Energy distribution of light-induced gap states in hydrogenated amorphous-silicon alloys

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(Received 23 August 1983; revised manuscript received 5 December 1983)

We have studied the effect of prolonged light exposure on the density and energy distribution of gap states in undoped hydrogenated amorphous-silicon alloys. The gap-state distribution in the upper half of the mobility gap has been obtained from measurements of steady-state and transient photoconductivity. The density of states at the Fermi level has been determined from the frequency dependence of capacitance of Schottky diodes. The results suggest that light exposure gives rise to new states in the upper half of the mobility gap.

Staebler and Wronski[1] showed that prolonged light exposure changes the dark conductivity and the photoconductivity of hydrogenated amorhpous silicon (a-Si:H) alloys. Since then, the effect of light exposure on the properties of a-Si:H alloys has received considerable attention. Several models[2–4] have been proposed to explain the light-induced effects; a variety of experimental techniques[5–16] has also been used to study the phenomenon. The experimental results show that light exposure creates new states in the mobility gap. The exact energy distribution of these states, however, is still a subject of controversy. Capacitance voltage[9,10] and transient current[11] measurements on undoped and phosphorus-doped a-Si:H Schottky diodes show that new states are created in the upper half of the mobility gap. Field-effect[12,13] measurements on undoped samples also agrees with these observations. Deep-level transient spectroscopy (DLTS)[14] experiments on P-doped samples, on the other hand, show that the distribution of density of states (DOS) in the upper half of the gap remains the same after light exposure. However, there is an increase in DOS below the midgap. Similar conclusions have been reached[16] from the study of temperature dependence of photoconductivity in undoped samples.

We have shown elsewhere[17] that the distribution of gap states can be determined by a combination of measurements of transient photoconductivity (TPC), steady-state photoconductivity (SPC), and the temperature and frequency dependence of the capacitance of a Schottky diode. In order to resolve the controversy, we have applied these techniques to determine the gap-state distribution of an undoped a-Si:H sample before and after light exposure.

Undoped a-Si:H samples were prepared on Corning 7059 glass substrates by rf glow-discharge decomposition of pure silane. The film thickness ranged from 6000 Å to 1 μm. Typical deposition conditions were as follows: substrate temperature 260 °C, pressure 0.2 Torr, and rf power 300 mW/cm^2. Schottky diodes, for use in the C-T-ω measurements, were prepared on one section of the glass substrate. The bottom Ohmic contacts were obtained by predepositing a NiCr film followed by a 500-Å $n+$ layer. The top metal contacts were made by evaporating Pd dots of 50% transmission.

Coplanar structures were used for TPC and SPC experiments. Both the dark current and the photocurrent were found to be Ohmic up to 10 kV cm^{-1}, the highest field used in the experiments. All measurements were carried out in a vacuum system with 10^{-6} Torr base pressure. To obtain the heat dry state (state A), the samples were annealed at 200 °C for 2 h in the vacuum system. For the light-degraded state (state B), the coplanar samples were exposed to 150 mW cm^{-2} of white light for 2 h at room temperature. For the Schottky diodes the light intensity was increased by a factor of 2 to account for the 50% transmission loss through the top Pd contact.

For the TPC experiments, a pulsed dye laser ($\lambda = 640$ nm) of 100-ps duration and 10-Hz repetition rate was used for the light source. Intensity of the laser was suitably attenuated to avoid bimolecular recombination. The signals after amplification were processed by Biomation Transient Digitizer and Tracor Signal Averager, and finally analyzed by computer.

For the SPC experiments, a quartz-halogen lamp with a set of neutral density filters was used to obtain the intensity dependence of photocurrent. In C-T-ω measurements,[18] a PAR lock-in amplifier operating in the frequency range of 5–200 Hz was used. Measurements were carried out between 80 and 120 °C which is below the temperature at which saturation of capacitance takes place. The Schottky diodes used for the experiments had ideality factors better than 1.2.

In Fig. 1, we present the transient photoconductivity data for an undoped a-Si:H sample in both the heat-dry state and light-degraded state. Below room temperature, one observes that currents decay much quicker for the degraded sample. The steady-state photoconductivity results for the same undoped a-Si:H sample in both states A and B are shown in Fig. 2. One finds that the light intensity dependence of photocurrent has changed substantially after light degradation. At room temperature and above, the slope of the log photocurrent versus log intensity plot in state B increases with intensity instead of being a constant as in state A. As the temperature is lowered, in state B the plot is linear, while in state A the slope reduces at higher intensities. At temperatures lower than 210 K, the plots in both states A and B are linear, with the slope in state B much higher than in state A.

The experimental results for TPC can be explained by considering the dispersive motion of charge carriers in the presence of traps. In dispersive transport,[19] at a given time t after the initial light pulse, the carrier packet probes the lo-

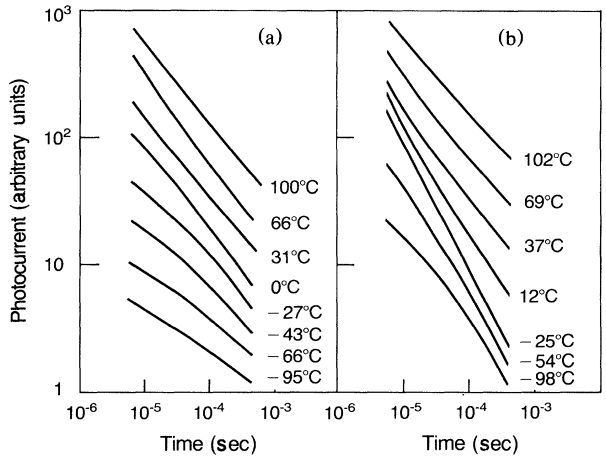

FIG. 1. Time dependence of photocurrent at different temperatures in a heat-dry state (a) and light-soaked state (b).

calized states at energy level $E_d(t)$, with

$$E_d(t) = E_c - kT \ln \nu_0 t \ , \tag{1}$$

where E_c is the energy of the conduction-band edge[20] and ν_0 the escape frequency associated with the traps and assumed to be a constant (5×10^{11} sec^{-1}). If states located around $E_d(t)$ can be described by an exponential distribution with characteristic temperature T_0 as given by

$$g(E) \propto \exp[-(E_c - E)/kT_0] \ , \tag{2}$$

then the current will show a power-law dependence on time as

$$i(t) \propto t^{-(1-T/T_0)} \ , \tag{3}$$

so one can determine the characteristic temperature T_0 of the gap-state distribution at energy level $E_d(t)$ by evaluating the slope of log$i$ vs log$t$ plot at time t and temperature T. Th inverse of the characteristic temperature T_0^{-1} so obtained is plotted against $E_c - E$ in Fig. 3.

The SPC data also can be analyzed to obtain T_0^{-1} as a

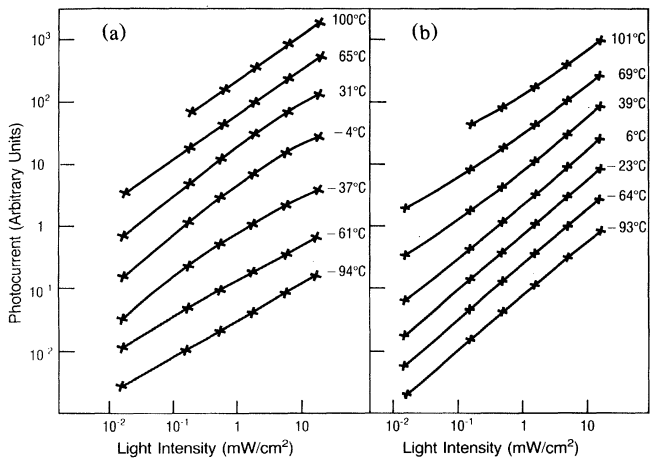

FIG. 2. Intensity dependence of steady-state photocurrent at different temperatures in a heat-dry state (a) and light-soaked state (b).

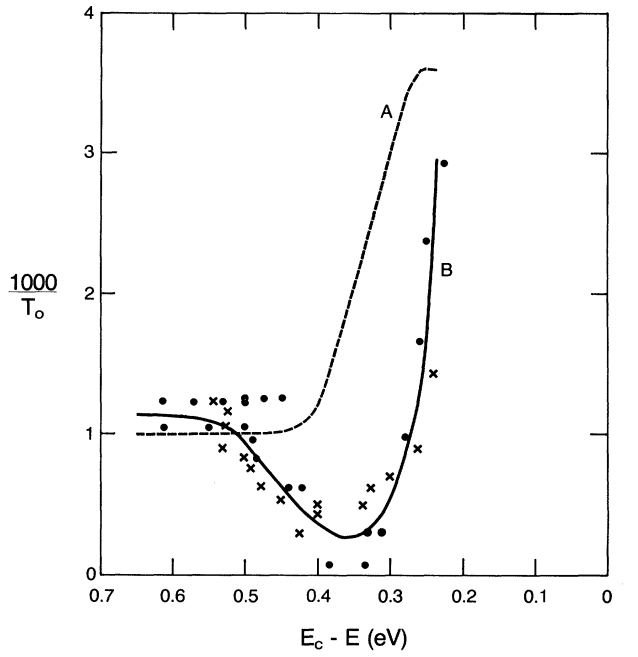

FIG. 3. T_0^{-1} as a function of $E_c - E$ for sample in a heat-dry state (A) and light-soaked state (B). ● and × refer, respectively, to the TPC and SPC data in state B.

function of $E_c - E$. According to Rose's model,[21] for an exponential distribution of traps as given by Eq. (2), the intensity dependence of photoconductivity is given by

$$\sigma_{ph} \propto I^{\gamma} \ , \tag{4}$$

with

$$\gamma = T_0/(T + T_0) \ . \tag{5}$$

In this experiment, the value of γ is essentially determined by the T_0 value of the trap distribution in the vicinity of the trap-Fermi level E_m, which for undoped a-Si:H is very close to the quasi-Fermi level E_{Fn}. For the sample used in this experiment, the activation energy is 0.71 eV in both states A and B. This gives the position of the dark Fermi level $E_F(0)$ at 0 K. If we take the temperature coefficient for the shift of the Fermi level to be half of that of the optical gap,[22] then the Fermi level at a given temperature T is given by

$$E_F(T) = E_F(0) - \beta T \ , \tag{6}$$

with $\beta = 2.2\times10^{-4}$ eV/k.

The position of quasi-Fermi level E_{Fn} depends on both light intensity and temperature. It can be calculated by

$$E_{Fn}(T) = E_F(T) + kT \ln(\sigma_{ph}/\sigma_{dark}) \ . \tag{7}$$

Using Eqs. (4)–(7), we can determine the energy dependence of T_0^{-1} value from the data given in Fig. 2. Since Eq. (4) is valid only when $E_{Fn} - E_F \geq kT_0$, we calculate T_0^{-1} only at the temperature and intensity range where E_{Fn} is shifted from E_F by more than 100 mV. The results are plotted in Fig. 3. Also shown in the figure is a curve drawn through the T_0^{-1} value as obtained from TPC and SPC data[17] for the same sample in state A. In agreement with our earlier observations for the sample in state A, we find

that TPC and SPC results are consistent with each other in state B as well. The value of T_0 in state B is found to be smaller than in state A for $E_c - E$ larger than 0.5 eV, indicating a more rapid change in DOS with energy. In the energy range 0.25 eV $< E_c - E <$ 0.5 eV, the T_0 value for state B is higher which implies a flatter distribution. To determine the complete energy distribution of the localized states, C-T-ω measurements were made on the Schottky structure grown during the same deposition run. For this sample, $g(E_F) = 2\times 10^{16}$ cm^{-3}eV^{-1} in state A and $g(E_F) = 1\times 10^{17}$ cm^{-3}eV^{-1} in state B. The resulting density of states is plotted in Fig. 4.

We notice that a large number of new states are created in the upper half of the mobility gap after light degradation. This is in general agreement with results from C-V, transient current, and field-effect measurements, but does not agree with DLTS results which show that the gap-state distribution in the upper half of the mobility gap remains unaltered after light exposure. We also observe from Fig. 4 that after light exposure, the shallower states in the energy range 0.25–0.3 eV below E_c actually go down in number. These results imply that while light exposure gives rise to new states close to Fermi level, some shallower states actually are removed during the process. We should mention that the resolution with which we can determine the energy in our experiments[17] is of the order of 50 meV. Since a shift of 50 meV in the energy scale in state B can remove the crossover in the DOS curves shown in Fig. 4, based on our experiments alone, we cannot definitely infer that the shallower states have gone down in number. It is, however, interesting to note that the field-effect data obtained by the Chicago group[12] also show a similar trend. The original data which were shown as a function of $E - E_F$ have been replotted in Fig. 4 as a function of $E - E_c$. In this case also, a reduction in the number of shallow states after light exposure is observed. It will be interesting to carry out measurements of DOS by independent techniques to confirm these observations.

We shall now examine an alternative explanation of our experimental data on the basis of creation of light-induced states in the lower half of the gap that have a large hole but small electron-capture cross section. These hole trapping centers can affect steady-state photoconductivity[21] thus explaining some of our experimental results. Creation of such states, however, is associated with certain other features in photoconductivity such as supralinear dependence of σ_{ph} on intensity and an increase in σ_{ph} with decrease in temperature. We do not see such features in our experimental data. Moreover, transient photoconductiviy which follows the transport of the electrons before they recombine will be unaffected by the creation of hole trapping states. Since we do observe changes in TPC data after light soaking, creation of states in the lower half of the gap alone cannot explain our results. We therefore believe that our interpretation based on creation of states above the midgap is justified. However, we certainly do not suggest that new states are not created in the lower half of the gap. Measurements of diffusion length and subband gap absorption in our laboratory[23] and elsewhere[24,25] suggest that new states are created below the midgap as well.

Our conclusion that light exposure gives rise to new states in the upper half of the mobility gap are in contradiction to the results from DLTS[14] and low-temperature photoconductivity measurements.[16] DLTS results were on P-doped samples and it is possible that the distribution of the light-induced gap states in P-doped samples is different. The low-temperature photoconductivity measurements[16] were carried out on undoped samples. These samples, however, have several properties quite different from our samples. For example, they show a supralinear intensity dependence of σ_{ph}, a peak in σ_{ph} around 130 K, and no change in room temperature σ_{ph} after light exposure. None of these features is observed in our samples or in those reported by RCA.[15] It is known that film properties depend critically on deposition conditions and incorporation of impurities. The light-induced effects are also probably sensitive to these conditions.

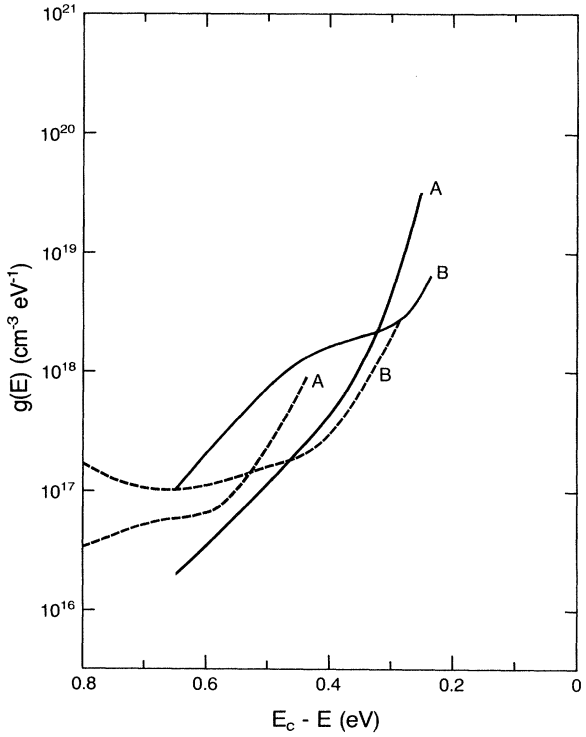

FIG. 4. Gap-state distribution of a-Si:H in a heat-dry state (A) and light-soaked state (B). —— our results obtained by transient and steady-state photoconductivity and C-T-ω measurements. – – –, obtained by field-effect measurements (Ref. 12).

In conclusion, we have studied the effect of light exposure on the gap-state distribution in undoped a-Si:H using a combination of steady-state and transient photoconductivity techniques. The energy range investigated varies from the midgap to about 0.3 eV below the conduction-band edge. The results suggest that light exposure gives rise to new states in the upper half of the mobility gap. This is in contradiction to recent DLTS results, but agrees with the conclusions from the field-effect and transient current measurements.

This work has been partially supported by grants from the Standard Oil Company (Ohio).

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