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Dispersive Transport and Recombination Lifetime in Phosphorus-Doped Hydrogenated Amorphous Silicon

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The recombination lifetime in phosphorus-doped hydrogenated amorphous silicon is determined from the dispersive photocurrent decay following a short-pulse excitation. The electron drift mobility and dispersion parameter α are obtained as well. It is found that α is temperature dependent as expected for extended-state transport controlled by multiple trapping. A lower limit to the extended-state mobility is determined: $\mu_c \gtrsim 1\ \mathrm{cm^2/V\cdot s}$.

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Transient photocurrent (TP) with a short pulse excitation is a simple but powerful technique for separating transport parameters that are lumped together in ordinary dc measurements. By phosphorus doping of hydrogenated amorphous Si (a-Si:H), we have observed TP decays extending over several orders of magnitude in time, allowing for a detailed analysis of the form of the decay. We introduce a new and direct measure of the carrier lifetimes and our results confirm that the increase in photoconductivity with phosphorus doping, previously observed,[1,2] is mainly due to an increase in recombination lifetime. For n-type a-Si:H, the dispersive nature[3] of the transport of the photoexcited carriers (electrons) is clearly revealed, and we have been able to investigate its doping and temperature dependence in detail. We observe for the first time that the dispersion is temperature dependent. We take this as evidence for trap-controlled[3-5] transport in extended states and obtain a lower limit to the extended-state mobility.

The TP decay was studied in a-Si:H films produced by glow discharge of SiH_4 with PH_3 added for n-type doping. The contacts were predeposited sputtered Mo stripes, 1 mm apart. The deposition of the a-Si:H films took place in an inductively excited 0.07-Torr plasma onto 250 °C fused-quartz substrates. The TP was excited by a N_2-laser–pumped dye laser (Rh6G) with peak power, pulse width, and repetition rate of 1 kW, 3 ns, and 20 Hz, respectively. The laser (photon ener-

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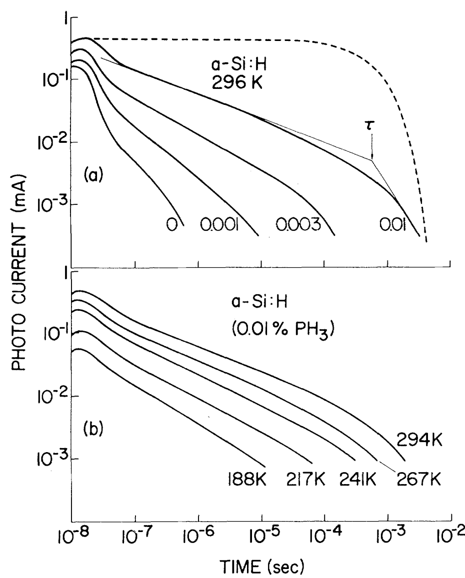

FIG. 1. Photocurrent decays in a-Si:H after short-pulse excitation. (a) At room temperature and different doping ratios, indicated by volume percent PH_3 in SiH_4. For 0.01% PH_3 and 296 K, the slopes $-(1-\alpha)$ and $-(1+\alpha)$ are shown with $\alpha = 0.62$, and intercepting at $\tau = 580\ \mu s$. The dashed curve is $\sim \exp[-t/\tau]$. (b) At doping ratio 0.01% PH_3 and different temperatures.

gy =2.1 eV) was focused to a power density of 40 kW/cm^2 producing an estimated carrier density of $2\times10^{18}\ cm^{-3}$ per pulse. The TP signal was transmitted, by a 50-Ω coaxial cable to a boxcar integrator with a 10 ns gate. The overall system time resolution was 20 ns (full width at half maximum).

Shown in Fig. 1, in a log-log plot, is the photocurrent $I(t)$ versus time elapsed after the excitation pulse for different dopings [Fig. 1(a)] and temperatures [Fig. 1(b)]. The overall TP consists of an initial current peak, on the time scale of our resolution, followed by a clear power-law dependence over more than two orders of magnitude in time, and finally a bendover towards a cutoff.

These TP decays are very similar to the current decays observed in time-of-flight experiments[6] that have been used extensively to measure drift mobilities in amorphous substances,[3] including a-Si:H.[7,8] The drift-mobility experiments have been successfully described by the continuous-time random-walk (CTRW) theory, developed by Scher and Montroll,[9] in which the anomalous transport is characterized by a *dispersion parameter* α $(0<\alpha<1)$ determining the exponent in the distribution function $\psi(t)\propto t^{-(1+\alpha)}$ which, in general terms, is the distribution of dwell times between successive transport events.

The resulting current decays are approximated by[9]

$$I(t)\propto\begin{cases} t^{-(1-\alpha)}, & t<\tau \\ t^{-(1+\alpha)}, & t>\tau, \end{cases} \qquad (1)$$

where τ is the transit time in a drift experiment. Since the contact separation in the present experiments (1 mm) corresponds to infinite transit times (on our time scale), we should observe TP decays following $I(t)\propto t^{-(1-\alpha)}$ in the absence of carrier recombination. Indeed, we observe the power-law dependence over a substantial length of time ($\gtrsim 10\ \mu s$) for the phosphorus-doped films proving that monomolecular recombinations are negligible during this time. Furthermore, the decay slope was independent of the initial carrier density, as checked by varying the excitation intensity over almost two orders of magnitude. This rules out bimolecular recombination to be the origin of, or of significant influence on, the power-law decay. Hence, we identify the power law as the inherent decay of dispersive transport from which we can determine the dispersion parameter α.

For $t>10\ \mu s$, the decay slope (in the log-log plot of Fig. 1) gradually changes towards a steeper decay as a result of carrier loss. In the present experimental geometry, as opposed to the time-of-flight experiment, the major loss is by recombinations in the bulk. The slope change therefore represents carrier recombinations and its observation provides a direct measure of carrier lifetimes. To specify precisely a recombination lifetime from our experiment, we need to set up and solve a detailed model for the dispersive transport as well as for the recombination. This has not yet been done. If, however, the transport is in extended states and the recombination also occurs predominantly from extended states, we will expect an expression like Eq. (1) to hold for $t\ll\tau$ and $t\gg\tau$, respectively, where now τ is an *effective carrier lifetime*, i.e., the lifetime of the whole distribution of carriers in extended states as well as in localized band-tail states.

In Fig. 1(a) we have used the above analogy to define and determine the carrier lifetime by the intercept of the initial and final slopes with values $-(1-\alpha)$ and $-(1+\alpha)$, respectively. Experimentally, the final slope is less well defined than the initial slope and theoretically the final decay may

in fact deviate from the above form depending on the detailed recombination mechanisms. However, this will not influence drastically the determination of τ.

The analogy to the time-of-flight experiment is an approximation in as much as a bulk recombination event is less well defined than annihilation in a blocking contact. The approximation is similar to replacing the exponential decay, shown as the dashed curve in the log-log plot of Fig. 1(a), by an abrupt cutoff at $t=\tau$. The difference is only significant for $t \simeq \tau$. On the other hand, we do observe a transition region between the initial and final slopes that extends over about two decades in time which is wider than typical for time-of-flight experiments.[3,7,8]

It is obvious from Fig. 1(a), that the recombination lifetime in a-Si:H is strongly increased by phosphorus doping. The maximum doping ratio 0.01% PH_3 in Fig. 1(a) (which is still a fairly low doping[1,2]) yields $\tau = 580$ μs and $\alpha = 0.62$ at $T = 296$ K. For stronger doping there is first a saturation and then a decrease[10] of τ and α probably because the Fermi level approaches the band-tail states active in the photocurrent decay.

The final parameter to fully specify the TP signal is the mobility which determines the current amplitude. We define a *time-dependent drift mobility* by the relation (for $t < \tau$)

$$I(t) = (QV_B/d^2)\mu_D(t), \tag{2}$$

where V_B is the bias voltage, d is the contact separation, and Q is the total charge generated in a laser pulse. In the experiment (Fig. 1), $QV_B/d^2 = 1.7\times10^{-3}$ J/cm^2. It is essential for our analysis that the contacts are Ohmic or act as such. To investigate this, we determine the average drift length of carriers in our experiment as defined by $l = (V_B/d)\int_0^\tau \mu_D(t)\,dt$. From Eq. (2) and Fig. (1) we find in all cases $l < 2$ μm, i.e., $l \ll d$, implying that a negligible fraction of carriers reaches the contacts before recombining in the bulk. Hence, the contacts are invisible and do not influence the observed current decays. Experimentally, we could observe that the photoresponse (dc as well as transient) of our samples is linear and symmetric in bias voltage up to $V_B \simeq 200$ V which is four times the voltage applied in our experiment. The drift mobility in dc transport is an average over lifetime of the above $\mu_D(t)$, whereas the drift mobility derived from time-of-flight experiments is averaged over the transit time. The latter unfortunately gives a field-dependent result.[3]

So far we have used the formal theory of CTRW to characterize, unambiguously, the TP decay without really specifying the transport mechanism. On the other hand the parameters α, τ, and μ_D have an intuitive physical meaning, and their dependence on external variables should ultimately reveal the microscopic transport mechanism. An important variable in that respect is the temperature. Figure 1(b) shows the temperature dependence of the TP decay in doped (0.01% PH_3) a-Si:H. The TP signal as a whole, and thereby μ_D, diminishes with decreasing temperature in a temperature-activated manner. Simultaneously, there is a slight, but definite, change in decay slope. In the investigated temperature range, the dispersion parameter varies nearly linearly with temperature as shown in Fig. 2. The linear variation $\alpha = T/T_0$ is in fact the strongest temperature dependence of α to be expected,[3,4] and it is consistent with an extended-state transport controlled by multiple trapping in an exponential distribution of trapping states given by[3,5]

$$N_t(\epsilon) = \begin{cases} 0, & \epsilon < \epsilon_t \\ (N_t/kT_0)\exp[-(\epsilon-\epsilon_t)/kT_0], & \epsilon > \epsilon_t, \end{cases} \tag{3}$$

where $\epsilon = E_c - E$ is the depth of the localized states below the mobility edge at E_c and ϵ_t is a minimum depth for these states to act as effective traps. N_t is the total density of effective traps and kT_0 measures the width of their energy distribution ($kT_0 = 40$ meV in Fig. 2).

The observed temperature dependence of α provides evidence that we are observing trap-con-

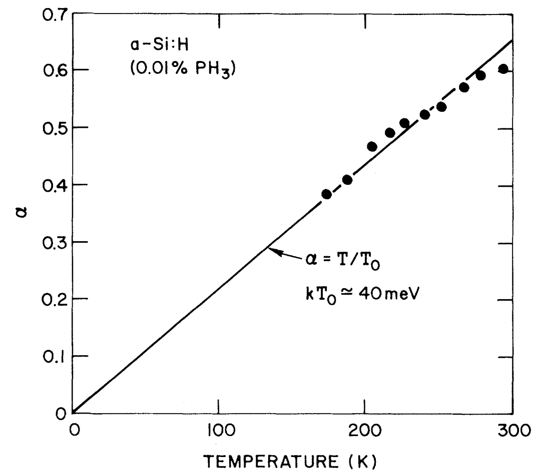

FIG. 2. Temperature dependence of dispersion parameter α for doped a-Si:H.

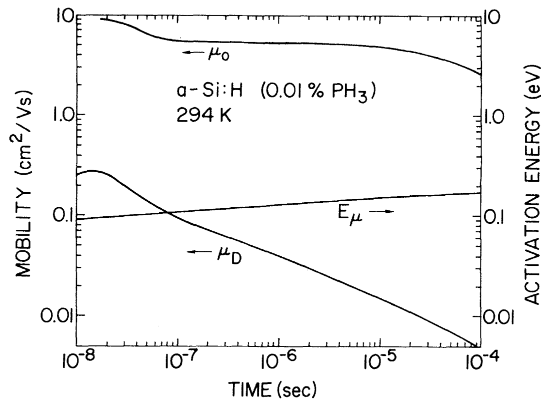

FIG. 3. Time dependence of mobility parameters for doped a-Si:H at room temperature.

trolled transport in extended states, and so does the magnitude of the mobilities derived from our measurements. Applying Eq. (2), we find an instantaneous drift mobility $\mu_D \simeq 0.2$ cm^2/V$\cdot$s at room temperature. This mobility is temperature activated with an activation energy $E_\mu \approx \epsilon_t \approx 0.1$ eV. However, because of the temperature-dependent dispersion, the activation energy changes with time during the decay. We may write

$$\mu_D(t)=\mu_0(t)\exp[-E_\mu(t)/kT], \quad (4)$$

where the prefactor μ_0 is proportional to the microscopic mobility μ_c of the extended states. The time dependences of μ_D, E_μ, and μ_0[Eq. (4)] are shown in Fig. 3 for a doped sample at room temperature. We notice that μ_0 is much less time dependent that μ_D and clearly separates the very initial ($t<50$ ns) decay and the final decay ($t>10$ μs) from which we determine the bulk carrier lifetime. The initial decay may be due to a fast parallel recombination channel, for example in the surface or the interface. The observed μ_0 deviates from the microscopic extended-state mobility μ_c by a factor containing the density of states and quantum efficiency. Assuming an exponential band tail $N(E)\propto\exp[(E-E_c)/kT_0]$ and a quantum efficiency of 1, we estimate $\mu_c \geqslant 0.1\mu_0$ $\simeq 1$ cm^2/V$\cdot$s which is in good agreement with theoretical estimates[11] and previous experiments.[7,12]

The observed mobilities, which are rather insensitive to different dopings,[10] suggest electron transport limited by trapping in localized, intrinsic, band-tail states. The shift of the Fermi level with doping, on the other hand, strongly affects the deep recombination centers and thereby the recombination lifetime.

Recent transient-luminescence[13] and induced-absorption[14] measurements show similar nonexponential decays attributed to dispersive diffusion. Since we believe that the measurements of Refs. 13 and 14 are probing deep, localized band-gap states, they are likely to be strongly influenced by hopping transport between these states. Lifetimes, mobilities, and dispersion parameters derived from such measurements may therefore deviate significantly from the present results.

Further TP measurements seem promising for the characterization and analysis of transport as well as relaxation and recombination in amorphous semiconductors.

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