Persistent photoconductivity in $Zn_{0.04}Cd_{0.96}Te$ semiconductor thin films

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Persistent photoconductivity (PPC) has been observed up to room temperature in $Zn_{0.04}Cd_{0.96}Te$ semiconductor thin films which were prepared by the laser ablation method. The decay of PPC in these materials follows a stretched-exponential function with very long lifetimes. A comparison of experimental results of PPC has also been obtained for the original bulk samples. Our results indicate that deep centers are responsible for the PPC observed in thin-film samples. A peculiar overshoot behavior in the PPC buildup transient has been observed at higher temperatures, which suggests that the deep center, when filled with an electron, has two possible states, a stable state and a metastable state. The decay-time constant τ and exponent β as functions of temperature have been measured in the thermally activated temperature region, from which the electron capture barrier has been determined. The PPC decay-time constants at different excitation photon dose levels have been measured.

I. INTRODUCTION

The phenomenon of persistent photoconductivity (PPC) in a wide class of materials has been extensively studied. PPC has been studied most extensively in $Al_xGa_{1-x}As$ semiconductors in which PPC is observable at temperatures below 150 K.[1-3] In $Al_xGa_{1-x}As$ semiconductors, the large lattice relaxation (LLR) phenomenon associated with the deep donor levels which are often called *DX* centers is believed to be the cause of PPC.[1] According to this model, at low temperatures photoexcited electrons live for a long period of time due to the large capture barrier that prevents the recapture of electrons by *DX* centers. Recently, it has been proposed that the negative-*U* character of the *DX* centers is responsible for the LLR phenomenon.[4,5]

Besides the extensive study of *DX* canters and PPC in III-V semiconductors, PPC has also been studied in many other semiconductors. Recently, PPC has been studied in II-VI semiconductor alloys including undoped $Zn_xCd_{1-x}Se$,[6] $Cd_xS_{1-x}Se$,[7] and $Zn_{0.02}Cd_{0.98}Te$,[8] and In-doped $Zn_xCd_{1-x}Te$.[9] In contrast to III-V semiconductor alloys, a significant feature exhibited by undoped II-VI semiconductor alloys is the existence of band-edge tail states caused by alloy disorder, which strongly affects the transport properties of photogenerated carriers.[10] Fundamental transport properties such as Anderson localization can be studied in the PPC state in II-VI semiconductor alloys. Recently, the hard gap in the density of states in the In-doped diluted magnetic semiconductors (DMS) $Cd_{0.91}Mn_{0.09}Te$ has been studied through the use of PPC.[11] PPC in the group-IV semiconductor SiC has also been observed very recently.[12] For Cl-doped $Zn_xCd_{1-x}Te$ (Ref. 13) with $0<x<0.5$, it was found that the activation energy of the defect changes with the Zn concentration and varies from -45 meV for $x=0$ to 270 meV for $x=0.25$ ($-$ means that the defect energy level is above the conduction band). In Cl-doped CdTe,[14] a potential barrier of 550 meV has been determined under hydrostatic pressure. A model of donor impurities with two nonequivalent lattice sites separated by a potential barrier caused by lattice relaxation has been proposed to explain the experimental results.

In this paper we report the PPC measurements performed on $Zn_{0.04}Cd_{0.96}Te$ thin-film samples which were prepared by the laser ablation method. PPC has been observed in these thin-film samples at elevated temperatures, and its behavior is different from that in the original bulk materials. The experimental results indicate that the deep centers are responsible for PPC observed in the thin-film samples. PPC buildup transients have been studied. At low temperatures, PPC increases monotonically with buildup time. However, we have observed an anomalous behavior in the buildup transients at higher temperatures, which shows that the photoconductivity increases with illumination time and goes through a maximum, then decreases upon further increase of illumination time. This behavior, which for simplicity will hereafter be called an overshoot, can be explained by assuming that the deep center, when filled with an electron, has two possible states: a stable state and a metastable state. The PPC decay kinetics can be characterized by stretched-exponential functions. The electron-capture barrier has been determined from the PPC decay measurements to be 125 meV.

Deep centers in a wide class of materials, whether they are introduced during the growth process or doping, exhibit a common phenomenon, i.e., PPC. Studying common features of defects in different materials through the use of PPC could help us to understand the origin of the deep level formation as well as their properties. This in turn may help to establish a common description for all defects in different materials. Technologically, understanding of optical and transport properties of II-VI semiconductor alloy thin films is also of importance for optoelectronic applications.

II. EXPERIMENT

The samples used for this study were $Zn_{0.04}Cd_{0.96}Te$ semiconductor alloy thin films which were prepared by

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the laser ablation method.[15,16] A pulsed Excimar laser ($\lambda=308$ nm) with a pulse energy density of about 10 J/cm^2 was used for laser ablation. The repetition rate of the laser was 10 Hz. The target was a high quality and nominally undoped bulk single crystal $Zn_{0.04}Cd_{0.96}Te$ grown by a modified horizontal Bridgement technique and was supplied by II-VI, Inc. The growth conditions for the target crystal can be found elsewhere.[17] The target bulk crystal was of $5\times10\times1$ mm^3, with a dark resistivity of about 10^7 Ω cm. A glass slide was used as a substrate. The deposition was performed at room temperature, and the separation between target and substrate was about 15 cm. The base pressure of the deposition chamber was about 10^{-6} torr. Under these conditions, the deposition rate is about a half monolayer per pulse. The thin-film samples used in this study are of 5×5 mm^2 in size, with a thickness of about 1 μm.

The surface morphology of the thin films has been studied by an atomic force microscope (AFM), which shows that thin films have smooth surfaces with a surface roughness of about 4 Å within a 1×1 μm^2-probed area. The structure of the thin-film samples has been determined by X-ray diffraction to be polycrystalline. Indium contact spots of about 1 mm in diameter and about 2 mm apart were made by using the evaporation method, and gold leads were attached to the In spots by using indium solder. The contacts were tested and confirmed to be ohmic at temperatures between 8 and 300 K. The dark resistivity of the thin-film samples at 300 K was about 100 Ω cm. The sample was attached to a copper sample holder and placed inside a closed-cycle He refrigerator. A mercury lamp together with a filter (Oriel 254 nm) was used as an excitation source so that the 254-nm line of the Hg lamp was the dominant output. The estimated excitation photon flux was about 10^{13} photons/cm^2 s. The data obtained at different conditions were taken in such a way that after each measurement the system was allowed to warm up to 320 K to restore the initial condition. Because of high-temperature PPC, the waiting time was about 24 h at 320 K.

III. RESULTS AND DISCUSSIONS

The decay of PPC has been measured in $Zn_{0.04}Cd_{0.96}Te$ thin-film samples at different temperatures. A slow decay is observed from low temperatures up to room temperature. Figure 1 shows a typical plot of PPC decay at $T=315$ K. In Fig. 1, the dark conductivity level has been subtracted from the data points, and the decay curve has been normalized to unity at $t=0$, the moment the illumination is terminated. Therefore, PPC as a function of time can be expressed as

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

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 initial dark conductivity level. Figure 2 shows the PPC decay behavior at three representative temperatures near 250 K. The amount of the excitation photon does is fixed at different temperatures. Several features can be seen from Figs. 1 and 2.

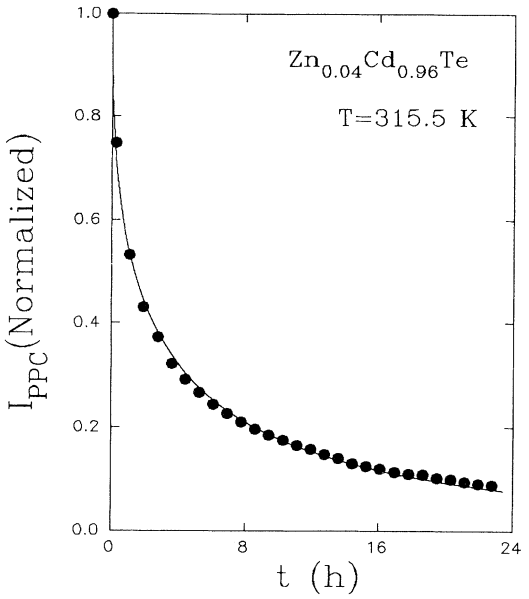

FIG. 1. The PPC decay (normalized) at $T=315.5$ K for a $Zn_{0.04}Cd_{0.96}Te$ thin-film sample which was prepared by the laser ablation method. The dark current is 0.56 μA and the buildup current is 4.15 μA. In the plot, the dark current has been subtracted and the solid line is the least-squares fitting using $I_{\rm PPC}(t)=\exp[-(t/\tau)^{\beta}]$, with $\tau=1.1\times10^4$ s and $\beta=0.46$.

First, the lifetime of PPC in $Zn_{0.04}Cd_{0.96}Te$ is still very long even at temperatures close to 300 K. For example, PPC is still about 62% of its initial buildup level after 5.5 h of decay at 275 K and is still about 10% of its initial buildup level after 24 h of decay at 315 K. Second, the PPC decay rate increases as temperature increases, as we

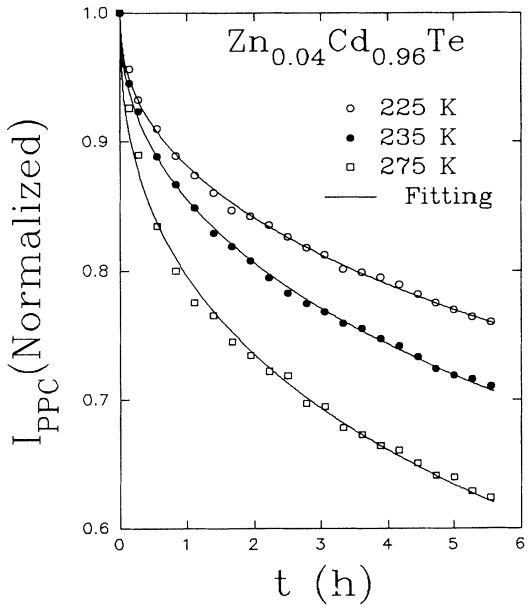

FIG. 2. The PPC decay (normalized) as a function of time at three different temperatures. The solid lines are the least-squares fitting using $I_{\rm PPC}(t)=\exp[-(t/\tau)^{\beta}]$.

expected. Third, the behavior of normalized PPC decay can be characterized by a stretched-exponential function,

$$I_{PPC}(t)=\exp[-(t/\tau)^{\beta}] , \quad (2)$$

where τ is the decay-time constant and β the decay exponent. The solid lines in Figs. 1 and 2 are fitted curves using Eq. (2). One can see that Eq. (2) fits data points very well. Previously, we have observed stretched-exponential decay behavior for PPC in $Zn_{0.3}Cd_{0.7}Se$,[6] $Cd_{0.5}S_{0.5}Se$,[7] and $Al_{0.3}Ga_{0.7}As$ (Ref. 18) semiconductors. In fact, experimentally observed relaxation kinetics in a wide range of materials can often be described either by the stretched exponential or by power law. It is believed that both these decay forms may be asymptotic forms of some kind of relaxation kinetics which describe a wide class of materials toward equilibrium under different conditions. It is widely accepted that the presence of disorder in the material leads to nonexponential decay. However, a recent theoretical calculation has also indicated that stretched-exponential relaxation can be generated by the use of interaction rather than disorder.[19] Thus the physical origin of nonexponential decay in many systems remains unclear.

Comparison experiments have also been carried out for an original bulk $Zn_{0.04}Cd_{0.96}Te$ sample from which the thin-film samples were prepared. Figure 3 shows the normalized PPC decay at three different temperatures for a bulk sample. One can see that PPC in the original bulk sample behaves very differently from that of the laser-ablation-prepared thin-film samples. First, the PPC effect is much less pronounced, and the decay of PPC in the bulk material is very fast, with typical lifetimes on the order of 10 s. We should point out that the dark and build-up current levels in the bulk crystal are on the nA scale. Second, the decay in Fig. 3 cannot be described by the stretched-exponential function of Eq. (2), but is better characterized by the power-law decay. Third, the decay rate of PPC decreases as temperature increases in the temperature region investigated, contrary to the behavior observed in the thin-film samples. Such a peculiar temperature dependence of the decay rate has also been observed in other undoped II-VI bulk semiconductor alloys, including $Zn_xCd_{1-x}Se$,[6] CdS_xSe_{1-x},[7] and $Zn_{0.02}Cd_{0.98}Te$,[8] which is believed to be associated with the tail states caused by alloy disorder.

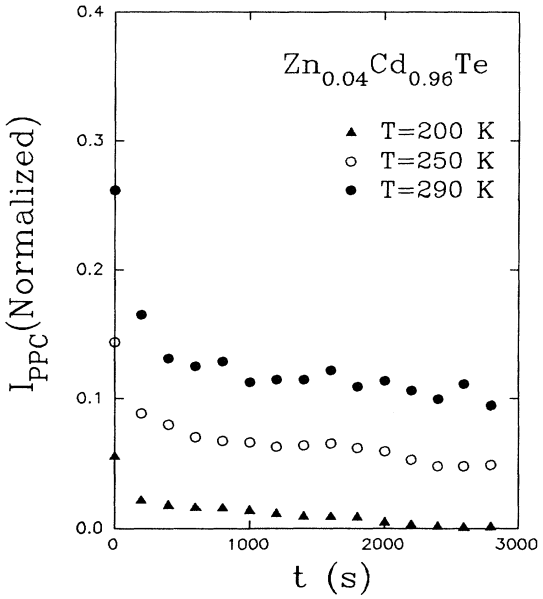

FIG. 3. The PPC decay (normalized) as a function of time at three different temperatures for an original $Zn_{0.04}Cd_{0.96}Te$ bulk crystal from which the thin-film samples were grown. Notice the scale for normalized I_{PPC} here is from 0 to 0.4 and the time scale is from 0 to 3000 s. The decay curves cannot be described by stretched-exponential functions.

By summarizing PPC decay behaviors in several types of undoped II-VI semiconductor alloys and also in impurity-doped semiconductors, one sees that in doped semiconductors defects exhibit a common phenomenon, i.e., PPC with very long lifetimes, and the PPC decay rate always increases with an increase of temperature in the entire PPC temperature region. Furthermore, since it is the defects that predominantly control the transport properties, the effect due to the tail states usually cannot be seen in many doped semiconductors. These comparison results seem to indicate that it is the deep centers which give rise to PPC in thin-film samples. The difference between the thin film and the original bulk crystals can be summarized as (1) the thin-film samples are polycrystals and the bulk samples are single crystals, and (2) the original bulk crystals are of high purity and the film samples contain defects which may be introduced during the laser ablation process. A strong candidate for the cause of the defect is oxygen, considering the fact that our deposition chamber is not an ultrahigh vacuum chamber. Further experimental investigations are needed in order to confirm this speculation.

We have also studied the photoconductivity buildup behavior in thin-film samples. Figure 4 shows the build-up transients for four different temperatures. The photoconductivity buildup is controlled by two processes: (1) carrier generation and (2) carrier recapture. We should point out the fact that in crystals which exhibit only the conventional photoconductivity (PC) effect, the PC saturates almost instantaneously with a typical transient time on the millisecond scale or less due to a very rapid capture process. The slow buildup transients such as those shown in Fig. 4, can only be observed in crystals which exhibit the PPC effect because the capture process is slow. Results in Fig. 4 therefore also indicate that the photogenerated charge carriers in thin-film samples are in the PPC state. At low temperatures, PPC increases monotonically with an increase of buildup time, and the PPC buildup transients can be written as $I(t)=I_0(1-e^{-\alpha t})$ just as those in Si-doped $Al_xGa_{1-x}As$,[20] with α being a rate parameter depending on both generation and capture rates. For a fixed light intensity, α increases with an increase of temperature because the electron-capture rate increases. As a consequence, the PPC saturation level also decreases as temperature increases. However, the most interesting result we find is that, at temperatures above 200 K, there is an overshoot behavior in the PPC buildup transients. As

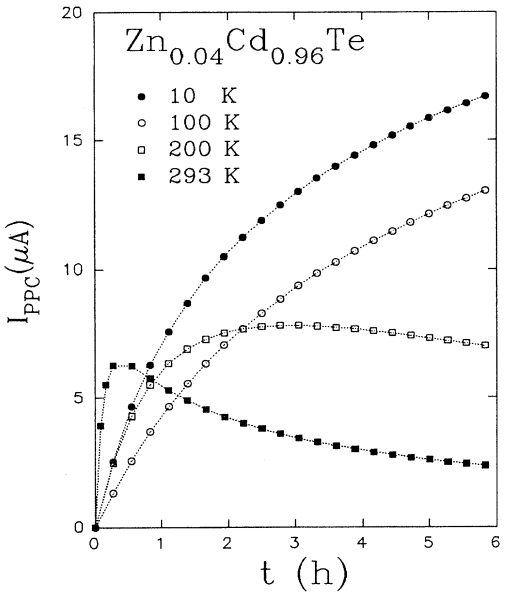

FIG. 4. PPC buildup transients at different temperatures. The light intensity is fixed for different temperatures. An overshoot behavior occurs at temperatures above 200 K. The low-temperature buildup ($T=10$ and 100 K) transients can be fitted by $I(t)=I_0(1-e^{-\alpha t})$, with α being a rate parameter depending on temperature and light intensity. The dotted lines are to guide the eyes.

shown in Fig. 4, at $T=200$ and 293 K, an initial increase of PPC is followed by a slow decrease. The time needed for PPC to reach the maximum depends on the excitation light intensity and temperature. In general, the higher the temperature, the earlier the PPC reaches a maximum. Figure 4 shows that PPC reaches a maximum at a later time at 200 K compared to that at 293 K. An important fact is that a prolonged excitation leads to a final steady PPC buildup level being higher than the initial dark level but much lower than the initial maximum buildup level.

One might think that this overshoot behavior is due to the decrease in electron mobility as a result of photoexcitation. In such a context, the electron-electron scattering and electron-ionized donor scattering increase due to the presence of more carriers and ionized impurities after photoexcitation. If this is the case, by terminating the light excitation after PPC has reached a maximum, one would expect to observe the PPC decay curve also going through a maximum. However, this behavior was never observed experimentally. Hence the interpretation of mobility decreasing due to photoexcitation is not consistent with experimental observation.

Similar overshoot behavior has been observed in amorphous selenium films,[21] Te-doped $Al_xGa_{1-x}As$,[22] N-doped $Al_{0.32}Ga_{0.68}As$,[23] and O-doped GaAs.[24,25] In amorphous selenium thin films, an impurity called the *S*-center was believed to be the cause of the overshoot behavior. The *S* center was believed to constitute two different impurity levels, with one of them being shallower and the other being a deep level with a potential well surrounded by a wide Coulomb potential barrier.[21] In Te-doped $Al_xGa_{1-x}As$, PPC reaches a maximum in a very short time of about 1 s, and the overshoot behavior observed has been taken as evidence of the negative-*U* character of the *DX* centers.[22] The overshoot in N-doped $Al_{0.32}Ga_{0.68}As$ was explained by the presence of two different *DX* levels in the sample.[23]

The overshoot behavior observed here suggests that the impurity involved has two different states. Most likely, the impurity when filled with an electron has two possible states: a stable state and a shallower metastable state, analogous to the shallow-deep bistability of the donor atoms in $Al_xGa_{1-x}As$ semiconductors. The energy configuration of the impurity level could give rise to an overshoot behavior in the PPC buildup transients if (1) the electron-capture barrier for the shallower state is smaller than that of the deep state, which should be the case; and (2) the optical ionization cross section for the shallower state is much smaller than that of the deep one. Under these conditions, the PPC buildup processes would include photoexcitation of electrons from the deep state to the conduction band, subsequent electron capture by the shallower state and the deep state, and transformation from the shallower state to the deep state. By considering these processes, the two rate equations for both the shallow and deep states can lead to an initial increasing then decreasing of the PPC buildup curve. Similar processes have been described previously for oxygen-related deep centers in GaAs.[24]

To study the overshoot behavior further, we have measured the PPC decay and buildup behaviors after PPC has reached a maximum at room temperature. As shown in Fig. 5, the light was turned on at $t=0$. After PPC reached a maximum at about 1800 s, the light was turned off and then turned on again at times indicated by the arrows in the figure. The light intensity is the same for the initial and the subsequent excitations. A very interesting result here is that, for the subsequent photoexcitation, the buildup level of PPC saturates at the level at which the light excitation was terminated, which is much lower than the initial maximum buildup level. This tells us that although the conductivity approaches the initial dark level upon terminating the photoexcitation, the impurity centers are again filled with electrons, but most of them are in a different metastable state. The results of Fig. 5 also indicate that the dark conductivity levels are almost comparable for the two impurity states, which implies that most likely the metastable state is not an effective-mass state.

We also observed that as the time interval between the light termination and the subsequent excitation increases, the latter buildup level increases and the initial condition can be completely restored by waiting for a long period of time (about 24 h at room temperature) under dark. These results suggest that there is a potential barrier between these two impurity states, and the transformation from the shallower to the deep state takes time. As a consequence, the transfer rate increases with temperature. At low temperatures, the transfer rate is negligibly small and the dominant processes in the course of PPC buildup are just photoexcitation from the deep state and electron capture by the shallower state. Therefore, the overshoot

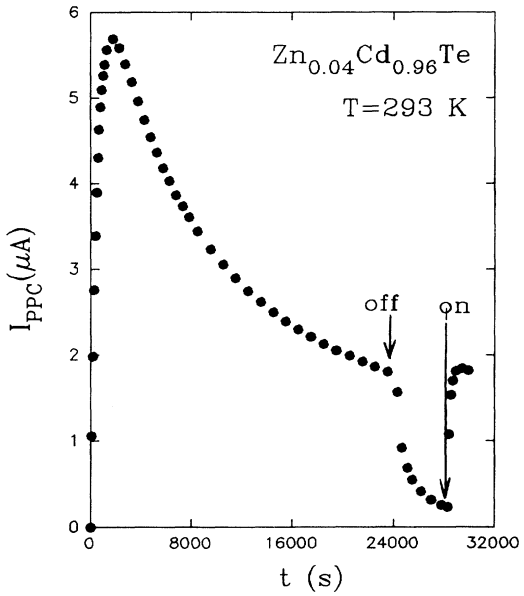

FIG. 5. The PPC buildup and decay transients at room temperature. The excitation light was turned on at $t=0$, and PPC reached a maximum level I_{max} at $t\sim1800$ s. The light was turned off and on again at times indicated by arrows. Notice that for the second time the buildup level saturated at a level which is below the initial maximum buildup level I_{max}.

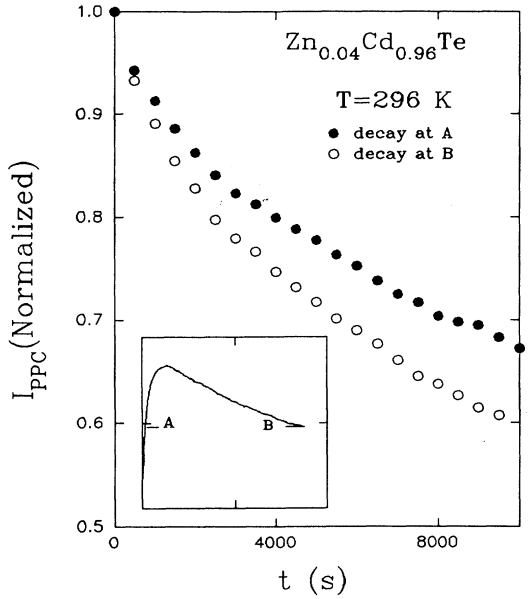

FIG. 6. The PPC decay at two different buildup states A and B, at which the buildup currents are exactly the same. The states A and B correspond to before and after the PPC has reached the maximum level.

behavior was not observed at low temperatures within the measured time period. In fact, we have carried out the buildup measurements over a 24 h period of time at 10 K, and no overshoot behavior was observed. On the other hand, at a fixed temperature, the overshoot behavior occurs earlier at higher excitation light intensity levels.

Figure 6 shows the PPC decay behavior measured at two different buildup states A and B, at which the buildup currents are exactly the same. However, state A is before the current maximum point and state B is after. From the current level, one cannot tell the difference between states A and B. However, the decay behaviors at these two states are different. As we can see, PPC decays more slowly at state A. In fact, we can measure the PPC decay before and after the current maximum point for many pairs of buildup states A and B. The difference in the decay behavior between states A and B increases as the time interval between A and B increases. The results in Fig. 6 agree with the explanation that there are two different impurity states, with the excited one being a metastable state.

We have also measured the electron-capture barrier associated with the deep level from the PPC decay. A plot of $\ln(\tau)$ vs $1/T$ for a $Zn_{0.04}Cd_{0.96}Te$ thin-film sample is shown in Fig. 7. A straight line is evident, from which the electron-capture barrier of 125 ± 6 meV is obtained. The time constant τ is obtained by fitting experimental data such as those in Figs. 1 and 2 with Eq. (2). At each temperature, the PPC decay was measured before the conductivity maximum was reached (point A in Fig. 6), and the buildup light intensity and time are fixed. The measured capture barrier is much larger than those in some of the undoped II-VI bulk materials. For example, the capture barrier is only about 10 meV in CdS_xSe_{1-x}.[7] The value of the capture barrier here is almost comparable with that of the DX center in $Al_xGa_{1-x}As$:Si.

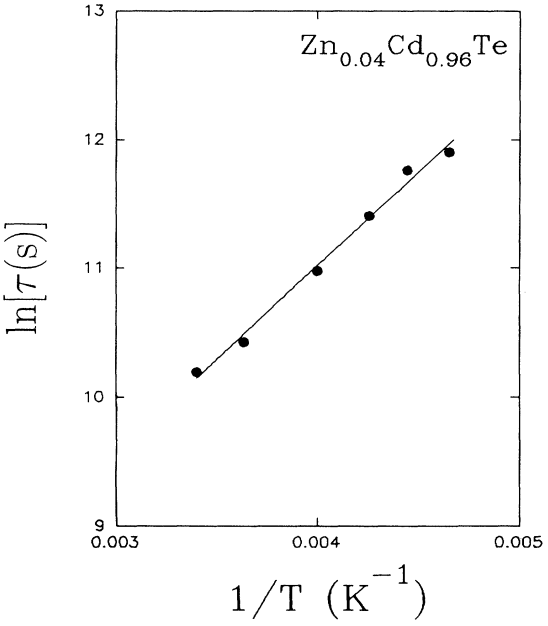

FIG. 7. The plot of $\ln(\tau)$ vs $1/T$ for a $Zn_{0.04}Cd_{0.96}Te$ thin-film sample, which gives an electron capture barrier $E_c=125\pm6$ meV. The time constant τ is obtained by fitting experimental data such as those in Figs. 1 and 2 with Eq. (2). At each temperature, the PPC decay was measured before the photoconductivity maximum was reached (point A in Fig. 6).

We also notice another interesting point here. The capture barrier in Si-doped $Al_{0.3}Ga_{0.7}As$ has been determined previously by the same type of measurements to be about 160 meV.[18] We see that although the capture barrier in $Zn_{0.04}Cd_{0.96}Te$ thin-film samples is smaller than that in $Al_{0.3}Ga_{0.7}As$, PPC can be observed at much higher temperatures in $Zn_{0.04}Cd_{0.96}Te$. It is well known that PPC in $Al_xGa_{1-x}As$:Si is observable only at $T<150$ K. In the thermally activated region, one can write

$$\tau=\tau_0\exp(E_c/kT)\ , \tag{3}$$

with E_c being the electron-capture barrier. The preexponential factor τ_0 has the relation

$$1/\tau_0=\sigma_n^{\infty}\langle v_n\rangle n_c\ , \tag{4}$$

where $\langle v_n\rangle$ is the average electron thermal velocity, σ_n^{∞} the electron-capture cross section at the limit of temperature $T\rightarrow\infty$, and n_c the electron concentration in the conduction band.[26] Our results then indicate that the preexponential factor τ_0 for the $Zn_{0.04}Cd_{0.96}Te$ thin-film samples here is much larger than that in $Al_xGa_{1-x}As$ since E_C is smaller. Figure 7 gives the value of τ_0 in thin-film samples of about 1.4×10^4 s. It has been reported previously that the prefactor τ_0 in $Al_{0.3}Ga_{0.7}As$ is about 5×10^{-11} s.[2] Since $\langle v_n\rangle$ and n_c are comparable in these two materials, the high-temperature PPC of the $Zn_{0.04}Cd_{0.96}Te$ thin film must be due to the fact that the capture cross section at $T\rightarrow\infty$, σ_n^{∞}, is much smaller in $Zn_{0.04}Cd_{0.96}Te$ thin-film samples compared to that in $Al_xGa_{1-x}As$.

Figure 8 is the plot of decay exponent β as a function of temperature. From Fig. 8, we can see that β depends very weakly on temperature. Although decay-time constant τ changes almost by one order of magnitude in this temperature region, β is almost a constant value of about

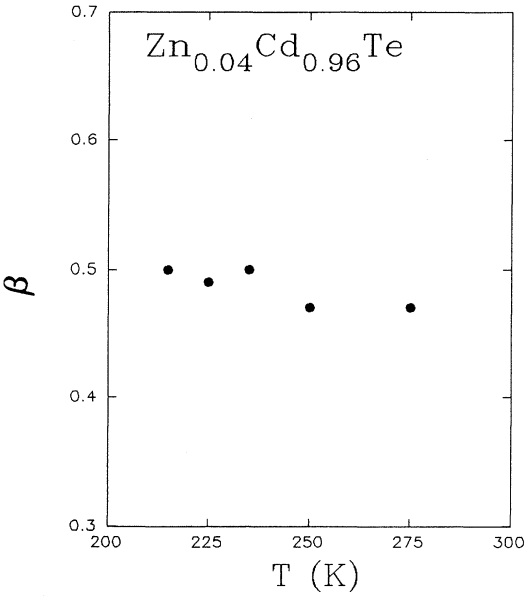

FIG. 8. The decay exponent β as a function of temperature in the activated temperature region.

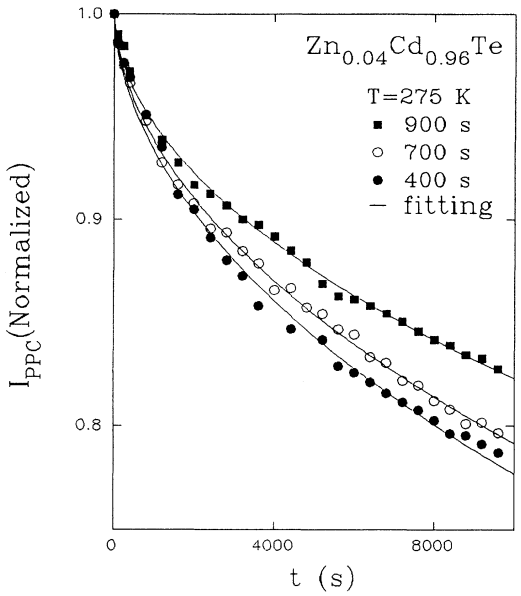

FIG. 9. The PPC decay at $T=275$ K for three different photon dose levels. The buildup times t_b are indicated in the figure. The light intensity was fixed. The solid lines are the least-squares fittings using Eq. (2).

0.5 in this temperature region. This result is different from that of $Zn_{0.3}Cd_{0.7}Se$ bulk materials, in which a temperature dependence of β was observed in a certain temperature region.[6] It is also different from the behavior in $Al_xGa_{1-x}As$, in which β increases almost linearly with temperature in the activated temperature region.[18] The value of β in the $Zn_{0.04}Cd_{0.96}Te$ thin film is also smaller than that in $Zn_{0.3}Cd_{0.7}Se$ bulk crystals.

We also investigated the dependence of the PPC decay behavior on the relative photoexcited electron concentration. In the first few thousand seconds, the PPC buildup level increases linearly with an increase of buildup time, which implies a linear increase of the photoexcited electron concentration. Thus the relative concentration can be controlled by varying the excitation photon does. Figure 9 shows such a dependence at $T=275$ K. As we can see from Fig. 9, the PPC decay rate decreases as the relative photoexcited electron concentration increases. The solid lines are the least-square fittings of data obtained by using Eq. (2). The fitted parameters are $\tau=1.973\times10^5$ s, 1.309×10^5 s, and 1.138×10^5 s for buildup times 900, 700, and 400 s, respectively. However, β is almost independent of buildup time t_b.

Another very interesting phenomenon observed in these materials is that one needs energetic photons (above band-gap energy) to empty the deep centers as well as to induce PPC. The optical ionization cross section as a function of photon energy has not yet been measured. However, different light sources have been used for excitation, including He-Ne laser, Hg, Ne, and Xe lamps. Among these sources, under the same level of excitation intensity, only an Hg lamp with a 254-nm filter gives a large response, and the responses from the other light sources are negligibly small. The energy gap of bulk

$Zn_{0.04}Cd_{0.96}Te$ is about 1.5 eV, and the dominant output from He-Ne laser, Ne, and Xe lamps are 632.8, 585–693, and 828 nm, respectively, corresponding to energies 1.96, 1.79–2.12, and 1.50 eV, respectively. Therefore, our results imply that we need photons with energies even larger than the energy gap of the materials to empty the deep centers as well as to induce PPC. However, the temperature-dependent dark conductivity gives the binding energy of the defect on the order of a few tens of meV. These results indicate that the defect exhibits a large Stokes shift.

Recently, it has been observed in mixed halide chain crystal solids that photons with energies larger than the energy gap are required for the excitation of the photoconductivity.[27] The materials in Ref. 27 were made from platinum atoms linked with halogen atom—chlorine, bromine, or iodine typically. It has been described as an ultragap absorption (absorptions to the blue of the band edge). The edge states occurring at the junctions between the two distinct materials were proposed to be responsible for the ultragap phenomenon in halide solids. We could use the lattice relaxation model to explain the Stokes shift. However, the amount of shift seems to be too large. In $Al_xGa_{1-x}As$, with the Stokes shift, the threshold excitation photon energy needed for emptying *DX* centers is still smaller than the energy gap of the material. Thus the origin of this large Stokes shift in $Zn_{0.04}Cd_{0.96}Te$ thin films is not understood and deserves further investigation. Experiments such as optical-absorption spectroscopy are needed in order to see whether this is an ultragap phenomenon. Furthermore, more experiments such as Hall and deep-level transient spectroscopy (DLTS) measurements may be needed in order to determine the exact energy configuration of the defect involved.

IV. CONCLUSIONS

PPC in $Zn_{0.04}Cd_{0.96}Te$ thin films prepared by the laser ablation method has been studied and compared to PPC in the original bulk materials. Different PPC behaviors in thin films and in bulk materials have been observed PPC in thin-film samples has a very long lifetime and persists even at elevated temperatures. The decay of PPC is found to follow stretched-exponential functions. It is believed that deep centers introduced during the laser ablation process are responsible for the long lifetime of PPC. An overshoot behavior in PPC buildup transients has been observed at higher temperatures, which can be explained by assuming that the impurity center when filled with an electron has two different states: a stable and an excited metastable state. This property is similar to that of *DX* centers $Al_xGa_{1-x}As$, but it seems that the metastable state is not an effective-mass state here. The electron-capture barrier has been determined from the stretched-relaxation behavior of PPC. Additionally, an "ultragap" has been observed, which shows that photons with energies even larger than the energy gap of the material are needed to excite electrons from the deep level as well as PPC.

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