Effect of selectively passivated layer on foldable low temperature polycrystalline silicon thin film transistor characteristics under dynamic mechanical stress

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Abstract

Article history:
Received 21 May 2017
Received in revised form 19 July 2017
Accepted 26 July 2017
Available online 7 August 2017

For the next generation display, foldable display is one of the attractive candidates. However, the degradation effects due to the mechanical stress on the device are unavoidable. A strain due to the mechanical stress generates cracks on the thin film transistors (TFTs). In this case, if the methodology guiding cracks is applied in the fabrication process, the device reliability can be enhanced. In this paper, a crack guided layer followed by the device fabrication process is deposited on p-type low temperature polycrystalline silicon (LTPS) TFT. Statistical analysis is also used to analyze the crack guided layer effects. To apply a strain on the foldable LTPS TFTs, 5000 cycles of dynamic mechanical stress with tensile and perpendicular directions were applied with 2-mm bending radius. Based on the results, TFT reliability can be enhanced by controlled the crack position using the crack-guided passivation layer.

Keywords:
LTPS TFT
Crack guided passivated layer
Dynamic mechanical stress
Foldable display

1. Introduction

As a next generation display, a foldable display is the most attractive candidate. For the foldable display, the selection of material system is critical to maintain the device reliability. The low temperature polycrystalline silicon (LTPS) is an attractive material that is suitable for foldable thin film transistor (TFT) because it exhibits high mobility, low processing temperature [1]. However, the repeated dynamic mechanical stresses can cause crack generation on the device, and it degrades device characteristics. Therefore, many studies have focused on the influence of compressive [2] or tensile [3] stress on the TFTs with single type of mechanical stress directions. Generally, since the cracks are generated at random locations, it is difficult to control the cracking position. However, there are some solutions to enhance a probability of the control the crack generation position. In previous research, the engraving crack guided (CG) structure work as a crack seed and it reduced device degradation during a dynamic mechanical stress [4]. However, the accurate etching process requires complicating process steps and increases fabrication cost.

In this paper, a passivated crack guided structures in selected areas on the p-type LTPS TFTs are fabricated to analyze the effect of crack guided structure on the device reliability. The accelerated mechanical stress tests with perpendicular and tensile strains are performed and the degradations of electrical characteristics of the tested TFTs are investigated. This proposed methodology can enhance the TFT reliability with better design of manufacturability.

2. Experiments and measurements

2.1. Device structure and measurement conditions

The experimented LTPS TFTs in this study are fabricated on a polyimide (PI) substrate with Cu/MoTi used as an electrode. Also, a silicon dioxide (SiO2) is used as a gate insulator and the polycrystalline silicon active layer is formed on top of the insulator layer. Also at the bottom of the substrate, polyethylene terephthalate (PET) is attached to increase a strain to the TFTs. In this paper, 3-types of the channel sizes (width/length [μm/μm] = 5/5, 5/10, and 5/20) are used. For the statistical analysis, the 18 samples are used for each channel size to verify the reproducibility.

Fig. 1 shows the schematic diagram of the experimented TFTs with the top-gate, top-contact structure. The current-voltage (I-V) characteristics of the tested TFTs are measured using a Keithley 236 source measurement unit (SMU). As the measurement condition, the drain voltage (VDS) is set to be 2.1 V and the gate voltage (VGS) is swept from −15 V to 5 V.
2.2 Mechanical stress and crack guided structure

The dynamic mechanical stress is applied using the flexible materials tester of Hansung systems incorporation. In this work, 2-mm (2R) bending radius is used for the accelerated dynamic mechanical stress experiment, and the strain is applied with tensile and perpendicular directions to the current path. Also, 5000 of bending cycles are used in this experiment. After every 1000 cycles of the dynamic mechanical stress test, the device laid in a re-flattened condition in order to measure the transfer curve. The crack guidance is deposited using sputter with 125 W RF powers during 20 min for a deposition process. In this process, titanium is used as a crack guided structure. The distance between the crack guided structure and the tested TFT is defined to be 3 mm.

3. Result and discussion

To calculate the strain on the tested TFTs, we assume that the strain ($\varepsilon$) is applied to the tested TFT where a neutral plane was formed in the middle of the total thickness. Using this approximation, the strain on the TFT device can be calculated as [5]:

$$\varepsilon = \frac{t_{\text{substrate}} + t_{\text{TFT}}}{2 \times R}$$  \hspace{1cm} (1)

where $t_{\text{substrate}}$ is thickness of the substrate and $t_{\text{TFT}}$ is thickness of the TFTs. The calculated strain with Eq. (1) for the 2R curvature is 1.67%.

The experiment results of dynamic mechanical stress with 5000 cycles are shown in Fig. 2. The cracks are generated on the titanium layer which is crack guided structure, and TFTs area cannot damaged by the stress.

To analyze the experiment result, on-current ($I_{on}$), mobility ($\mu_{FE}$), and subthreshold swing ($S_{sub}$) are calculated with normalized average and standard deviation. The on-current is defined as the $V_{GS} = -15$ V. The threshold voltage shift ($\Delta V_{th}$) is calculated as variation of a turn-on voltage, and the field effect mobility in the linear region is calculated as [6]:

$$\mu_{FE} = \frac{L G_m}{W C V_{DS}}$$  \hspace{1cm} (2)

However, after the 5000 cycles of dynamic mechanical stress, the normalized mobility calculated with moving average due to the device degradation with the characteristic fluctuation. The calculated results are shown in Table 1. The normalized data is calculated as:

$$N_{\text{data}} = \frac{N_{\text{bending}}}{N_{\text{initial}}}$$  \hspace{1cm} (3)

where $N_{\text{data}}$ is the normalized data, $N_{\text{initial}}$ is the data without the mechanical stress, and $N_{\text{bending}}$ is the data after the stress test with specific bending cycles.

In addition, the results of dynamic mechanical stress test are shown in Fig. 3. The transfer curves also normalized with Eq. (3). The electrical characteristics with crack guided structures are stable on every channel sizes. In the other hands, the result without crack guided structure shows degraded device characteristics on the every channel size. The degraded device characteristics are caused by generated cracks that disturb the movement of the carriers, especially in the channel layer of the TFTs [7]. Also, the charge accumulation in the channel becomes difficult due to the changed potential distribution. For these reasons, the characteristics are degraded on the TFTs without crack guided structure. Since the cracks are randomly generated, changes in the characteristics of TFT are not constant. However, when compared with the average changes and the increased standard deviation in Fig. 3 and Table 1, the effect of the crack guided structure is clearly shown. Without crack guided layer, the average of on-current and mobility are significantly reduced and the standard deviation is increased. In addition, the threshold voltage shift is increased. On the other hand, on-current, mobility and threshold voltage shift are stable with crack guided structure. Furthermore, the average variation of the subthreshold swing does not seem to be large, but the standard deviation is significantly reduced with crack guided layer. In addition, the longer channel length devices less degraded by dynamic mechanical stress, and it is clearly shown in Fig. 3.
The on-current is 23.8% more degraded on 5 μm channel length than 20 μm channel length device after 5000 cycles of dynamic mechanical stress. This based on beam theory, and the length dependent critical strain can be known as the following Eq. (4) [8]:

$$ \varepsilon_{\text{critical}} = \frac{\pi^2 h_s^2}{12L} $$

where $h_s$ is the substrate thickness and $L$ is the beam length. According to the beam theory, the crack is generated when the total strain exceed the critical strain. In Eq. (4), as the beam length increased, the critical strain is decreased. Normally, the longer channel length device was more degraded on the mechanical stress with parallel strain. However, in this experiment, the longer channel length device has less degraded since the bending direction is tensile and perpendicular to current path in this experiment. In this study, the channel length represents the beam width. The critical strain is increased as the channel length is increased and the strain is inversely proportional to the beam area. In this calculation, the area represents the multiplication result of thickness and width of the beam. Also, the stress intensity boundary correction factor and the beam or plate width is in inverse proportion [9]. Therefore, the increased channel length increases the beam area and the strain on the beam is decreased with increasing the beam width. As a result, the crack is easily generated on the shorter channel length due to the small critical strain value.

On the other hand, the passivated crack guided structures at selected areas are fabricated with titanium, and it is more brittle than substrate material. The ductile materials have extensive plastic deformation and energy absorption before fracture. In contrast, the brittle materials have a little plastic deformation and low energy absorption before they are destroyed [10]. Therefore, the selectively passivated crack guided structure which is brittle material is easier to generate cracks. Also, crack guided structure increase the total thickness, and the strain on the surface is also increased. Based on the result, the area with crack

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Channel length</th>
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<tbody>
<tr>
<td></td>
<td>5 μm</td>
</tr>
<tr>
<td>Without CG</td>
<td>$I_m$</td>
</tr>
<tr>
<td></td>
<td>$\mu_{eg}$</td>
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<tr>
<td></td>
<td>$S_{sub}$</td>
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<tr>
<td></td>
<td>$\Delta V_{th}$</td>
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<tr>
<td>With CG</td>
<td>$I_m$</td>
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<td>$\mu_{eg}$</td>
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<td></td>
<td>$S_{sub}$</td>
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<tr>
<td></td>
<td>$\Delta V_{th}$</td>
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Table 2
ANOVA analysis in crack guided structure effect.

<table>
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<tr>
<th>Channel length</th>
<th>Statistical significance (p-value)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$I_m$</td>
</tr>
<tr>
<td>5 μm</td>
<td>0.000</td>
</tr>
<tr>
<td>10 μm</td>
<td>0.000</td>
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<tr>
<td>20 μm</td>
<td>0.000</td>
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Fig. 3. The normalized transfer curves after 5000 cycles of dynamic mechanical stress from different conditions with various channel sizes.

Fig. 4. Normalized on-current results after 5000 cycles of dynamic mechanical stress test with various channel sizes for with and without crack guided structures.
guided structure is more fragile than other area under the same mechanical stress.

In order to confirm the reproducibility of the experimental results statistically, the analysis of variance (ANOVA) method is used to extract the p-values for each channel length and summarized in Table 2. The ANOVA method is the statistical method to determine the statistical significance by comparison of two variances [11]. As an example, if the p-value of 0.05 indicates that the probability that the factor in the crack guided structure is statistically impacted on the TFT degradation by the mechanical stress with 95% confidence interval. Results indicate that on-current variation is affected by crack guided structure on every channel size with 99.99% confidence interval and the threshold voltage shift variation is affected by crack guided structure on every channel size with 90% confidence interval. In addition, for the mobility, the p-values for 5 and 10 μm channel lengths are statistically also significant and the p-value for 20 μm channel length device has little larger value than the cases for 5 and 10 μm channel lengths. For the subthreshold swing, the p-value for 10 μm channel length shows statistically significant with 95% confidence interval and the p-values for 5 and 20 μm channel length devices have larger value than the case for 10 μm channel length. It is due to the degradation tendency of randomly generated crack position during the mechanical stress for the TFTs without the selectively passivated layer. Some of the TFTs have crack generation on the channel region resulting in severe degradation of TFT characteristics. However, some of the TFTs have crack generation on other region resulting in much less degradation of TFT characteristics. In addition, the degradation probability of the 20 μm channel length device is relatively reduced compared to the 5 μm and 10 μm devices due to the decreased strain. Therefore, the 20 μm channel length device is more stable, and the number of non-degraded device is increased, so that the effect of the crack guided structure is relatively reduced. As a result, the characteristic variations are increased, and the calculated standard deviations are also increased resulting in the increase of the p-value. On the other hand, the device with the selectively passivated layer is stable after the mechanical stress. The reason is the crack guided structure decreases the probability of the crack generation on the channel area and it can prevent the device degradation. Therefore, the characteristic variations of the TFTs and their standard deviations are also small. Based on the statistical analysis, it can be concluded that the TFTs with the selectively passivated layer enhance the TFT reliability by avoiding the randomly generated cracks in the TFT channel region.

4. Conclusion

In this paper, the reliability of the foldable p-type LTPS TFT with the crack guided passivation layer by the accelerated mechanical stress test was analyzed. To strain on the foldable LTPS TFT, the 5000 cycles of the dynamic mechanical stress with the tensile and perpendicular direction were applied with the 2-mm radius. It was observed that the accelerated dynamic mechanical stress tests without crack guided structures were generated cracks on the TFTs and they resulted in the degradation of the TFT characteristics. On the other hand, the TFT characteristics with the passivated crack guided structure were maintained due to the crack avoidance in the area of the tested TFTs. It was also observed that the longer channel TFT was more stable on the mechanical stress with tensile and perpendicular strain. The TFT characteristics with the selectively passivated layer were stable after mechanical stress due to the reduced probability of generating the cracks on the channel. On the other hand, the TFT characteristics without the crack guided structure were degraded and the characteristic variation was also increased due to the crack generation in the channel region. In order to confirm the statistical significance, the ANOVA was performed and it can be concluded that the device characteristics were affected by the selectively passivated layer on every channel size. Based on the results, the reliability of the foldable TFTs can be enhanced with the selectively passivated layer. Furthermore, this can be the cost effective method and also provide better manufacturability.

Acknowledgements

This research was supported by the LG Display (2014-11-1905). This work was also supported by Institute of BioMed-IT, Energy-IT and Smart-IT Technology (BEST), a Brain Korea 21 plus program, Yonsei University (2017-11-0013).

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