Disorder and persistent photoconductivity in $Zn_xCd_{1-x}Se$ semiconductor alloys

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A theoretical formula based on carrier scattering in systems with a certain degree of disorder has been derived, which describes well the buildup transients of persistent photoconductivity and carrier transport due to the conduction-band tail states in semiconductor alloys. Important parameters, including the distribution of tail states caused purely by alloy disorder, can be obtained by comparing our theory with experimental data. The formula derived here has general validity for describing the conductivity due to the tail states in other systems with either structure (amorphous), location (impurity), or alloy disorder. [S0163-1829(96)06927-5]

The effects of disorder on the transport properties of semiconductors, including conductivity, carrier localization, and the metal-insulator transition (MIT), have been an important subject for many years.[1–3] However, important localization parameters, including the distribution of tail states, critical carrier concentration, and carrier mobility edges, are often not directly accessible experimentally. In particular, there have been far fewer transport experiments on unintentionally doped semiconductor alloys because there are no measurable charge carriers in these materials, although the effects of alloy disorder on the optical properties (e.g., exciton localization) of semiconductors have been known for years.[4,5] Due to disorder, at $T=0$, the photoexcited electrons in the conduction band are localized (or in the band-edge tail states) at low concentrations. As the electron concentration increases to a critical value n_c, the electron quasi-Fermi-level E_F will be lined up with the conduction-band mobility edge E_m, at which point MIT will occur in semiconductors. Photoexcited charge carriers in the persistent photoconductivity (PPC) state provide a unique system with a number of advantageous features for studying properties of carrier localization, MIT, and disorder structures in semiconductors. The key features in the PPC state are the very long lifetimes of photoexcited charge carriers and the continuous variation of the electron concentration in the conduction band in a single sample.[6–8] The physical origin of PPC in different semiconductors has been an important subject in the last decade.[9–13] By recognizing the parabolic buildup behavior of PPC contributed by the conduction-band tail states, we have previously shown an exponential tail-state distribution and estimated the associated parameters for $Zn_{0.3}Cd_{0.7}Se$.[6,7]

In the present work, we have derived a general formula which describes the buildup transients of PPC and carrier transport due to conduction-band tail states in semiconductor alloys. By comparing it with our experimental results, we have obtained important physical parameters of MIT in $Zn_xCd_{1-x}Se$. Our theoretical formula derived here should be valid in general for describing the conductivity contributed by the tail states in systems with either structure (amorphous), location (impurity), or alloy disorder. The sample used for this study was a $Zn_{0.3}Cd_{0.7}Se$ unintentionally doped semiconductor alloy. Experimental details can be found elsewhere.[6] The excitation intensity flux used for the measurements was of the order of 10^{12} photons/cm^2 s.

The conductivity σ as functions of temperature T and photoexcited electron concentration n in semiconductors with a certain degree of disorder can be described by[2]

$$\sigma(T,n)=-\int_{-\infty}^{+\infty}(\partial f/\partial E)\sigma(E)dE, \tag{1}$$

where $f(E)=[1+e^{(E-\mu)/kT}]^{-1}$ is the Fermi distribution function of the photoexcited electrons in the conduction band, μ is the chemical potential energy, and $\mu(T=0)=E_F$ is the quasi-Fermi-level. $\sigma(E)$ is the conductivity at energy E which depends on the electron concentration n. Conductivity caused by hole transport can be neglected because of their heavier mass, which has been confirmed experimentally.[6,7] In the low concentration regime where the electron quasi-Fermi-level E_F is below the mobility edge E_m, the conductivity is due to electron hopping in the localized states, and the conductivity $\sigma(E)$ is given by the Kubo-Greenwood formula as[2]

$$\sigma(E)=C[N(E)]^2, \tag{2}$$

where C is a proportionality constant and $N(E)$ is the density of states (DOS) at energy E, which can be written as

$$N(E)=(N_0/E_0)\exp[(E-E_m)/E_0](E\leqslant E_m), \tag{3}$$

where E_0 is the tail-state distribution parameter and N_0 is the total DOS below the mobility edge E_m, both of which depend on the alloy disorder structures of semiconductor alloys. From Eqs. (1)–(3), conductivity at different temperatures T and carrier concentration n, $\sigma(T,n)$, can thus be written as

$$\sigma(T,n)=(C/kT)(N_0/E_0)^2\times\int_{-\infty}^{+\infty}\frac{\exp[2(E-E_m)/E_0]}{[e^{(E-\mu)/kT}+1][e^{-(E-\mu)/kT}+1]}dE. \tag{4}$$

In writing Eq. (4), we have assumed that $N(E)$ above the mobility edge takes the same form as Eq. (3). A more accurate form of $N(E)$ above the mobility edge has been presented previously by Redfield.[14] However, under the condition of $\alpha=E_0/kT\gg 1$, which is satisfied for II-VI semiconductor alloys at low temperatures and concentra-

tions, using Eq. (3) or the form proposed by Redfield for the DOS above E_m will not alter the results of the integration of Eq. (4), as confirmed by our numerical calculation. In other words, the conductivity contributed by the electrons above the mobility edge can be neglected when the total electron concentration and temperature are low. By using this simpler form, we do not have to introduce as many fitting parameters. The chemical potential energy at a temperature T, $\mu(T)$, can be obtained from the total electron concentration n by the equation

$$n=\int_{-\infty}^{+\infty}N(E)f(E)dE=N_0\exp\{[\mu(T)-E_m]/E_0\}I, \quad (5)$$

or $\mu(T)=E_m+E_0\ln(n/N_0I)$ with

$$I=\int_{-\infty}^{+\infty}\frac{e^y}{1+e^{\alpha y}}dy, \quad (6)$$

and $\alpha=E_0/kT$. On the other hand, the photoexcited electron concentration as a function of the PPC buildup time t, $n(t)$, is described by the following equation;[15]

$$n(t)=n_0(1-e^{-\gamma t})=(n_0\gamma)t \quad (\gamma t\ll 1), \quad (7)$$

where γ is related to the PPC decay rate. From Eqs. (4)–(7), we have, for $\alpha=E_0/kT\gg 1$ and $\gamma t\ll 1$,

$$\sigma(T,t)=(C/kT)(N_0/E_0)^2\int_{-\infty}^{+\infty}\frac{\exp[2(E-E_m)/E_0]}{[(N_0I/n_0\gamma t)^{\alpha}e^{E/kT}+1][(N_0I/n_0\gamma t)^{-\alpha}e^{-E/kT}+1]}dE. \quad (8)$$

We can obtain E_0 and $N_0/n_0\gamma$ by fitting the measured PPC buildup curves at different temperatures, $\sigma(T,t)$, with Eq. (8). By approximating the Fermi distribution by a step function (i.e., $T\rightarrow 0$), Eqs. (1)–(3) can lead to a parabolic PPC buildup behavior[6]

$$\sigma(T=0,t)=\sigma_0(1-e^{-\gamma t})^2\approx At^2(\gamma t\ll 1, E_F<E_m), \quad (9)$$

The above derived formula for PPC buildup transient has been used to compare with our experimental results. The open dots in Fig. 1 are the PPC buildup data measured at $T=171$ K. The dark current has been subtracted and the starting time ($t=0$) is chosen at the moment the light was turned on. The solid and dotted lines are the least-squares fits of data with Eqs. (8) and (9), respectively. They fit the data almost identically, which further asserts the assumption that the conductivity due to states above the mobility edge can be neglected. However, important parameters such as E_0 can be obtained directly only from data fitting with Eq. (8). For example, E_0 obtained from the solid fitting curve in Fig. 1 is about 27 meV, which is a bit larger than the previous value of about 21 meV as extracted indirectly.[7]

We have also used Eq. (8) to compare with PPC buildup transients at different temperatures, which are shown in Fig.

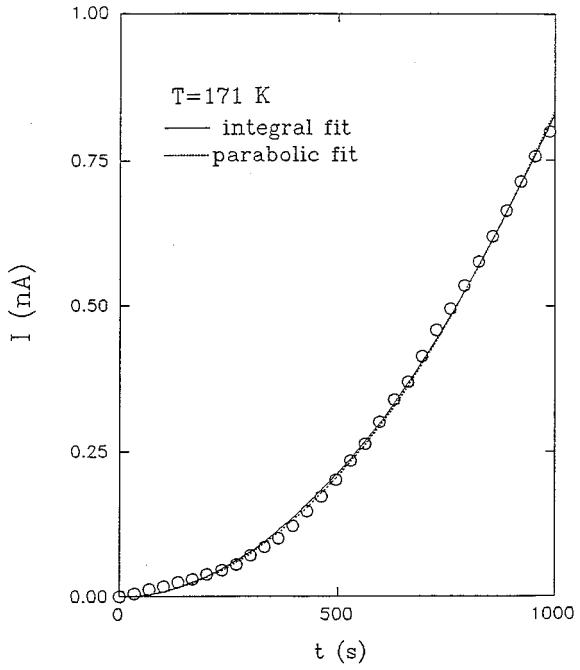

FIG. 1. PPC buildup transient obtained at one representative temperature $T=171$ K. The solid and dotted curves are least-squares fits of data (open dots) with an integral fit of Eq. (8) and a parabolic fit of Eq. (9), respectively.

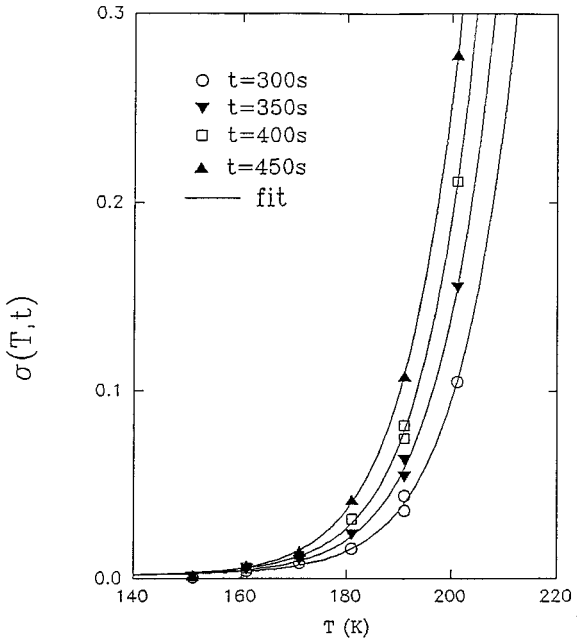

FIG. 2. Temperature dependence on the conductivity in the PPC states at several different buildup times t_0. The solid lines are the least-squares fits of data with Eq. (8).

2. The data were obtained by measuring the PPC buildup transients $\sigma(T,t)$ at different temperatures (T) and plotted as $\sigma(T,t_0)$ versus temperature for four representative buildup times $t_0=300$, 350, 400, and 450 s. As we see, the data fit Eq. (8) very well, as illustrated by the solid least-squares fitting curves. Each fitting curve gives a value of 27 meV for E_0, which demonstrates that Eq. (8) indeed correctly describes the PPC buildup transients and carrier transport in semiconductor alloys at different temperatures and concentrations.

In conclusion, effects of disorder of the transport properties of semiconductor alloys have been probed by PPC measurements. Conductivity at different temperatures and carrier concentrations has been formulated and compared with our experimental results. The method described above can also be applied to other disordered systems, such as transport properties in amorphous materials.

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