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Effect of NH_3 plasma treatment of gate nitride on the performance of amorphous silicon thin-film transistors

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The effect of NH_3 plasma treatment of the hydrogenated amorphous silicon nitride (a-SiN_x:H) gate insulator on the performance of hydrogenated amorphous silicon (a-Si:H) thin-film transistors (TFTs) has been studied for different deposition conditions of the gate nitride. The TFT subthreshold slope and threshold voltage decrease with increasing rf power of gate nitride deposition. When increasing the rf power from 25 to 100 W, an increase in field-effect mobility, from 0.29 to 0.37 $cm^2/V\,s$, is obtained. The NH_3 plasma treatment causes a general increase in subthreshold slope and threshold voltage. It also degrades the field-effect mobility as large as 40%. However, the desirable effect of the plasma treatment is that the resulting devices have a higher stability exhibited by a 25% reduction of hysteresis width of transfer characteristics and by their higher resistance to prolonged positive gate field application. Based only on the electrical measurements, an exact model of the plasma interaction with the a-SiN_x:H could not be developed. However, it is postulated that both radiation damage and nitridation/amination can occur.

I. INTRODUCTION

Hydrogenated amorphous silicon thin-film transistors (a-Si:H TFTs) have received considerable interest in recent years in basic research as well as in their commercial application such as switching elements for liquid-crystal flat panel displays.[1,2] The reasons for this interest are their current on/off ratio of larger than 10^6 and the fact that they can be fabricated on inexpensive, large-area glass substrates at a temperature below 350 °C. The present characteristics of a-Si:H TFTs are adequate for the switching element in large-matrix liquid-crystal displays. However, for other applications such as the peripheral driver circuitry and basic logic circuits, their performance needs to be further improved. Of particular importance are the TFT speed and stability issues. One approach is to improve the material properties of a-Si:H and amorphous silicon nitride (a-SiN_x:H) gate insulator, especially near their interface.

Much of the research on improving material quality has been focused on gate a-SiN_x:H. This is because it is a three-element alloy and its quality as a gate material is greatly dependent on its deposition conditions. Many research groups have published results concerning this aspect. However, the basic physics and chemistry have not yet been fully understood.

Plasma technologies have been used extensively in the last decade not only for the fabrication of very-large-scale integrated (VLSI) circuits, but also for the modification of various material properties. It was observed that nitridation of silicon can occur by NH_3 plasma treatment,[3] and this kind of reaction is also chemically possible with other materials. This would give another degree of freedom in a fabrication process. However, studies have shown that plasma-induced defects in the SiO_2/Si structure are similar to those created by other radiation sources, which results in the trapping of positive charge in the oxide, generation of interface states, and neutral traps. In the fabrication processes of a-Si:H TFTs, NH_3 is a common deposition gas and its plasma consists of various nitriding species and excited hydrogen which is often beneficial due to its ability for dangling bond passivation. Therefore, it would be very interesting and important to know whether the NH_3 plasma will improve or degrade the interface properties of the a-SiN_x:H/a-Si:H structure. In our experiments, the gate a-SiN_x:H was first treated with NH_3 plasma, and this was then followed by a-Si:H deposition as is typical for staggered inverted TFTs. This report gives results obtained directly from a-Si:H TFTs by measuring their transfer characteristics and by other bias-temperature stressing experiments.

II. EXPERIMENT

The TFTs used in this work have the inverted staggered structure. The substrates were thermally oxidized silicon wafers, which are a convenient substitute for glass substrates. After the patterning of sputter-deposited chromium gates, wafers were transported into a 30-kHz planar plasma-enhanced chemical vapor deposition (PECVD) system, which has a ground electrode of diameter 28 cm. For conventional devices, two layers, a-SiN_x:H and a-Si:H with nominal thickness of 1500 and 700 Å, were then deposited consecutively in one pump-down cycle. For all wafers used in this study, the a-Si:H films were deposited from a glow discharge of pure SiH_4 at a substrate temperature of 260 °C and rf power of 6 W. The gas pressure was 0.35 Torr and flow rate was 50 sccm. For the deposition of SiN_x, the substrate temperature was fixed at 320 °C and the gas pressure at 0.6 Torr, and the flow rates of gases were $NH_3/N_2/SiH_4 = 50/50/5$ (sccm). The rf powers used were 25, 50, and 100 W.

For those runs with NH_3 plasma treatment immediately following SiN_x deposition, a pump-out of residual gases was followed by 10 min of NH_3 plasma treatment

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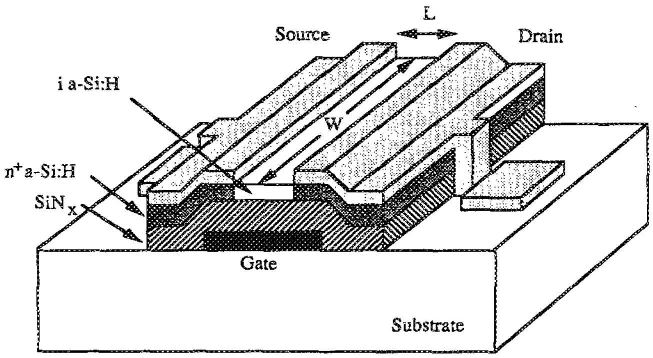

FIG. 1. A three-dimensional view of the a-Si:H TFT test device.

performed at a rf power density of 40.8 mW/cm^2 with a gas pressure of 0.5 Torr and flow rate of 50 sccm. The gas change-over prior to a-Si:H deposition was done by purging the system with 50 sccm of SiH_4 and by repetition of pump-down ((90 mT)/purge (600 mT) for three times. Source-drain contacts were obtained by phosphorous ion implantation and by sputtering Al-Si for the contact metal. The completed structure is shown in Fig. 1.

Electrical characteristics of the TFTs were measured on packaged devices with an HP 4140B picoammeter/dc voltage source, which is controlled by an HP 9000 series 236 computer. The threshold voltage and field-effect mobility were determined from the x intercept and slope of the square-law model.[4] All current was measured with a hold time of 10 s after each voltage change.

III. RESULTS AND DISCUSSION

A. TFT subthreshold characteristics

Figure 2 (a) is representative of the transfer characteristics of a-Si TFTs deposited at a rf power of 100 W with no plasma treatment, while Fig. 2(b) for the corresponding plasma-treated devices. All devices measured showed an current on/off ratio of larger than 10^7. However, differences exist in the two important parameters of the transfer characteristics, namely, (1) the subthreshold slope (S), defined as the inverse of logarithmic I_D-V_G slope which is $dV_{GS}/d(\log I_D)$ and (2) the width of hysteresis.

The subthreshold slope S is directly related to the ability to shift the Fermi level through the distribution of gap states $N(E)$ and therefore is a useful measure of the effective density of gap state[5] in the bulk a-Si:H and any interface states present between the insulator and a-Si:H. An approximate relation can be written as[6]

$$N_i=\frac{\epsilon_0}{K_{\mathrm{Si}}}\left(\frac{K_{\mathrm{ins}}}{k_BTd_{\mathrm{ins}}}\right), \qquad (1)$$

where ϵ_0 is the permittivity of free space, K_{Si} and K_{ins} are the dielectric constants of amorphous silicon and gate insulator, respectively, T is the measurement temperature, and d_{ins} the thickness of the gate insulator. For all devices, the a-Si:H was deposited under the same conditions. The gate nitride deposition conditions were identical except for rf power of levels of 25, 50, and 100 W. For those NH_3 plasma-treated SiN_x surfaces, the conditions were also kept constant. Hence, the subthreshold slope S gives information exclusively about the interface, i.e., the smaller the S, the smaller the interface state density. Figure 3 shows the subthreshold slope dependence on rf power of SiN_x deposition and on NH_3 plasma treatment. It can be seen that S decreases with increasing rf power density, especially at higher values. At the time of this report, the N/Si ratio of the gate a-SiN_x:H has not been experimentally determined under the different rf power densities. However, research on PECVD SiN_x:H has already indicated that N/Si ratio increases with rf power.[7,8] Although the correlation between N/Si ratio and the SiN_x:H/a-Si:H interface property is still not fully understood, the results of Fig. 3 tend to

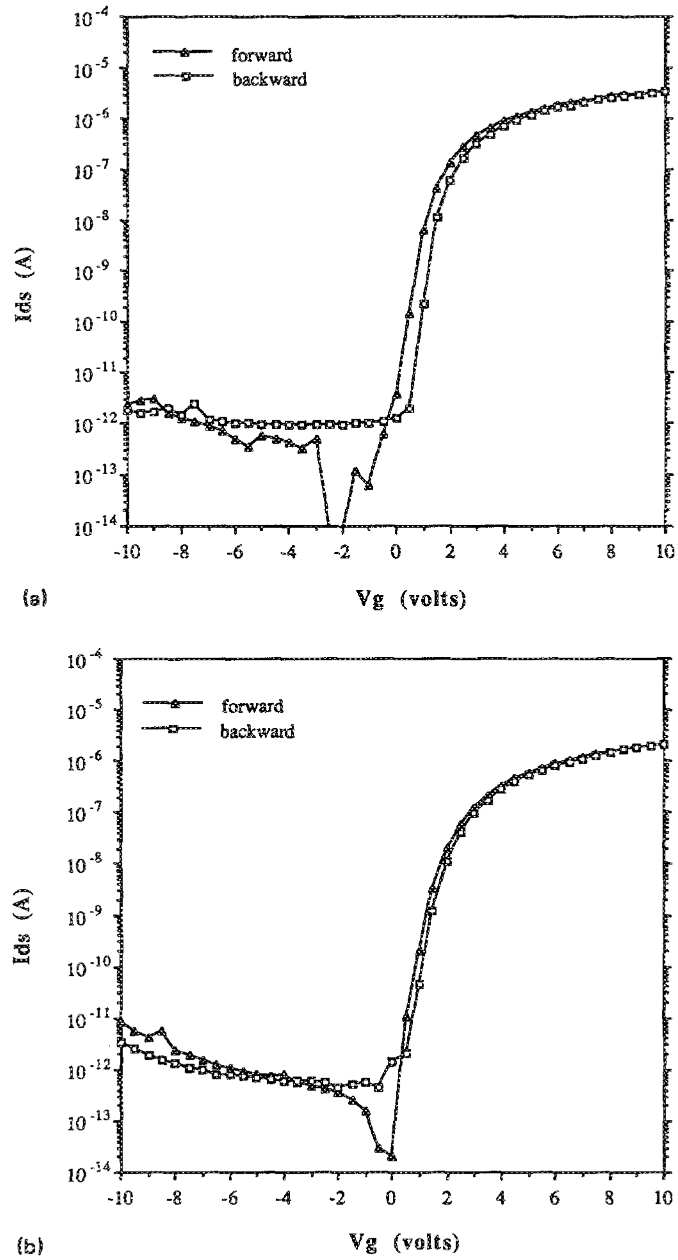

FIG. 2. Transfer characteristics (V_{ds} = 2V) for a gate nitride deposited at 100 W. (a) With no NH_3 plasma treatment, (b) with NH_3 plasma treatment.

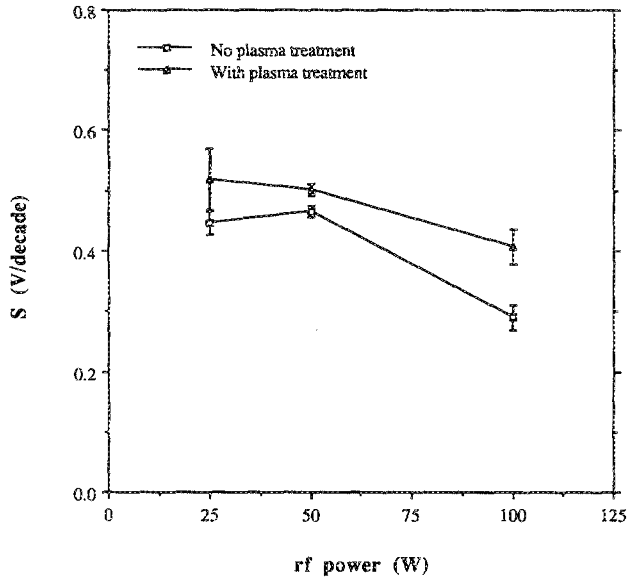

FIG. 3. Subthreshold slope dependence on rf power of gate nitride deposition and on NH_3 plasma treatment.

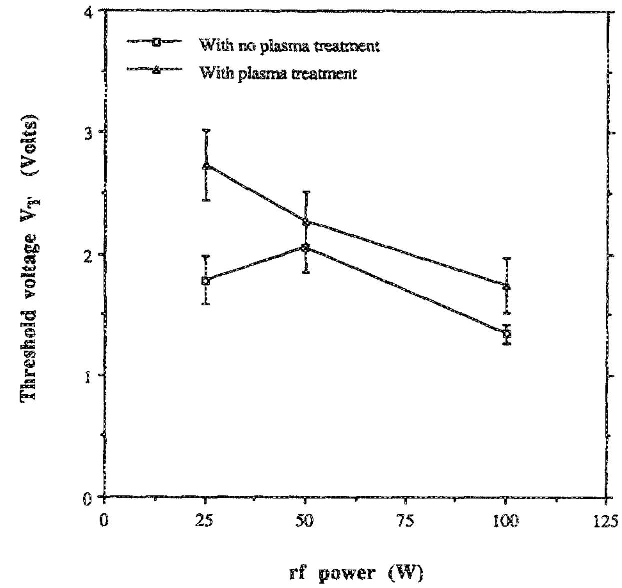

FIG. 4. Threshold voltage variations at different rf power values of gate nitride deposition and the effect of NH_3 plasma treatment.

agree that higher rf power deposition and therefore more N-rich SiN_x:H make a better interface with a-Si:H.[9]

The NH_3 plasma treatment caused a general increase in subthreshold slope for all rf power depositions of gate nitride, as seen in Fig. 3. This effect may be explained as follows. First, energetic species such as electrons, ions, and photons in the plasma may induce radiation damage, creating interface defects/traps and therefore increasing the TFT subthreshold slope. Second, plasma surface nitridation and/or amination may occur. The latter makes the SiN_x surface more N rich, which leads to lower subthreshold slope. One or both of these competing effects could occur. However, for the particular plasma conditions used in the present experiment the first mechanism appears to dominate the plasma-surface interaction as far as the effective interface states is concerned. The larger increase in S at 100 W is consistent with the assumption that SiN_x:H there may already be N rich and therefore radiation damage may be the entire reason.

B. Threshold voltage and field-effect mobility

Unlike the case of crystalline metal-oxide-semiconductor field-effect transistor (MOSFET), threshold voltage (V_T) in a-Si:H TFTs has not been rigorously defined from first principles. However, for the purpose of comparison, the standard square-law MOSFET expression was used in this study. The saturation condition was met by connecting the gate and drain electrodes together. The threshold voltage and field-effect mobility are then obtained from the x intercept and the slope of a linear fit to the $I_D^{1/2}$-vs-V_G characteristics. For all devices measured, the fitting is quite good.

The threshold voltage in a-Si:H TFTs is also sensitive to deep interfacial charge (Q_{it}) as well as trapped charge (Q_{tr}) in the gate insulator. Therefore, any variation in these charges causes a shift in V_T given by

$$\Delta V_T = -[(\Delta Q_{it} + \Delta Q_{tr})/C_{ins}], \qquad (2)$$

where C_{ins} is the gate nitride capacitance per unit area. Figure 4 shows the square-law threshold voltage dependence on rf power and the influence of NH_3 plasma treatment. The data points are averaged values over at least three devices. Although the data for untreated devices are somewhat scattered, high rf power deposition at 100 W appears to lead to a lower threshold voltage. This indicates a lower interface states and is correlated well with its lower subthreshold slope exhibited in Fig. 3. Also shown in Fig. 4 are the increased threshold voltages for all plasma-treated devices.

The field-effect mobility calculated from the square-law model is shown in Fig. 5. Again, larger rf power deposition of the gate insulator is preferred for a higher field-effect mobility. When increasing the rf power from 25 to 100 W, an increase in field-effect mobility, from 0.29 to 0.37 cm^2/V s, was obtained. This is once again consistent with the above conclusion that gate nitride deposited at higher rf power has a better interface with a-Si:H. However, a mobility degradation as large as 40% occurs after NH_3 plasma treatment. This reduction is believed due to buildup of interface traps and generation of fixed charges, and therefore the increased Coulomb scattering by charged centers at the interface. The slow trapping on those interface states close to the band edge may also contribute to the degradation. Both the threshold voltage and field-effect mobility variations indicate that NH_3 plasma treatment create additional interface states.

C. Field-induced instability

As discussed previously, a continuous application of a positive gate voltage causes a threshold voltage shift and

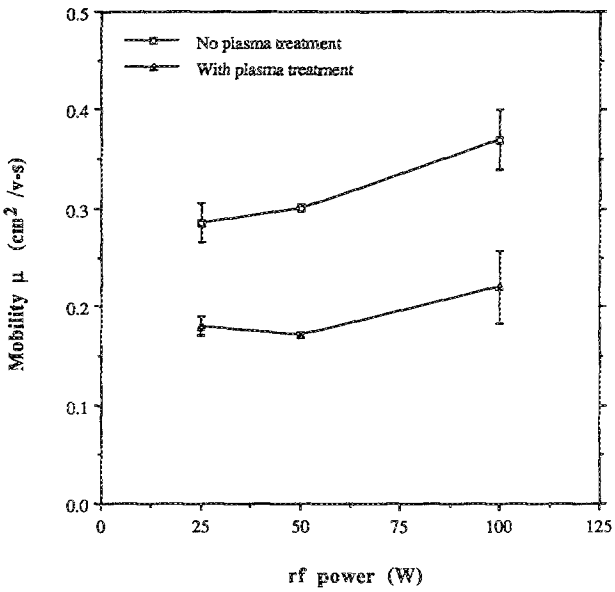

FIG. 5. Field-effect mobility as a function of rf power of gate nitride deposition and the influence of NH_3 plasma treatment.

therefore the observed hysteresis in the I_D-vs-V_G characteristics. For the present experiment, a delay time of 10 s was used after each voltage change and the entire transfer curve took about 14 min to complete. This longer measurement time causes the electron trapping deeper into the gate nitride, kinetically allows the generation of metastable states in a-Si:H, and makes these effects more significant. Therefore, the width of I_D-vs-V_G hysteresis itself is a very convenient measure of device stability. For a gate voltage swing from -10 to $+10$ V, all devices give a hysteresis of less than 0.7 V. Another interesting feature is that the NH_3 plasma treated devices exhibit at least a 25% reduction in the hysteresis width. As such, the average values are 0.4 V for gate nitride deposited at 25 W and 0.3 V for those deposited at 50 and 100 W.

A commonly employed method as a stability test is the bias-temperature stress (BTS). Here the BTS measurements were performed after the method used by Powell.[10] A gate voltage of 10 V was continuously applied and a constant temperature of 80 °C was maintained. The source-drain current was then continuously recorded for 4×10^4 s at a low drain voltage of 0.5 V. Transfer characteristics and threshold voltage were measured both before and after the BTS.

Figures 6 (a)–6(c) give the time dependence of drain currents $I_D(t)$ normalized by the initial values of $I_D(1)$ for the three rf power values used. It can be seen that the rate of decay of $I_D(t)/I_D(1)$ is smaller for all the NH_3 plasma-treated devices, especially for time less than 100 s. Figure 7 shows the absolute ON-current decay curves corresponding to Fig. 6(b). Although the initial current is lower in the plasma-treated device, the absolute final current is larger than the device without plasma treatment.

The time dependence of $I_D(t)/I_D(1)$ has been attributed to a shift of threshold voltage V_T (Ref. 11) and a decrease of field-effect mobility. The threshold voltage shift

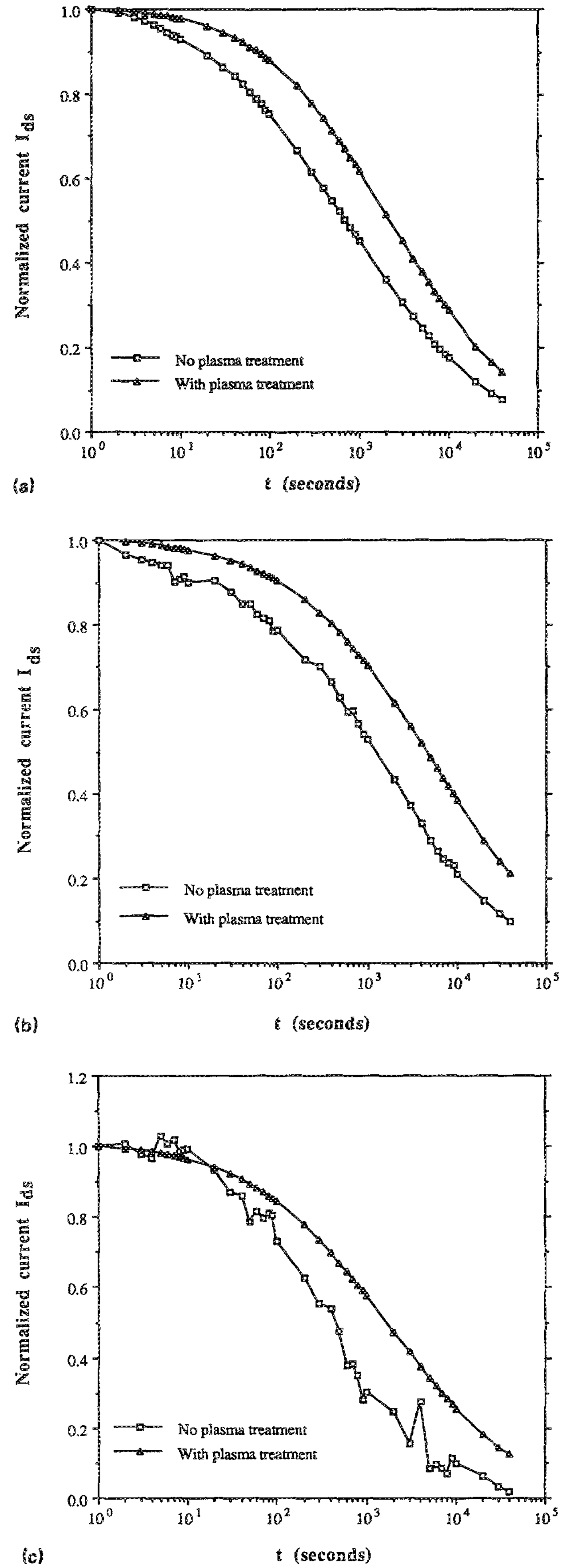

FIG. 6. Normalized time dependence of the ON-current of a-Si:H TFTs under a gate bias stress of 10 V. The source-drain voltage was 0.5 V and temperature was 80 °C. The gate nitride were deposited at the following rf powers: (a) 50 W, (b) 25 W, and (c) 100 W.

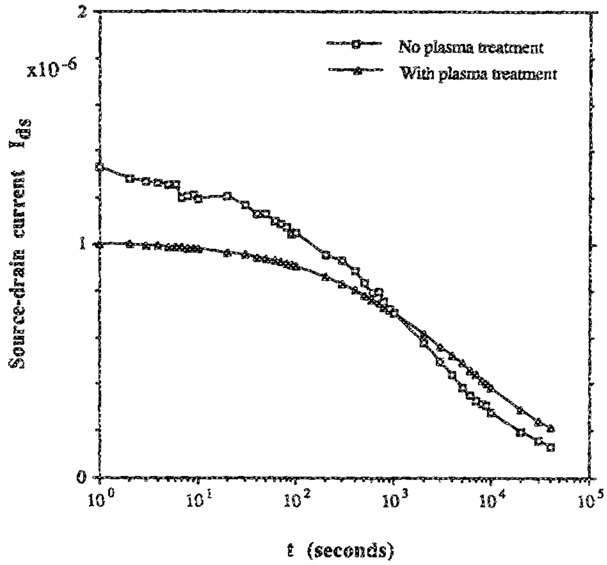

FIG. 7. Absolute On-current decay corresponding to Fig. 6 (b).

is mainly due to charge trapping in slow states which are located in the a-SiN$_x$:H near the interface and due to metastable states created in a-Si:H below the flat-band Fermi level. The relative contribution of these two mechanisms depends on bias stress voltage, temperature as well as the fabrication conditions of a-Si:H TFTs.[12] The decrease in field-effect mobility or the increase in subthreshold slope S is related to the generation of additional states above the flat-band Fermi level at or near the interface of a-Si:H. Both of these effects have been observed in the BTS experiments. The flat-band voltage shift is as large as 6 V. The subthreshold slope increase is about 16% and the degradation of field-effect mobility is less than 6%. These two degradation mechanisms are believed to be independent processes.[13] Since the a-Si:H layers for all devices were nominally deposited under the same condition, it can be assumed that contribution to the $I_D(t)/I_D(1)$ current decay from a-Si:H are the same. Further support for this view can be determined from Table I which lists the subthreshold slope and mobility ratios after and before BTS. These ratios are very close, within the errors of experiment and data analysis, for NH_3-treated and the corresponding untreated cases. Therefore, the difference in $I_D(t)/I_D(1)$ decay must come from the difference in SiN$_x$ quality near the interface. It has been argued[14,15] that silicon dangling

TABLE I. Subthreshold slope and mobility ratios after and before BTS.

		rf power of nitride deposition		
Ratio	NH_3 plasma	25 W	50 W	100W
S_{after}/S_{before}	no	1.13	1.16	···
	yes	1.16	1.18	1.16
μ_{after}/μ_{before}	no	0.95	0.94	0.86
	yes	0.97	0.95	0.98

bonds are responsible for charge trapping in a-SiN$_x$:H. The charge injection can occur by direct tunneling from states in a-Si:H into traps in a-SiN$_x$:H and/or by Fowler–Nordheim tunneling into the nitride conduction band, followed by deep trapping.[11] Therefore, N-rich nitride should be more resistant to electron injection because it has less silicon dangling bonds (traps)[16] and because its larger band gap and hence the corresponding energy barrier for electron injection. Recently, charge-injection measurements on Al/SiN$_x$/c-Si capacitors further confirmed that N-rich nitride had lower charging rate.[17] From the above arguments and results of previous sections, it is justified to postulate that the NH_3 plasma treatment resulted in nitriding reaction or amination and the resulting gate insulator is less susceptible to field-induced threshold voltage shift.

The observations in this section demonstrate that NH_3 plasma treatment is beneficial as far as device stability is concerned. However, the true plasma-surface reaction is still open for examination. Further spectroscopic analysis should shed light on the elemental composition of the nitride surface and resolve the interaction mechanism. As for the application side, in view of the single plasma conditions used in the present experiment, studies on the plasma treatment with respect to rf power, gas flow, pressure and temperature may improve the stability enhancement without inducing much degradation in mobility.

IV. CONCLUSION

The electrical characteristics of a-Si:H TFTs were studied for different deposition conditions of gate nitride and for the effect of NH_3 plasma treatment. In general, devices with gate nitride deposited a higher rf power give larger field-effect mobilities, lower subthreshold slope, and threshold voltage. Under the particular conditions used, it is found that NH_3 plasma treatment causes a general increase in subthreshold slope and threshold voltage. Field-effect mobility degradation was also observed. However, the positive effect is that the NH_3 plasma-treated devices exhibit higher stability as exhibited by smaller hysteresis of transfer characteristics and by higher resistance against prolonged positive gate-field application. An exact model of the plasma interaction with the a-SiN$_x$:H surface could not be developed only on the basis of the present electrical measurements without a spectroscopic analysis. However, it is suggested that both radiation damage and nitridation/amination can occur. In view of the single plasma conditions used for the surface treatment of gate nitride, it may be possible to manipulate the near-interface nitrogen content of the gate nitride by adjusting macroscopic plasma parameters without noticeable radiation damage.

ACKNOWLEDGMENTS

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