Photoconductivity response time in amorphous semiconductors

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The photoconductivity response time of amorphous semiconductors is examined theoretically on the basis of standard definitions for free- and trapped-carrier lifetimes, and experimentally for a series of a-$Si_{1-x}C_x$:H alloys with $x < 0.1$. Particular attention is paid to its dependence on carrier generation rate and temperature. As no satisfactory agreement between models and experiments emerges, a simple theory is developed that can account for the experimental observations on the basis of the usual multiple-trapping ideas, provided a small probability of direct free-carrier recombination is included. The theory leads to a stretched-exponential photocurrent decay.

I. INTRODUCTION

Combined measurements of the steady-state photoconductivity and its decay were first carried out by Moustakas and Weiser[1] in order to study the drift mobility of photocarriers in amorphous arsenic telluride. Since that pioneering work the method has been applied to amorphous germanium by Moustakas and Paul,[2] to hydrogenated amorphous silicon (a-Si:H) by Fuhs, Milleville, and Stuke,[3] and Crandall,[4] to n- and p-doped a-Si:H by Hoheisel and Fuhs[5] and Fritzsche *et al.*[6] and to hydrogenated amorphous silicon-carbon alloys by Öktü *et al.*[7]

In this method, the drift mobility μ_d of the photocarriers is determined from the steady-state photoconductivity

$$\sigma_{\rm ph} = e\,\mu_0\,\tau_0\,G \tag{1}$$

and the initial decay time τ_i of the photocurrent $I_{\rm ph}$ after termination of the exciting light at $t = 0$,

$$\frac{1}{\tau_i} = -\frac{1}{I_{\rm ph}}\left.\frac{dI_{\rm ph}}{dt}\right|_{t=0}, \tag{2}$$

by the relation

$$\mu_d = \frac{\mu_0\,\tau_0}{\tau_i}. \tag{3}$$

In Eqs. (1)–(3), μ_0, e, and G are the microscopic free-carrier mobility, the electron charge, and the electron-hole generation rate, respectively. τ_0 is the so-called free-carrier lifetime.

The use of Eq. (3) implies the assumption that τ_i is, in fact, equal to the carrier lifetime τ_r, determined as

$$\tau_r = \frac{N}{G}, \tag{4}$$

where N is the total concentration of photoinduced electrons in the steady state under generation rate G. This concentration is much higher for usual experimental conditions than the concentration of electrons in the dark; the latter will consequently be neglected. The concentration N is equal to the sum of the concentration of free carriers n and that of carriers trapped in the localized states N_t. For typical experimental conditions, $n \ll N_t$ and the quantity N can therefore be identified with N_t, the concentration of trapped electrons. As a rule the method is used at sufficiently high temperatures ($T > 150$ K), for the photocurrent to be provided by carriers in extended states above the mobility edge. From the concentration of these carriers n, the quantity τ_0 in Eq. (1) is determined by the relation

$$\tau_0 = \frac{n}{G}. \tag{5}$$

This lifetime of *free* carriers τ_0 should be distinguished from the carrier lifetime τ_r, determined by Eq. (4). It is generally assumed that in the indicated temperature range recombination is due to the most mobile carriers, i.e., the carriers in the extended states, and that hopping can be neglected. We will adhere to those usual assumptions in this paper.

Identification of the measured quantity τ_i with the carrier lifetime τ_r is based on the assumption that the thermal equilibrium (involving repeated trapping and release as in the multiple-trapping calculation of Schmidlin[22]) between free and trapped carriers is established on a time scale which is shorter than the measured time τ_i.[5,8] If we assume that, immediately after we switch off the light, recombination continues the same way it did in the steady state, then we have to assume that, immediately after time τ_0 the concentration of electrons in the system has decreased by the amount n. Hence the decrease in the concentration of the free electrons is equal to $n \cdot n/N$ because the fraction of free electrons is n/N. Therefore

$$\frac{dn}{dt} \simeq \frac{n \cdot n/N}{\tau_0} \tag{6}$$

and the quantity τ_i determined by Eq. (2) is

$$\tau_i = \frac{n}{dn/dt} = \tau_0 \frac{N}{n}, \tag{7}$$

which is by definition equal to the lifetime of electrons τ_r, as seen from Eqs. (4) and (5).

The drift mobility μ_d is defined as

$$\mu_d = \frac{\mu_0 \tau_0}{\tau_r}. \tag{8}$$

If relation (7) is valid, then the response-time method can be used to investigate μ_d by the Eq. (3). However, it is not *a priori* clear whether the quantity τ_i determined by Eq. (2) coincides with the carrier lifetime τ_r determined by Eq. (7). Deep trapping of photo-generated carriers might extend their lifetime beyond the experimental observation time of τ_i. It has in fact been emphasized by Vaněček *et al.*[9] that in order to determine the lifetime τ_r from measurements of the decay of the photocurrent, the response (decay) time should be measured with sufficiently strong steady-state bias illumination to reduce effects of deep trapping. Indeed, strong bias light produces a high concentration of photoinduced carriers and pushes the quasi-Fermi level to the band edge, thus making the thermal exchange between free and trapped carriers fast enough for Eq. (7) to be valid.

Such optical-bias experiments were recently carried out for hydrogenated amorphous silicon (*a*-Si:H) by Chen and Tai[10] and Haridim, Zelikson and Weiser.[11] In both papers exponential decay of the secondary photocurrent was observed. The dependence of the corresponding decay time $\tau_{\rm exp}$ and of photoconductivity on generation rate were also investigated. Whereas the well-known generation rate dependence of the photoconductivity

$$\sigma_{\rm ph} = e\mu_0 n \propto G^{\gamma} \tag{9}$$

was observed in both Refs. 10 and 11 with a room-temperature value of $\gamma \approx 0.9$, in Ref. 10 and $\gamma \approx 0.85$ in Ref. 11, the generation rate dependencies of $\tau_{\rm exp}$ are different. While both have the form

$$\tau_{\rm exp} \propto G^{-\beta}, \tag{10}$$

β equals 0.38 in Ref. 10 and is close to 0.7 in Ref. 11. Both papers interpret the measured time constant $\tau_{\rm exp}$ as the carrier lifetime τ_r. This interpretation is at variance with an earlier study of Bullot *et al.*[8] who concluded that the generation rate dependence of τ_r must be governed by the same exponent γ which describes the light-intensity dependence of the photoconductivity. In other words, the β in Eq. (10) should equal the γ from Eq. (9) if $\tau_{\rm exp}$ is to correspond to the carrier lifetime. Although response time and photoconductivity measurements which are governed by the same exponent γ were already reported by Wronski and Daniel,[12] no formal derivation of this relationship seems to have been given to date.

In the next section we, therefore, show that if the measured response time is equal to the carrier lifetime τ_r, as is generally assumed (see, e.g., Refs. 10 and 11), then the dependence (10) should be observed with $\beta = \gamma$. In Sec. III we then confront the problem of the response times which do not qualify as τ_r. We report on our measurements of the photocurrent decay from the steady state. The quantity τ_i determined by Eq. (2) has the generation rate dependence (10), but with β much smaller than γ. Similar experiments carried out by other groups produced the same results. The measured τ_i values show an activated temperature dependence, again in agreement with observations from other groups. While this response time τ_i clearly has some definite properties, it is also too fast to qualify as the excess carrier lifetime by standard photoconductivity arguments. In Sec. IV we then suggest a simple theory, which describes how photocurrent decays after light termination for times shorter than τ_r. Conclusions from our investigation are summarized in Sec. V.

II. GENERATION-RATE DEPENDENCE OF THE LIFETIME OF TRAPPED CARRIERS τ_R

As other authors who have studied response times (see, e.g., Refs. 10 and 11), we assume for simplicity that the density of (localized) states (DOS) below the mobility edge decreases exponentially towards midgap,

$$g(\mathcal{E}) = \frac{N_0}{\mathcal{E}_0} e^{-\mathcal{E}/\mathcal{E}_0}, \tag{11}$$

where N_0 is the total concentration of tail states and $\mathcal{E}_0$ is the typical energy scale of the tail. In Eq. (11), the energy is taken zero at the mobility edge and increases into the gap.

In the steady state under continuous generation rate G, the distribution of electrons can be described by a modified Fermi-Dirac function[13]

$$f(\mathcal{E}) = \frac{Rn/(Rn+p)}{1+\exp\frac{\mathcal{E}-\mathcal{E}_{ft}}{kT}}. \quad (12)$$

In this equation n and p are the concentrations of free excess electrons and holes, and R is the ratio of capture cross sections for electrons and holes by localized states. $\mathcal{E}_{ft}$ is a trapped-electron Fermi level above which an excess electron is likely to be reemitted to the conduction band and below which it is likely to recombine with a hole. We assume that we may use $n \gg p$ so that, unless R is very small, the factor $Rn/(Rn+p)$ is close to unity. Hence, the distribution function of Eq. (12) is very similar to an ordinary Fermi-Dirac function and to a very good approximation the characteristic energy $\mathcal{E}_{ft}$ can be replaced by the quasi-Fermi level for electrons $\mathcal{E}_q$ determined by the relation

$$n = N_c e^{-\mathcal{E}_q/kT}, \quad (13)$$

where N_c is the concentration of thermally accessible delocalized states above the mobility edge.

Most trapped electrons have energies in the vicinity of $\mathcal{E}_q$, because for deeper states the distribution $f(\mathcal{E})$ does not change with energy while the DOS decreases exponentially according to Eq. (11), whereas for shallower states the DOS increases but the distribution function $f(\mathcal{E})$ for electrons decreases faster when $kT < \mathcal{E}_0$. The latter condition is easily fulfilled up to room temperature in a-Si:H. Then the concentration of trapped carriers N_t, which make up the large majority of photocarriers in the system, can be approximated as

$$N_t \simeq \int_{\mathcal{E}_q}^{\infty} g(\mathcal{E})d\mathcal{E} = N_0 e^{-\mathcal{E}_q/\mathcal{E}_0} = N_0\left(\frac{n}{N_c}\right)^{\alpha}, \quad (14)$$

with

$$\alpha = \frac{kT}{\mathcal{E}_0}. \quad (15)$$

Using Eqs. (4), (9), and (14), we come to the generation-rate dependence of τ_r

$$\tau_r = \frac{N_t}{G} = N_0\left(\frac{n}{N_c}\right)^{\alpha}\frac{1}{G} \propto G^{\alpha\gamma-1}. \quad (16)$$

This expression has been obtained by many authors (see, e.g., Haridim, Zelikson, and Weiser[11]). It was further shown by Rose[14] (as many things mentioned here so far) and checked by Bullot *et al.*[8] that for the exponential distribution of traps (11)

$$\gamma = \frac{1}{1+\alpha}. \quad (17)$$

Substituting Eq. (17) in Eq. (16), we readily obtain

$$\tau_r \propto G^{-\gamma}. \quad (18)$$

Therefore the lifetime of trapped carriers under conventional assumptions must have the generation rate dependence (18). Any measured response time which is to be interpreted as such carrier lifetime should hence, as a minimum, have this generation rate dependence. It may be emphasized that the conventional assumptions referred to above are just the Simmons and Taylor statistics for photogenerated electrons in the steady state[13] and the exponential DOS of the band tail. None of the expressions (16)–(18) depend in any way on a particular recombination model. Nevertheless, Chen and Tai[10] recently called on the dependence (16) to distinguish between monomolecular and bimolecular recombination models. We obviously cannot agree with their approach. Haridim, Zelikson, and Weiser[11] made use of the same relation (16) to determine the value of α and hence that of $\mathcal{E}_0$ through Eq. (15). But it should be clear from Eq. (18) that if one interprets the measured response time as τ_r, the exponent in the dependence $\tau_r(G)$ does not contain any additional information in comparison to the exponent γ in the dependence $\sigma_{\rm ph}(G)$. From Eq. (18) it also follows, in view of the relations (5) and (9), that the drift mobility will depend on the generation rate G as

$$\mu_d = \mu_0\frac{n}{N} = \mu_0\frac{\tau_0}{\tau_r} \propto G^{2\gamma-1}. \quad (19)$$

In the next section we report on our measurements of the photoconductivity response time τ_i and its dependence on the generation rate and temperature in a series of a-Si:H and lightly alloyed a-Si_xC_{1-x}:H samples. They do not show the $G^{-\gamma}$ dependence and consequently imply that it is not the lifetime of trapped carriers τ_r which is usually measured as the initial response time τ_i.

III. DECAY OF THE PHOTOCURRENT FROM THE STEADY STATE. EXPERIMENTAL RESULTS

The initial response time of the steady-state photocurrent upon termination of the illumination has recently been studied[7] for a series of a-$Si_{1-x}C_x$:H alloys with low carbon content (including $x = 0$). All samples showed thermally activated behavior according to

$$\tau_i \propto \exp(\Delta/kT), \quad (20)$$

with $\Delta \simeq 0.12$ eV, over a temperature range of ~ 140 to 300 K. This dependence agrees with the data reported by Hoheisel and Fuhs[5] for undoped a-Si:H, where $\Delta \simeq 0.14$ eV can be resolved, and with the results obtained by Moddel and Viktorovich[15] for comparably prepared samples, which give $\Delta \simeq 0.11$ eV.

We have now extended the study of some of the samples with measurements at 200 K of the light-intensity dependence of photocurrents and (for $x = 0.02$) initial response time. The 200 K temperature was chosen since it lies in the middle of the range of activated behavior for the a-Si:H samples. The results are summarized in Table I. Since the uncertainties on the reported γ and β values are well below 10%, it is clear from Table I that γ and β are truly different for the $x = 0.02$ sample. Similar results were obtained by others: low values of $\beta \simeq 0.2$ to 0.3 near 200 K were measured for a-Si:H by Kazanskii

TABLE I. Experimental data from the a-$Si_{1-x}C_x$:H samples: carbon content x; measured values γ and β (200-K) of the power-law exponent for the generation-rate dependence of the photoconductivity and of the initial photodecay; logarithm of the 200-K photoconductivity to dark conductivity ratio σ_{ph}/σ_d; dark current activation energy $\mathcal{E}_\sigma$, and calculated values according to Eq. (21) for the quasi-Fermi energy $\mathcal{E}_q$.

x	γ	β	$\ln \frac{\sigma_{ph}}{\sigma_d}$	$\mathcal{E}_\sigma$ (eV)	$\mathcal{E}_q$ (eV)
0	0.70		13.8	0.75	0.51
0.02	0.76	0.38	13.8	0.76	0.52
0.06	0.89		9.5	0.88	0.72
0.10	0.91		6.2	1.03	0.92

and Yarkin[16] and by Güngör *et al.*,[17] while the parameter γ remained above 0.7 in these studies. It should be noted that parameters such as γ and β are temperature dependent, and should be used accordingly. Their value will — as a rule — rise with temperature. The dark current activation energy $\mathcal{E}_\sigma$, which is also shown in Table I, refers of course to the higher-temperature region where such behavior is seen.

From the above results and the theoretical background described in Secs. I and II, we can conclude that the measured initial decay of the photocurrent has nothing to do with the lifetime of trapped carriers and should not be used for investigation of the drift mobility by the widely used expression Eq. (3).

One comes to the same conclusion by evaluation of the release time of the trapped carriers from the quasi-Fermi level $\mathcal{E}_q$. Using the routine procedure[11,18] to evaluate $\mathcal{E}_q$ through the formula

$$\mathcal{E}_q = \mathcal{E}_{f_0} - kT \ln \frac{\sigma_{ph}}{\sigma_{dark}}, \tag{21}$$

we obtain in our a-Si_xC_{1-x}:H samples values of $\mathcal{E}_q \geq 0.5$ eV depending on x (see Table I). The thermal release time of the carriers trapped at $\mathcal{E}_q$ to the mobility edge can be evaluated as $t_{rel}(\mathcal{E}_q) \simeq \nu_0^{-1} \exp(\mathcal{E}_q/kT)$, where ν_0 is the attempt-to-escape frequency. Using the values $\nu_0 \simeq 10^{12}$ s^{-1}, $\mathcal{E}_q = 0.5$ eV, and $T = 200$ K, one obtains $t_{rel}(\mathcal{E}_q) \geq 1$ s. In comparison, the measured response time τ_i is usually in the order of microseconds. Hence the decay of photocurrent in the experiment begins long before the typical photoinduced electron, trapped in the vicinity of $\mathcal{E}_q$, can be released to the conducting states to participate in transport or recombination. When in spite of all this, the τ_i values and Eq. (3) are used for calculating μ_d, as was done in Ref. 7, good agreement with μ_d values from time-of-flight (TOF) experiments was obtained. This is a direct consequence of the fact that TOF also fails to reflect the true n/N ratio, as was pointed out by Bullot *et al.*[8] In the next section we present a theory which describes the decay of the photocurrent at times shorter than $t_{rel}(\mathcal{E}_q)$.

IV. DECAY OF THE PHOTOCURRENT FROM THE STEADY STATE. THEORY

Let us now discuss how the photocurrent decreases after the termination of the steady-state optical excitation. As described above, in the steady state the energy distribution $f(\mathcal{E})$ of electrons is determined by Eq. (12) with $\frac{Rn}{Rn+p} \simeq 1$ and $\mathcal{E}_{f_t} \simeq \mathcal{E}_q$. The concentration of free electrons $n(0)$ at the moment the light is turned off (treated as $t = 0$ in what follows) is given by Eq. (13). The distribution of electrons at that time is schematically shown in Fig. 1. The time dependence of the photocurrent is determined by the time dependence $n(t)$ of the concentration of free carriers, which in turn is determined by trapping of free carriers in localized tail states, their release from these states and their recombination. We will assume that, at least at the early stages of the relaxation, the lifetime of free carriers τ_0 is the same as in the steady state, i.e., if a carrier is above the mobility edge, it takes a time τ_0 for it to be captured by some recombination center and disappear from the system. Another possibility for the free electron is its capture in a tail state. Let us denote the corresponding time for a free electron to be captured to any tail state as τ_c. Of course, $\tau_c \ll \tau_0$ and the probability that a free electron is captured rather than recombines after its appearance above the mobility edge is

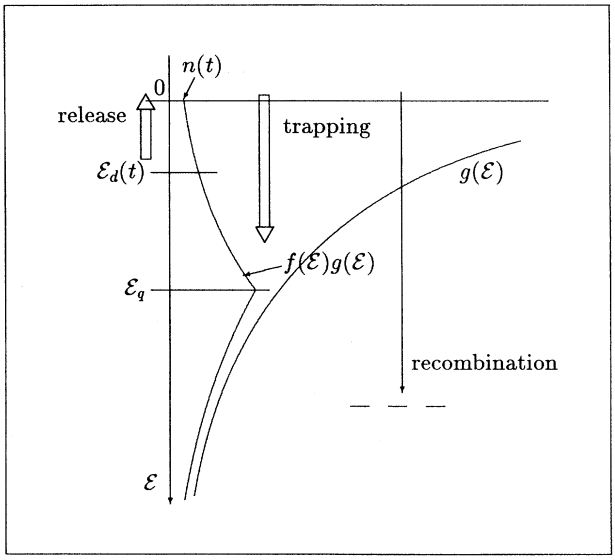

FIG. 1. Schematic representation of the energy dependence of total and occupied localized-states densities, the time-dependent demarcation energy, and the transition processes.

$$W_c = \frac{1}{1+\tau_c/\tau_0} \simeq 1. \tag{22}$$

However, if we neglect the probability for a free electron to recombine, we cannot obtain any significant decrease in the concentration of free electrons at times shorter than $t_{\rm rel}(\mathcal{E}_q)$, as shown below.

We will first neglect the recombination entirely and show that $n(t) \simeq n(0)$ over the whole time range $t < t_{\rm rel}(\mathcal{E}_q)$. It is very convenient to use the conventional multiple-trapping (MT) model[19] to describe this time evolution of $n(t)$. The demarcation energy

$$\mathcal{E}_d = kT \ln \nu_0 t \tag{23}$$

governs the ratio of free to trapped carriers[19]

$$n(t) = \mathcal{N} \frac{N_c}{N[\mathcal{E}_d(t)]} e^{-\mathcal{E}_d(t)/kT}, \tag{24}$$

where $\mathcal{N}$ is the total concentration of electrons involved in the MT process at time t, and $N[\mathcal{E}_d(t)]$ is the concentration of localized states which provide the thermal exchange with the delocalized states at that time, and which — for the distribution (11) — can be approximated as

$$N[\mathcal{E}_d(t)] \simeq \int_{\mathcal{E}_d(t)}^{\infty} g(\mathcal{E}) d\mathcal{E} = N_0 e^{-\mathcal{E}_d(t)/\mathcal{E}_0}. \tag{25}$$

The only difference between the conventional MT model for the transient experiment[19] and our system concerns the initial condition. At $t = 0$ we start from the Boltzmann distribution of trapped electrons that has been generated by the steady-state illumination, rather than from an empty band. The number of electrons $\mathcal{N}(t)$ which then becomes available for the transient MT process increases with t according to

$$\mathcal{N}(t) = \int_0^{\mathcal{E}_d(t)} f(\mathcal{E}) g(\mathcal{E}) d\mathcal{E} \simeq \frac{N_0}{N_c} n(0) (\nu_0 t)^{1-\alpha}, \tag{26}$$

where Eqs. (11), (12), (13), and (23) have been used. Substituting Eq. (26) into Eq. (24), we see that the time dependence $(\nu_0 t)^{1-\alpha}$ of Eq. (26) is canceled by the time dependence $(\nu_0 t)^{-1+\alpha}$ of the ratio $\exp[\mathcal{E}_d(t)/kT]/\exp[-\mathcal{E}_d(t)/\mathcal{E}_0]$ in Eq. (24). So, if recombination is neglected there is no time dependence of the photocurrent — to first approximation — until the moment $t_{\rm rel}(\mathcal{E}_q)$ when $\mathcal{E}_d$ reaches the quasi-Fermi level $\mathcal{E}_q$ and the concentration $\mathcal{N}(t)$ no longer increases with t. For $t > t_{\rm rel}(\mathcal{E}_q)$ the conventional $n \propto t^{-1+\alpha}$ dependence should occur, if one neglects recombination.

That the above argument is only an order-of-magnitude one is easily understood, and confirmed by Monte Carlo simulations.[20] Indeed, as soon as the external excitation is stopped, the nonequilibrium charge distribution will start to relax. However, as time-of-flight experiments have demonstrated — in agreement with the MT theory—the decrease of the free-carrier concentration in the absence of recombination will not be faster than the $t^{-1+\alpha}$ mentioned above.

Consequently, direct recombination should not be neglected if one is to understand the experimental data. Even if the probability of such an event is small compared to the probability of capture in a localized state, it will significantly influence the result, given the fact that the capture time τ_c is much shorter than the carrier lifetime τ_0. The reason is that in order to be captured by a trap deeper than $\mathcal{E}_d(t)$ a typical electron will on the average have been trapped to, and released from shallower states as often as m times, with

$$m \simeq \frac{N_0}{N[\mathcal{E}_d(t)]}. \tag{27}$$

This ratio reflects the simple fact that the fraction of states $N(\mathcal{E}_d)/N_0$ with energies deeper than $\mathcal{E}_d(t)$, i.e., with $\mathcal{E} > \mathcal{E}_d(t)$, is exponentially small for the DOS of Eq. (11). Substituting Eqs. (25) and (23) into Eq. (27) we obtain

$$m \simeq (\nu_0 t)^{\alpha}. \tag{28}$$

Although the probability to recombine at each trapping event is very small, it becomes considerable after m trapping events. Hence the concentration of electrons participating in the MT process at time t is $\mathcal{N}(t)$ determined by Eq. (26), multiplied by the probability $(W_c)^m$ for an electron to avoid recombination during m trapping events. Using Eqs. (22), (26), and (27) we thus obtain

$$\mathcal{N}(t) = \left(\frac{1}{1+\frac{\tau_c}{\tau_0}}\right)^{(\nu_0 t)^{\alpha}} \frac{N_0}{N_c} n(0) (\nu_0 t)^{1-\alpha}. \tag{29}$$

Substitution of Eq. (29) in Eq. (24) leads to

$$n(t) \simeq n(0) \exp\left[-(\nu_0 t)^{\alpha} \left| \ln \frac{1}{1+\frac{\tau_c}{\tau_0}} \right| \right]. \tag{30}$$

This equation describes the decrease of free-electron concentration upon termination of a steady-state excitation. The decay is nonexponential in accordance with all experimental results available. Figure 2 shows a comparison

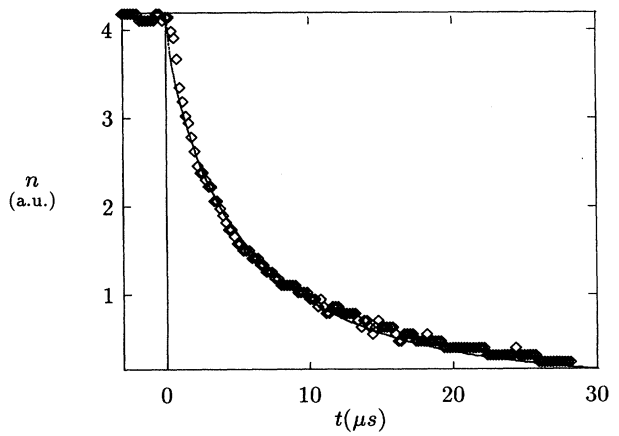

FIG. 2. Photocurrent decay of a a-$Si_{.98}C_{.02}$:H gap cell at 200 K, and (smooth line) calculated current values using Eq. (30) with $\nu_0 = 10^{12}\ s^{-1}$, $\alpha = 0.73$, and $\tau_c/\tau_0 = 1.1 \times 10^{-5}$.

between an experimental decay curve and a calculated one given by Eq. (30) with $\nu_0 = 10^{12}$ s^{-1}, $\alpha = 0.73$, and $\tau_c/\tau_0 = 1.1 \times 10^{-5}$. The latter two values are results of a curve-fitting procedure. The agreement between the measured and calculated curves is obviously good, and the fitting parameters have physically meaningful values.

Independent of the above curve-fitting routine, a useful estimate of system parameters can already be obtained from the measured response times τ_i by comparing their behavior to that of a characteristic decay time τ_d, defined as the value of t at which the exponent in Eq. (30) is equal to -1, i.e., when the photocurrent has decreased by a factor of e. In our experiments described in Sec. III, the typical values of τ_d at $T = 200$ K are between 10^{-5} s and 10^{-6} s. According to Eq. (30) these values correspond to

$$\tau_d \simeq \nu_0^{-1} \left| \frac{1}{\ln\left(1 + \frac{\tau_c}{\tau_0}\right)} \right|^{1/\alpha} \simeq \nu_0^{-1} \left(\frac{\tau_0}{\tau_c}\right)^{1/\alpha}. \quad (31)$$

This implies a ratio τ_c/τ_0 of typically 3×10^{-5} if we assume that $\nu_0 \simeq 10^{12}$ s^{-1} and $\alpha \simeq 2/3$. The choice of $\alpha = 2/3$ corresponds to our experimental $T = 200$ K and the generally observed[21] slope $\mathcal{E}_0/k \simeq 300$ K of the upper band tail. This value does differ from the $\alpha \simeq 0.35$ that corresponds by Eq. (17) to the measured value of $\gamma \simeq 0.75$ because this latter value is characteristic for the lower energy slope at the level of the steady-state quasi-Fermi energy $\mathcal{E}_q$. To model the complete photocurrent decay, one would actually have to use an $\mathcal{E}_d(t)$-linked function $\alpha(t)$.

The temperature dependence of τ_d, which is contained in α in Eq. (31) can be written explicitly as

$$\tau_d = \nu_0^{-1} \exp\left(\frac{\mathcal{E}_0 \ln(\tau_0/\tau_c)}{kT}\right) \quad (32)$$

which agrees with the experimentally observed activated behavior (20). If we use the numerical values for τ_c/τ_0 and $\mathcal{E}_0$ from either the fit to Eq. (30) or the estimate based on Eq. (31) we obtain a value of ~ 0.25 eV for the activation energy Δ in Eq. (20). While, as anticipated, this energy falls considerably short of the $\mathcal{E}_q$ shown in Table I, it is larger than the Δ obtained from the experimental τ_i data. This reflects the fact that τ_i characterizes the initial photocurrent decrease where direct, temperature-independent recombination is a relatively more important factor than at later times, as, e.g., τ_d, where thermalization of the nonequilibrium charge distribution has progressed some way.

Nevertheless, τ_d remains a useful quantity for examining the photocurrent decay. The generation-rate dependence of τ_d is determined by the generation-rate dependence of the ratio τ_0/τ_c. The capture time τ_c will be independent of G but for the lifetime τ_0 we obtain from Eqs. (5) and (9)

$$\tau_0 = \frac{n}{G} \propto G^{\gamma-1}. \quad (33)$$

With Eq. (31) this results in

$$\tau_d \propto G^{-(1-\gamma)/\alpha} = G^{-\beta}. \quad (34)$$

For the values $\gamma \simeq 0.75$ and $\alpha = 0.67$ (where γ should indeed, through τ_0, refer to the full distribution of localized states, and α only to the upper part as τ_d relates to the initial response), we obtain $\beta \simeq 0.37$, in good agreement with the experimental value.

V. CONCLUSIONS

The main results of our study may be summarized as follows.

(1) On the basis of standard photoconductivity relations, and with the usual assumption that the photocurrent response time corresponds to the lifetime of trapped carriers in the vicinity of the quasi-Fermi level, we have shown that the dependence of that response time on the generation rate G does not contain additional information about trapping or recombination processes in a-Si:H, above what is already contained in the well-known exponent γ of the $\sigma_{\rm ph} \propto G^\gamma$ dependence.

(2) From measurements of the photocurrent decay in a-Si:H and some a-Si$_x$C$_{1-x}$:H alloys we have been able to deduce that initial decay times from steady state should not, as a rule, be identified with the lifetime of trapped carriers. They generally show a light-intensity dependence $\tau_i \propto G^{-\beta}$ with $\beta \neq \gamma$, and hence should not be used for the investigation of carrier drift mobility.

(3) Most importantly, a simple theory is developed for the initial decay of the photocurrent from its steady-state value. The theory allows us to understand measured generation-rate and temperature dependencies of the initial decay time.

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