Dispersive and Nondispersive Transport in Amorphous Semiconductors in Presence of Bias Illumination

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A model for the transient behavior of photoconductivity and induced photoabsorption under bias illumination is derived for the saturated band-tail regime. For weak bias and strong pulse excitation, the usual dispersive transport decay is obtained, while at strong biases and weak excitation, the transport becomes nondispersive resulting in steep decay slopes. The model explains some puzzling experimental results on photoconductivity and photoabsorption in presence of bias illumination.

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Dispersive transport in amorphous semiconductors is generally interpreted in terms of the multiple-trapping model as applied by Tiedje and Rose[1] and Orenstein and Kastner[2] to photoabsorption (PA) and photoconductivity (PC) measurements. Although this model appears to account for many experimental data,[3–5] some difficulties arise as pointed out by Schiff[6] and Zeldov and Weiser.[7] Recent measurements by Pandya and Schiff[8] and Pfost, Vardeny, and Tauc[9] of PC and PA with bias illumination also cast doubt on the applicability of the multiple-trapping model. Low-energy photoabsorption measurements[10] have led to the introduction of a saturated band-tail (SB) model by the present authors.[7,10] The purpose of this Letter is to extend this model to the case of PA and PC measurements in the presence of bias illumination and to show that the puzzling data obtained by Pandya and Schiff[8] and some inconsistent results of Pfost, Vardeny, and Tauc[9] can be readily explained by the model presented here.

The original saturated band-tail model[7,10] considered the decay of the photocarriers produced by an excitation pulse which have saturated at least the deeper states in the band tail. A general expression for the recombination rate can be written as

$$d(n+N)/dt = -an - bNn - cn^2, \tag{1}$$

where n is the density of the excited carriers in states above the mobility edge and N that of the trapped carriers in the tail; a is the monomolecular recombination constant, b, the bimolecular "free-to-bound" recombination constant, and c, the "free-to-free" recombination constant.

The model was developed to deal with a wide range of excitation intensities including saturation of the entire band tail. To simplify our discussion we limit ourselves here to weaker excitations for which the approximation $N >> n$ holds, so that n and N can be expressed as

$$n = \int_0^\infty g(\epsilon) f(\epsilon) d\epsilon = N_c \exp(\epsilon_q / KT), \tag{2}$$

$$N = \int_\infty^0 g(\epsilon) f(\epsilon) d\epsilon = (N_t / \mathrm{sinc}\,\pi\alpha) \exp(\alpha\epsilon_q / KT). \tag{3}$$

Here $f(\epsilon)$ is the Fermi-Dirac distribution with quasi-Fermi level ϵ_q, N_c the effective density of states above the mobility edge, N_t the total density of states in the exponential tail; $g(\epsilon)$ is the density of states distribution [$g(\epsilon) = N_t \exp(\epsilon/KT_0)/KT_0$ for $\epsilon < 0$] and $\alpha \equiv T/T_0$ ($\alpha < 1$). To obtain the time dependence of PA and PC one must solve Eqs. (1), (2), and (3) simultaneously. The results are shown in Table I, where we also include the results of the multiple-trapping model.[2] Note that the saturated band-tail model gives steeper decays for the monomolecular recombination case compared with the multiple-trapping model, whereas for bimolecular recombination both models predict the same decays of PA and PC at long times. The bimolecular free-to-free recombination (c term) gives rise to relatively slower decays and its effect can dominate mainly at short times.

We now turn to the discussion of the saturated band-tail model in presence of bias illumination. For the sake of simplicity we accept the widely used assumption that the dominant recombination process is bimolecular. Equation (1) should then be written as

$$dN/dt = -bNn + G, \tag{4}$$

where G is the generation rate due to the bias illumination. As seen below, the inclusion of the generation term, neglected by Pfost, Vardeny, and Tauc,[9] has a profound effect on the transient

TABLE I. Comparison of time dependence of photoabsorption (PA) and photoconductivity (PC) at long times due to monomolecular (MR) and bimolecular (BR) recombination processes according to saturated band-tail (SB) model *without bias illumination* and multiple-trapping (MT) model.

Recomb. process \ Model	SB			MT	
	MR	BR	BR (c term)	MR	BR
PA	$t^{-\alpha/(1-\alpha)}$	$t^{-\alpha}$	$t^{-\alpha/(2-\alpha)}$	$t^{-\alpha}$	$t^{-\alpha}$
PC	$t^{-1/(1-\alpha)}$	t^{-1}	$t^{-1/(2-\alpha)}$	$t^{-1-\alpha}$	t^{-1}

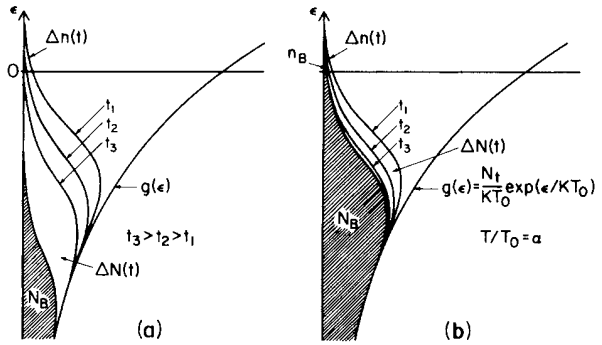

FIG. 1. Evolution of $\Delta N(t)$ and $\Delta n(t)$ for the cases of (a) $\Delta N >> N_B$ and (b) $\Delta N << N_B$.

behavior of the excess carriers. Constant bias without pulsed excitation yields $bN_Bn_B = G$ in the steady state where n_B and N_B are the densities of the mobile and trapped "bias carriers" produced by the bias illumination. By use of Eqs. (2) and (3) a sublinear dependence of N_B on generation rate G is obtained[5]:

$$N_B = (G/bN_c)^{\alpha/(1+\alpha)}(N_t/\mathrm{sinc}\,\pi\alpha)^{1/(1+\alpha)}. \quad (5)$$

A pulsed photoexcitation causes an increase in the densities of the carriers by $\Delta n(t)$ and $\Delta N(t)$ ("photocarriers"), respectively. Equation (4) can then be written as

$$d(\Delta N)/dt = -b(\Delta N\Delta n + \Delta N n_B + N_B\Delta n). \quad (6)$$

Equation (6) together with Eqs. (2) and (3) should now be solved for $\Delta N(t)$ and $\Delta n(t)$ which are measured by PA and PC, respectively. The exact solution of Eq. (6) gives a transcendental expression which is too lengthy to present here but in order to gain insight into the physical processes it is sufficient to consider two extreme cases. First, we assume a strong excitation pulse and weak bias so that $\Delta N >> N_B$. Equation (6) then reduces to

$$d(\Delta N)/dt = -b\Delta N\Delta n, \quad (7)$$

which is, as expected, similar to saturated band tail without bias illumination and results in $\Delta N \propto t^{-\alpha}$ and $\Delta n \propto t^{-1}$ at long times, in accordance with Table I. The evolution of ΔN and Δn for this case is shown schematically in Fig. 1(a).

In the case of strong bias and a weak pulse $\Delta N << N_B$. Using Eqs. (6), (2), and (3) and some algebraic manipulations we obtain the following differential equation:

$$d(\Delta N)/dt = -(1+\alpha)bn_B\Delta N/\alpha = -(1+1/\alpha)bN_c(N_B\,\mathrm{sinc}\,\pi\alpha/N_t)^{1/\alpha}\Delta N \equiv -\Delta N/\tau, \quad (8)$$

with the straightforward solution

$$\Delta N(t) = \Delta N(0)\exp(-t/\tau). \quad (9)$$

Here $\Delta N(0)$ is the density of photocarriers generated by the pulse and τ is defined in Eq. (8). The corresponding result for Δn is

$$\Delta n(t) = (N_c/N_B\alpha)(N_B\,\mathrm{sinc}\,\pi\alpha/N_t)^{1/\alpha}\Delta N(0)\exp(-t/\tau). \quad (10)$$

The striking feature of Eqs. (9) and (10) is that at long times PA and PC both decay exponentially with the same time constant so that the transport becomes *nondispersive*. Referring to Fig. 1(b) the effect becomes obvious. Bias illumination fills up the deep traps and the excess photocarriers form a "thin shell" on top of the "bias carriers." The density of the mobile photocarriers thus becomes a constant fraction of the total density of photocarriers and their average mobility becomes time invariant, leading to nondispersive transport.[11] As expected, the effective lifetime decreases with increase in bias intensity: $1/\tau \propto N_B^{1/\alpha} \propto G^{1/(1+\alpha)}$ as seen from Eqs. (5) and (8).

We now discuss the experimental data of Refs. 8 and 9 in light of the theoretical results obtained by us. First, we point out that the PC measurements on a-Si:H[8] show a very steep decay at long times which sets in earlier with increasing bias. Furthermore, the PC *increases* with bias illumination at short times. Both effects are contrary to the

multiple-trapping model which predicts a PC decay rate no faster than $t^{-1-\alpha}$ at long times (Table I) and does not predict the intensity dependence found by Pandya and Schiff at short times. Both effects are readily predicted by our treatment. Equation (10) shows that at long times the decay becomes exponential for strong biases and hence much faster than $t^{-1-\alpha}$. The increase in PC with enhanced bias at short times is easily understood from Fig. 1(b). An increase in bias fills up ever more shallow band-tail states and thus enhances the density of photocarriers above the mobility edge. The resulting increase in PC according to Eq. (10) is sublinear with bias intensity: $\Delta n(0) \propto N_B^{(1-\alpha)/\alpha} \propto G^{(1-\alpha)/(1+\alpha)}$. Both these effects, in agreement with experimental data of Pandya and Schiff, are seen in Fig. 2(a) where we plot the exact solution of Eq. (6) for weak excitation with commonly accepted values for the various parameters. Note the absence of any crossover in the corresponding plot of PA in Fig. 2(b), which in the case of PC occurs at $t \simeq (1-\alpha)\tau$ with τ defined in Eq. (8).

Figures 3(a) and 3(b) show PC and PA results for the case of strong excitation and a range of bias illuminations starting from zero bias. We emphasize the gradual increase in the slope of the decay with bias for shorter times in Fig. 3(b), as observed by Pfost, Vardeny, and Tauc[9] in their high-temperature measurements, e.g., 250 K in a-Si:H. We see that this increase occurs without having to invoke the delicately balanced restrictions imposed on midgap-states dynamics postulated in Ref. 9. In their mechanism these midgap states prevent saturation of the band tail in the absence of bias illumination by capturing photocarriers during the thermalization process. Bias illumination, on the other hand, saturates these states *without* occupying the band tail and also forces the recombination process to become monomolecular. Thus, as seen from Table I, PA should change from a $t^{-\alpha}$ behavior (multiple trapping with bimolecular recombination) to a final $t^{-\alpha/(1-\alpha)}$ slope at strong

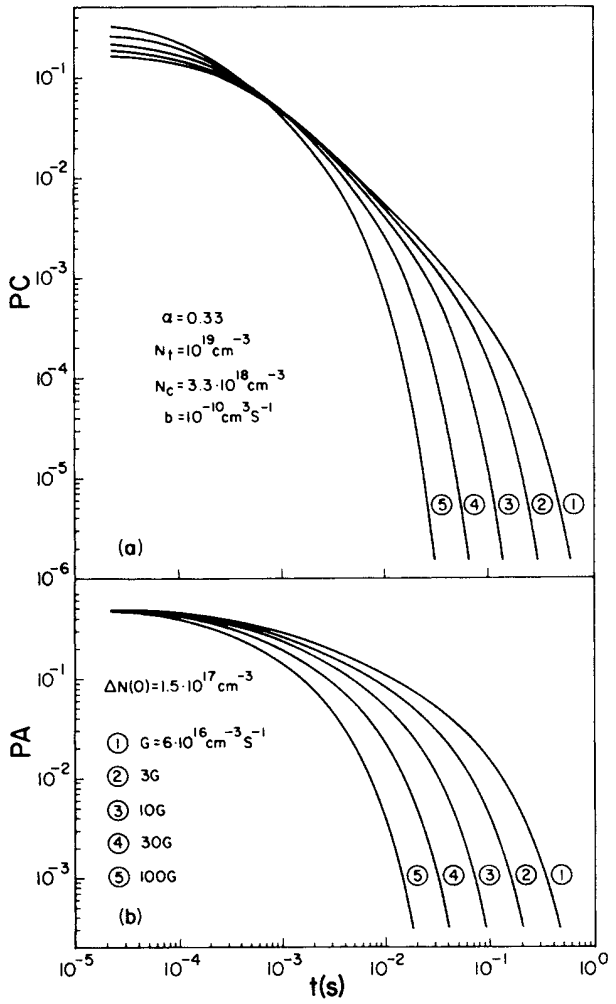

FIG. 2. Time dependence of PC and PA at weak excitation and different biases G.

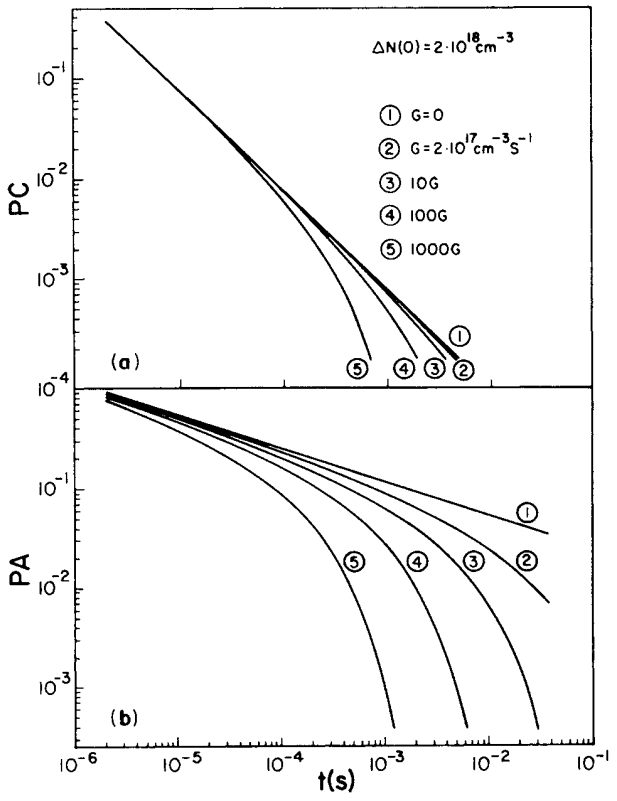

FIG. 3. Decays of PC and PA at strong excitation and different biases G. Parameters as in Fig. 2.

bias (saturated band tail with monomolecular recombination), as seemingly borne out by their experiment. However, the slope of PA as a function of N_B shows no asymptotic approach to the $\alpha/(1-\alpha)$ value. It is this plot which is relevant since N_B is a strongly sublinear function of bias intensity according to Eq. (5). We therefore claim that the data of Pfost, Vardeny, and Tauc cover only a short time interval, at early times of Fig. 3(b), and that an extension of their measurements to longer times or stronger biases would have revealed the much steeper slopes shown in Fig. 3(b). We also mention in passing that if the model proposed by Pfost, Vardeny, and Tauc were valid the time behavior of PC during the thermalization process before recombination would be proportional to $t^{-1-\alpha}$ rather than $t^{-1+\alpha}$ without bias illumination, since the midgap levels would affect the carrier thermalization in a manner equivalent to that of recombination centers. No such behavior has been observed.[12,13] Moreover, it can be shown that the proposed model cannot explain the PC data of Pandya and Schiff with regard to either the steep slopes at long times or the crossover at short times.

In conclusion, we have developed a saturated band-tail model in the presence of bias illumination which predicts an increase in the rate of decay of transient photoabsorption and photoconductivity as bias intensity increases. At high bias illuminations, when the density of the photocarriers drops below that of the bias carriers, the transport becomes *non-dispersive:* Both PA and PC become proportional to $\exp(-t/\tau)$ with τ decreasing with bias intensity. We also find that for short times the PC *increases* with bias illumination. The above results of the model are in good agreement with transient PC data on a-Si:H.[8] We also explain PA data[9] on a-Si:H[9] without having to invoke the more complicated model used in Ref. 9. We believe that simultaneous measurements of PA and PC over a wide range of decay times with various bias and excitation intensities can be a valuable tool for study of dispersive transport and recombination in amorphous semiconductors.

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