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Abnormal Behavior of Threshold Voltage Shift in Bias-Stressed a-Si:H Thin Film Transistor under Extremely High Intensity Illumination

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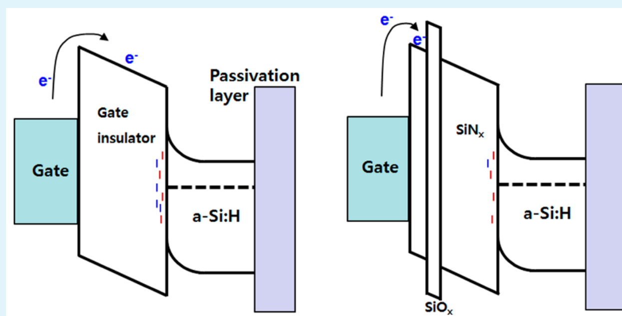
ABSTRACT: We report on the unusual behavior of threshold voltage turnaround in a hydrogenated amorphous silicon (a-Si:H) thin film transistor (TFT) when biased under extremely high intensity illumination. The threshold voltage shift changes from negative to positive gate bias direction after ~30 min of bias stress even when the negative gate bias stress is applied under high intensity illumination (>400 000 Cd/cm^2), which has not been observed in low intensity (~6000 Cd/cm^2). This behavior is more pronounced in a low work function gate metal structure (Al: 4.1−4.3 eV), compared to the high work function of Cu (4.5−5.1 eV). Also this is mainly observed in shorter wavelength of high photon energy illumination. However, this behavior is effectively prohibited by embedding the high energy band gap (~8.6 eV) of SiO_x in the gate insulator layer. These imply that this behavior could be originated from the injection of electrons from gate electrode, transported and trapped in the electron trap sites of the SiN_x/a-Si:H interface, which causes the shift of threshold voltage toward positive gate bias direction. The results reported here can be applicable to the large-sized outdoor displays which are usually exposed to the extremely high intensity illumination.



KEYWORDS: *amorphous silicon, thin film transistor, threshold voltage, electron traps, high intensity illumination*

I. INTRODUCTION

Hydrogenated amorphous silicon (a-Si:H) is widely used as an active layer in active matrix liquid crystal displays (AMLCDs) and can be prepared at a lower temperature over a large area with a simple process, offering a sufficient field effect mobility for pixel thin film transistor (TFT) driving.[1−8] Also, it has attracted a great deal of attention as a solar cell,[9,10] and recently, position sensors with nanostructured film[10,11] and image sensors[12] were reported, which could be used in flexible devices using plastic films.[13−15] However, these state of art devices still have instability problems of threshold voltage shift under constant direct current (DC) operation. After prolonged gate bias stress, the electrical properties are undesirably deviated from the initial values.[16−18] Additionally, it was reported that a-Si:H and amorphous oxide semiconductor showed the persistent photoconductance effect, which could be another instability issue that should be overcome.[19] Even though this issue has been avoided using an appropriate addressing method, this instability in voltage shift is a challenge in the a-Si:H based device that should be understood thoroughly for long-term stable operation.

The gate bias instability of a-Si:H TFTs has been studied for several decades and has generally been explained by two mechanisms: charge trapping within the gate insulator associated with trap sites and defect states created by the breaking of weak bonds within a-Si:H.[20−26] At negative gate bias stress, the threshold voltage commonly shifts toward the negative gate voltage region due to the hole trapping, in which the holes are injected from a-Si:H active layer.[16,21,27] Recently, however, as the stress voltage increases, the turnaround phenomenon of the threshold voltage shift was reported, attributed to the compensation of hole trapping and state creation.[28] Currently, we observe this turnaround behavior under high intensity illumination, which has not been reported yet. This turnaround phenomenon is essential to thoroughly understanding the underlying mechanism and for fabricating the stable devices.

In this study, we report on the unusual behavior of bias-stress induced a-Si:H TFT under extremely high intensity illumination. In our system, the turnaround behavior of threshold voltage from negative to positive bias direction was observed under extremely high intensity illumination when only negative gate bias was applied. For this, various light intensities, TFT structures, and characterizations were applied to observe the behavior of threshold voltage shift. On the basis of these, we analyzed the underlying mechanism of this behavior, showing that the electrons from contact gate metal played a key role in supplying electrons into the gate insulators, which are trapped at the interface between gate insulator and a-Si:H active layer. Since recent large AMLCDs such as digital signage display have

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been designed for outdoor use, higher illumination for the backlight is desired to increase the visibility. This phenomenon has thus direct technological impact and motivates deeper studies of the cause of instability in a-Si:H TFTs.

II. EXPERIMENTAL PROCEDURES

The TFT employed in this work was a conventional inverted staggered bottom gated structure. After the deposition and patterning of gate metals with Ti/Cu (30/300 nm), the a-SiN_x (450 nm), a-Si:H (200 nm), and n^+ a-Si:H (50 nm) were deposited consequently for gate insulator, active layer, and ohmic contact layer with plasma enhanced chemical vapor deposition method at 320 °C. The active area was patterned with conventional UV photolithography and dry etching with SF_6 based gas. Source/drain metals (Mo/Al/Mo = 50/250/100 nm) were then deposited and patterned, followed by the passivation of the device with a-SiN_x (200 nm) grown at 280 °C. Finally, the contact holes were opened by dry etching process. The width and length of the fabricated devices were 25 and 5 μm, respectively. The schematic TFT device structure used in these experiments are shown in Figure 1a.

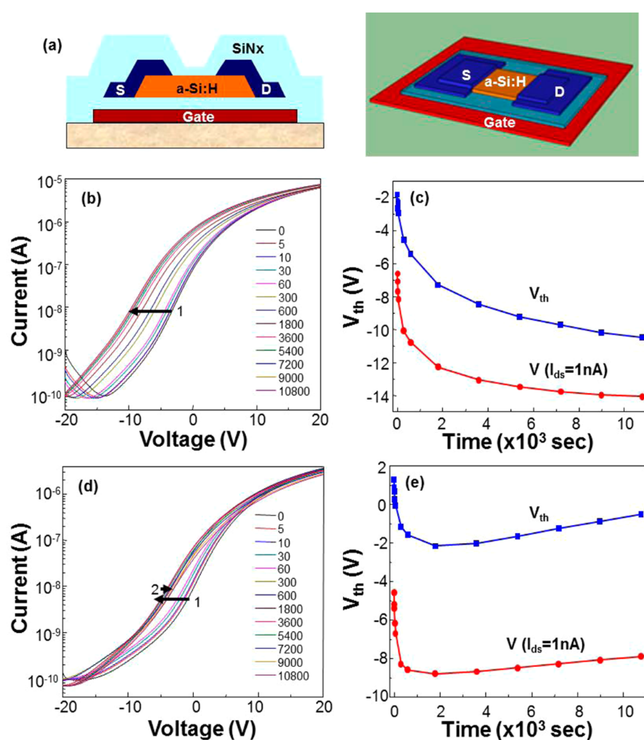

Figure 1. (a) Schematic TFT structure used in these experiments. Evolution of transfer current−voltage (I−V) curves in a-Si:H TFT with the V_{gs} = −25 V and V_{ds} = 10 V for 3 h under the illumination of (b) 6000 and (d) 400 000 cd/cm^2. Resultant temporal evolutions of threshold voltage shift in a-Si:H TFT under the illumination of (c) 6000 and (e) 400 000 cd/cm^2.

The electrical and bias stress tests were carried out with a probe station within a light shield box. To observe the light-induced degradation in TFT, a white LED was employed, capable of controlling the light intensity over 400 000 cd/cm^2, which was compared with the low intensity illumination (~6000 cd/cm^2). The negative gate bias of −25 V and drain voltage of 10 V were applied at 60 °C (NBTIS). The bias stress was applied for 3 h and monitored for behavior of threshold voltage with time in the photo states. The energy band gap was measured using electron energy loss spectroscopy (EELS) and the energy difference between E_F and E_v was observed by X-ray photoelectron spectroscopy (XPS).[29,30]

III. RESULTS AND DISCUSSION

Figure 1 shows the comparative evolutions of transfer current−voltage (I−V) curves in a-Si:H TFT under the same negative gate bias-stress (V_{gs} = −25 V, V_{ds} = 10 V, T = 60 °C) with only different light intensity conditions (6000 vs 400 000 cd/cm^2). For a lower light intensity of 6000 cd/cm^2 (Figure 1b), the normal negative shift of threshold voltage as a function of stress time was observed. The resultant temporal evolution of threshold voltage shift in a-Si:H TFT is displayed in Figure 1c. The threshold voltage at each stress time was obtained from the extrapolation (intercept to x-axis) of the drain current (blue). Additionally, the gate voltage change at the drain current of 1 nA (red) was estimated, which to be useful when the subthreshold slope was changed with stress time. For 3 h of NBTIS under low intensity illumination, the threshold voltage shifted about ∼−7.5 V and the gate voltage changed at I_{ds} = 1 nA was ∼−8.7 V. This behavior in threshold voltage is in good agreement with the previous results observed in a-Si:H TFT under the conventional NBTIS condition, explained as the holes trapping at the interface of a-SiN_x gate insulator and a-Si:H active layer.[16,21] When the a-Si:H TFT was stressed under extremely high illumination over 400 000 cd/cm^2, the abnormal behavior of evolutions in transfer I−V (Figure 1d) as well as its threshold voltage change were observed (Figure 1e). Until the stress time of around 1800 s, there appeared the similar behavior with low intensity NBTIS showing the shift toward the negative gate bias direction about −3.3 V; however, after ∼1800 s, the threshold voltage shift of ∼1 V toward positive gate voltage region was observed. In particular, the subthreshold swing was slightly increased with stress time, as shown in Figure 1d. This behavior can be interpreted as the degradation and the creation of dangling bonds, known as the Staebler−Wronski effect.[31] This implies that threshold voltage turn-around phenomenon was accompanied by the increase of dangling bonds due to the high intensity illumination condition.[32]

Theoretically, when the threshold voltage moves toward positive gate bias direction under the high intensity illumination condition in negative gate bias, two possible origins of trapped charges can be considered in a-Si:H TFT; the increase of electrons trapping or the decease of holes trapping.[20−26] For the electrons trapping to be increased, the extra electrons should be supplied into the gate insulator during the bias stress, and the injected electrons should be transported toward the a-SiN_x/a-Si:H interface. On the contrary, the reduced holes trapping would accompany the decrease in hole trap sites at the interface of a-SiN_x and a-Si:H.[21,25,26] In this context, we applied three strategies in manners that can verify the cause of this unusual behavior among these two hypothetical mechanisms, clarifying the source of trapped carriers.

The first strategy was to check the dependence of work function (WF) in gate metals on the abnormal behavior of threshold voltage under high intensity NBTIS test. If the electrons could be supplied and injected into the gate insulator under extremely high intensity illumination condition, it is expected that the amount of electrons should be easily injected in case of low WF gated metal TFT than that of higher one. Therefore, two kinds of metal with different WF (Al (WF: 4.1−4.3 eV) vs Cu (WF: 4.5−5.1 eV)) were prepared.[33] In order to increase the credibility of the result, two kinds of TFTs (10 TFTs in each condition) were tested and analyzed statistically. The field effect mobilities of fabricated TFTs were nearly same

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as ~0.4 $cm^2/(V\ s)$. (The detailed measurement method was described elsewhere.[16]) Figure 2a shows the resultant temporal evolution of threshold voltage shift under high intensity NBTIS with Cu and Al gated a-Si:H TFT. The schematic energy band diagrams of Cu and Al-gate/gate insulator (SiN_x) structure are illustrated in Figure 2b. In the case of Al gated TFT, most of TFTs showed the unusual behavior of threshold voltage turnaround, on the other hand, only some of Cu gate TFT turned around in threshold voltage. The difference between the two groups was verified statistically. This provides one of the clues that the electrons from near the Fermi level of gate metal with an aid of high intensity illumination might be injected into gate insulator, resulting in the trapping of electrons at the a-SiN_x/a-Si:H interface.

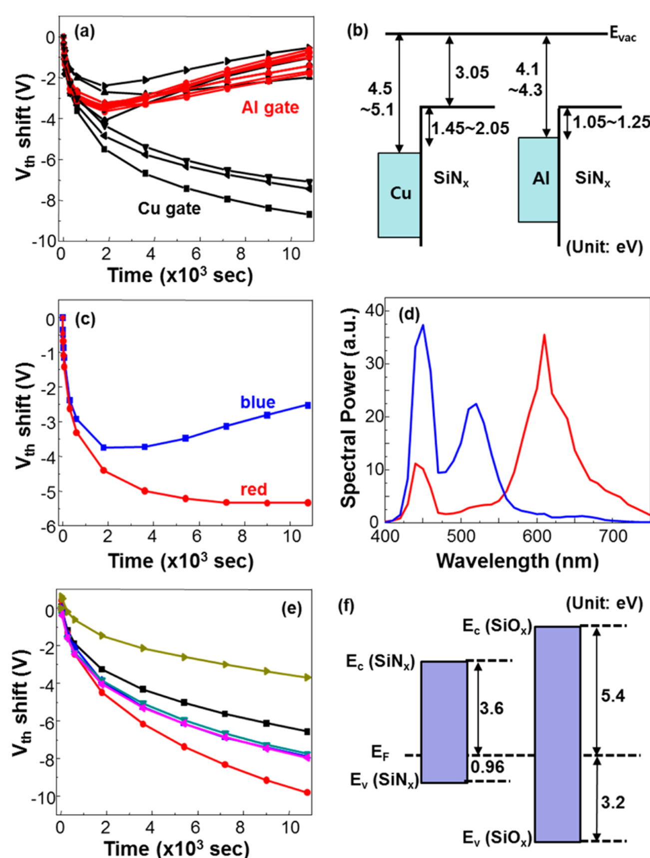

Figure 2. Temporal evolutions of threshold voltage shift with various conditions. (a) Dependence of work function in gate contact metal (Al (red) and Cu (black)) and (b) schematic energy band diagrams of Cu and Al/gate insulator (SiN_x) structure, evaluated from ref 33. (c) Dependence of incident light wavelength on the abnormal behavior in NBTIS test and (d) spectral power of incident beam (short and long wavelength) as a function of wavelength. (e) New concept TFT including thin SiO_x layer within the gate insulator (SiN_x). This concept was introduced, and its threshold voltage behavior was monitored under extremely high intensity condition NBTIS test. (f) Electronic energy band structure measured/calculated by EELS and XPS.

Second, the dependence of incident light wavelength in NBTIS test on the abnormal threshold voltage shift was examined in order to find the cause of this behavior. If the electrons could be injected into the gate insulator under high intensity NBTIS, it is expected that the amount of injected electrons would be much higher in the wavelength of blue region (short wavelength) which has higher photon energy than that of red region (long wavelength) with relatively low photon energy.[34,35] Thus, two different wavelengths of light were injected respectively during high intensity NBTIS, and the resulting behavior was compared. As shown in Figure 2c, when the light corresponding to blue region with high photon energy was illuminated on the a-Si:H TFT under high intensity NBTIS, in most cases, the abnormal threshold voltage turnaround was observed. Meanwhile, when the longer wavelength of red region was illuminated during NBTIS, no turnaround behavior was found in our experiment. Each electroluminescent spectrum converted into spectral power is displayed as a function of wavelength in Figure 2d. The main peak of each spectrum was 610 nm (red) and 450 nm (blue), and their corresponding photon energies were 2.03 and 2.76 eV, respectively. Also the total energy integrated from each spectrum was slightly higher in longer wavelength (red) than that of shorter wavelength (blue) by 1.14 times, meaning that the photon energy of each spectrum is more critical in the turnaround behavior of threshold voltage than the total energy. This result provides other evidence that the injected electrons from gate metal could be the source of trapped carriers, resulting in the positive turnaround of threshold voltage under high intensity illumination. It has been reported that in NBTIS test of a-Si:H TFT, the photon energy is closed related to a creation of subgap states and the charge trapping is determined by the relation between the photon energy and the band offset.[35] Therefore, the energy barrier from Cu gate to gate insulator is estimated to be 1.5−2.1 eV (Figure 2b) that the amount of electron could be injected into a-SiN_x gate insulator with an aid of short wavelength of photon energy (2.76 eV).

Finally, we modified the TFT structure by inserting thin SiO_x layer within the SiN_x gate insulator in order to provide the function that blocks the injected electrons, which offered the opportunity to obstruct the transport of electrons injected from gate electrode. It is expected that this thin SiO_x layer effectively blocks the hopping of electrons among the applied negative bias because it has high energy bandgap of ~9 eV as well as it was reported that SiO_x has lower defect density in comparison with SiN_x gate insulator,[36] suppressing the diffusion of charged carriers.[37] The thickness of inserted SiO_x layer was 10 nm at depth of 10 nm from gate metal/SiN_x and total capacitance of gate insulator was identical to previous one by adjusting thickness of SiN_x gate insulator layer. It was reported that the amount of threshold voltage shift originated by the injection of electrons from gate metal is proportional to the distance of transported carriers.[38] Based on this, it is desirable to form the thin SiO_x blocking layer near the gate metals; however, it is inevitable that the gate metal was oxidized during the SiO_x deposition resulting in the deterioration of electrode. In the process point of view, the insertion of SiO_x thin layer was more effective than replacing of SiN_x into SiO_x, because the SiN_x gate insulator showed the higher process compatibility in dry etching. Moreover, the TFT *I*−*V* characteristics were deteriorated when a-Si:H comes in contact with SiO_x layer. When the initial transfer *I*−*V* curves were compared after modifying the gate insulator layer with the insertion of very thin layer, no significant change was observed. Figure 2e shows the resultant evolution of threshold voltage in the newly SiO_x layer introduced TFT structure. The band offset and the energy band structures of a-SiO_x and a-SiN_x are schematically illustrated in Figure 2f, offering larger conduction band offset (2.2 eV) to be felt as large injection barrier for electrons. In repeated high

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illumination NBTIS test with several other devices, no abnormal turnaround behavior was observed, meaning that the transport of injected electrons from gate electrode was effectively blocked by the potential barrier, resulting in the normal behavior of threshold voltage shift even in high intensity illumination NBTIS.

Considering the aforementioned experimental results, the abnormal behavior of threshold voltage could be strongly related to the injection of electrons from gate metals under high intensity of NBTIS. Figure 3 shows the schematic energy band

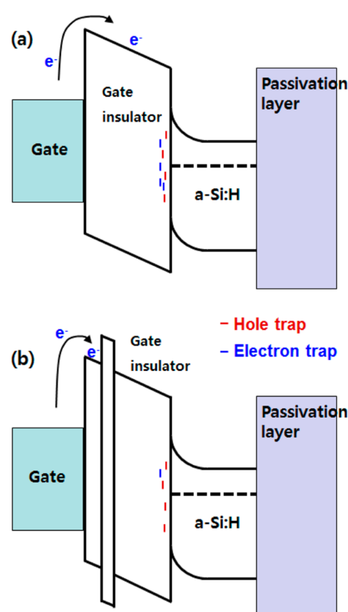

Figure 3. Schematic energy band diagrams under negative gate bias stress with high intensity illumination in a-Si:H TFT of (a) a conventional gate insulator scheme (SiN_x) and (b) a thin SiO_x layer inserted in the SiN_x gate insulator.

diagrams of normal (Figure 3a) and thin SiO_x layer inserted TFT structure (Figure 3b). Under NBTIS condition with extremely high intensity light, higher amount of electrons can be injected with an aid of photon energy from gate electrode, which was confirmed by the associated experiments that showed the dependence on the light wavelength and the WF of gate metals in the abnormal behavior of a-Si:H TFT. Both the low WF of contact metal and the shorter wavelength of incident light infer the possibility of injection of electrons from gate electrode. Once the electrons are injected into the gate insulator, it is expected that the injected electrons transport via negative gate bias through the conduction band and reach the SiN_x/a-Si:H interface, finally trapped in the electron sites. The turnaround behavior was usually observed after 30 min of the initial negative directional shift. Generally, the holes trapping rate at the interface under constant negative gate bias stresses is generally decreased with the stress time and the electron trapping rate at the interface is increased with an aid of illumination. Therefore, the delayed turnaround behavior can be understood by the competition of holes and electrons trapping at the interface and the higher trapping rate of electrons provided from gate electrode. However, in thin SiO_x layer inserted TFT within gate insulator layer, the transport of electrons from gate electrode side to trap sites is blocked by the potential energy barrier, resulting in the only negative shift of threshold voltage in a-Si:H TFT by the holes traps, as shown in Figure 3b. The injected electrons from gate electrode could be a leakage current source; however, the calculated and measured current level based on our TFT dimension is extremely low (10^{-15}–10^{-14} A), which can be negligible in the operation of TFT.

IV. CONCLUSION

In conclusions, under extremely high intensity NBTIS, we observed the threshold voltage shift turnaround even in the negative gate bias, in which the it shifted toward negative direction of −3.3 V, but after the stress time of around 1800 s, it moved toward positive bias direction of ∼1 V. This behavior was verified by the associated experiments, the dependence of work function in gate metal (Al vs Cu), incident wavelength of light (blue vs red), and the modified gate insulator structure, expecting that it could be originated from the injection of electrons from gate electrode as well as the transport to the SiN_x/a-Si:H interface. The transported carriers are trapped in the electron trap sites, causing the shift of threshold voltage toward positive gate bias direction. Currently, there increase a variety of large-sized AMLCDs for outdoor displays, such as digital signage and outdoor billboards, which are expected to be new fields of application in AMLCD panels. And, a high intensity backlight should be built within the LCD module for their visibility during the daytime, which raises the risk of abnormal operation of these displays. Therefore, these studies provide clear implications for stable operation of a-Si:H TFTs under extreme intensity illumination conditions.

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Notes

The authors declare no competing financial interest.

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