Metastable Defects in Amorphous-Silicon Thin-Film Transistors

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When a positive gate voltage is applied to an amorphous-silicon thin-film transistor, electrons become trapped in states close to the silicon-dielectric interface. This is studied by a new technique involving the transient discharge current produced under illumination. It is suggested that the behavior may involve metastable dangling bonds generated within the amorphous silicon as a consequence of the field-effect–induced increase in electron concentration. This constitutes an important new instability mechanism for amorphous-silicon thin-film transistors.

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Amorphous-silicon thin-film transistors (TFT's) are currently of great commercial interest. The best such devices presently available are fabricated with a hydrogenated-amorphous-silicon (*a*-Si:H) active layer and an amorphous-silicon-nitride gate dielectric, both grown by the glow-discharge technique.[1] The trapping of charge in the region of the semiconductor-dielectric interface is of considerable importance in determining device stability. A TFT subjected to a large positive gate voltage for a long period exhibits a large positive shift in threshold voltage. This was interpreted in terms of electron injection into the nitride.[2] Additionally, from studies of the silicon-nitride interface, Street and Thompson[3] have suggested that appreciable charge storage occurs in the silicon, involving states of depth 0.25 eV, plus deeper centers not resolved by their particular experimental technique. TFT's have also been shown to alter their characteristics as a result of prolonged illumination,[4] in line with the known creation of metastable dangling-bond states as observed in the Staebler-Wronski effect.[5]

In this paper, we describe a new photoconductive technique for the study of excess trapped carriers. The devices used were prepared by the glow-discharge decomposition of silane in a capacitatively coupled reaction chamber, as described elsewhere.[6] The experimental process involves the photoinduced discharge of devices in which charge has been allowed to accumulate during a period of application of a gate voltage. To avoid complications associated with transient changes in source-drain current under illumination, these electrodes were linked [Fig. 1(a)]. As indicated in Fig. 1(b), a gate field was applied for a period t_g and then removed. Under these conditions, the source and drain contacts are injecting, and excess electron majority carriers are drawn across the *a*-Si:H layer towards the silicon-nitride interface, in a time much shorter than the t_g values used here. After a time delay of t_d, the specimen was briefly illuminated, yielding a discharge current pulse which was detected across resistor *R*. Illumination for 150 msec at a flux of 10^{16} cm^{-2} sec^{-1} was sufficient to produce a complete discharge. The total charge *Q*, assessed by integration of the transient current through *R*, established the residual number of carriers trapped. Figure 2(a) displays the influence upon *Q* of delay time and temperature. To obtain reproducible data, it was necessary to anneal the specimen at 450 K for about 30 min between individual measurements (see below). The decay curves are not of simple exponential form, but exhibit dispersion suggestive of a range of trapped-carrier–release time constants. Assuming this to arise from variations in trap depth, we may express the decay characteristic in the form

$$Q(t)=Q_0\int\frac{N(E)}{N_t}\exp\left[\frac{-t}{\tau(E,T)}\right]dE \qquad (1)$$

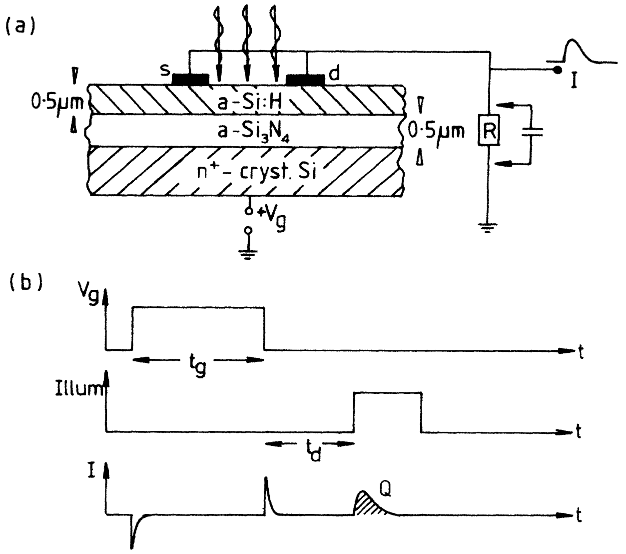

FIG. 1. Experimental (a) configuration and (b) procedure for the study of the "photoinduced discharge" phenomenon.

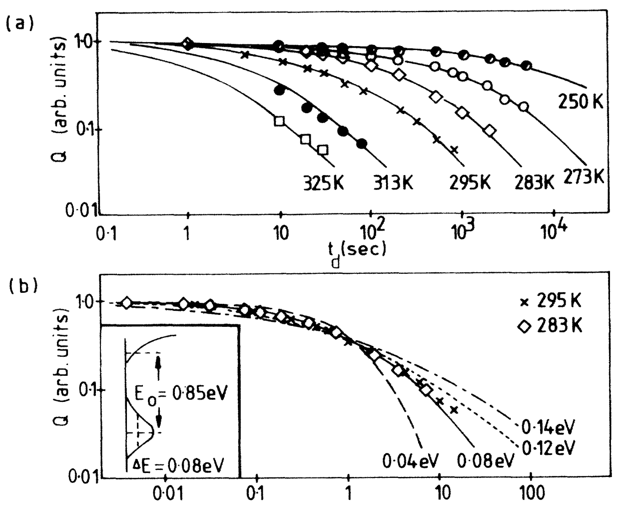

FIG. 2. (a) Discharge response, Q, as a function of elapsed time following termination of the gate field. The solid lines in (a) represent the behavior expected for the trap distribution in the inset of (b). Part (b) illustrates the sensitivity of the fit to changes in the width ΔE of the trap distribution.

with $\tau(E,T)=\nu^{-1}\exp(E/kT)$ and $N_t=\int N(E)dE$.

For a Gaussian trap energy distribution $N(E)$ [Fig. 2(b), inset], one may obtain a fit to the experimental data by varying the standard deviation of the distribution, ΔE, the central trap depth, E_0, and the attempt-to-escape frequency, ν (assumed constant with E). Such a fit is quite sensitive, and indicates a center depth E_0 of 0.85 ± 0.05 eV, a standard deviation ΔE of 0.08 ± 0.02 eV, and an attempt-to-escape frequency of about 10^{12} Hz. The solid lines in Fig. 2(a) represent the fitted curves for the above values of model parameters, while Fig. 2(b) indicates the sensitivity of the fit to changes in ΔE.

Use of a rectangular rather than a Gaussian distribution of traps yields similar figures for the degree of broadening and other parameters. Also, the fitted values are found to be virtually independent of the magnitude of the gate voltage used in the charging phase. In our Q vs t_d measurements so far, the gate voltage has been applied for a fixed period, t_g, of 20 sec. The effect, if any, of changes in this application time will be a subject for further study.

The influence of t_g upon the magnitude of the phototransient, at various temperatures, is shown in Fig. 3. Here the delay time, t_d, was fixed at 2 sec. However, even during this short period, some trapped charge will be lost by thermal release. In computing the vertical scale of Fig. 3, this has been allowed for by using the previously described fitting procedure to obtain a value for Q_0 [defined as in Eq. (1)]. The magnitude of the discharge pulse increases continuously with t_g, over a period of at least several hours. During the charging phase, the spatial distribution of excess electrons and the band bending in the surface region will change progressively. These factors, together with associated changes in the charge trapping phenomenon (see below), give rise to the complex overall form of Fig. 3. Modeling of the charging process will be attempted in a future study, while in the present paper we concentrate upon exploring the discharge characteristics via the total integrated residual trapped charge Q. Such measurements appear largely insensitive to the details of the charging phase, provided that a consistent initial procedure is maintained.

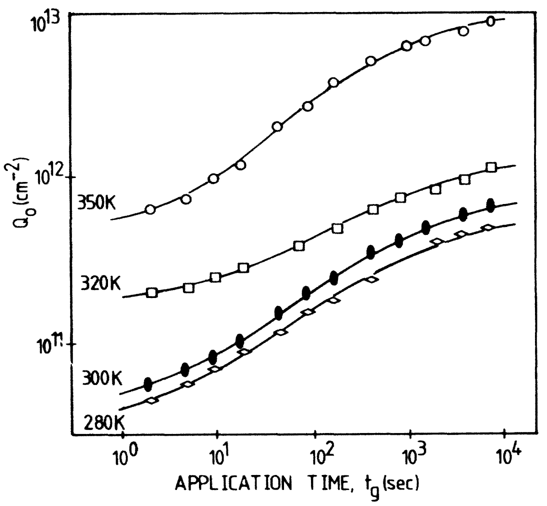

FIG. 3. Influence of the period of application of the gate field, t_g, upon the magnitude of the photodischarge response at zero delay time.

As indicated above, illumination occurred through the free surface of the a-Si:H, rather than via the silicon-nitride interface. However, provided that the photon energy exceeded the optical gap, variation of the wavelength (and thus absorption depth) had little effect. At sub-band-gap energies, the magnitude of Q approached zero. Thus, internal photoemission may be ruled out. Rather, we believe that a process akin to xerographic discharge is taking place. During application of the gate voltage, electrons become trapped in states close to the interface. Subsequent illumination causes generation of excess carriers within the a-Si:H layer, and the redistribution of these to neutralize the residual trapped charge gives rise to the observed current. Thus, even though the illumination does not directly release the trapped carriers, the magnitude of Q at a given time establishes the amount of charge remaining trapped in the "deep" centers.

With respect to the actual mechanism of trapping close to the interface, several processes are possible. These include tunneling into the dielectric, trapping into states at the semiconductor-dielectric boundary, and localization in deep states within the amorphous silicon layer. It is probable that the actual behavior involves a combination of such contributions, with detailed aspects of both preparation conditions (in particular, those relating to the quality of the semiconductor-dielectric interface) and experimental technique determining which is dominant. Before giving further consideration to this question, we present additional experimental data.

The general phenomenon may be further explored by use of the procedure indicated in Fig. 4(a). The gate voltage is applied for a considerable time, following which the trapped charge is nullified by a sufficiently lengthy pulse of illumination. However, rather than proceeding with thermal annealing as in the case of the measurements shown in Fig. 2, a further short (1 sec) application of gate voltage occurs. Following this, the amount of trapped charge is again determined by the flash-illumination method. The process yields secondary pulses of considerably greater amplitude (Q') than those observed when freshly annealed samples are subjected to a single charge-discharge cycle with a t_g of 1 sec.

The "annealing out" of this pulse-enhancement phenomenon may be explored by varying the delay between the initial and the secondary charge-discharge cycles. Figure 4(b) displays the results, with the vertical axis again corrected to $t_d = 0$ to give Q_0'. Annealing is very slow at room temperature, with a decay of only about 30% over a 150-h period. Rates increase at higher temperatures, with the activation energy for annealing being about 1.5 eV. The observation of an enhanced secondary discharge pulse might, in principle, be explained in terms of the influence of residual charge which tunneled into the dielectric during the initial cycle. However, while such a process may well take place, it is difficult to reconcile not only with the 10^{12} Hz prefactor for release, but also with the 0.85 and 1.5 eV activation energies determined for release and annealing. In our opinion, the presence of such large activation energies, taken together with the fact that *different* activation energies are observed for the two processes, suggests that trapping in the dielectric cannot be the *only* mechanism involved.

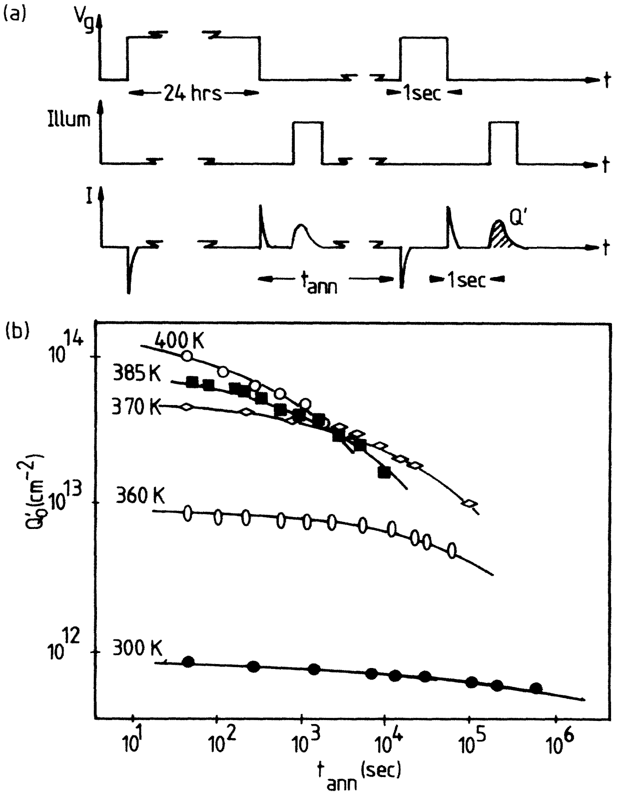

FIG. 4. (a) Procedure for and (b) results of an examination of the annealing out of the photodischarge response.

A new mechanism, which appears consistent with all of the experimental characteristics, is that of the creation of metastable dangling-bond states within the *a*-Si:H layer close to the dielectric interface. Then, Fig. 3 represents the buildup in the concentration of such states during the period of application of gate voltage. For the procedure of Fig. 4, metastable defects accumulating over the initial period of gate-voltage application are discharged (but not eliminated) by the first illumination pulse. With the second application of the gate voltage, those states which have not been annealed out during the delay period are repopulated, and this is detected with the second illumination flash. For this model, the vertical axes of Fig. 3 and 4(b) represent the areal densities of excess metastable states.

Evidence in support of the identification of the defects as dangling bonds is provided by comparing the data in Figs. 2–4 with those from other investigations. Johnson and Biegelsen[7] have performed a study in which capacitance and ESR measurements are carried out during the photodepopulation of deep states. The measurements allow an identification of silicon dangling-bond states located 0.8 to 0.9 eV below the conduction-band mobility edge, and broadened into a Gaussian distribution with standard deviation 0.12 eV. These values are in good agreement with our estimates from the data of Fig. 2. Moreover, the dangling-bond states identified as responsible for the Staebler-Wronski effect itself[8] have been shown to anneal out at a rate which is thermally activated with activation energy 1.5 eV, again in correspondence with the value obtained in the present study.

As suggested by Street,[9] the creation of metastable defects may be explained via an extension of Mott's $8-N$ rule. If phosphorus doping is used to move the Fermi level into the conduction-band tail, a silicon atom just below E_F will have five electrons and be in an unstable configuration. The situation is resolved by the formation of dangling-bond defects:

$$2\mathrm{Si}_4^0 + e \rightarrow \mathrm{Si}_3^- + \mathrm{Si}_3^0. \qquad (2)$$

We believe that a similar process is to be expected if the tail states are populated via some other means such as optical illumination (the Staebler-Wronski effect, and the shift of threshold voltage in TFT's following illumination), field-effect–induced band bending (the present case), the application of high electric fields, etc.

The neutral Si_3^0 dangling bond created by the above process might capture a second electron. However, it is difficult to envisage why an energy of 1.5 eV should be needed to re-form the broken Si–Si bond upon elimination of the excess electrons. The actual mechanism is likely to be more complex, possibly involving interaction between the broken bond and hydrogen or other "impurity" atoms, or the presence of internal voids. Such factors have been introduced[10–12] in the interpretation of the Staebler-Wronski effect, and in particular it has been shown that the activation energy for diffusion of hydrogen in *a*-Si:H is very similar to the 1.5 eV observed here.[11] Of course, more than one type of center may be generated, and we note that shallow states such as those identified by Street and Thompson[3] would release charge too fast for their detection in the present experiments.

The creation of defect states in amorphous-silicon thin-film transistors, as a consequence of field-effect–induced changes in carrier density, constitutes a newly identified mechanism capable of influencing the performance and long-term stability of such devices. Other processes, notably tunneling into and trapping deep within the dielectric layer, will also occur and may dominate under different conditions of film preparation or experimental procedure. We note, however, that the photodischarge experiments described above constitute a sensitive technique for the study of deep-trapping effects, irrespective of the trapping mechanism concerned. On this basis, we propose to undertake further investigations to explore both the detailed charging-discharging behavior and the factors controlling the dominant instability mechanism.

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