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Threshold voltage instability and polyimide charging effects of LTPS TFTs for flexible displays

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In this paper, we investigate the V_{th} shift of p-type LTPS TFTs fabricated on a polyimide (PI) and glass substrate considering charging phenomena. The V_{th} of the LTPS TFTs with a PI substrate positively shift after a bias temperature stress test. However, the V_{th} with a glass substrate rarely changed even with increasing stress. Such a positive V_{th} shift results from the negative charging of fluorine stemmed from the PI under the gate bias. In fact, the C–V characterization on the metal–insulator–metal capacitor reveals that charging at the SiO_2/PI interface depends on the applied gate bias and the PI material, which agrees well with the TCAD simulation and SIMS analyses. As a result, the charging at the SiO_2/PI interface contributes to the V_{th} shift of the LTPS TFTs leading to image sticking.

Recently, flexible displays have attracted considerable attention as next-generation drivers in display industries^{1,2}. Because low-temperature polycrystalline silicon (LTPS) thin-film transistors (TFT) have the advantages of low temperature process integration and high mobility, they have rapidly become popular in flexible displays and applications. However, the usage of excimer laser annealing (ELA) for the crystallization of amorphous silicon (a-Si) and chemical vapor deposition (CVD) for the process of gate insulation produce hysteresis loops in the device characterization, due mainly to the material and physical constraints of defects and non-uniformity^{3,4}. In turn, such intrinsic limitations impact fluctuations of electric current that flows into the organic light emitting diodes (OLED), leading to TFT instability and display performance disturbance, including halo and image sticking^{5,6}. In addition, moisture and oxygen penetration are serious deficiencies of all plastic substrates available for OLED flexible display applications^{7,8}. In particular, OLED's lifetime decreases when exposed to oxygen and moisture. When fabricating a device on a flexible plastic substrate, an inorganic layer (barrier) such as SiO_2 , SiN_x , or Al_2O_3 is deposited on the plastic substrate to prevent moisture and oxygen from penetrating into the OLED⁹. Although the main causes of residual images on OLED displays are inherently related to the process variation of the backplane process and deterioration of the OLED material^{10,11}, TFT instability can aggravate image sticking under low frequencies and always-on-display applications¹². A few papers are available for the elucidation of the mechanism and reliability physics of the positive V_{th} shift of p-type LTPS TFT and image sticking in regards to the substrate material, process integrity, and bias stress test conditions¹³.

In this paper, information is given to elucidate the mechanism of the positive V_{th} shift when the gate bias is applied to p-type LTPS TFTs fabricated on PI, as compared to a glass substrate. In order to probe the effects of charging on LTPS TFTs, three different metal–insulation–metal (MIM) capacitors were prepared for the C–V characterization. Finally, we delve into V_{th} shift behaviors in the material properties of PI associated with the vertical structure of LTPS TFTs. The secondary ion mass spectrometry (SIMS) physical characterization and TCAD simulation are focused on the fluorine profile at the interface and effects of the polarity of charging on V_{th} shift behaviors.

Results and Discussion

V_{th} shift behaviors of LTPS TFTs fabricated on PI and glass substrates. Figure 1a shows the I_D – V_G plot of p-type LTPS TFTs with glass and PI substrates on the top gate structure, before and after a gate stress of -30 V for 4,000 s at 70 °C. In Fig. 1b, ΔV_{th} after BTS was plotted as a box plot using 5 TFTs fabricated on the glass and PI substrate. On average, the ΔV_{th} of the TFT fabricated on glass showed a slight change, less than -0.02 V, and the ΔV_{th} of the TFT fabricated on the PI showed a positive shift with an average 0.83 V. In addition, I_{on}

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Figure 1. (a) I_D - V_G plot of P-type LTPS TFTs before and after the BTS. Note that the P-type LTPS TFTs were fabricated on glass (black filled circle) and PI (blue filled triangle) substrates and (b) ΔV_{th} before/after BTS of TFTs fabricated on glass and PI substrates.

Figure 2. (a) Schematic of 4-pad characterization (floating gate, source, gate and drain) and (b) normalized V_{th} behaviors of P-type LTPS TFTs fabricated on the on glass (black filled circle) and PI (blue filled triangle) substrates.

increased from 2.08×10^{-5} A to 2.46×10^{-5} A, and field effect mobility increased from 85 to $113 \text{ cm}^2/\text{Vs}$. However, under the identical stress conditions, the parameters of the LTPS TFT fabricated on glass substrate are rarely changed. It is somewhat interesting to note that the V_{th} of p-type LTPS TFTs with a PI substrate is positively shifted under the negative gate bias. It is speculated that the negative charging is generated from the PI substrate below the gate insulation layer.

In order to further probe the positive V_{th} shifts, 4-pad evaluation was conducted. As shown in Fig. 2a, a bias of 50 V was applied to the floating gate adjacent to the LTPS TFT to minimize the effects of the poly channel on electrical charging in the PI substrate. V_{th} behaviors are shown in Fig. 2b. As shown, the LTPS TFT with a glass substrate demonstrates stabilized V_{th} behaviors throughout stressing at 70 °C up to 80,000 s. Note that Region I, II, and III represent the temperature and bias conditions used; 70 °C without bias, 70 °C with 50 V, and room temperature without bias, respectively. From Region I to II, the V_{th} of the TFT with a PI substrate increases and positively shifts with increasing time. The V_{th} tends to decrease and then return to the initial V_{th} after 1 h in Region III. In turn, Region III is intended to observe the recovery behaviors of the V_{th} of the LTPS TFT with a PI substrate. Since the recovery of the V_{th} observed in Region III could result in display image disturbance, such as image sticking defined as residual images, efforts in electrical and physical characterization are inevitable. One would argue that the positive V_{th} shifts of the TFT with a PI substrate mentioned are related to design flaws somehow associated with the layout design of the metal route, which can impact TFT stability as electrical fields arise from adjacent metals near TFT devices. However, such artifacts were eliminated by design review throughout circuit simulation.

Since the V_{th} stability of TFT devices plays an important role for display image performance, particularly for image sticking, the relationship between the ΔV_{th} vs. image sticking was investigated. Using the checkerboard test pattern, the image sticking index is estimated by comparing luminance changes before and after stressing¹³. The white area adjacent to black patterns in the checkerboard becomes darker after stressing, which indicates

Figure 3. Correlation between PI charging induced V_{th} shift and image sticking for an LTPS TFT with a PI substrate.

Figure 4. Schematics of the vertical structure for the MIM capacitors and SEM image; (a) Ag/SiO₂/Ag, (b) Ag/PI/Ag, (c) Ag/SiO₂/PI/Ag and (d) the cross-sectional analysis of the MIM capacitor shown in (c).

image sticking. Figure 3 shows the correlation between PI charging induced ΔV_{th} and image sticking. It is shown that the larger the ΔV_{th} , the higher the propensity for image sticking. These results show that the correlation between V_{th} shift and image sticking needs to be further discussed with electrical and physical characterization.

MIM capacitor fabrication, C–V measurement and physical SIMS characterization. In an effort of probing the V_{th} behaviors mentioned above, three different metal–insulator–metal (MIM) capacitors, such as Ag/PI/Ag, Ag/SiO₂/Ag and Ag/SiO₂/PI/Ag were prepared for the C–V measurements conducted by varying voltage at a frequency of 100 kHz. SiO₂ is the barrier layer of the LTPS TFT, and the thickness and process conditions are the same with the measured TFT. Figures 4a–d show the schematics of the vertical structure for the MIM capacitors, i.e., Ag/SiO₂/Ag, Ag/PI/Ag, Ag/SiO₂/PI/Ag, and the cross-sectional analysis of the MIM capacitor. An Ag metal electrode was sputtered onto the spin-coated PI and SiO₂, deposited using the PECVD process. As a result, the PI and PI/SiO₂ function as the insulators between the metal electrodes.

Using Eq. (1), the physical dimension, dielectric constant, and capacitance of each capacitor are estimated and summarized in Table 1.

$$\frac{1}{C_{Total}} = \frac{1}{C_{SiO_2}} + \frac{1}{C_{PI}} + \frac{1}{C_{PI/SiO_2}} \quad (1)$$

Figure 5 shows the results obtained from the C–V measurements. It is apparent that changes in capacitance depend on the MIM capacitors. The capacitances of the SiO₂ and PI dielectric insulators between the Ag

	SiO ₂	PI	PI/SiO ₂
Thickness (μm)	0.13	1.5	–
Dielectric constant	3.8	3.91	–
Capacitance (F)	6.37×10^{-9}	7.56×10^{-10}	9.39×10^{-11}
$\Delta Q/q$ for 30 V stress (/cm ²)	2.7×10^{10}	5.3×10^{10}	2.0×10^{11}

Table 1. MIM capacitance and parameters from C–V measurement. **Figure 5.** C–V characterization for 3 different MIM capacitors with increasing voltage; (a) Ag/SiO₂/Ag, (b) Ag/PI/Ag, (c) Ag/SiO₂/PI/Ag, and (d) the dependency of the MIM capacitors on the applied voltage.

electrodes rarely change, even with increasing voltage (see Fig. 5a,b). However, the capacitance of the SiO₂/PI dielectric tends to increase with increasing voltage. It was also found that the magnitude of capacitance turns into the initial state after 1 h of halting bias, as shown in Fig. 5c. In Fig. 5d, the capacitance of the SiO₂/PI rapidly increases with increasing voltage. Such results agree well with the recovery of the V_{th} described in Fig. 2b. Thus, it is legitimate that the positive V_{th} shift of a TFT with a PI substrate is attributed to charging between the SiO₂ and PI interface. As such, charge generation at the interface between the SiO₂ and the PI plays an important role for TFT device stability, particularly for the PI substrate.

In sequence, SIMS analysis is adopted to explicate the positive V_{th} shifts of p-type LTPS TFTs with a PI substrate. To understand the effects of PI on the V_{th} shift, two different PIs with low and high crosslink density, named PI-A and PI-B, were chosen to prepare the Ag/SiO₂/PI/Ag capacitor. We first suspected that oxygen or moisture had penetrated from the PI. Changes in hydrogen ions (H⁺), hydroxyl group (OH⁻), and oxygen ions (O⁻) before/after bias stress of Ag/SiO₂/PI/Ag capacitors were confirmed through SIMS analysis. Figure 6 shows the results of SIMS analysis before and after bias stress of MIM capacitors fabricated based on PI-A and PI-B. There was no change in H⁺, OH⁻, or O⁻ before/after bias stress, confirming that there was no penetration of oxygen or moisture from PIs. Figure 7 shows the correlation between the fluorine profile at the SiO₂/PI interface and capacitance, characterized by SIMS and C–V measurement. Comparatively, the SIMS analyses revealed that PI-A has a higher fluorine content than PI-B at the interface (see Fig. 7a,c). In consequence, C–V measurements shown in Fig. 7b,d show that the capacitance of the MIM capacitor with PI-B is rarely changed even with increased stressing at 70 °C. It has been reported that the negative fluorine ions, F⁻, are subjected to transfer and trapped in the SiO₂ under the bias¹⁴. As a result, SIMS analyses evidences that a mobile ion F⁻ in the SiO₂/PI interface contributes to the positive shifts of LTPS TFTs with a PI substrate. This suggests that the amount of charging generated in the PI is dependent on the material property of the PI. Hence, the material property of the PI is a crucial factor that can influence LTPS TFTs with a PI substrate. It has been also found that PI charging that significantly affects TFT reliability can be successfully suppressed by the selection of a proper PI with high volume resistivity¹⁵. However, the charge generation and transfer into the barrier layer remained in unripe areas.

Figure 6. Hydrogen, hydroxy group and oxygen profiles obtained by SIMS measurements of capacitors before/after bias stress; (a) Ag/SiO₂/PI-A/Ag and (b) Ag/SiO₂/PI-B/Ag.

Figure 7. SIMS characterization of Ag/SiO₂/PI/Ag capacitor focused on fluorine profile at the interface; (a, b) with PI-A type and (c, d) with PI-B type. Note that PI-A is less crosslink density than PI-B.

TCAD simulation for charge generation at the interface between the SiO₂ and PI. Based on empirical data collected from reliability assessments, Silvaco TCAD was used to simulate the effects of charging at the SiO₂/PI interface on the TFT transfer curve. Figure 8 shows the I_D - V_G plot of an LTPS TFT with a PI substrate. As shown, the negative charging in the SiO₂/PI interface shifts the V_{th} to the positive direction, while the positive charging results in a negative V_{th} shift. Accordingly, when $-2 \times 10^{11}/\text{cm}^2$ charging is generated at the interface between the SiO₂ and the PI, the estimated V_{th} shift toward the positive direction is 0.84 V.

Table 2 contains the estimated TFT parameters, such as V_{th} , μ_{FE} , subthreshold swing (SS), and on/off ratio, based on the given charge injections shown in Fig. 8.

Figure 9 is given to explain the hole concentration of an LTPS TFT with a PI substrate with the bias conditioned at $V_{GS} = 30$ V and $V_{DS} = 0.1$ V. The Reference (black filled circle) and $-2 \times 10^{11}/\text{cm}^2$ (blue filled triangle) represent the LTPS TFT with and without charging at the SiO₂ and PI interface. Recall that $2 \times 10^{11}/\text{cm}^2$ is obtained from the C-measurement summarized in Table 1. As shown in the inset in Fig. 9, when the negative bias is applied to the gate of the LTPS TFT, hole carriers tend to be accumulated near the channel and then

Figure 8. I_D - V_G plot based on the amount of charge trapped at the SiO_2 and PI interface by TCAD simulation.

Charge Injection ($/\text{cm}^2$)	V_{th} (V)	μ_{FE} ($\text{cm}^2/\text{V}\cdot\text{s}$)	SS (V/dec)	On/off ratio
Ref.	-1.47	82	0.43	4.21×10^8
1×10^{11}	-1.92	75	0.40	3.93×10^8
2×10^{11}	-2.27	69	0.33	3.79×10^8
-1×10^{11}	-1.02	90	0.45	4.57×10^8
-2×10^{11}	-0.63	101	0.46	5.58×10^8

Table 2. Estimated TFT parameters with respect to charge injection from the SiO_2/PI interface by TCAD simulation.

Figure 9. TCAD simulation for hole concentration (cm^{-3}) versus channel depth (nm) of an LTPS TFT with a PI substrate. Reference represents a LTPS TFT with a PI substrate without charge injection at the SiO_2/PI interface.

exponentially decrease. However, when negative charging exists at the PI substrate, hole concentration decreases then increases below the channel depth of 30 nm. It is known that the negative charges at the interface between the SiO_2 and PI result in an early turn-on V_{th} leading to increased field effective mobility and I_{on} , which is similar to the I_D - V_G characteristic observed from the double gate TFTs^{16,17}. Hence, the state of charging at the interface determines the characteristics of the LTPS TFTs with a PI substrate.

Conclusions

Considering the direction of V_{th} shift of p-type LTPS TFTs with gate bias stress, the charge trapping mechanism, depending on the type of the substrate in the top gate structure, are comprehensively investigated. Unlike the glass substrate, the positive V_{th} shift of p-type LTPS TFTs with a PI substrate under the BTS test results from the negative charging of fluorine at the interface between the SiO_2 and PI is proven by C-V measurement and SIMS characterization. In fact, the fluorine stems from the PI substrate under gate bias stress. Furthermore, TCAD simulation reveals that the direction of the V_{th} shift strongly depends on the polarity of charge trapping at the SiO_2 and PI interface. The larger V_{th} shifts are prone to the higher propensity of image sticking. Hence,

care must be taken for the selection of PI in order to ensure display image performance in advanced flexible display technologies.

Methods

P-type LTPS TFTs were fabricated on either a PI or glass substrate through the standard backplane process, in which plasma enhanced chemical vapor deposition (PECVD) was used for a-Si and SiO₂ (barrier) deposition and crystallized into poly-Si by using excimer laser annealing (ELA). Thus, the vertical structure of the p-type LTPS TFTs consists of the gate/gate insulator/poly-Si/buffer/barrier/PI or glass substrate on the top gate structure. In a pixel circuit driver, 4/4 μm transistor and 200 μm /200 μm capacitance were monitored by I–V and C–V measurement. V_{th} behaviors were monitored as a function of bias stress on the gates of the LTPS TFTs. To probe electrical charging in PI, three different metal–insulator–metal (MIM) capacitors, Ag/PI/Ag, Ag/SiO₂/Ag, and Ag/SiO₂/PI/Ag, were prepared for the C–V measurements. Changes in capacitance were measured as a function of voltage level. Moreover, the effects of charging in PI on the LTPS TFTs were taken into account by selecting different types of PIs such as PI-A and PI-B. Fluorine profiles were carefully analyzed by SIMS characterization. Finally, the effects of PI charging on the LTPS TFTs were consummated by using TCAD simulation.

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Author contributions

H.K., J.P., T.K., J.S. and B.C. designed this work. H.K. and S.B. fabricated the devices, and H.K., J.P., T.K., S.B., J.S. and B.C. measured the electrical characteristics of the devices and performed analysis. H.K. performed SEM analysis of the MIM capacitor in Fig. 4d. H.K. and J.P. conducted the TCAD simulation. Figures 8 and 9 are plots extracted through TCAD simulation. All authors discussed the findings and contributed to writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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