Japanese Journal of Applied Physics
Vol. 44, No. 48, 2005, pp. L 1456–L 1459

A Study of Electrical Damage to a-Si:H Thin Film Transistor during Plasma Ashing by a Pin-to-Plate Type Atmospheric Pressure Plasma

Yong-Hyuk LEE, Se-Jin KYUNG, Jong-Hyuk LIM and Geun-Young YEOM*

Department of Materials Science and Engineering, Sungkyunkwan University, Suwon 440-746, Korea

(Received March 29, 2005; accepted September 7, 2005; published November 18, 2005)

In this study, the effect of the plasma ashing of the photoresist on a-Si:H thin film transistor (TFT) devices carried out using an atmospheric pressure plasma on the electrical damage to the TFT devices was investigated. By exposing the TFT devices to the plasma with a photoresist ashing rate of about 860 nm/min for up to 120 s, their electrical characteristics were significantly degraded, possibly due to charge trapping in the SiN_x of the passivation layer and gate insulator and to bond breaking in a-Si:H. The degradation of the field effect mobility, I_{off}, and I_{on}/I_{off} ratio of the devices is believed to be mostly related to the bond breaking in the a-Si:H and charge trapping caused by the UV radiation, while the change in the threshold voltage appears to be mostly related to the surface charging caused by the charged species in the plasma. The damaged TFT devices, however, could be fully repaired by conventional annealing in a furnace at 290°C in N_2 for 60 min. [DOI: 10.1143/JJAP.44.L1456]

KEYWORDS: atmospheric pressure plasma, TFT-LCD, a-Si:H

Recently, the use of many types of atmospheric pressure plasmas, such as dielectric barrier discharge (DBD), corona discharge, and rf torch plasmas, has been investigated in various fields. In the field of electronics, atmospheric pressure plasmas are used for thin film deposition and etching, surface cleaning, surface modification, etc. In particular, in the field of thin film transistor-liquid crystal displays (TFT-LCDs), the use of atmospheric pressure plasmas to clean the TFT-LCD substrate is being seriously considered to replace UV/O_3 cleaning or wet cleaning, due to their lower environmental impact and operational cost. Atmospheric pressure plasmas could also be used for the photoresist ashing of the TFT devices used for TFT-LCDs after the etching of the photoresist patterned devices, provided that the photoresist ashing rate on the large substrate area is uniform and high enough.[1–6)]

During the plasma ashing process, TFT devices are easily damaged due to the charging of the devices and bond breaking in the a-Si:H used as the gate material of the TFTs.[7–11)] In this study, TFT devices were exposed to an atmospheric pressure plasma for the purpose of photoresist ashing and the electrical damage to the TFT devices and damage mechanism were investigated. The repair of the damaged TFT devices was also investigated.

Figure 1 shows the TFT device component of the TFT-LCD used in this study. The device was composed of glass/gate electrode (Cr)/gate insulator (SiN_x)/a-Si:H/source and drain electrodes/passivation (SiN_x) and was covered with photoresist for the etching of the via holes. To remove the remaining photoresist after the etching of the via holes, a plasma ashing technique was used involving the use of an atmospheric pressure plasma system.

Figure 2 shows the atmospheric pressure plasma system, the pin-to-plate dielectric barrier discharge (DBD) inline system used in the experiment.[12)] As shown in this figure, the plasma source was composed of a pyramid type multi-pin power electrode, a blank plate ground electrode, and dielectrics on each electrode. The thickness of the dielectrics was 1.5 mm and the gap between them (i.e., the air gap) was 4 mm. Due to the high electric field at the tip of the pyramid pins, the generation of a high density plasma at a low voltage was susceptible to occur and, consequently, the use of a dielectric barrier between the electrodes prevented the formation of filamentary discharges during the operation of the plasma. The size of the atmospheric pressure plasma source was $100 \times 1000\,mm^2$ and the source was installed in the in-line glass transport roller system. Therefore, the glass substrates could be transported linearly through the plasma source using the roller. The voltage applied to the multi-pin power electrode was 18 kV (20–30 kHz) and a mixture of He (10 slm) and O_2 (3 slm) was used as the discharge gas. Under these conditions, the photoresist ashing rate was about 860 nm/min, and the glass substrates with the above TFT devices without photoresist were exposed to the plasma for 30 to 120 s. In addition, to investigate the damage mecha-

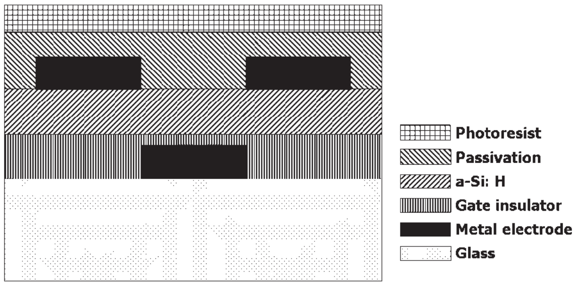

Fig. 1. Schematic diagram of the back channel inverted-staggered TFT used in this study.

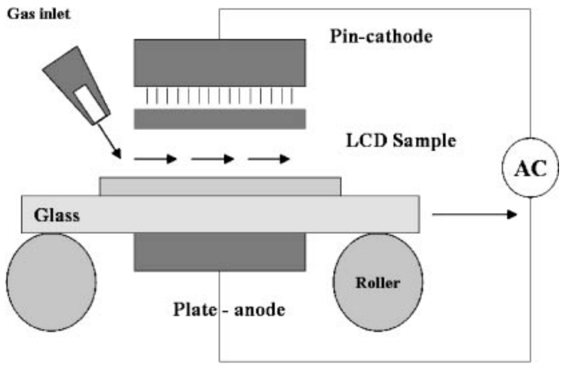

Fig. 2. Schematic diagram of the atmospheric pressure plasma system used for plasma ashing in this study.

nism, the TFT devices were exposed to a UV source (365 nm, 600 W) for periods ranging from 2 to 10 min, in order to investigate the effect of UV radiation on the damage to the device, and were also exposed to an inductively coupled plasma (ICP) with and without a DC bias voltage for 2 min. The operational condition of the ICP was an O_2 flow rate of 20 sccm, a pressure of 10 mTorr, and an inductive power of 600 W. During the operation of the atmospheric pressure plasma, the temperature at the surface of the TFT-device was monitored by means of an optical pyrometer (Luxtron, Model 100 C-non contact). However, when the exposure time was varied from 30 to 120 s, the surface temperature remained at less than 50°C.

After the exposure of the TFT devices to the plasma or UV, their electrical characteristics (transfer characteristics; V_g–I_d at constant V_d) were investigated using a semiconductor parameter analyzer (HP4145B), in order to observe the effect of the charges and UV in the plasma on the damage caused to the devices. To investigate the repair of the TFT devices damaged by the plasma, the devices exposed to the plasma were annealed in a furnace at 290°C in N_2 for 60 min and their transfer characteristics (V_g–I_d) were investigated.

Figure 3 shows the transfer characteristics of the TFT devices at $V_d = 15$ V measured as a function of the He/O_2 atmospheric pressure plasma exposure time in the range of 30 to 120 s. As a reference, the transfer characteristic of the TFT devices which were not exposed to the plasma is also included. As shown in this figure, as the plasma exposure time was increased from 30 to 120 s, the threshold voltage, V_{th}, which is the voltage at the intersection of the V_G axis and the tangential line extending from the $I_d^{1/2}$ vs V_G curve, increased from 0.34 V for the reference device to 3.12 V for the device exposed to the plasma for 120 s. In addition, when the plasma exposure time was increased from 0 to 120 s, the leakage current I_{off} measured at a V_G of −7.5 V increased from 1.06 to 24.16 pA and the I_{on}/I_{off} ratio decreased from 2.12×10^6 to 2×10^4. From the following equation, the field effect mobility (μ_{FE}) can be calculated.

$$g_m = \frac{\partial I_D}{\partial V_G}\bigg|_{V_D=15\,\mathrm{V}} = \mu_{FE} C_i \frac{W}{L} V_D$$

where g_m is the transconductance, W is the channel width, L is the length of the channel, and C_i is the capacitance of the gate insulator. Under our experimental conditions, W is 5 μm, L is 24 μm, and C_i is 150 pF. For the reference sample, the calculated field effect mobility (μ_{FE}) is 0.354 cm²/(V·S), however, after exposing the device to the plasma for 120 s, it was decreased to 0.037 cm²/(V·S).

Therefore, by exposing the TFT devices to the plasma, their electrical properties were severely degraded. In general, the damage to the TFT devices originates from the effects of the ion bombardment, charging and UV radiation during the plasma processing. Even though the operating AC voltage is as high as 18 kV in the case of the atmospheric pressure plasma, due to the extremely small mean free path of about 66 nm [$\lambda_{mfp} \cong 5/P$ (mTorr) cm], it is believed that the ion bombardment effect is negligible. Therefore, the damage shown in Fig. 3 appears to be related to the charging and UV radiation during the exposure to the plasma.

To investigate the significance of the UV and charging induced damage during the exposure to the atmospheric pressure plasma, the TFT devices were exposed to UV radiation at a wavelength of 365 nm and a power level of 600 W for durations ranging from 2 to 10 min, as well as to a typical ICP with and without biasing at −100 V for 2 min. The results are shown in Fig. 4. As shown in this figure, the UV irradiation of the TFT devices for 10 min decreased their field effect mobility from 0.354 to 0.15 cm²/(V·S) and decreased their I_{on}/I_{off} ratio from 2.12×10^6 to 6.3×10^5. Also, the threshold voltage, V_{th}, was increased from 0.34 to 1.84 V. In the case of the TFT devices exposed to the ICP

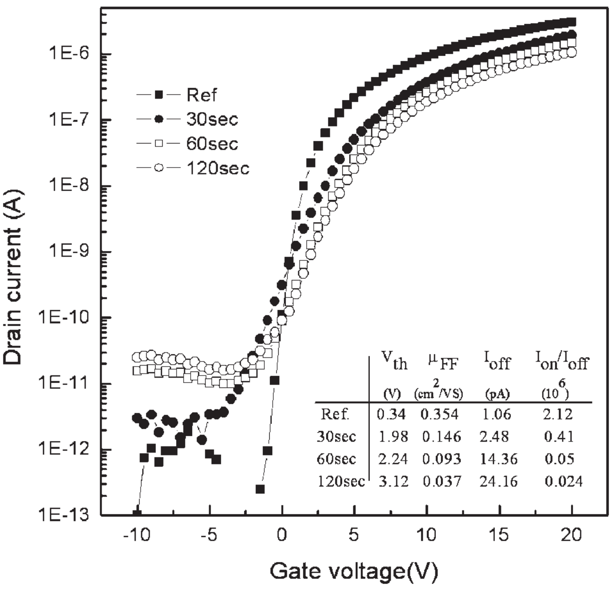

Fig. 3. Transfer characteristics of the TFT devices measured as a function of the plasma treatment time; ref., 30, 60, and 120 s using the atmospheric pressure plasma (with a mixture of?) He (10 slm)/O_2 (3 slm) and an input voltage of 18 kV for plasma ashing.

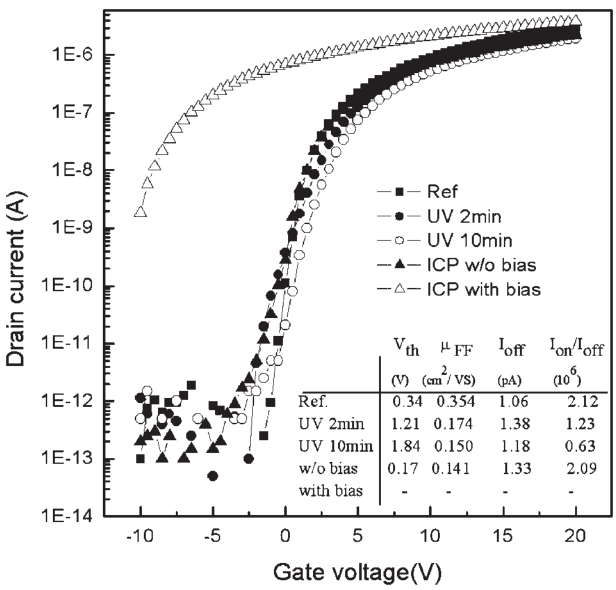

Fig. 4. Transfer characteristics of the TFT devices exposed to UV radiation for various times, *viz.* 2 and 10 min, at a power level of 600 W and a wavelength of 365 nm and to an inductively coupled plasma with/without a bias voltage for 2 min at an O_2 flow rate of 20 sccm, a pressure of 10 mTorr, a source power of 600 W and a bias voltage of −100 V.

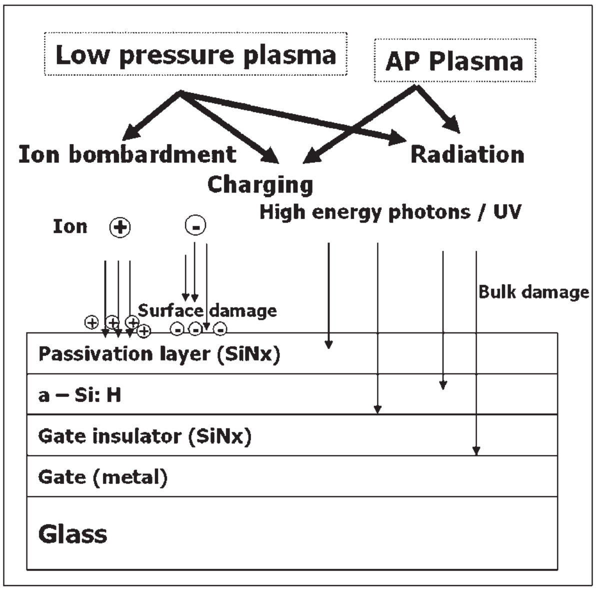

Fig. 5. Mechanism of surface and bulk damage to the a-Si:H TFT devices caused by their exposure to the atmospheric pressure plasmas or low pressure plasmas.

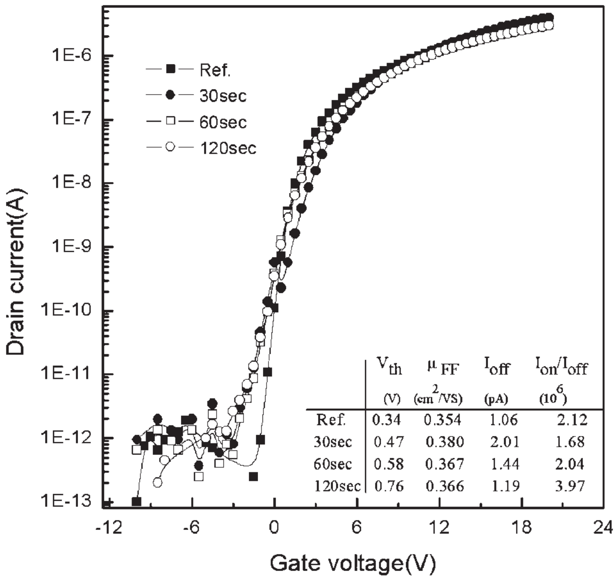

Fig. 6. Transfer characteristics of the TFT devices after annealing at 290°C in N_2 for 60 min. The TFT devices were exposed to the plasma with the conditions described in Fig. 3 before annealing.

without biasing the change in the value of V_{th} from 0.17 V for the reference device to a negative value, was obtained without significantly changing the value of I_{off} and the I_{on}/I_{off} ratio, even though there was some change of the mobility. When the TFT devices were exposed to an ICP with a DC bias voltage of -100 V, as shown in Fig. 4, a significant change in the value of V_{th} was obtained.

The mechanism by which the damage is caused to the TFT devices during their exposure to the atmospheric pressure plasma can be represented as shown in Fig. 5. The decrease in the field effect mobility and increase in the I_{on}/I_{off} ratio appear to be related to the bulk damage to the a-Si:H, given that the Si–Si bonds near the a-Si:H are known to be easily broken by the UV radiation, etc. Also, the UV radiation can break the SiN_x bonds in the passivation layer and the gate insulator. In particular, the charge trapping on the SiN_x of the gate insulator caused by the bond breaking induced by the UV radiation can affect the V_{th} value significantly. The increase in the V_{th} value induced by the UV radiation appears to be related to the charge trapping near the gate insulator caused by the UV radiation. In the case of the TFT devices exposed to the ICP without a bias voltage, the slight change in the value of V_{th} is believed to be related to the surface charging of the SiN_x passivation layer, and the significant change in the value of V_{th} for devices exposed to the ICP with a bias voltage of -100 V is believed to be related to the surface damage of the SiN_x layers in addition to the surface charging. The decrease in the value of V_{th} for the TFT devices exposed to the ICP from that observed for the reference sample, as compared to the increase in the value of V_{th} for the devices exposed to the atmospheric pressure plasma appear to suggest that the charging status of the TFT device is changed by the exposure to the plasma.

The TFT devices exposed to the atmospheric pressure plasma, as shown in Fig. 3, were annealed using a conventional annealing process which repairs the damage induced during the processing of the TFT device. The annealing process consisted of furnace annealing at 290°C in N_2 for 60 min. Figure 6 shows the transfer characteristics (V_g–I_d at $V_d = 15$ V) of the TFT devices exposed to the atmospheric pressure plasma (corresponding to the results shown in Fig. 3) after the annealing process. As shown in this figure, the characteristics of the TFT, such as V_{th}, I_{off}, I_{on}/I_{off}, and the field effect mobility (μ_{FE}), were similar to those of the reference device after annealing in a furnace at 290°C in N_2 for 60 min. The recovery of the transfer characteristics afforded by the annealing process is believed to be due to the removal of the trapped charges at the gate insulator and passivation layer, as well as to the (repair) of the broken bonds in the a-Si:H layer.

In this study, the effect of atmospheric pressure plasma processing for the purpose of plasma ashing on the electrical damage of the TFT devices and its damage mechanism were investigated. The recovery of the damaged TFT devices was also investigated. In the processing of TFT-LCD devices, if the wet processing steps such as the photoresist removal is replaced by a dry processing technique such as plasma ashing by an atmospheric pressure plasma, the environmental impact caused by the large amount of chemical waste that is generated can be decreased significantly and the cost can be greatly reduced due to the lack of need for expensive chemicals. However, during the plasma processing, the TFT devices are easily damaged due to the charging of the devices and the bond breaking in the a-Si:H used as the gate material of the TFTs. Following the exposure of the TFT devices to an atmospheric pressure plasma with a photoresist ashing rate of about 860 nm/min for up to 120 s, the electrical characteristics of the TFT devices were also significantly degraded, due to the charge trapping at the passivation layer and gate insulator and the bond breaking in the a-Si:H. The changes in the values of I_{off}, I_{on}/I_{off}, and the field effect mobility (μ_{FE}) appear to be mostly related to the bond breaking in the a-Si:H and the charge trapping caused by the UV radiation, while the change in the value of V_{th}

appears to be mostly related to the surface charging caused by the charged species in the plasma. However, the TFT devices damaged by the atmospheric pressure plasma were fully repaired by annealing in a furnace at 290°C in N_2 for 60 min.

Acknowledgments

This work was supported by the National Research Laboratory (NRL) Program of the Korean Ministry of Science and Technology.

1) M. Stuzmann, W. B. Jackson and C. C. Tsai: Phys. Rev. B **32** (1985) 23.
2) S. Sheng, E. Sacher and A. Yelon: J. Non-Cryst. Solids **282** (2001) 165.
3) B. Pivac, M. Pavlovic, I. Kovacevic, B. Etlinger and I. Zulim: Vacuum **71** (2003) 135.
4) P. Stradins: Sol. Energy Mater. Sol. Cells **78** (2003) 349.
5) R. S. Crandall, D. E. Carlson, A. Catalano and H. A. Weakliem: Appl. Phys. Lett. **44** (1984) 200.
6) Y. Kuo: Appl. Phys. Lett. **67** (1995) 2173.
7) G. Lavareda, C. N. de Carvalho, A. Amaral, E. Fortunato and P. Vilarinho: Mater. Sci. Eng. B **109** (2004) 264.
8) Y. Kuo: Appl. Phys. Lett. **67** (1995) 3174.
9) Y. Kuo: Appl. Phys. Lett. **61** (1992) 2790.
10) S. Kang, S. C. Bae and S. Y. Choi: Appl. Phys. Lett. **77** (2000) 1188.
11) H. H. Choe and S. G. Kim: Semicond. Sci. Technol. **19** (2004) 839.
12) Y. H. Lee, S. J. Kyung, C. H. Jeong and G. Y. Yeom: Jpn. J. Appl. Phys. **44** (2005) L78.