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Time and temperature dependence of instability mechanisms in amorphous silicon thin-film transistors

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We have measured the time and temperature dependence of the two prominent instability mechanisms in amorphous silicon thin-film transistors, namely, the creation of metastable states in the *a*-Si:H and the charge trapping in the silicon nitride gate insulator. The state creation process shows a power law time dependence and is thermally activated. The charge trapping process shows a logarithmic time dependence and has a very small temperature dependence. The results for the state creation process are consistent with a model of Si dangling bond formation in the bulk *a*-Si:H due to weak Si—Si bond breaking stabilized by diffusive hydrogen motion. The logarithmic time dependence and weak temperature dependence for the charge trapping in the nitride suggest that the charge injection from the *a*-Si:H to the nitride is the rate limiting step and not subsequent conduction in the nitride.

There is considerable interest in instability mechanisms in hydrogenated amorphous silicon (*a*-Si:H) in general and in amorphous silicon thin-film transistors (TFTs) in particular. The most important instability in amorphous silicon thin-film transistors is the threshold voltage shift that is observed after prolonged application of a gate voltage (bias stress). This effect has been studied extensively over the last few years, both for its practical importance in device applications and for the fundamental insight that can be gained into the basic properties of amorphous materials.

In an early letter,[1] we studied the time, temperature, and bias dependence of the threshold voltage shift in amorphous silicon–silicon nitride thin-film transistors. We attributed the threshold voltage shift solely to charge trapping in the nitride, and we proposed that the temperature dependence was due to thermally activated hopping in the nitride. Later, an alternative model for the threshold voltage shift was proposed,[2] namely, that it was due to the creation of metastable states in the *a*-Si:H. The latter experimental evidence was based on the charge emission characteristics of transistors biased into depletion after a period of positive bias stress. However, although we showed that the charge emission comes only from states in the *a*-Si:H layer and the signal increases after positive bias stress,[3] the magnitude of the signal reflects the total charge trapped in both the *a*-Si:H and the nitride and so the technique cannot distinguish between the two mechanisms as the cause of the initial positive threshold voltage shift.

Conclusive evidence for the existence of the state creation process in thin-film transistors came from experiments using ambipolar thin-film transistors.[4] These experiments were able to distinguish between state creation in the *a*-Si:H and charge trapping in the nitride and so resolve the true cause of the threshold voltage shift. Furthermore, the ambipolar TFT experiments allowed us to quantify each mechanism, even when both occurred simultaneously. The results showed that both mechanisms occurred, but they had a very different bias dependence, so that state creation dominated at low positive bias, but charge trapping in the nitride dominated at larger forward bias. The charge trapping in the nitride increased if we made the nitride more Si-rich, such that for Si-rich nitrides the charge trapping mechanism could dominate even at low fields. Systematic variation of the nitride, while keeping the amorphous silicon the same, confirmed that the state creation process occurred in the *a*-Si:H, whereas the charge trapping took place in the nitride.[5]

Knowledge of these important results leads to the realization that the original experiments reported in Ref. 1 were done on a sample and at a field where state creation was the dominant mechanism and not charge trapping in the nitride as originally proposed. Ironically, the bias stress conditions used in Refs. 2 and 3 resulted in large threshold voltage shifts, mainly due to charge trapping in the nitride.

In this letter, we report new experimental measurements of the time and temperature dependence of the threshold voltage shift for different bias voltages and so identify the time and temperature dependence for each mechanism. The gate bias dependence of the threshold voltage shift showed the behavior previously reported,[5] with a bias V_{GC} at which the charge trapping in the nitride increases rapidly. First, we choose a sample with a slightly Si-rich nitride, where V_{GC} was about 50 V. Figure 1 shows the time dependence of the threshold voltage shift for different applied biases. At 100 V, where charge trapping dominates, the threshold voltage shift is logarithmic in time, $\Delta V_T \sim r_d \log (1 + t/t_0)$, where r_d is a constant. When we plot the same results on a log-log plot [Fig. 1(b)], we find that the threshold voltage shift at 20 V, where state creation dominates, is given by a power law, $\Delta V_T \sim a(t/t_0)^{\beta}$, with β about 0.5. Figure 2 shows the temperature dependence of the threshold voltage shift. The state creation process shows an activation energy of 0.35 eV as previously reported,[1] but incorrectly identified with hopping conduction in the nitride, whereas the charge trapping process is now shown to be virtually temperature independent.

A logarithmic time dependence for threshold voltage shifts is commonly seen for metal-nitride-oxide-semiconductor (MNOS) memory devices,[6] where charge trapping is clearly taking place. It is also observed in other TFT systems.[7] A logarithmic time dependence is quite generally pre-

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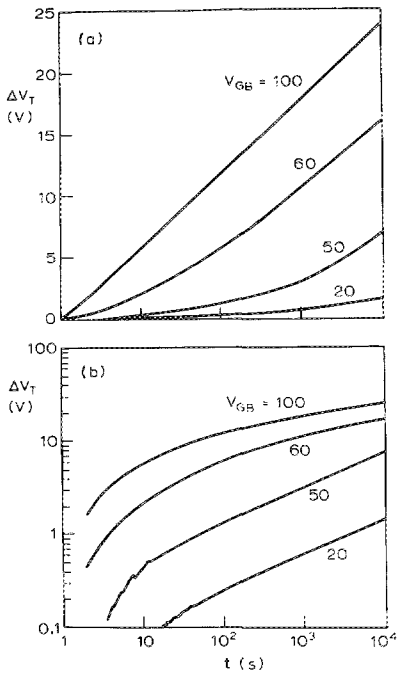

FIG. 1. Threshold voltage shift as a function of time for various positive bias stress voltages V_{GB}. ΔV_T is plotted (a) on a linear scale and (b) on a logarithmic scale.

dicted for charge injection into an insulator, when the injection current depends exponentially on the density of previously injected charge and the charge is trapped near the semiconductor interface.[6,8] This can occur in several ways. For example, the injection process can be by direct tunneling from states in the semiconductor to traps in the insulator, which progressively fill from the interface.[9] The tunneling current depends exponentially on the tunneling distance, which increases in proportion to the density of filled traps. Alternatively, the charge can be injected into the nitride conduction band by Fowler–Nordheim tunneling, followed by deep trapping not too far from the semiconductor interface.[6] Here the injecting current depends exponentially on the injecting field, which decreases due to the screening of previously trapped charge.[8]

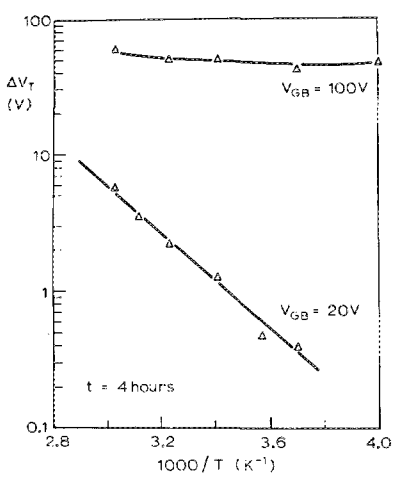

FIG. 2. Temperature dependence of the threshold voltage shift after 4 h bias stress. Bias stress voltage V_{GB} is 20 V and 100 V.

The weak temperature dependence is generally predicted,[6,9] since if there is any temperature dependence at all, it comes from the supply function and appears in the t_0 term.[1] Temperature-dependent effects could occur if there was subsequent redistribution of the trapped charge by conduction in the nitride,[1] as observed in MNOS devices at higher temperatures,[10] but the present results suggest this is not significant, at least for positive bias, near-stoichiometric nitrides and moderate temperatures! Therefore, we now observe charge trapping in amorphous silicon transistors that shows the same time and temperature dependence as generally found for charge trapping in other MIS systems. The rate limiting process governing the threshold voltage shift is the charge injection from the *a*-Si:H to the silicon nitride with charge trapping near to the semiconductor interface and no redistribution of the trapped charge in the nitride. We still think the nitride traps are Si dangling bonds located in the nitride.[5]

Now consider the state creation in the *a*-Si:H. There have been several recent reports that state creation in *a*-Si:H observed in various experiments has a common origin related to the breaking of weak Si—Si bonds and the dispersive diffusion of hydrogen.[11,12] Jackson and Moyer[13] have compared state creation in TFTs to other observations and concluded the same model applies.

For a weak Si—Si bond to break and be stabilized by hydrogen motion, the weak bond has to be occupied by an electron and a hydrogen atom has to diffuse to that site. We assume the bond breaking reaction proceeds by a single electron capture at the weak bond, as shown by Muller,[12] and that these weak bonds are a subset of the conduction band tail states. If we apply this model to the state creation process in a TFT, then the rate of creation of Si dangling bonds (cm^{-2}) is proportional to the density of weak bond sites N_{WB}, the occupancy of the weak bond sites, which is the same as the occupancy of the tail states, and to the diffusion coefficient of hydrogen, D_H. The occupancy of the tail states is n_{BT}/N_{BT}, where n_{BT} is the density of band tail electrons and N_{BT} is the density of band tail states. The hydrogen diffusion is dispersive, so the diffusion coefficient can be represented as a power law in time $D_H = D_0 t^{-\alpha}$ and $\alpha = 1 - \beta$.[14] Therefore, we can write

$$\frac{dN_{DB}}{dt} \sim N_{WB} \frac{n_{BT}}{N_{BT}} D_0 t^{\beta - 1}. \tag{1}$$

In a thin-film transistor, the above threshold characteristic is determined by the band tail states and the threshold voltage by the deep states. Writing C as the capacitance, we have

$$C(V_G - V_T) = n_{BT} \tag{2a}$$

and

$$C\Delta V_T = \Delta N_{DB}. \tag{2b}$$

Substituting into Eq. (1) and integrating leads to the stretched exponential form for the normalized threshold shift, which was observed experimentally by Jackson and Moyer.[13]

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$$[V_G - V_T(t)]/[V_G - V_T(0)] = \exp[(t/t_0)^{\beta}] \ . \quad (3)$$

Here the t_0 term contains the density of weak bonds, the density of band tail states, and the diffusion coefficient of hydrogen. The threshold voltage shift should saturate at a value of $V_G - V_T(0)$, simply because n_{BT} is then negligible. In our experiments this is observed, but only at elevated temperatures in a reasonable time interval. In most experiments the threshold voltage shift due to the state creation is small and so Eq. (3) approximates to

$$\Delta V_T = (V_G - V_T)(t/t_0)^{\beta}. \quad (4)$$

This expression is well observed in our experiments. Both the power law in time (as in Fig. 1) and the proportionality to $V_G - V_T$.[1,5] The latter means that the rate of defect creation is indeed proportional to the density of band tail carriers and t_0 is independent of n_{BT}.

In order to more accurately determine the temperature dependence of the t_0 term, we perform a further series of bias stress experiments. However, instead of keeping the bias constant, we progressively adjusted the bias during the stress to maintain the source-drain current constant (this we term constant-current stress). This is equivalent to keeping the density of band tail electrons constant and so the power law time dependence in Eq. (4) should be maintained irrespective of the magnitude of the threshold shift.

Figure 3 shows some results for a sample which has negligible charge trapping in the nitride, since $V_{GB} = 24$ V and $V_{GC} > 80$ V. The power law dependence is observed, with β increasing with temperature from 0.45 to 0.65. The inset in Fig. 3 shows the time to achieve a threshold voltage shift of 5 V, as a function of temperature. This has an activation energy $E_a = 0.9$ eV which is the activation energy of t_0. The results are similar to previous observations of metastable state formation by various means.[13] The magnitude of E_a and a temperature-dependent β are consistent with dispersive hydrogen diffusion. Note that in the hydrogen diffusion model, the activation energy E_a is related to, but not equal to, the activation energy of the hydrogen diffusion.[15] We conclude that state creation in a-Si:H is consistent with a model of silicon dangling bond formation by weak Si—Si bond breaking stabilized by dispersive hydrogen motion.

The activation energy of the threshold voltage shift after a constant stressing time is $E'_a = \beta \times E_a = 0.5 \times 0.9 = 0.45$ eV. For a wide variety of samples, we find $E'_a = 0.4\ (\pm 0.1)$ eV. The effective activation energy is lower if the bias stress experiment is done under conditions of constant gate voltage (as in Fig. 2 and Ref. 1), since the $V_G - V_T$ term in Eq. (4) is not constant in time and the degree of change is temperature dependent.

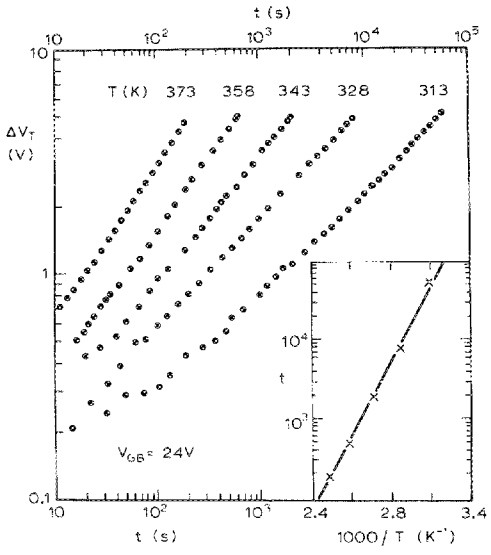

FIG. 3. Time dependence of the threshold voltage shift in a constant-current bias stress experiment at different temperatures. The inset shows the time to obtain a shift of 5 V, as a function of temperature.

In summary, we observe two distinct instability mechanisms responsible for the threshold voltage shift in a-Si TFTs under positive bias stress. The time and temperature dependences of these mechanisms can be explained in terms of previously proposed models for charge trapping in the nitride and dangling bond state creation in the a-Si:H.

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