Effect of recombination on transient photoconductivity in *a*-Si:H

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Transient secondary photocurrent in *a*-Si:H is discussed with the use of a multiple-trap model that takes into account recombination. Photocurrent decays as $t^{-\beta}$ even when the recombination of extended-state electrons is taken into consideration, and β depends on the recombination rate. Excitation pulse width also affects the photocurrent decay, with decay being slow for long pulse widths. These features are confirmed by experiment.

Several authors have demonstrated dispersive transport in *a*-Si:H using the time-of-flight method.[1] They observed transient primary photocurrent in sandwich cells with blocking contacts. In this case, the recombination effect can be ignored because electrons and holes which are created at the surface are separated by an electric field. The multiple-trap model[2,3] and continuous-time random-walk model[4] have successfully explained these experimental results. On the other hand, recombination cannot be ignored for transient secondary photocurrent in planar gap cells with ohmic contacts because electrons and holes are distributed uniformly. Hvam *et al.*[5] estimated recombination lifetime from the bending point of the $\log i_p$-$\log t$ plot assuming that this recombination lifetime has the same effect on secondary photocurrent as the transit-time effect does on the primary photocurrent. In this paper, secondary photocurrent decay is calculated using a model in which it is transported by electrons in extended states under the influences of trapping, detrapping, and recombination. Effects of trap state distribution, temperature, recombination mechanisms, and excitation pulse width were evaluated, and good agreement between the calculated and experimental values was obtained.

The photocurrent is carried by electrons in extended states in which they are occasionally trapped and detrapped by localized states, and then recombine with holes. The rate equations for electrons in extended states and discrete localized states are

$$n_e \frac{dp_e}{dt} = n_e \sum_i n_i p_i u_i - n_e p_e \sum_i n_i v_i - w_0 n_e p_e + g \ , \quad (1)$$

$$n_i \frac{dp_i}{dt} = n_e n_i p_e v_i - n_i p_i (n_e u_i + r_i) \ , \quad (2)$$

where p_e and p_i are the occupation probability of the extended states and ith localized state, respectively. n_e and n_i are level densities and it is assumed that

$$n_i = N_t \exp[-(E_c - E_i)/kT_c] \ , \quad (3)$$

where E_c and E_i are the energy of the conduction-band mobility edge and localized state, respectively. Definitions of other notations are as follows: detrap probability, u_i; trap probability, v_i; recombination rate from ith localized state, r_i; recombination rate from extended states, w_0; and excitation by photoabsorption, g. In order to make the rate equations linear, monomolecular recombination mechanism is assumed and the recombination rate is independent of hole density. Another approach is necessary when bimolecular recombination is dominant. Photoexcitation $g(t)$ is a step function as

$$g(t) = \begin{cases} g_0 & (-W_p \leq t \leq 0) \\ 0 & (t > 0) \end{cases} \ , \quad (4)$$

and W_p is a pulse width. Rate equations (1) and (2) are different from those of the conventional multiple-trap model[3] in respect to the following three points: (i) Recombinations of electrons at extended states and localized states are considered, (ii) pulse width is finite, and (iii) electrons are uniformly distributed in space.

Equations (1) and (2) are solved as

$$n_e p_e(t) = g(t) * L^{-1}(1/a(s)) \ , \quad (5)$$

$$a(s) = \tau^{-1}\left[\bar{s} + 1 - \sum_i \frac{n_i}{n_e} \frac{\bar{u}_i \bar{v}_i}{\bar{s} + \bar{u}_i + \bar{r}_i}\right] \ , \quad (6)$$

$$\tau^{-1} = w_0 + \sum_i n_i v_i \ , \quad (7)$$

where $\bar{s} = \tau s$, $\bar{u}_i = n_e \tau u_i$, $\bar{v}_i = n_e \tau v_i$, and $\bar{r}_i = \tau r_i$ are dimensionless numbers. L represents the Laplace transform and the asterisk means the convolution integral. For simplicity, the trap probability v_i of the ith localized state is independent of i and equal to v_0. The detrap probability u_i is thermally activated and expressed as

$$u_i / v_i = \exp[-(E_c - E_i)/kT] \ . \quad (8)$$

Calculations are carried out for two cases; i.e., (I) when recombination of localized-state electrons is

dominant and (II) when that of extended-state electrons is dominant.

Firstly, we will consider the case (I) ($w_0=0$). Recombination probability of all localized states are assumed to be equal, i.e., $r_i=r_0$. In this case, Eqs. (1) and (2) can be solved analytically. The summation over i in (6) is replaced by integration over the localized-state energy:

$$a(s) \sim kTN_t(n_e v_0)^{1-\alpha}(s+r_0)^{\alpha}/n_e \ , \tag{9}$$

$$n_e p_e(t) \propto t^{-(1-\alpha)} \exp(-r_0 t) \quad \left[\alpha=\frac{T}{T_c}\right] \ . \tag{10}$$

The photocurrent decays as $t^{-(1-\alpha)}$ for $t<1/r_0$, and $\log i_p$-$\log t$ plot sharply bends at $t=1/r_0$. If bending were observed in the $\log i_p$-$\log t$ plot experimentally, it should correspond to the recombination lifetime of localized-state electrons.

Secondly, we consider the case of (II) ($r_i=0$):

$$L^{-1}\left[\frac{1}{a(s)}\right]=\sum_i A_i \exp(\bar{\alpha}_i \bar{t}) \ , \tag{11}$$

$$A_i=\prod_k (\bar{\alpha}_i+\bar{u}_k+\bar{r}_k) \Big/ \prod_{k(\neq i)} (\bar{\alpha}_i-\bar{\alpha}_k) \ , \tag{12}$$

$$\bar{\alpha}_i=\alpha_i \tau, \quad \bar{t}=t/\tau \ ,$$

where α_i is defined as $a(\alpha_i)=0$ ($\alpha_i<0$).[3] With the initial condition $p_e(-W_p)=p_i(-W_p)=0$, (5) can be written as

$$n_e p_e(t)=g_0 \tau \sum_i \frac{A_i}{\bar{\alpha}_i} e^{\bar{\alpha}_i \bar{t}}(e^{\bar{\alpha}_i \bar{W}_p}-1) \ , \tag{13}$$

$$\bar{W}_p=W_p/\tau \ .$$

The results of numerical calculations using (11)–(13) for the various recombination rates $\bar{w}_0=\tau w_0=w_0/(w_0+\sum_i n_i v_i)$ are shown in Fig. 1. Twenty discrete localized states which are separated by 30 meV from each other are used. Results are not influenced by these parameters when a sufficient number of localized states is assumed. Even if the recombination effect is considered, the photocurrent decays as $t^{-\beta}$, and there is no bending point in the $\log i_p-\log t$ plot in contrast with case (I).

The ratio of the number of electrons in extended states and that of the total surviving electrons decreases with time since electrons trapped in localized states increase. Since only electrons in extended states can recombine, the effective recombination rate for the total surviving electrons decreases with time. This should be the reason why the photocurrent decays as $t^{-\beta}$, even if recombination exists. This feature is qualitatively consistent with the results obtained by Movaghar who considered the continuous-time random-walk model with effect of recombination.[6]

When the recombination rate is 0, the gradient β is $1-T/T_c$. This agrees with the results obtained with the conventional multiple-trap model without the recombination effect.[2] The gradient β, however, gets larger as the recombination rate gets larger, and it can be greater than 1. These features are quite different from the conventional multiple-trap model in which β can never be greater than 1.

The effect of pulse width W_p was studied. Figure 2 shows the calculated transient behaviors of photocurrent for pulse width of 0.1 and 10τ. The recombination rate from extended state $\bar{w}_0$ was set at 0.3. The straight line of the $\log i_p-\log t$ plot shifts when the pulse width changes, and the decay is slow for long pulse widths. It is a striking feature of the multiple-trap model that the photocurrent decay changes by pulse width because the distribution rate of electrons between extended and localized states at $t=0$ depends on the pulse width. For long pulse widths the photoexcited electrons are trapped by lo-

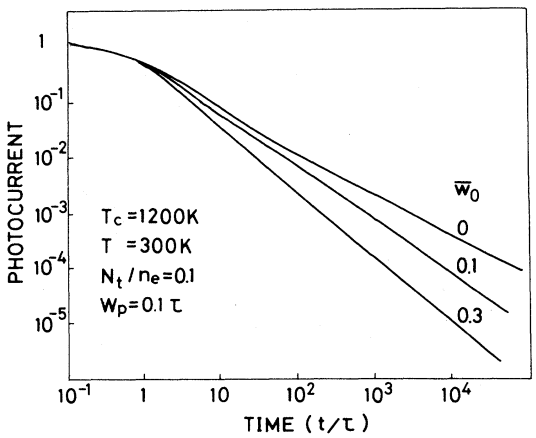

FIG. 1. Calculated photocurrent decay for three recombination rates of electrons in the extended states. Recombination rate is represented by $\bar{w}_0$ ($0<\bar{w}_0<1$).

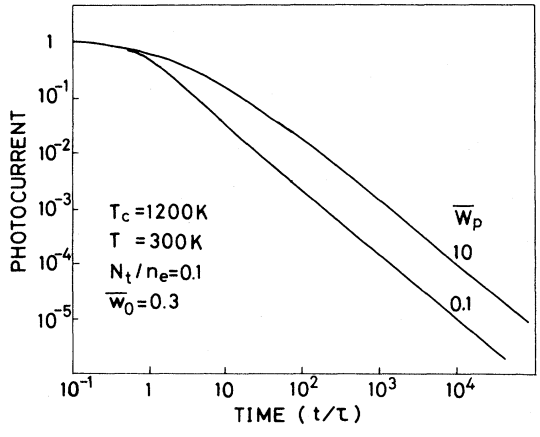

FIG. 2. Calculated photocurrent decay for two excitation pulse width of 0.1 and 10τ. Decay curve shifts with changes in pulse width. Recombination rate $\bar{w}_0$ is 0.3.

calized states during excitation ($-W_p \leq t \leq 0$), and these trapped electrons, which are thermally detrapped to the extended states, make the photocurrent decay slow.

We investigated the secondary photocurrent of nondoped *a*-Si:H experimentally. Samples were prepared by conventional glow discharge of SiH_4 onto SiO_2 substrates. Photoconductivity was measured using top surface aluminum electrodes with gap cell geometry. The pulsed beam of the Ar laser (0.51 μm) or the second harmonics of yttrium aluminum garnet (YAG) laser (0.53 μm) was illuminated uniformly over the gap cell, and the transient photocurrent was measured by a box-car integrator applying dc bias between electrodes. Detailed experimental procedures are described in Ref. 7. The solid line in Fig. 3 shows the experimental photocurrent decay (time origin was set at the end of pulses) for two pulse widths of 200 nsec and 10 μsec. Temperature of the sample is 280 K. The photocurrent decay is not exponential, but is expressed as $t^{-\beta}$, and β is greater than 1 for pulse width of 200 nsec. Moreover, the decay curve shifts with the pulse width. It should be noted that β, which is greater than 1, cannot be explained by the multiple-trap model without recombination ($\beta = 1 - T/T_c$). On the contrary, these experimental features are consistent with our model when recombination from the extended state is taken into consideration. The dashed curve in Fig. 3 shows the results of calculations with the following parameters: $T_c = 1200$ K, $N_t/n_e = 0.1$, $\bar{w}_0 = 0.4$, and $\tau = 220$ nsec. The characteristic temperature T_c which describes the exponential distribution of the trap states was measured by the bias-voltage dependence of its space-charge limited current[8] using the same sample as for the photocurrent measurement. Good agreement between the experiment and calculation was obtained, and both the value of β and its pulse width dependence were explained.

Hvam *et al.* have reported secondary photocurrent decay in P-doped *a*-Si:H. Photocurrent decays as $t^{-(1-\alpha)}$ ($\alpha = T/T_c$) and then the $\log i_p - \log t$ plot bends sharply. These features are consistent with calculations for case (I). The Fermi-level shift caused by P doping should change the characteristics of recombination centers, and the recombination mechanism may be different for nondoped and P-doped samples.

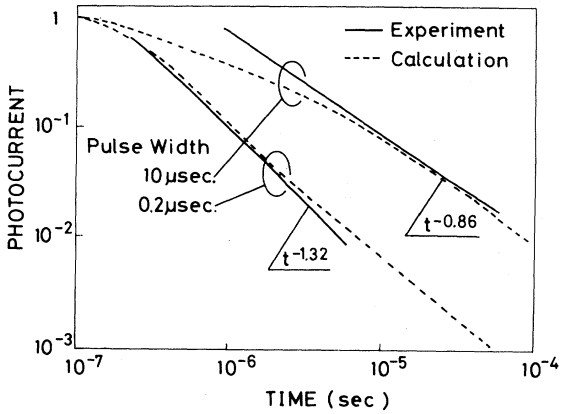

FIG. 3. Experimental (solid line) and calculated (dashed line) photocurrent decay in *a*-Si:H. Temperature is 280 K. Calculations were carried out with parameters described in the text.

Photocurrent decay time has been measured by several authors.[9–11] Reported decay times are quite different from each other, and, for example, range from 10–1000 msec,[10] 2 msec,[9] 100 nsec (nondoped sample[5]) to 50 psec.[11] It is clear that these discrepancies are caused by differences of the excitation pulse width, because photocurrent decay is affected by the pulse width as deomonstrated in this paper. Therefore, it is not meaningful to determine the electron lifetime from photocurrent decay time.

The multiple-trap model which takes into account recombination effects has been presented. Two recombination mechanisms, recombination from trap and extended states, have been considered. These two mechanisms affect secondary photocurrent decay quite differently. The decay curve bends sharply at the lifetime of electrons in trap states when the former recombination mechanism is dominant. On the other hand, the photocurrent decays as $t^{-\beta}$ ($\beta > 1 - T/T_c$) when the latter is dominant. Compared with the experimental photocurrent decay, it is clear that recombination from the extended states is dominant for nondoped *a*-Si:H. According to the model, β can be greater than 1, and the photocurrent decay curve shifts when the excitation pulse width changes. These features have been confirmed by experiment.

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