

## Electric-field-enhanced persistent photoconductivity in a $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ semiconductor alloy

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Persistent photoconductivity (PPC) has been investigated in a  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  semiconductor alloy. A transition from a photoconductivity phase to a PPC phase has been observed and a coexistence curve that separates these two phases has been obtained. We find that such a transition can be controlled by the bias voltage and excitation photon dose. The relaxation of PPC is found to follow a power law,  $I_{\text{PPC}}(t) \propto t^{-\alpha}$ . The decay parameter  $\alpha$  is obtained as a function of the bias voltage, which shows that the carrier decay rate decreases almost linearly with increasing bias voltage in the PPC phase. A possible mechanism is the presence of random local-potential fluctuations in the sample, which strongly influence the carrier transport properties. The fluctuations could be induced either by alloy disorder or impurity compensation.

### I. INTRODUCTION

Persistent photoconductivity (PPC), light-induced conductivity that persists for a very long period of time after illumination, has been observed in a wide variety of semiconductors. Recently, there has been a considerable amount of experimental and theoretical effort directed towards the understanding of PPC. However, a full understanding of PPC in different materials is still lacking.

Most studies of PPC have concentrated on  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , in which the  $DX$  center that undergoes a large lattice relaxation is believed to be the origin of PPC.<sup>1,2</sup> In these materials, PPC results because recapture of electrons by  $DX$  centers is prevented by a capture barrier at low temperatures. The nature of the  $DX$  center is under intensive investigation.<sup>3-7</sup> Consequently, PPC is very often taken as evidence for atomic defect centers in semiconductors that have unusual properties. Nonetheless, it has been shown that PPC could be caused by interface barriers in heterojunction materials.<sup>8,9</sup> Previous work on impurity-doped and compensated semiconductors has also indicated that random local-potential fluctuations (RLPF) caused by an impurity distribution could be another cause for PPC.<sup>10</sup>

Recently, PPC also has been observed in nominally undoped  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  and  $\text{CdS}_{0.5}\text{Se}_{0.5}$  II-VI semiconductor alloys.<sup>11</sup> A phase transition in the PPC mode at a critical temperature  $T_C$ , at which the stored charge carriers experience a phase transition from localized to delocalized states, has been observed. Contrary to  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , PPC in II-VI semiconductor alloys can be quenched optically by far infrared radiation.<sup>12</sup> These experimental results indicate that the carrier transport properties in II-VI semiconductor alloys are strongly influenced by RLPF. It was shown theoretically that compositional fluctuations in II-VI semiconductor alloys can produce band-edge fluctuations and hence energy band tails.<sup>13</sup> As

a consequence, excitons can be localized by RLPF, which has been observed in  $\text{CdS}_x\text{Se}_{1-x}$  and  $\text{Zn}_x\text{Cd}_{1-x}\text{Te}$ .<sup>14-16</sup> Therefore, it is plausible that PPC in some nominally undoped II-VI semiconductor alloys is a consequence of the spatial separation of the photoexcited charge carriers by RLPF induced by alloy disorder. On the other hand, it is also known that RLPF exists in highly compensated semiconductors.<sup>17</sup> Due to the presence of RLPF, which could be induced either by alloy disorder or impurity compensation, low-energy electrons are localized in the sites of the potential minima and are spatially separated from the photoexcited holes because the potential minima for electrons are the potential maxima for holes. This causes the photoexcited charge carriers to have a long recombination lifetime. The charge transport occurs either via activated electron hopping between the localized states or by activating electrons into the states above the mobility edge, while holes remain localized because of their heavier mass.<sup>11,17</sup>

In the PPC state, the carrier concentration can be varied continuously in a single sample through the variation of the excitation photon dose, which is the product of the excitation photon flux and the illumination time. In fact, PPC in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  (Ref. 18) and  $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$  (Ref. 19) have been used previously to study metal-insulator transitions at low temperatures. These earlier findings have opened an avenue for investigating fundamentally important transport properties, including the localized-to-delocalized-state transition, hopping conduction, band-tail states, and the localization parameters in disordered semiconductors. Most investigations of this subject have focused on doped semiconductors, in which the variation of the carrier concentration is achieved by changing the doping levels. However, it is rather difficult to obtain important parameters through a comparison between experimental results obtained from different samples because the distribution of band-tail states may

change from sample to sample. More recently, the distribution of the conduction-band-tail states in a  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  has been probed by PPC buildup transients, from which an exponential tail has been confirmed.<sup>20</sup> Additionally, we have also observed, in a single sample, a localized- to delocalized-state transition in the PPC buildup transients at constant temperatures as the electron concentration (or the excitation photon dose) increases to a level at which the electron quasi-Fermi level crosses over the mobility edge.<sup>20</sup> These experimental results indicate clearly that there are unique advantages to investigating the transport properties in the PPC state.

In this paper, PPC has been studied in a  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  semiconductor alloy. The nature of PPC in CdTe is still a subject of controversy. Previous investigations indicated that deep levels are responsible for PPC in impurity-doped or heat-treated CdTe (Ref. 21) and  $\text{Zn}_x\text{Cd}_{1-x}\text{Te}$ .<sup>22</sup> A large Stokes shift of about 1.2 eV in CdTe (Ref. 23) and 0.6 eV in  $\text{Zn}_{0.2}\text{Cd}_{0.8}\text{Te}$  (Ref. 22) has been observed, implying a large lattice relaxation of these deep centers. On the other hand, a mechanism of macroscopic barriers arising from the coexistence of pure and impure regions in the sample being responsible for the PPC in CdTe has also been proposed.<sup>24</sup> Here, we report experimental observation of a transition from a photoconductivity (PC) phase to a PPC phase in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ . Such a transition is found to depend on the applied bias (or electric field) and the excitation photon dose. Our observations indicate that the temperature for this transition in a single sample can be changed by varying the bias and excitation photon dose in the PPC state. These findings may also be useful from the point of view of device applications, because the phenomenon of PPC in II-VI semiconductor alloys can be utilized for infrared detection<sup>12</sup> and other applications.<sup>10</sup> Furthermore, investigations from different approaches are necessary in order to explore the intricate nature of PPC in different materials.

## II. EXPERIMENT

The sample used in this study was a  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  nominally undoped semiconductor alloy grown by a modified horizontal Bridgman technique<sup>25</sup> and was supplied by II-VI, Inc. The sample was of dimensions  $5 \times 10 \times 1 \text{ mm}^3$ , with a dark resistivity at room temperature of about  $10^6 \Omega \text{ cm}$ . Gold leads were attached to the sample using indium solder and Ohmic contacts about 1 mm in diameter and 3 mm apart were formed on the sample surface. The sample was attached to a copper sample holder inside a closed-cycle He refrigerator, with care taken to ensure good thermal contact yet electrical isolation. A mercury lamp, together with appropriate filters, was used as an excitation source. The data obtained at different conditions were taken in such a way that the system was always allowed to warm up to room temperature and relax to equilibrium after each measurement, then cooled down in darkness to the desired temperature of measurements. This was necessary to ensure that each set of data had the same initial condition. Measurements of PPC buildup and decay at different photon

dose conditions were taken by illuminating the sample for different time intervals while keeping the intensity the same. The typical excitation photon flux used for the measurements was on the order of  $10^{14}$  photons/cm<sup>2</sup>s. The current was measured by a Keithley digital electrometer (model 617) interfaced with a computer. The variable bias was supplied by batteries in conjunction with a microchip and a variable resistor. Comparison experiments were carried out for an  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  epitaxy layer of 2- $\mu\text{m}$  thickness, doped with  $3.3 \times 10^{17} \text{ cm}^{-3}$  Si, grown on a semi-insulating GaAs (100) substrate. Ohmic contacts 1 mm in diameter and about 3 mm apart were formed by indium alloying on the layer surface.

## III. RESULTS AND DISCUSSIONS

PPC was measured at different conditions in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ . At a fixed temperature, there is a low bias limit  $V_L$  below which PPC is negligibly small and only a very small conventional photoconductivity (PC) can be induced, i.e., photoexcitation-induced conductivity decays to the dark equilibrium level very quickly after the termination of the excitation light source. For example, at 9 K, PPC becomes significant only for bias voltages above 2.0 V. An increase in bias voltage results in an enhancement of the PPC and the PPC relaxation time. On the other hand, at a fixed bias, there is also a low-temperature limit  $T_L$  below which no PPC can be detected, and the PPC effect becomes more pronounced as the temperature increases. These effects can be seen in Fig. 1, where the representative PPC decay data obtained at different conditions are shown. As the bias (electric field) or temperature increases, both the dark and the buildup conductivity increase, which is expected even for conventional PC. In order to see the effects on PPC, it is essential to subtract the dark level from the data points and normalize the decay curve to unity at  $t=0$ , the moment the illumination is terminated, so that the PPC as a function of time can be expressed as

$$I_{\text{PPC}}(t) = [I(t) - I_d] / [I(0) - I_d], \quad (1)$$

where  $I(0)$  is the conductivity level immediately after the termination of the light source,  $I(t)$  the conductivity at the decay time  $t$ , and  $I_d$  the dark conductivity level. Figure 1(a) shows the normalized PPC decay data obtained at 9 K for three different voltages. An enhancement in the PPC and the PPC relaxation time with an increase of the bias is evident. Figure 1(b) shows the normalized PPC decay behaviors obtained at a constant bias of 2.1 V for 9 and 150 K. It is clear that the PPC effect becomes more pronounced and the PPC relaxation time increases at 150 K. The data in Figs. 1(a) and 1(b) were obtained for a buildup time of 10 s. If one increases the buildup time, both the level and the relaxation time of PPC increase. Such an effect is depicted in Fig. 1(c), where a comparison between the decay behaviors for 10 and 50 s buildup times is depicted.

The observed behaviors in Fig. 1 indicate the existence

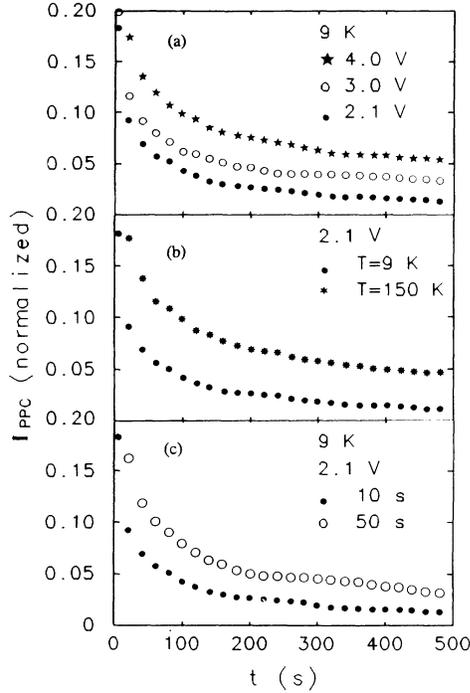


FIG. 1. Representative PPC decay plots for  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  at different conditions. Each curve has been normalized according to Eq. (1) to unity at  $t=0$ , the moment the excitation light is terminated. (a) At 9 K for three different bias voltages and 10-s buildup time: the curve (●) is for  $V=2.1$  V, where  $I_d=0.03$  nA and  $I(0)=0.60$  nA; the curve (○) is for  $V=3.0$  V, where  $I_d=0.17$  nA and  $I(0)=1.67$  nA; and the curve (★) is for  $V=4.0$  V, where  $I_d=1.36$  nA and  $I(0)=6.57$  nA. (b) At a bias of 2.1 V for two different temperatures and 10-s buildup time: the curve (●) is for  $T=9$  K, where  $I_d=0.03$  nA and  $I(0)=0.60$  nA; and the curve (\*) is for  $T=150$  K, where  $I_d=0.30$  nA and  $I(0)=1.83$  nA. (c) At 9 K and a bias of 2.1 V: the curve (●) is for 10-s buildup time, where  $I_d=0.03$  nA and  $I(0)=0.60$  nA; and the (○) is for 50-s buildup time, where  $I_d=0.03$  nA and  $I(0)=0.77$  nA. Experimental error in  $T$  is about  $\pm 0.5$  K and in  $V$  is about  $\pm 0.05$  V. The excitation photon flux used is on the order of  $10^{14}$  photons/cm<sup>2</sup> s.

of two phases corresponding to a PC and a PPC region. The decay behavior of the normalized PPC can be characterized by a power law,

$$I_{\text{PPC}}(t) \propto t^{-\alpha} \quad (t > t_0), \quad (2)$$

where  $\alpha$  is the decay parameter and  $t_0$  is the system response time about 1 s. This can be seen from Fig. 2, where the experimental results of Fig. 1(a) have been replotted in a logarithmic scale and a linear behavior for the PPC decay at three different applied voltages is evident. A condition belonging to the PPC phase is recognized for  $\alpha < 1$ . At  $\alpha > 1$ , the PPC component becomes negligible and the lifetime of the photoconductivity at the half-signal point is of the order of the system response of about 1 s. In general, one can reach the PPC phase by increasing either bias voltage or temperature. Consequently, a coexistence curve,  $V_L$  versus  $T$ , that separates the

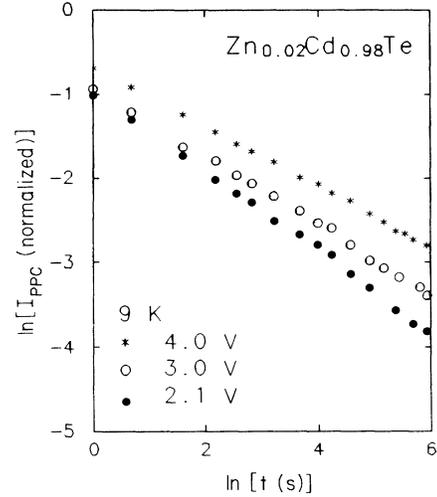


FIG. 2. Logarithmic plots of the PPC decay curves in Fig. 1(a). The linear behavior indicates that the PPC decay in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  follows the power law  $I_{\text{PPC}}(t) \propto t^{-\alpha} (t > t_0)$ , with  $t_0$  about 1 s.

PPC phase from the PC phase can be obtained. Such a curve can be obtained by measuring the minimum bias needed for observing the PPC,  $V_L$  at different temperatures  $T$ . It can be seen that each point along the curve represents a phase-transition point. This means that at a fixed temperature  $T$ , no PPC can be induced at a bias voltage  $V_b$  that is less than  $V_L$ , and the PPC relaxation time increases with an increase of the bias in the region of  $V_b > V_L$ . On the other hand, at a fixed bias  $V_b$ , no PPC can be observed at temperatures  $T < T_L$  and the PPC relaxation time increases with an increase of temperature in the region of  $T > T_L$ . Furthermore, the shape of the coexistence curve depends on the excitation photon dose.  $V_L$  as a function of  $T$  has been measured for four different excitation photon doses, as shown in Fig. 3. Notice that the areas above and below the coexistence curves represent the PPC phase and the PC phase, respectively. Figure 3 shows that both the minimum bias needed for inducing the PPC at a fixed temperature and the lowest temperature required for observing the PPC at a fixed bias decrease with an increase of excitation photon dose.

The existence of a low-temperature limit  $T_L$  at a fixed bias for observing the PPC effect cannot be explained solely in terms of the deep centers that undergo a large lattice relaxation. In such a context, the conductivity is caused by transport of photoexcited electrons in the conduction band and PPC has resulted because recapture of electrons by deep centers is prevented by a capture barrier. Thus, at higher temperatures, electrons would gain more thermal energy and so overcome the capture barrier more easily. Therefore, the mechanism of the deep centers would lead to a stronger PPC effect at lower temperatures. For example, the  $\text{DX}$  centers are a well-known cause for the PPC effect in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  ( $x > 0.22$ ). In  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , there is only a temperature upper limit  $T_U$  ( $\sim 150$  K), at which the PPC thermally quenches instan-

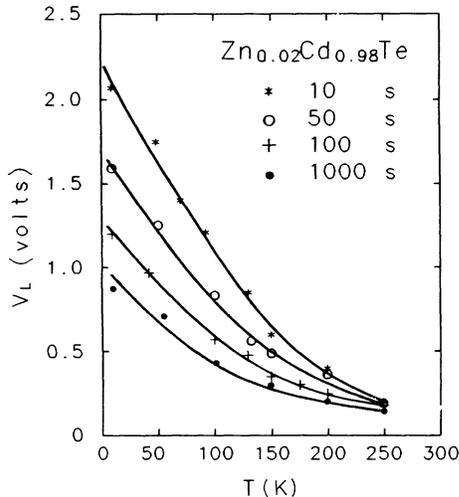


FIG. 3. Coexistence curves, which separate the PPC phase from the PC phase, obtained for four different illumination times. These are the plots of the minimum value of bias needed for inducing the PPC,  $V_L$ , vs the temperature,  $T$ . Notice that the areas above and below the coexistence curves represent the PPC and PC phases, respectively. The solid lines are guides to the eyes.

taneously. The photogenerated electrons still have velocities varying from 0 to the Fermi velocity  $v_F$  due to the Fermi distribution of the electrons in the conduction band even at  $T=0$  K if they are not captured on the shallow-impurity levels. Thus PPC is observable in the entire temperature region below 150 K in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .

It is known that in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , the formation of the  $DX$  centers can produce a shallow-deep transition of donor levels, which is a subject currently under intensive study.<sup>26</sup> As a result, the photoexcited carriers may be captured on a shallow level of the effective-mass-type excited states of the  $DX$  centers. Such a behavior has been observed in indirect-gap  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , in which the effective-mass donor states associated with the lowest  $X$  band start to capture electrons at very low temperatures, typically below 10 K.<sup>26</sup> Recently, it has also been proposed theoretically that self-compensation of As and P acceptor impurities in ZnSe results primarily from a large lattice relaxation, which leads to the formation of a positively charged  $A^+$  defect center and consequently the PPC effect.<sup>27</sup> According to this model, the deep-shallow transition of acceptor levels could also occur in doped II-VI semiconductors. However, as the sample studied here is a nominally undoped  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ , the effect of the foreign impurities is not expected to be involved here. Additionally, the shallow-deep transition of impurity levels has never been experimentally observed in II-IV semiconductors and still very little is known about the properties of deep centers in different types of II-VI semiconductors. The bistability of deep centers could account for the observed PC phase at lower temperature in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ , similar to the case in the indirect-gap  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ . Nonetheless, it would be very surprising if the effective-mass-type excited states of deep centers could capture carriers even up to 250 K, unless such

centers have peculiar properties in II-VI semiconductors. More investigation is needed in order to clarify this point. At this stage, we are not quite convinced that the deep-shallow transition due to the formation of the  $DX$ -type centers could account for the observed PC and PPC transition behavior in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ .

The existence of a minimum bias needed for observing the PPC effect is also a surprise. It is expected that once the electrons are being excited into the conduction band, under a bias that is sufficient to induce PC, a PPC effect should always be present, as long as the temperature is not too high to quench thermally the PPC instantaneously. Furthermore, the mean kinetic energy of the electrons increases with an increase of bias. Therefore, the decay rate of the electrons is expected to increase with an increase of bias. For comparison, we have also investigated the dependence of the PPC decay on the bias for  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  at 60 K. Figure 4 shows the representative normalized PPC decay curves obtained for three different voltages. Contrary to the behavior exhibited by  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  shown in Fig. 1(a), an increase of the PPC decay rate with an increase of the bias has been observed. The behavior shown in Fig. 4 for  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  is expected for common thermal capture processes.

The observed behaviors in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  show evidence for the mechanism of RLPF. In some undoped II-VI semiconductors, an intrinsic lattice defect may act as a donor or an acceptor. Thus, in our sample, the RLPF may be caused by compositional fluctuations or impurity compensation. It is known that the disorder effect is usually much less important in III-V than in II-VI semiconductor alloys.<sup>13</sup> Because of the presence of RLPF, decreasing the temperature does not necessarily guarantee a stronger PPC effect. This is due to the fact that in a random fluctuating potential, the conductivity is induced either via electron hopping between the localized states or

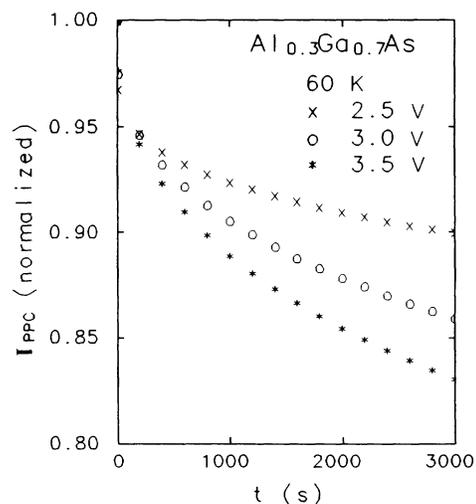


FIG. 4. Normalized PPC decay plots for  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  obtained at 60 K for three different applied voltages. Contrary to the behavior exhibited by  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  shown in Fig. 1(a), the PPC decay rate in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  increases with an increase of the bias.

by activating electrons into the levels above the mobility edge. At sufficiently low temperatures or bias voltages, during the course of photoexcitation, some fraction of electrons can occupy the higher-energy states to induce the conductivity. Nonetheless, terminating the illumination results in a rapid localization of charge carriers in local potential minima. Thus, only a very small PC can be observed. The areas below the coexistence curves shown in Fig. 3, i.e., the PC phases, represent such cases. Therefore, the observed rapid decay in the PC phase is most likely due to charge carrier localization (or storage) in random-local-potential minima, but not due to a depletion or recombination of charge carriers. This charge storage effect is confirmed by the fact that, after illuminating the sample at low temperatures for a certain period of time, followed by warming, the sample has a significantly higher conductivity compared with its dark conductivity.

In a random fluctuating potential, as temperature or bias voltage increases, the energy and, hence, the mobility of the carriers also increases. Thus, the photoconductivity, which is induced by carrier hopping between the localized states or percolating through the conduction network constructed by the low-energy sites, becomes more pronounced at higher temperatures. Therefore, the behavior shown in Fig. 3 is most likely associated with a mobility transition. In fact, the excitation-photon-dose-dependent behavior is also consistent with this interpretation. In general, the quasi-Fermi level, as well as the carrier mobility, increases with an increase of the carrier concentration, or the excitation photon dose. Therefore, the area below the coexistence curve decreases with an increase of the excitation photon dose. According to this interpretation, the PC phase below the coexistence curve corresponds to the localized region and the PPC phase represents the delocalized region. The dependence of the PPC decay behavior on the excitation photon dose was also studied for  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ . In  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , at  $T > 40$  K, the relaxation-time constant  $\tau$  decreases with an increase of the excitation photon dose. This is due to the fact that as the excitation photon dose increases, the quasi-Fermi level in the conduction band increases, which effectively decreases the capture barrier at the  $DX$  centers. We see that the PPC behaviors in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  and  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , including their dependencies on temperature, bias, and excitation photon dose, are all quite different.

Some of the different PPC behaviors exhibited by II-VI and III-V semiconductor alloys have been pointed out previously.<sup>11,12</sup> The relaxation of PPC in  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$ ,  $\text{CdS}_{0.5}\text{Se}_{0.5}$ , and  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  was found to follow the stretched-exponential function,  $I_{\text{PPC}}(t) = I_{\text{PPC}}(0) \exp[-(t/\tau)^\beta]$ , ( $\beta < 1$ ), at low temperatures. The relaxation-time constant  $\tau$  in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  could be larger than  $10^{13}$  s at low temperatures due to the fact that the capture cross section of the  $DX$  centers is very small at low temperatures.<sup>28</sup> However, the relaxation-time constants  $\tau$  on the order of  $10^3$  s in  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$  and on the order of  $10^2$  s in  $\text{CdS}_{0.5}\text{Se}_{0.5}$  have been observed. In fact,  $\tau$  as long as those in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  at low temperatures has never been observed in II-VI semiconductor alloys.

This means that the PPC decay rates observed in II-VI semiconductor alloys including  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  at different conditions are always much larger than those in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  at low temperatures. This can also be seen from different scales of the representative normalized decay plots shown in Figs. 1 and 4. This implies that different carrier decay mechanisms may be involved in II-VI and III-V semiconductor alloys.

The physical origins for the stretched-exponential and the power-law relaxations are not very clear at this stage. However, it is believed that they may be asymptotic forms of some kind of relaxation kinetics that describe a wide class of disordered systems toward equilibrium under different conditions.<sup>29,30</sup> From Fig. 2, we see that the slope of the plots, which is  $\alpha$ , decreases with an increase of bias. This means that the decay rate of the photoexcited charge carriers decreases with an increase of bias, or electric field. Furthermore, the decay rate also decreases as the temperature or excitation photon dose increases, as depicted in Fig. 1. This implies that the carrier decay rate does, in fact, decrease with an increase of the carrier energy in certain regions, which is contrary to the behavior expected for common thermal capture processes. In the presence of RLPF, as the temperature, applied voltage, or excitation photon dose increases, the electron energy as well as the mobility increases, and so more electrons can be activated into the states above the mobility edge. The observed behaviors then suggest that the decay rates for the electrons in the states above the mobility edge are smaller than those in the hopping transport regime, which is observed in all investigated II-VI semiconductor alloys including  $\text{Zn}_{0.3}\text{Cd}_{0.7}\text{Se}$ ,  $\text{CdS}_{0.5}\text{Se}_{0.5}$ , and  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$ . Conversely, in  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ , the capture rate of electrons at  $DX$  centers increases with an increase of the carrier energy, which is well confirmed by many experiments. Thus, our results suggest that the transport properties of the photoexcited charge carriers in II-VI semiconductor alloys are strongly affected by RLPF. The reason for such a behavior is not yet quantitatively un-

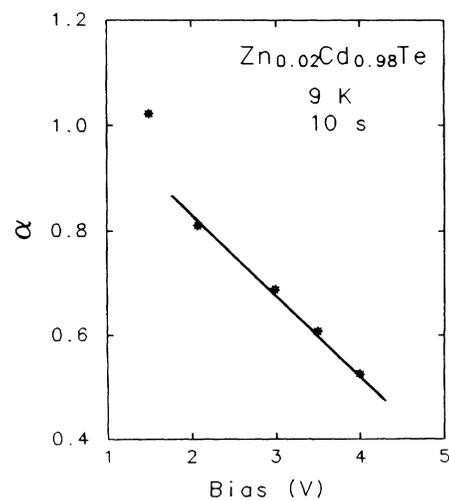


FIG. 5. The power-law decay parameter  $\alpha$  vs applied voltage  $V$  at 10 K for 10-s buildup time. The solid line is a guide to the eye.

derstood, but it could be qualitatively explained in terms of an effect of redistribution of electrons in such a random fluctuating potential.<sup>11</sup>

In order to see how the decay rate varies with the carrier energy, we plot the dependence of  $\alpha$  on the bias (or electric field) obtained at 10 K for 10 s buildup time in Fig. 5. A linear dependence in the PPC phase is observed. In the field region from about 6.5–15 V/cm (contact separation is about 3 mm), such a dependence can be written approximately as

$$\alpha = \alpha_0 - \kappa F, \quad (3)$$

where  $F$  is the electric-field strength, and  $\alpha_0$  ( $\approx 1.14$ ) and  $\kappa$  ( $\approx 0.047$  cm/V) are two constants. If one assumes that the energy gained by the photoexcited electrons is proportional to the electric field, then the experimentally observed behavior in Eq. (3) suggests that, in a random fluctuating potential, the decay rate of the charge carriers decreases almost linearly with an increase in the carrier energy in certain regions. We think that such an observation may be important for studies of current difficult problems associated with charge-carrier transport properties in disordered and percolative solids.

#### IV. CONCLUSIONS

In conclusion, persistent photoconductivity has been studied in a  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  semiconductor alloy. We found that there is a minimum bias  $V_L$  that is needed for inducing the PPC effect at a constant temperature. At

the same time, there is a low-temperature limit  $T_L$  below which no PPC can be observed at a fixed bias. A coexistence curve,  $V_L$  versus  $T$ , that separates the PC phase from the PPC phase has been obtained. Each point along this coexistence curve represents a phase-transition point. The phase-transition behavior can be changed by varying the excitation photon dose. The decay kinetics of the PPC have also been investigated and a power-law behavior for the PPC decay in  $\text{Zn}_{0.02}\text{Cd}_{0.98}\text{Te}$  was found. The observed electric-field enhancements of the PPC and the PPC relaxation time suggest that the decay rate of the charge carriers in the delocalized state decreases almost linearly with an increase in the total energy of the charge carriers, which is contrary to the behavior expected for common thermal capture processes. These results indicate that the carrier transport properties in II-VI semiconductor alloys are strongly affected by random-local-potential fluctuations arising either from compositional fluctuations or impurity compensation.

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