parameters, including the threshold voltage (V_{th}), field effect mobility (μ_{FE}), maximum drain current ($I_{D.MAX}$) and subthreshold swing (S_{sub}). For both cases of dynamic and static mechanical stresses, increase of V_{th} and decrease of μ_{FE} and $I_{D.MAX}$ were observed in the compressive direction. This trend was inversed when tensile stress was applied. The degradation of electrical characteristics originates from the change of lattice constant after mechanical stress. However, S_{sub} increases under dynamic tensile stress while it remains unchanged within 5% under static tensile stress. Transient analysis while bent condition was conducted to investigate the change of parameters in time.

1. Introduction

Beyond flexible display, foldable displays and their applications are being actively researched. For example, foldable displays of which bending radius is smaller than 5 mm were presented by major display companies, such as LG Display and Samsung Display, at CES 2016. Thin-film transistor (TFT) fabricated on flexible polyimide (PI) substrates, which is suitable for foldable and flexible displays, are now being researched due to their promising properties [1]. The low temperature polycrystalline silicon (LTPS) TFT, one of many types of TFTs, has been widely used in recent displays. The LTPS TFT has the highest performance in terms of mobility (40–100 cm^2/Vs), and it can be easily implemented in CMOS architectures [2]. To achieve successful advances in foldable displays prior to mass manufacturing, the reliability of the devices and substrates should be guaranteed when they are stressed mechanically. Dynamic and static mechanical stresses are both important for foldable display applications such as foldable tablet. There have been a few studies published regarding the dynamic and static mechanical stresses on LTPS TFTs [3–5]. Münzenrieder et al. investigates the effect on indium gallium zinc oxide TFTs for dynamic mechanical stress [6]. Also, Janfaoui et al. [4] showed the effects of static mechanical stress on the electrical parameters. However, their studies lack of the connection of dynamic and static stresses. Thus, it is necessary to clarify the effect of dynamic and static mechanical stresses on LTPS TFTs. In this paper, we investigate the effects of mechanical stress on LTPS TFTs. Within this study, two different types of mechanical stress tests that include both dynamic and static mechanical stresses were performed on n-type LTPS TFTs. For both types of tests, electrical parameters were analyzed after compressive and tensile stresses with a bending radius of 2.5 mm.

2. Experiments

2.1. Test structure fabrication

Top gate structure TFTs were fabricated on a polyimide (PI) substrate as shown in Fig. 1. Then a polycrystalline silicon channel was formed on top of the buffer layer. After LTPS channel formation, SiO_2 gate insulator layer was deposited before Cu/MoTi was deposited by sputtering as the gate metal. After interlayer dielectric deposition using SiO_2, Cu/MoTi was used for source and drain electrode deposition. Finally, SiO_2 was used as a passivation layer.

The tested TFTs had two different gate sizes. Both types of TFTs had the same gate length but different channel widths. The width/length ratios (W/L) for the TFTs were 1 and 9, respectively.

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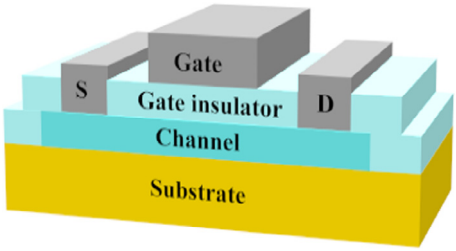

Fig. 1. Schematic of the structure of an LTPS TFT.

2.2. Mechanical stress tests

For the reliability tests of LTPS TFT, mechanical stress experiments including dynamic and static bending were performed with a bending radius of 2.5 mm which is corresponding to the strain of 0.35% [7]. The stress direction was tensile (upward) or compressive (downward), as shown in Fig. 2(a) and (b). For both stress directions, the bending axis was perpendicular to the channel length so that any cracks generated by the mechanical stress were perpendicular to the direction of current flow.

Mechanical stress tester and 2.5 mm radius bending chuck shown in Fig. 3(a) and (b) were used to apply the dynamic and static mechanical stresses, respectively. 100,000 times of bending cycles were repeated for the dynamic stress while total 72 h of mechanical stress was applied for the static stress. In case of dynamic stress, total duration for those repetitions was about 72 h (0.99 s per 1 cycle). Hence, the total duration of mechanical stress tests for both types was matched so that we can compare the results. Before and after the mechanical stress experiments, the tested TFTs were measured while flat. In order to investigate the electrical parameters transition while bent, the tested TFTs were additionally measured during the tensile static mechanical stress test every 24 h.

3. Results and discussion

3.1. Electrical parameter extraction

The current-voltage (I-V) characteristics were measured using a Keithley 236 source measure unit (SMU). For evaluation purposes, the electrical parameters were extracted from the I-V characteristics at V_{DS} = 2.1 V, and $I_{D.MAX}$ was defined as the drain current at V_{GS} = 20 V. The field effect mobility (μ_{FE}) was calculated using Eq. (1) [8]:

$$\mu_{FE} = \frac{L \cdot g_m}{W \cdot C_i \cdot V_{DS}}, \tag{1}$$

where g_m is the transconductance and C_i is the oxide capacitance.

The threshold voltage (V_{th}) was calculated by linear extrapolation in the linear region. In addition, the subthreshold swing (S_{sub}) was determined using Eq. (2) [9]:

$$S_{sub} = \left(\frac{\partial V_{GS}}{\partial \log(I_{DS})}\right) \tag{2}$$

For comparison purposes, the value of each parameter was normalized using the initial value measured at zero strain. Since every experiment was replicated three times to ensure sufficient statistical variability, the mean value for each parameter is shown. The maximum standard deviation from our experiments was 0.149. Also, the tested TFTs show good initial electrical characteristics including positive V_{th} (<3 V) and small S_{sub} (<0.6 V/dec).

3.2. Experimental results

Fig. 4 illustrates the energy band of electrons at the silicon atoms versus the lattice constant [9]. Based on the energy band theory, the energy states of the electrons in silicon atoms are split into conduction bands and valance bands when silicon atoms become close enough to form a lattice structure. That lattice structure determines the bandgap energy of the material. In the case of

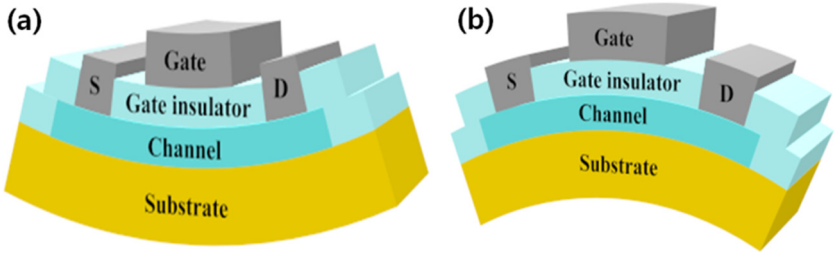

Fig. 2. Schematics of the (a) compressive and (b) tensile stress.

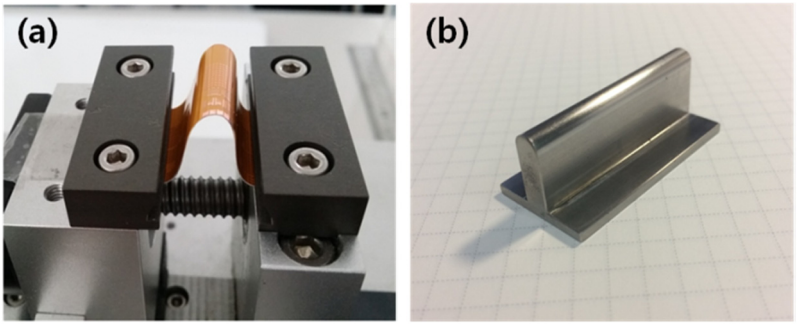

Fig. 3. (a) Mechanical stress tester used in the dynamic mechanical stress tests and (b) bending chuck used in the static mechanical stress tests.