The thermal annealing effect on electrical performances of a-Si:H TFT fabricated on a metal foil substrate

Chang-Wook Han[1,2], Woo-Jin Nam[1], Chang-Dong Kim[1], Ki-Yong Kim[1],
In Byeong Kang[1], In-Jae Chung[1], and Min-Koo Han[2]

[1] **LG.PHILIPS LCD R&D Center Anyang, Gyongki-do 431-080, Korea**
TEL:82-31-450-7445, e-mail: hcw@lgphilips-lcd.com
[2] **School of Electrical Engineering, Seoul National University, Seoul 151-742, Korea**

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Abstract

Hydrogenated amorphous silicon thin film transistors (a-Si:H TFTs) were fabricated on a flexible metal substrate at 150 °C. To increase the stability of the flexible a-Si:H TFTs, they were thermally annealed at 230 °C. The field effect mobility was reduced because of the strain in a-Si:H TFT under thermal annealing.

1. Introduction

Hydrogenated amorphous silicon (a-Si:H) thin film transistors (TFTs) which were fabricated on a metal foil substrate are good candidates for flexible active matrix organic light-emitting diodes (AMOLED) [1]. Flexible metal foil may be a most promising candidate for flexible AMOLED displays because of their features of thin-thickness, ruggedness, and excellent barrier against oxygen and moisture [2]. The a-Si:H TFTs are a mature technology to use in low cost and large sized displays. Furthermore, recent enhancements of OLED efficiency have given a wider opportunity for a-Si:H TFTs to drive AMOLED.

However, metal foil is not easily processed with traditional TFT equipment that is compatible with rigid glass substrates. To utilize traditional TFT equipment, the metal foil may be bonded to a rigid carrier of glass [3]. The adhesive used for bonding the stainless steel substrate to a rigid glass substrate reduces the maximum process temperature from the value that the substrate itself would withstand. The a-Si:H TFTs fabricated at the lower temperature have shown a rather large threshold voltage shift (ΔV_{TH}) under bias temperature stress (BTS) than those fabricated at a higher temperature [4]. As the increased threshold voltage of a-Si:H TFTs reduces the current of the OLED driven at constant voltage, the ΔV_{TH} of a-Si:H TFTs should be suppressed to prolong the life of the AMOLED.

In this paper, we fabricate a-Si:H TFT on a metal foil substrate at 150 °C and also present the results of a study of thermal annealing to increase the electrical stability.

2. Experimental

We fabricated a-Si:H TFTs on a 76-μm-thick metal foil substrate. A multi-barrier as initial surface passivation was coated on the metal foil in order to reduce the surface roughness of the metal substrate. The passivation layer also serves the mechanical bond between the TFT layers and the substrate. A root-mean-square (RMS) roughness of the passivated-surface was 10 nm. The structure of a-Si:H TFTs was an inverted staggered type which was made by a conventional 5-photomask process. Silicon nitride (SiNx), a-Si:H and a-Si:H doped with phosphorus layers were grown at 150 ℃ by plasma enhanced chemical vapor deposition (PECVD) continuously. After a-Si:H TFTs were fabricated on the metal foil, they were annealed at 150 °C, 200 °C and 230 °C to improve the electrical stability for one hour under a nitrogen atmosphere in a convection oven.

3. Results and discussion

We obtain transfer characteristics of a TFT with W=30 μm and L=6 μm shown in Fig.1. The off current is about 10^{-13} A and the on current at gate voltage of 20 V is about 10^{-6} A at a drain voltage of 10

V, resulting in an on-off current ratio of 10^7. We obtain a subthreshold slope ~ 0.63 V/decade, demonstrating a sharp device turn-on. We also obtain a threshold voltage and mobility of 1.0 V and 0.54 cm^2/Vs, respectively, in the saturated regime.

There have been many discussions related to a stability of a-Si:H TFTs as a backplane for AMOLEDs [5]. The stability of the TFTs could increase after post annealing over process temperature. The TFTs fabricated on the metal foil at 150 °C could thermally anneal over 150 °C because the metal foil had a high process temperature compatibility [2]. Fig.1 also shows the transfer characteristic of a-Si:H TFT fabricated on the metal foil as the post-annealing temperature. As the post-annealing, the on-current slightly decreased and the threshold voltage did not be changed significantly.

To investigate the stability of the thermal-annealed a-Si:H TFTs, BTS measurements were carried out under a prolonged gate bias of +15 V and drain bias of +15 V at 65 °C for 3,500 seconds. Fig.2 shows the dependence of ΔV_{TH} on post-annealing temperature. The ΔV_{TH} was reduced from 4.6 to 3.0 V as the post-annealed temperature increased from 150 to 230 °C. The current ratio (*I/Io*) shown in the inset of Fig.3 increased from 0.54 to 0.67 after thermal annealing at 230 °C indicating a longer life of the TFTs to drive the OLEDs.

On the other hand, the μ_{fe} decreased about 29 percent from initial mobility after a-Si:H TFTs fabricated on the metal foil was thermally annealed at 230 °C as shown in Fig.3. This decrease was larger than that of the TFTs fabricated on a glass substrate after thermal annealing at 230 °C.

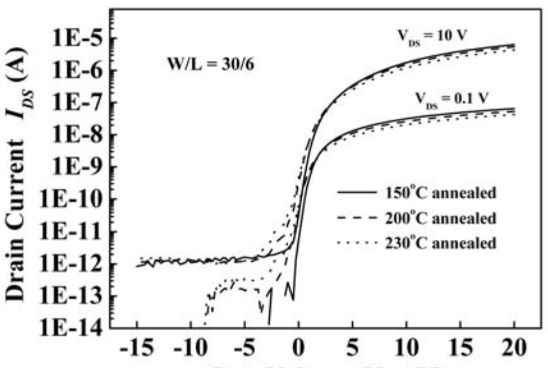

Fig. 1. The transfer characteristic of a-Si:H TFTs fabricated on the metal foil dependent on the annealing temperature.

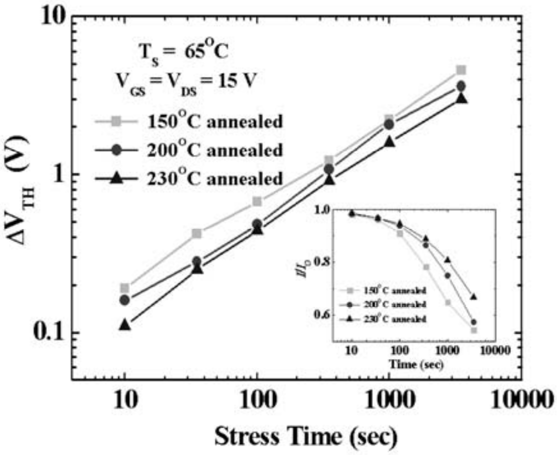

Fig. 2. The dependence of ΔV_{TH} and I/I_o on the post annealing temperature

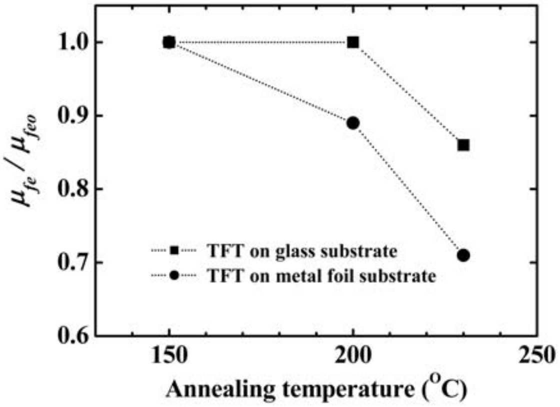

Fig. 3. The relative mobility plotted as a function of the post-annealing temperature. a-Si:H TFTs on a glass substrate (■), metal foil substrate (●).

In the case of the TFTs fabricated on a glass substrate, the μ_{fe} decreased about 14 percent from initial mobility after thermal annealing at 230 °C.

The μ_{fe} was concerned with a localized state distribution in the a-Si:H film. The increment in the width of the tail states occurred with the decrease of μ_{fe}[6]. We measured the source-drain current activation energy versus gate voltage (V_{ds} = 15 V) for the thermal annealed a-Si:H TFTs. The minimum activation energy, approached at the highest gate voltage (30 V), was a measure of the tail state distribution. The activation energy showed values of 78, 89, and 105 meV for the a-Si:H TFTs annealed at 150, 200 and 230 °C as shown in Fig.4, respectively.

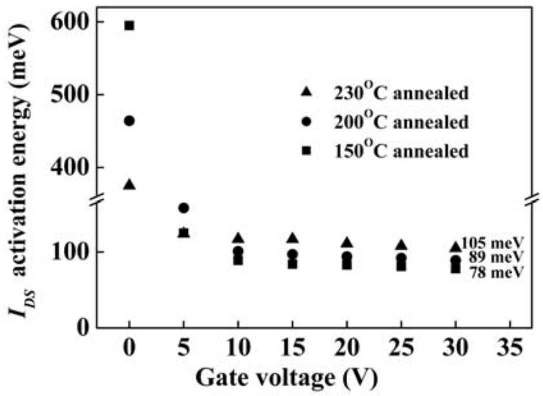

Fig. 4. The drain current activation energy of the a-Si:H TFTs fabricated on a metal foil substrate as a function of the annealing temperature showing a minimum activation energy at V_{GS} = 30 V.

We considered two causes of the drop in mobility which affected the tail state distribution. First, it was similar to the cause of the drop in mobility when the a-Si:H was deposited at high temperature. In the high temperature range, the release of hydrogen atoms (H_2) induced a strained structure in the a-Si:H TFTs [7]. We investigated the amount of H_2 in the a-Si:H films and hydrogenated silicon nitride (SiN_x:H) films thermally annealed at different temperatures through secondary-ion mass spectroscopy (SIMS). The amount of H_2 in SiNx:H films decreased from 450 to 300 counts per second as the annealing temperature increased from 150 to 230 °C as shown in Fig.5. The release of H_2 from SiN_x:H film might make the interface between the a-Si:H film and the SiN_x:H film strain.

Second, we considered the stress due to the thermal mismatch between the metal foil and thin films consisting of a-Si:H TFTs resulting from an additional drop in mobility compared to the glass substrate.

In general, most of the thin films which consisted of the a-Si:H TFTs had a lower coefficient of thermal expansion (α) than metal foil ($\alpha \approx 18 \times 10^{-6}/^{\circ}C$ for the metal foil, $\alpha \approx 4 \times 10^{-6}/^{\circ}C$ for the a-Si:H and a-SiN_x:H thin film) [8]. After thermal annealing and cool-down, the strain (ε) appeared in the TFT films due to the thin thickness as compared to the thick-substrate. Then ε is given directly by the differential thermal expansion [9]:

$$(\alpha_f - \alpha_s)(T_a - T_o) = \varepsilon_f = \left[\frac{1-\upsilon}{Y}\right]_f \sigma_f \qquad (1)$$

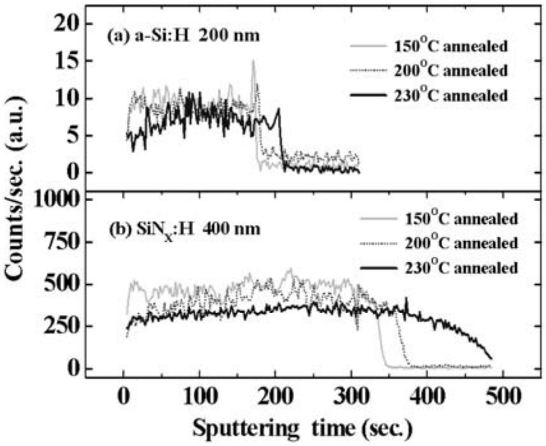

Fig. 5. SIMS profiles of hydrogen atoms from (a) a 200 nm a-Si:H layer and (b) a 400 nm SiN_x:H on silicon wafer as annealing temperature: 150 , 200 and 230 °C.

In Eq. (1), α_f and α_s are the coefficients of thermal expansion for the TFT films and the metal foil; T_a is the annealing T; T_o is the T after cool-down; υ is Poisson's ratio; Y is Young's modulus; and σ_f is the residual stress to the TFT films. It is not easy to calculate the stress to the TFT films because TFT consists of many kinds of films. Hence, we can simplify TFT films as a single SiNx film due to its large portion of TFT films. We assumed $\alpha_f = 4 \times 10^{-6}/^{\circ}C$ [8], T_a = 230 °C, υ = 0.24 [10], and Y = 183 GPa [10] for the SiNx film. A compressive stress (-0.67 GPa) calculated from Eq. (1) may strain the TFT films on metal foil after the post-annealing. This stress might make the tail state distribution of a-Si:H wider which caused an additional drop of mobility.

To compensate for stress on TFT films under thermal annealing we deposited metal thin film as the buffer layer at the back side of the flexible a-Si:H TFTs fabricated on the metal foil. After TFT fabrication, the metal foil substrate, which carried the a-Si:H TFTs, was separated from the rigid glass substrate. And chromium (Cr) and gold (Au) as the buffer layer were thermally evaporated at the back side of metal foil before annealing. The thickness was 100 nm and the substrate was not heated during evaporation. After they were annealed at 230 °C, we measured electrical characteristics of a-Si:H TFTs.

In the case of the Cr thin film, the μ_{fe} decreased similar to the mobility-drop at the glass substrate as shown in Fig 6. When we applied Cr as the buffer layer, the mobility-drop due to thermal stress was almost recovered to the level of the glass substrate

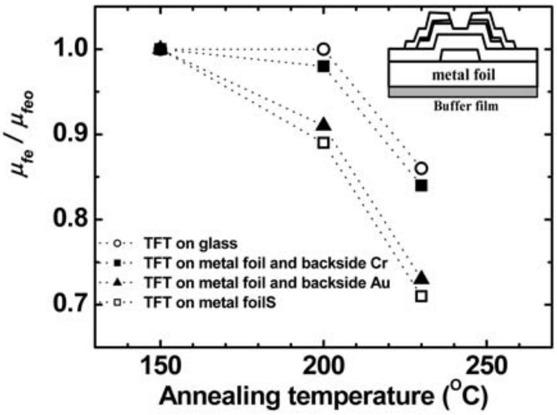

Fig. 6. The relative mobility plotted as a function of the post-annealing temperature. a-Si:H TFT on a glass substrate (○), stainless steel substrate (□), Cr thin film of 10 nm (■), and Au thin film of 10 nm (▲) thickness at the back side of a flexible a-Si:H TFT.

that was not considered the thermal stress because of it's stiffness. If we consider the Cr thin film and metal foil substrate we can contemplate how Cr thin film acted as a buffer layer to compensate for stress on the TFTs. After thermal annealing and cool-down, the strain (ε) appeared in the Cr thin film due to the thin thickness as compared to the thick-substrate. Then ε is given directly by the differential thermal expansion [9]:

$$(\alpha_{bf}-\alpha_{s})(T_{a}-T_{o})=\varepsilon_{df}=\left[\frac{1-\upsilon}{Y}\right]_{bf}\sigma_{bf} \qquad (2)$$

In Eq. (2), α_{bf} and α_s are the coefficients of thermal expansion for the buffer film and the metal foil; T_a is the annealing T; T_o is the T after cool-down; υ is Poission's ratio; Y is Young's modulus; and σ_{bf} is the residual stress to the buffer film. For example, we assumed $\alpha_{bf} = 4.9 \times 10^{-6}/^{o}C$ [11], $T_a = 230$ °C, $\upsilon = 0.21$ [11], and Y = 200 GPa [12] for the Cr buffer film. A compressive stress (-0.68 GPa) was found for Cr on metal foil using Eq. (2). A compressive stress in the Cr buffer-film at the back side of the metal foil substrate suppressed the stress in the TFT films at the front side under thermal annealing. When we applied the 100 nm-thick gold (Au) film as a buffer-layer, it did not suppress the drop in mobility as shown in Fig. 3. In the case of the Au buffer layer, the residual stress in the Au film was about -0.09 GPa after thermal annealing at 230 °C as we assumed $\alpha_{bf} = 14.2 \times 10^{-6}/^{o}C$ [13], $\upsilon = 0.35$ [14] and Y = 78 GPa [14] to use Eq. (2). It was not enough to compensate for the stress in the TFT films.

4. Summary

When a-Si:H TFTs were fabricated at 150 °C on the metal foil and thermally annealed, the ΔV_{TH} was reduced from 4.6 to 3.0 V at $V_{GS} = V_{DS} = 15$ V, 65 °C and for 3,500s and the current of OLED was expected to be maintained for a longer time as the post-annealing temperature increased. The μ_{fe} of the post-annealed TFT at a higher temperature than the process temperature was reduced because of the released hydrogen atoms and residual compressive stress in a-Si:H TFT under thermal annealing at 230 °C. The Cr thin film was deposited at the back side of the metal foil substrate to suppress compressive stress in TFT films. We were able to increase the stability of the flexible a-Si:H TFTs by post-annealing without sacrificing μ_{fe} very much.

5. References

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