Kinetics of persistent photoconductivity in $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ semiconductor alloys

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The kinetics of persistent photoconductivity (PPC) in $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ has been investigated. The PPC relaxation behaviors in both materials can be well described by stretched-exponential functions, $I_{PPC}(t) = I_{PPC}(0)\exp[-(t/\tau)^\beta]$ $(\beta < 1)$. For $Al_{0.3}Ga_{0.7}As$, the relaxation-time constant τ, as a function of the relative photoexcited electron concentration n, is measured through the variation of the excitation photon dose in the temperature region $T \geq 10$ K. At low temperatures, we found that in $Al_{0.3}Ga_{0.7}As$, τ decreases and reaches a minimum value as n increases in the low-concentration region but it increases with increasing n in the higher-concentration region. Such a turning-over behavior observed in $Al_{0.3}Ga_{0.7}As$ is believed to be due to the crossover from a nondegenerate to a degenerate regime as the electron concentration increases. At higher temperatures, τ observed in $Al_{0.3}Ga_{0.7}As$ decreases monotonically with increasing electron concentration, which is consistent with the fact that the degenerate carrier concentration is more difficult to attain at higher temperatures. The PPC-buildup transients in $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ have also been measured and formulated at different conditions and are shown to be very different. These results have shown that the PPC-buildup transients contain information not only about electron excitation but also electron recapture. The photoionization cross section of DX centers, σ_{DX}, in $Al_{0.3}Ga_{0.7}As$ has been obtained from the PPC-buildup-transient measurements. The experimental results indicate that the transport properties in $Al_{0.3}Ga_{0.7}As$ are controlled by DX centers as expected, but in II-VI semiconductor alloys in the low-electron-concentration region they are governed nonetheless by tail states induced by compositional fluctuations.

I. INTRODUCTION

The nature of DX centers, deep-level traps associated with donors, in $Al_xGa_{1-x}As$ has been intensively investigated.[1-4] It is now widely accepted that the photoexcitation of electrons from DX centers to the conduction band is the origin for the persistent photoconductivity (PPC) observed in $Al_xGa_{1-x}As$ $(x > 0.22)$ at low temperatures, $T < 150$ K. In these materials, there is PPC because the recapture of electrons by DX centers is prevented by a thermal barrier at low temperatures.[5-7] The capture kinetics of electrons at DX centers, which have been studied by several groups,[8-10] have not yet been well established. The time dependence of the capture transient is found to be highly nonexponential, making data analysis very difficult. The average capture time constant as well as the capture barrier can only be estimated from the $\frac{1}{2}$- or $\frac{1}{3}$- signal point. However, as soon as the temperature becomes lower than about 60 K, the capture cross section is so small that the time constant at the $\frac{1}{2}$- or $\frac{1}{3}$-signal point becomes immeasurably long. The highly nonexponential capture kinetics observed in $Al_xGa_{1-x}As$ materials has been attributed primarily to the variation of the electron quasi-Fermi level in the conduction band during the capture process at a constant temperature.[8]

Recently, the kinetics of electron capture at DX centers in $Al_{0.3}Ga_{0.7}As$ have been investigated by using PPC measurements. We found that at temperatures $T < 90$ K, the relaxation of PPC, or equivalently, the time dependence of the capture transient, in $Al_{0.3}Ga_{0.7}As$ can be well described by a stretched-exponential function, $I_{PPC}(t) = I_{PPC}(0)\exp[-(t/\tau)^\beta]$, where τ is the relaxation time constant and β the decay exponent.[11] This observation allows us to determine systematically the relaxation time constant and the decay exponent in entire temperature region of interest. A relaxation time constant as large as 5×10^{13} s at 10 K was observed. The capture barrier was also obtained from PPC measurements, which was consistent with that obtained from other methods. A transition (not a phase transition) from a thermally activated capture to a weakly temperature-dependent capture at about 40 K has also been observed, which is consistent with the theoretical prediction from the model of tunneling capture via multiphonon emission in configurational space. Such a model predicts a thermal activation capture at high temperatures and a nearly temperature-independent capture cross section at $T \to 0$ K. At higher temperatures, $T > 90$ K, the PPC decay in $Al_{0.3}Ga_{0.7}As$ is frequently describable by a power law. The PPC relaxation in II-VI semiconductor alloys has also been observed to follow a stretched-exponential behavior, in which the conduction of stored charge carriers in random local potential fluctuations induced by compositional fluctuations was proposed to be the cause of PPC.[12,13]

Our previous results also showed that II-VI and III-V semiconductor alloys exhibit very different PPC behaviors. A phase transition in the PPC mode, the existence of room-temperature PPC, and an optical infrared

quenching of PPC have been observed in II-VI semiconductor alloys but not in $Al_x Ga_{1-x} As$. These differences are believed to be due to the existence of large potential fluctuations caused by compositional fluctuations in II-VI semiconductor alloys. In III-V semiconductor alloys, the effect of the alloy disorder to the transport properties is negligibly small because the potential fluctuation is very small.[14,15]

In this paper, the PPC decay behavior in $Al_{0.3}Ga_{0.7}As$ has been investigated at different electron concentration levels or PPC buildup levels through the variation of excitation photon dose. We found that the electron-capture process depends strongly on the photoexcited electron concentration n. At low temperatures, τ decreases with an increase of n in the low-concentration region; however, τ increases with an increase of n in the high-concentration region. The electron concentration, at which the turning-over behavior of τ occurs, increases with increasing temperature. These results have been interpreted as a consequence of the existence of two different electron-decay processes in the nondegenerate and degenerate regimes. From these observations, the previous finding[11] of two different regions of a thermally activated capture and a tunneling capture via multiphonon emission represent the nondegenerate and degenerate cases, respectively. Based on these findings, one can control the PPC lifetime through the variation of the excitation photon dose, which could be useful for practical applications. PPC buildup transients in $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ have also been measured at different excitation photon intensities, and very different results have been obtained. The experimental results showed that the PPC saturation level in $Al_{0.3}Ga_{0.7}As$ not only depends on the concentration of DX centers but also depends on the generation rate and the recombination rate of electrons. The electron-decay parameters associated with the buildup of PPC have been obtained at different conditions for both $Al_{0.3}Ga_{0.7}Se$ and $Zn_{0.3}Cd_{0.7}Se$ and are consistent with calculations. It is also shown that transport properties in II-VI semiconductor alloys are strongly affected by alloy disorder.

II. EXPERIMENT

The samples used in this study were a $Al_{0.3}Ga_{0.7}As$ epitaxial layer of 2 μm and a bulk $Zn_{0.3}Cd_{0.7}Se$. The $Al_{0.3}Ga_{0.7}As$ sample was doped with 3.3×10^{17} cm^{-3} Si, grown on a semi-insulating GaAs (100) substrate, and was supplied by Spire Corp. Ohmic contacts 1 mm in diameter and about 7 mm apart were formed by indium alloying on the layer surface. The $Zn_{0.3}Cd_{0.7}Se$ sample is of size $5 \times 10 \times 1$ mm^3 with dark room-temperature resistivity of about 10^9 Ω cm. More detailed information about the samples can be found elsewhere.[11,12] The samples were attached to a copper sample holder, which is inside a closed-cycle He refrigerator, with care taken to ensure good thermal contact, yet electrical isolation. A temperature controller enabled us to stabilize the temperature to within 0.1 K. A neon lamp was used as an excitation source for $Al_{0.3}Ga_{0.7}As$ along with some appropriate filters so that a few lines within the region of 6000

Å $< \lambda_{exc} < 7050$ Å dominated the output of the neon lamp. A mercury lamp was used as an excitation light source for $Zn_{0.3}Cd_{0.7}Se$ along with appropriated filters so that two lines at 435.8 and 546.1 nm dominated the output of the mercury lamp. A 1.5-V bias was supplied by a battery. The data obtained at different conditions were taken in such a way that the system was always heated up to room temperature to convert the illuminated sample to its initial state and then cooled down again in darkness to the temperature of measurements. The equilibration time at each temperature was about 40 min.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Electron concentration dependence of PPC decay in $Al_{0.3}Ga_{0.7}As$

The PPC-decay kinetics have been investigated at different temperatures previously.[11] At temperatures $T < 90$ K, PPC decay can be well described by a stretched-exponential function,

$$I_{PPC}(t) = I_{PPC}(0) \exp[-(t/\tau)^\beta] \ (\beta < 1) \ ,$$

where $t = 0$ is the moment the excitation being terminated. $I_{PPC}(0)$ is the buildup current at $t = 0$. At temperatures $T > 90$ K, PPC relaxation is frequently describable by a power-law decay.[13] There is evidence that both stretched-exponential and power law PPC decays are asymptotic forms of the actual decay kinetics at different conditions. However, the exact form of the PPC relaxation behavior is unknown at this stage. Experimentally, we have observed that PPC is still about 98% or higher of its initial level after 3000-s decay at temperatures $T < 60$ K. At temperatures $T > 40$ K, electron capture is thermally activated, while at low temperatures ($T < 40$ K), a weakly temperature-dependent decay rate has been observed.[11]

In order to understand how the PPC capture process depends on the electron concentration, or quasi-Fermi level, we have investigated the PPC decay behavior for different PPC-buildup levels, $I_{PPC}(0)$. Different $I_{PPC}(0)$ can be obtained by changing the illumination time t_i, while keeping the excitation light intensity constant. In the region where the PPC-buildup levels are much lower than the saturation level, $I_{PPC}(0)$ is proportional to t_i; so is the electron concentration n. In Fig. 1, we plot the PPC decay curves obtained at 20 K in the form of $\ln[\ln I_{PPC}(0) - \ln I_{PPC}(t)]$ versus $\ln t$ for two representative excitation photon doses, corresponding to $t_i = 700$ s, $I_{PPC}(0) = 4.76$ mA (*) and $t_i = 900$ s, $I_{PPC}(0) = 4.97$ mA ($\bigcirc$) The photon flux N_{ph} used is about 3×10^{13} /cm^2 s. Figure 1 depicts a linear behavior, which means that the decay is well described by stretched-exponential functions. The slope of these linear plots represents the decay exponent β, and the intersection correlates to the relaxation time constant τ. As we can see from Fig. 1, the two curves are almost parallel to each other, which implies that β is independent of the excitation photon dose at a constant temperature. This has been confirmed by varying the excitation photon dose by two orders of magni-
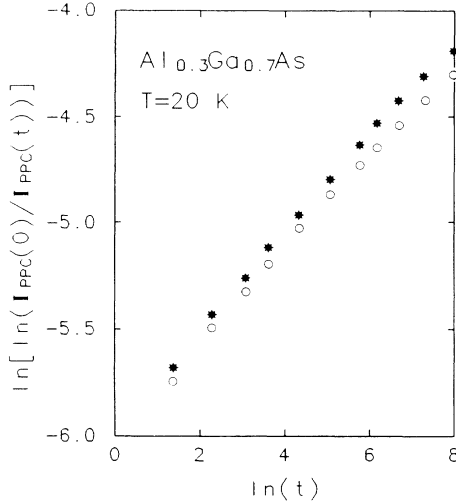
FIG. 1. Plots of PPC decay curves in the form of $\ln[\ln I_{PPC}(0) - \ln I_{PPC}(t)]$ vs $\ln t$ obtained at two different photon doses, corresponding to buildup time $t_i = 700$ s ($*$) and $t_i = 900$ s ($\bigcirc$) and photon flux $N_{ph} = 3 \times 10^{13}/$ cm^{2}s at $T = 20$ K for $Al_{0.3}Ga_{0.7}As$. Here, $t = 0$ is defined at the moment of the excitation light being terminated, and the dark current has been subtracted. The linear behavior indicates that the PPC decay is well described by a stretched-exponential function, $I_{PPC}(t) = I_{PPC}(0) \exp[-(t/\tau)^\beta]$.
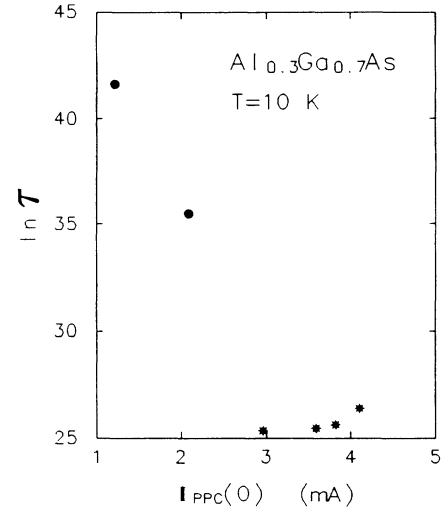

FIG. 2. Plot of PPC decay time constant τ determined from stretched-exponential functions ($*$) vs PPC buildup level $I_{PPC}(0)$ at $T = 10$ K for $Al_{0.3}Ga_{0.7}As$. The excitation photon flux is about 3×10^{13} / cm^2 s. Different values of $I_{PPC}(0)$ were obtained by varying the illumination time t_i. In the region of low excitation photon dose [$I_{PPC}(0) = 1.25$ and 2.14 mA], the PPC decay curves plotted as Fig. 1 deviate from a linear behavior. However, the effective decay time constants τ^* were estimated from the stretched-exponential functions ($\bullet$).

tude. At a given excitation photon dose, there is a certain temperature above which τ has an activated temperature dependence of the form $\tau \propto \exp[E_C - E_F)/kT]$ and the decay exponent β increases with an increase of temperature. Here, E_C denotes the electron capture barrier of the DX centers measured from the conduction-band edge and E_F is the electron quasi-Fermi level. Below that temperature, τ is only weakly dependent on the temperature, while β is nearly independent of the temperature. Experimental results showed that the temperature that separates such two distinctive decay regimes depends on the photoexcited electron concentration n; it decreases with decreasing n.

The dependence of τ on n has a rather complex form. Figure 2 is a plot of the PPC decay time constant $\tau(*)$ versus the PPC-buildup level $I_{PPC}(0)$ at $T = 10$ K for $Al_{0.3}Ga_{0.7}As$. The buildup times, for example, are $t_i = 10$, 30, 100, 300, 500, and 700 s for different values of $I_{PPC}(0)$ in Fig. 2. For longer buildup times, $I_{PPC}(0)$ is no longer proportional to t_i; nonetheless, the electron concentration n is always proportional to $I_{PPC}(0)$. Thus we plot $\ln \tau$ versus $I_{PPC}(0)$ instead of t_i in Fig. 2. We should point out that, at low buildup levels, e.g. $I_{PPC}(0) = 1.25$ and 2.14 mA, the relaxation is no longer well described by stretched-exponential functions; nonetheless, the effective decay time constant τ^* can still be estimated from the stretched-exponential function as indicated by dots ($\bullet$). A strong dependence of τ on $I_{PPC}(0)$ or n has been observed. For example, τ changes by about seven orders of magnitude as $I_{PPC}(0)$ varies from 1.25 to 2.97 mA. In the low concentration region up to $I_{PPC}(0) = 2.97$ mA, τ decreases with an increase of $I_{PPC}(0)$ to a minimum value

and then increases with an increase of $I_{PPC}(0)$. However, the dependence of τ on $I_{PPC}(0)$ in the higher-concentration region becomes much weaker.

Another point we want to note here is that there are two ways of building up PPC to a certain level. One way is by varying the illumination time t_i while keeping N_{ph} constant, as we have done here. Another way is by varying the photon flux while keeping the illumination time constant. $I_{PPC}(0)$ in most cases depends only on the photon dose, which implies that one can attain the same level of $I_{PPC}(0)$ by varying either the illumination time or excitation intensity by an identical factor. The dependence of τ on $I_{PPC}(0)$ has also been measured under different conditions by changing the excitation light intensity while keeping t_i constant. We found that for higher intensities, the PPC decay behavior deviates from the stretched-exponential functions, which makes data analysis difficult. This may be due to the fact that the electrons are not under quasiequilibrium after excitation with high excitation light intensities.

Figure 3 shows the PPC decay time constant τ versus $I_{PPC}(0)$ at $T = 20$ K, with the other conditions being the same as in Fig. 1. In the region of low concentration [$I_{PPC}(0) = 2.44$ and 2.95 mA], the stretched-exponential function is again only an approximation for the PPC decay behavior, and the corresponding effective relaxation time constants τ^* are indicated by dots ($\bullet$). A similar dependence of τ on $I_{PPC}(0)$ has been observed. However, by comparing Fig. 3 with Fig. 2, we can see that the turning-over behavior of τ at 10 K occurs around $I_{PPC}(0) = 2.97$ mA, while at 20 K it occurs around $I_{PPC}(0) = 4.3$ mA. The buildup time t_i for obtaining

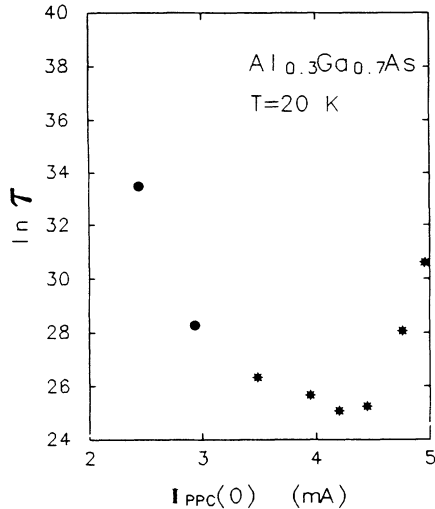FIG. 3. Plot of PPC decay time constant τ (*) vs PPC build-up level $I_{\mathrm{PPC}}(0)$ at 20 K with all other conditions being the same as in Fig. 1. In the region of low excitation photon dose [$I_{\mathrm{PPC}}(0)=2.44$ and $=2.95$ mA], the effective relaxation time constants τ^* were estimated from stretched-exponential functions (●).

$I_{\mathrm{PPC}}(0)=2.97$ mA at 10 K is 100 s and for $I_{\mathrm{PPC}}(0)=4.21$ mA at 20 K is 450 s. This indicates that the electron concentration at which the turning over occurs increases with an increase of temperature. Thus we expect that it will be more difficult to observe this turning-over behavior at higher temperatures, since the corresponding electron concentration n may become too high to achieve in the investigated region or it may become even larger than the DX concentration N_{DX} in the sample.

The relaxation time constant τ as a function of the relative electron concentration n has also been studied at higher temperatures. Figure 4 shows a representative
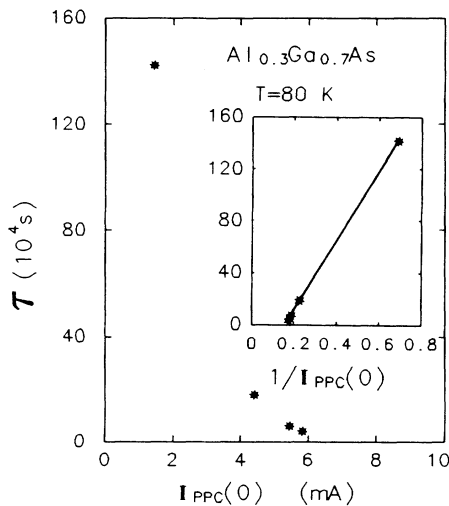

FIG. 4. Plot of PPC decay time constant τ vs buildup level $I_{\mathrm{PPC}}(0)$ at $T=80$ K for $\mathrm{AL_{0.3}Ga_{0.7}As}$. The other conditions are the same as in Fig. 1. The inset is the plot of τ vs $1/I_{\mathrm{PPC}}(0)$ with the scale for τ unchanged, and a linear relation is evident.

plot of τ versus PPC-buildup level $I_{\mathrm{PPC}}(0)$ at $T=80$ K for $\mathrm{Al_{0.3}Ga_{0.7}As}$ with the other conditions the same as in Fig. 1. At this temperature, τ decreases monotonically with an increase of $I_{\mathrm{PPC}}(0)$. The turning-over behavior exhibited at low temperatures is not observable at 80 K, which is consistent with our expectation. Another point is that the variation of τ with $I_{\mathrm{PPC}}(0)$ becomes much weaker at 80 K compared with those at 10 and 20 K. Notice the use of logarithmic scales for 10 and 20 K but a linear scale for 80 K. The inset of Fig. 4 shows the plot of τ versus $1/I_{\mathrm{PPC}}(0)$ with the scale of τ unchanged. A linear behavior is evident, which implies that the dependence of τ on $I_{\mathrm{PPC}}(0)$ at $T=80$ K in the investigated region can be written as

$$\tau=C_1+C_2/I_{\mathrm{PPC}}(0) , \qquad (1)$$

where C_1 and C_2 are two constants. A least-squares fitting gives $C_1=-4.27\times10^5$ s and $C_2=2.68\times10^6$ mA s. We see that τ becomes very small for large values of $I_{\mathrm{PPC}}(0)$. We should point out that the PPC saturation level under this particular excitation light intensity is about 6.28 mA.

The experimentally observed behavior of τ as a function of the relative electron concentration shown in Figs. 2–4 may be accounted for by the following considerations. At a fixed temperature, the quasi-Fermi level will increase as the electron concentration increases. This effectively reduces the capture barrier. Therefore, τ decreases with an increase of n at $T=80$ K and also at 10 and 20 K in the low concentration region. However, a degenerate state of electrons can be attained by a further increase in n at low temperatures. In the degenerate state, only electrons in the states near the quasi-Fermi level $(E_F\pm kT)$ can participate in the capture process due to multiphonon-emission process. Electrons in the states much below the quasi-Fermi level cannot be involved in the decay process in the early times because most of the states below the level E_F-kT have been occupied. So the relative number of electrons captured by the DX centers decreases with increasing n in the degenerate state. This effect accounts for the turning-over behavior observed at low temperatures. The value of $I_{\mathrm{PPC}}(0)$ at which τ turns over corresponds to the degenerate electron concentration at that temperature. From this argument, we expect that the degenerate electron concentration or $I_{\mathrm{PPC}}(0)$ at which the turning over behavior occurs will increase with increasing temperature. This is exactly what we have observed. At $T=80$ K, we cannot attain the degenerate concentration of electrons in the conduction band, and τ decreases monotonically with an increase of $I_{\mathrm{PPC}}(0)$ in the entire investigated region.

In the nondegenerate case, e.g., at $T=80$ K, the electron-capture process can be described by the high-temperature limit, or Boltzmann statistics, i.e., thermally activated electron capture at DX centers, and τ can be written as[8,11]

$$\tau=\tau_0\exp[(E_c-E_F)/kT] , \qquad (2)$$

where τ_0 is a constant. From Eq. (2), at a constant temperature, τ depends only on the quasi-Fermi level E_F, or

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equivalently the buildup electron concentration n, which is proportional to $I_{PPC}(0)$, and τ decreases as E_F or n increases. For the nondegenerate electron gas, the quasi-Fermi level E_F has a logarithmic dependence on the electron concentration n,

$$E_F = kT \ln(\lambda^3 n) , \tag{3}$$

where $\lambda = h(2\pi m k T)^{-1/2}$, h is Planck's constant, and m is effective mass of electrons.[16] This leads to the following expression for τ:

$$\tau = (\tau_0/n)[(2\pi m k T)/h^2]^{3/2} \exp(E_c/kT)$$

$$\propto 1/n \propto 1/I_{PPC}(0) . \tag{4}$$

Therefore, according to Eq. (4), at a constant temperature, the PPC relaxation time constant τ is inversely proportional to the electron concentration in the conduction band or $I_{PPC}(0)$. This is demonstrated in the inset of Fig. 4. We want to point out that Eq. (4) and hence Eq. (1) are valid only in certain region; i.e., n must be smaller than n_0, the degenerate concentration, since they only apply to the nondegenerate case. In the degenerate state, the situation becomes much more complicated and further investigations are needed.

It is interesting to compare the electron concentration dependence of τ in $Al_{0.3}Ga_{0.7}As$ with that in $Zn_{0.3}Cd_{0.7}Se$. We also observed that in $Zn_{0.3}Cd_{0.7}Se$, the PPC relaxation time constant τ behaves according to $\tau \propto 1/n$ at different conditions, but with a negative slope. This means that τ increases with an increase of n in $Zn_{0.3}Cd_{0.7}Se$, contrary to the behavior observed in $Al_{0.3}Ga_{0.7}As$ at higher temperatures. The connections between the stretched-exponential PPC decay behaviors and the inversely proportional relation between τ and n observed in $Zn_{0.3}Cd_{0.7}Se$ and $Al_{0.3}Ga_{0.7}As$ have not yet been established and remain to be investigated.

B. PPC buildup transient of $Al_{0.3}Ga_{0.7}As$

PPC buildup transients for $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ have also been measured at different excitation intensities. The representative behaviors are shown in Fig. 5, in which the experimental results for $Al_{0.3}Ga_{0.7}As$ are obtained at $T = 60$ K (∗) and those for $Zn_{0.3}Cd_{0.7}Se$ are obtained at $T = 170$ K (○). The excitation photon flux N_{ph} is $3 \times 10^{12}/$ cm^{2}s and $10^{12}/$ cm^{2}s for $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}$ Se, respectively. The dark current has been subtracted. It is clear that the transient behaviors of PPC in these two materials are very different. The current in $Al_{0.3}Ga_{0.7}As$ is in the order of 10^{-4} A and in $Zn_{0.3}Cd_{0.7}Se$ is in the order of 10^{-11} A. For $Al_{0.3}Ga_{0.7}As$, the rate of increase of $I(t)$, $dI(t)/dt$, decreases with an increase of illumination time in the investigated time region. In contrast, for $Zn_{0.3}Cd_{0.7}Se$, both $I(t)$ and its rate of increase $dI(t)/dt$ increase with an increase of illumination time in the first 300 s. The PPC buildup transients for $Al_{0.3}Ga_{0.7}As$ can be well described by[17,18]

$$I(t) = I_{max}(1 - e^{-\alpha t}) , \tag{5}$$
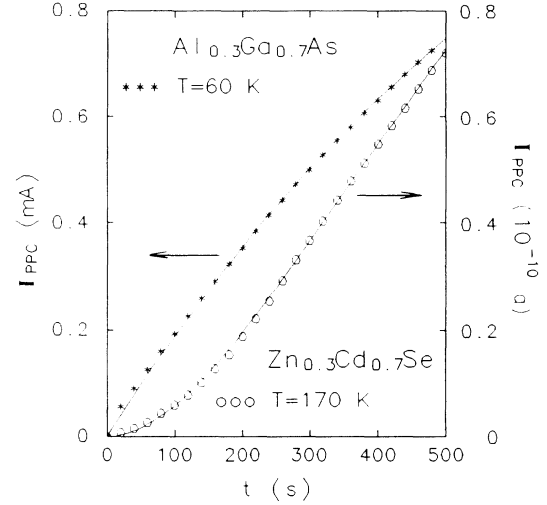
FIG. 5. PPC buildup transients for $Al_{0.3}Ga_{0.7}As$ at $T = 60$ K (∗) and $Zn_{0.3}Cd_{0.7}Se$ (○) at $T = 170$ K. The excitation photon flux N_{ph} is $3 \times 10^{12}/$ cm^{2}s and $10^{12}/$ cm^{2}s for $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$, respectively. The dark current has been subtracted. The solid curves for $Al_{0.3}Ga_{0.7}As$ is a fitting using $I(t) = I_{max}(1 - e^{-\alpha t})$ and for $Zn_{0.3}Cd_{0.7}Se$ is a fitting using $I(t) = I_{max}(1 - e^{-\alpha t})^2$.

where I_{max} is the saturation level and α is a decay parameter associated with the PPC buildup process. In Eq. (5), t is the illumination time, which is measured from the moment the excitation light is turned on. The solid curve for $Al_{0.3}Ga_{0.7}As$ in Fig. 5 is the plot of Eq. (5), which fits experimental results very well. The fitting parameters are $I_{max} = 1.54$mA and $\alpha = 1.32 \times 10^{-3}$ s^{-1}. The PPC-buildup transients in $Al_{0.3}Ga_{0.7}As$ have also been measured at different temperatures and excitation light intensities and all show the similar behavior.

In order to see the dependence of the PPC buildup behavior on the excitation photon intensity, we formulate Eq. (5) as follows. The electron concentration in the conduction band during the illumination is described by[19]

$$dn/dt = g(N_{DX} - n) - \omega n . \tag{6}$$

Here $g = N_{ph}\sigma_{DX}$ is the electron optical generation rate, where N_{ph} is the photon flux and σ_{DX} the photoionization cross section of the DX centers; ω is the electron decay rate in the PPC buildup process. The term $(N_{DX} - n)$ indicates the fact that the number of the excited electrons in the conduction band is proportional to the concentration of occupied DX centers. The second term, ωn, describes the number of electrons being recaptured during the PPC buildup process. The thermal emission of electrons from the DX centers has been neglected, since the emission barrier is twice as large as the capture barrier.[3] From Eq. (6), we have

$$n(t) = n_{max}[1 - e^{-(g+\omega)t}] , \tag{7}$$

where $n_{max} = gN_{DX}/(g + \omega)$. Equation (7) indicates that the maximum electron concentration n_{max} in the conduction band is not N_{DX} but $gN_{DX}/(g + \omega)$, which is less

than N_{DX}. This fact has been experimentally observed previously.[17] Only in the case where $\omega \ll g$, i.e., at low temperatures or very high excitation light intensities, can one possibly pump all the electrons from DX centers to the conduction band. Although ω is very small in general, g is also very small in many cases because of the small values of σ_{DX}, which strongly depends on excitation photon energy. Thus in most cases only a certain percentage of DX centers can be photoionized. It can be seen from Eq. (7) that at early times, the electron concentration increases linearly with illumination time, i.e., $n(t) = gN_{DX}t$. Under the assumption that the electron mobility μ is independent of the electron concentration and by comparing Eq. (7) with Eq. (5), we have

$$I_{max} = Ae\mu n_{max} = \frac{Ae\mu gN_{DX}}{\omega + g} = \frac{Ae\mu N_{DX}\sigma_{DX}N_{ph}}{\omega + N_{ph}\sigma_{DX}},$$
(8)

and

$$\alpha = \omega + g = \omega + \sigma_{DX}N_{ph} .$$
(9)

In Eq. (8), $A = SV/d$, where S is the sample cross-section area for current conduction, $V(=1.5\text{ V})$ is the bias applied to the contacts, and d is the distance between two contacts.

From Eq. (9), we expect that the decay parameter associated with the PPC buildup, α, of Eq. (5) increases linearly with an increase of excitation photon flux N_{ph}. I_{max} and α at 60 K for $Al_{0.3}Ga_{0.7}As$ have been obtained as functions of excitation photon flux N_{ph} from fitting Eq. (5) with experimentally measured PPC buildup transients. Figure 6 is the plot of the PPC saturation level I_{max} versus photon flux N_{ph} at $T=60$ K, in which the solid curve is a fitting using Eq. (8). The fitting is in a reasonable agreement with experimental results. The fitted values are $\omega/\sigma_{DX} = 2.9 \times 10^{11}$ /cm^2 s and $Ae\mu N_{DX} = 1.84$
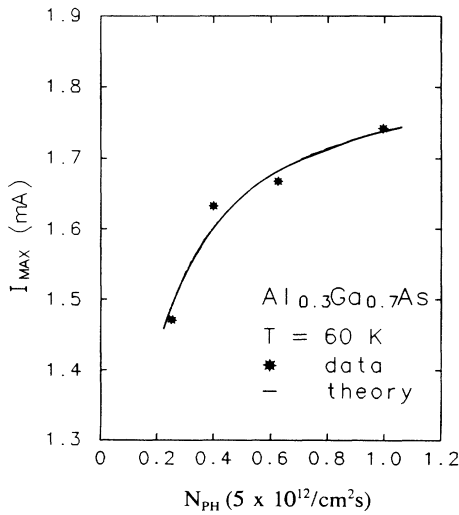
mA. With experimental parameters, we obtain the electron mobility in the order of 1000 cm^2/V s, which is consistent with the previously measured value obtained by Hall measurements for a similar sample.[20] With the known fitting value for $Ae\mu N_{DX}(=1.84\text{mA})$, the maximum electron concentration n_{max} that can be excited to the conduction band at different excitation intensities can also be obtained from Fig. 6. For example, when $N_{ph} = 1.2 \times 10^{12}$ cm^2 s, we have $I_{max} = 1.47$ mA, which corresponds to $n_{max}/N_{DX} = 1.47/1.84 = 80\%$. The important point here is that the PPC-buildup transient not only contains information about electron excitation, such as σ_{DX}, it also contains information about electron capture by DX centers. This should not be surprising, since the saturation of PPC in buildup transient is caused by the process of electron capture. At the stage where the PPC saturation occurs, the number of electrons being excited is exactly equal to the number being captured. Figure 7 shows the plot of α versus excitation photon flux N_{ph} for $Al_{0.3}Ga_{0.7}As$ at $T=60$ K, and a linear behavior is evident, consistent with Eq. (9). The solid line is the least-squares fitting using Eq. (9). The fitted values are $\omega = 9.40 \times 10^{-5}$ s^{-1} and $\sigma_{DX} = 3.5 \times 10^{-16}$/cm^2. This gives $\omega/\sigma_{DX} = 2.6 \times 10^{11}$ /cm^2 s, which is in agreement with the value obtained from Fig. 6. The photoionization cross section σ_{DX} obtained here agrees quite well with the value obtained previously by other experimental techniques.[2,3] Thus we have demonstrated here that the photoionization cross section of DX centers in $Al_{0.3}Ga_{0.7}As$, σ_{DX}, can be obtained from PPC-buildup-transient measurements.

C. PPC buildup transient of $Zn_{0.3}Cd_{0.7}Se$

Figure 5 also shows a representative PPC buildup transient at $T=170$ K for $Zn_{0.3}Cd_{0.7}Se$ ($\bigcirc$). The solid line for $Zn_{0.3}Cd_{0.7}Se$ in Fig. 5 is a least-squares fitting using

$$I(t) = I_{max}(1 - e^{\alpha t})^2 .$$
(10)

FIG. 6. The PPC saturation level I_{max} versus excitation photon flux N_{ph} for $Al_{0.3}Ga_{0.7}As$ at $T=60$ K. The solid line is a least-squares fitting using Eq. (8).
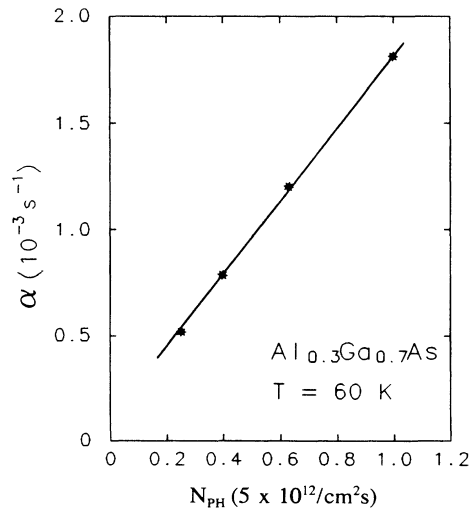

FIG. 7. Decay parameter associated with the PPC buildup process α vs excitation photon flux N_{ph} for $Al_{0.3}Ga_{0.7}As$ at $T=60$ K. The solid line is a least-squares fitting using Eq. (9).

In Eq. (10), t is again the illumination time, measured from the moment the excitation light is turned on. We see that experimental results can be well described by Eq. (10). The fitting parameters are $I_{max} = 1.85 \times 10^{-10}$ A and $\alpha = 1.96 \times 10^{-3}$ s^{-1}. I_{max} again is the PPC saturation level. The physical origin for such a buildup behavior is now completely understood and has been discussed previously.[18] For small t, Eq. (10) implies a parabolic dependence of the PPC buildup level on the illumination time, i.e., $I(t) \propto t^2$, contrary to the initial linear dependence exhibited by Al$_{0.3}$Ga$_{0.7}$As. Such a sharp difference can be seen from Fig. 5.

The PPC buildup behavior of Eq. (10) in Zn$_{0.3}$Cd$_{0.7}$Se is predominantly caused by electron conduction in band-tail states that arise from compositional fluctuations. Because of this fluctuation, in the low carrier concentration region, electrons are localized in the tail states and the conductivity is induced by electrons hopping between the localized states. As a consequence, the electron mobility in such a case is no longer independent of electron concentration, and the conductivity of the sample is described by $\sigma = -\int (\partial f / \partial E) \sigma(E) dE$,[21] where $f(E)$ is the Fermi distribution function for electrons and $\sigma(E)$ is the conductivity at energy E, which depends on the electron concentration or illumination time and is described by the Kubo-Greenwood formula.[21] Notice that in the discussion presented here, the conductivity caused by hole transport has been neglected because of their heavier masses. It can be shown that the dependence of the electron concentration n on the illumination time for II-VI semiconductor alloys also follows Eq. (7) except that now $g = N_{ph} \alpha' \eta / n_t$, with the assumption that it is a band-to-band excitation, where α' is the photon absorption coefficient and η is the quantum efficiency. Furthermore, the maximum electron concentration in the conduction band is now described by $n_{max} = g n_t / (g + \omega)$, where n_t is the highest possible stored electron concentration in such a fluctuating potential. The physical significance of n_t can be understood. The quasi-Fermi level increases as the stored electron concentration n increases; however, when n increases up to a certain level, wave functions of electrons and holes start to overlap and hence any further increase of the illumination time can no longer increase the concentration of the stored charge carriers, because they recombine immediately after the excitation, as in the case of the conventional photoconductivity; thus there is a certain energy level in the conduction band below which electrons are in the PPC state, and consequently n_t can be obtained by integrating from the minimum energy to this level. If one assumes that the tail of the density of states (DOS) is exponential,[22] then Eq. (10) can be obtained,[18] which describes well the PPC buildup transients in Zn$_{0.3}$Cd$_{0.7}$Se in the low carrier concentration region. Therefore, our experimental results also demonstrate that the distribution of the tail states in disordered systems may be probed by utilizing the PPC buildup transients. In particular, the tail states in II-VI semiconductor alloys are shown here to decrease exponentially with energy.

The reason the effect of the tail states is negligible in Al$_{0.3}$Ga$_{0.7}$As is that the amplitude of the fluctuating potential caused by compositional fluctuation is proportional to γ^4, where γ is the rate of variation of the band edge with the composition x, $\gamma = dE_g / dx$ (Refs. 14 and 15). For III-V semiconductor alloys, γ is small, and so the potential fluctuation was predicted to be on the order of 10^{-2} meV. For wide-band-gap II-VI semiconductor alloys, the large difference in the value of E_g promises a considerably greater potential fluctuations of the band edge on the order of a few tens of meV. Thus the DX centers play a dominant role in determining the transport properties in doped Al$_x$Ga$_{1-x}$As. However, the transport properties in II-VI semiconductor alloys are governed by random potentials or compositional fluctuations, especially in the region of low electron concentration.

It was shown that for II-VI semiconductor alloys, when the conductivity is caused by electron transport in the tail states and when the carrier concentration is low, one has $I(t) \sim n^2(t)$. Hence

$$\alpha = \omega + g = \omega + N_{ph} \alpha' \eta / n_t , \qquad (11)$$

and

$$I_{max} = \frac{C g^2 n_t^2}{(\omega + g)^2} = \frac{C \alpha'^2 \eta^2 N_{ph}^2}{(\omega + N_{ph} \alpha' \eta / n_t)^2} , \qquad (12)$$

where C is a proportionality constant depending on the matrix element of localized electrons and the slope of the exponential band-tail states[18] and ω is the electron-decay rate in the PPC buildup process. From Eq. (11), we expect that the decay parameter associated with the PPC buildup process α is also proportional to the photon flux N_{ph}. We have obtained α at different intensities by fitting PPC buildup transients with Eq. (10) for Zn$_{0.3}$Cd$_{0.7}$Se at $T = 170$ K, which is plotted in Fig. 8, and a linear dependence of α on N_{ph} is evident. The solid line is a least-squares fitting using Eq. (11), with the fitting parameters $\omega = 1.3 \times 10^{-3}$ s^{-1} and $\alpha' \eta / n_t = 7.3 \times 10^{-16}$ cm^2. So the decay parameter α in Al$_{0.3}$Ga$_{0.7}$As and Zn$_{0.3}$Cd$_{0.7}$Se in-
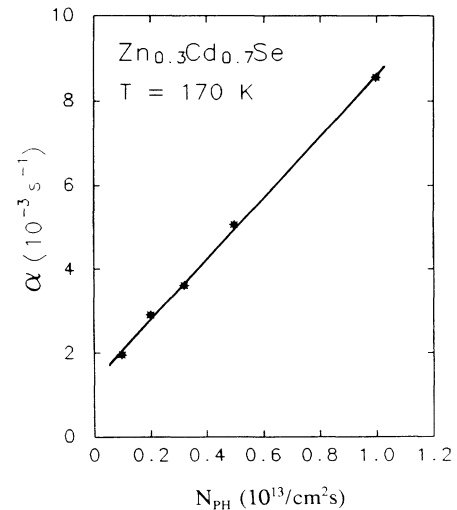

FIG. 8. Decay parameter associated with the PPC buildup process α vs excitation photon flux N_{ph} for Zn$_{0.3}$Cd$_{0.7}$Se at $T = 170$ K. The solid line is a least-squares fitting using Eq. (11).
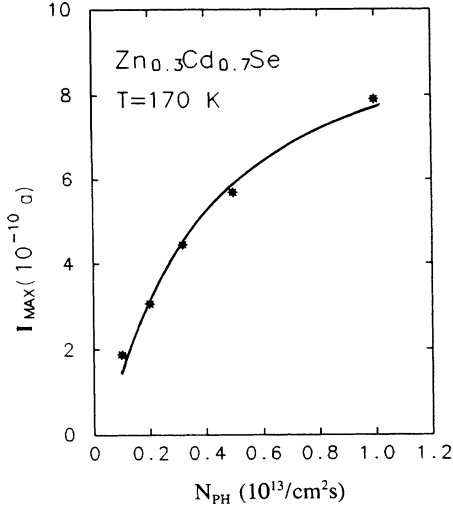
FIG. 9. The PPC saturation level I_{max} vs excitation photon flux N_{ph} for $Zn_{0.3}Cd_{0.7}Se$ at $T=170$ K. The solid line is a least-squares fitting using Eq. (12).

creases linearly with increasing photon flux N_{ph}. However, the electron-decay rate in the PPC buildup process ω is larger in $ZN_{0.3}CD_{0.7}Se$, which seems consistent with the fact that PPC decays faster in II-VI semiconductor alloys than in $Al_xGa_{1-x}As$.

Figure 9 shows the plot of the PPC saturation level I_{max} as a function of the photon flux N_{ph} for $Zn_{0.3}Cd_{0.7}Se$ at $T=170$ K. I_{max} increases with an increase of N_{ph} as we expected. The solid line is a least-squares fitting using Eq. (12), and is in good agreement with experimental results. The fitting parameters are $Cn_t^2=1.05\times10^{-9}$ A and $\omega n_t/\alpha'\eta=1.7\times10^{12}/$ cm^2 s, which is consistent with the value obtained from Fig. 8 ($\omega n_t/\alpha'\eta=1.8\times10^{12}/$ cm^2 s).

We emphasize that Eqs. (11) and (12) are only valid for the case of low carrier concentration, or, more precisely, when the electron quasi-Fermi level is around or below the electron mobility edge. In the case where the electron Fermi level is above the mobility edge, PPC buildup transient in $Zn_{0.3}Cd_{0.7}Se$ is expected to follow Eq. (5), just as in $Al_{0.3}Ga_{0.7}As$. In that case, the effect of the tail states or the influence from potential fluctuations is negligible, and hence the electron mobility becomes independent of carrier concentration. The changing of the PPC buildup transient behavior from that of Eq. (10) to Eq. (5) as the Fermi level crosses over the mobility edge has been observed in $Zn_{0.3}Cd_{0.7}Se$.[18] Although I_{max} increases with an increase of N_{ph} in both $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$, the behaviors are quite different; namely I_{max} follows Eq. (8) for $Al_{0.3}Ga_{0.7}As$ but it follows Eq. (12) for $Zn_{0.3}Cd_{0.7}Se$. In the case when both DX and potential fluctuations are important, as in some II-VI compensated semiconductors, such as in CdTe or its alloy, Eqs. (10)–(12) still describe the PPC buildup transient, except that $a'\eta/n_t$ and n_t have to be replaced by σ_{DX} and N_{DX}, respectively.

In the above, PPC buildup and decay have been de-

scribed separately. Since now we know both the buildup and decay forms, we can write one single equation that describes the entire PPC kinetics:

$$I(t)= \begin{cases} I_{max}[1-\exp(-\alpha t)] & (t<t_0) \quad\quad\quad\quad (13a) \\ I_{max}[1-\exp(-\alpha t_0)]\exp\{-[(t-t_0)/\tau]^\beta\} \\ \quad\quad\quad\quad\quad\quad\quad\quad (t\geq t_0), \quad (13b) \end{cases}$$

for $Al_{0.3}Ga_{0.7}As$ at $T<90$ K, and

$$I(t)= \begin{cases} I_{max}[1-\exp(-\alpha t)]^2 & (t<t_0) \quad\quad\quad (14a) \\ I_{max}[1-\exp(-\alpha t_0)]^2\exp\{-[(t-t_0)/\tau]^\beta\} \\ \quad\quad\quad\quad\quad\quad\quad\quad (t\geq t_0), \quad (14b) \end{cases}$$

for $Zn_{03.}Cd_{0.7}Se$ at the low electron concentration region. In Eqs. (13) and (14), time t is measured from the moment the excitation light is turned on ($t=0$), and t_0 represents the moment the excitation light is terminated. There are four independent parameters, I_{max}, α, τ, and β, which describe completely PPC buildup and decay at different conditions. Notice that α, representing the electron-decay parameter associated with the PPC buildup process, has a different physical significance compared to the decay rate $(1/\tau)$ measured from the PPC decay process. Although both α and τ here are correlated with the electron relaxation, their connection is unknown at this stage and remains to be investigated.

IV. CONCLUSIONS

The PPC decay and buildup transients in $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ have been investigated. The PPC decay kinetics at different electron concentration levels in the temperature region of $T>10$ K in $Al_{0.3}Ga_{0.7}As$ have been measured; at low temperatures ($T<20$ K), the decay time constant τ is found to decrease with an increase of electron concentration n in the low concentration region, but it increases with an increase of n in the higher concentration region; this has been attributed to the crossover from a nondegenerate to a degenerate regime as the electron concentration increases; at $T=80$ K, the degenerate concentration cannot be attained and the decay time constant of PPC as a function of the electron concentration can be described by a thermally activated capture of electrons at the DX centers, and τ monotonically decreases with increasing n, following a $\tau\propto1/n$ behavior, which is consistent with the logarithmic dependence of the electron quasi-Fermi level with concentration n in the nondegenerate regime. Based on our findings, one can vary the PPC lifetime by controlling the excitation photon dose, which could be useful for device applications. The PPC buildup transients have been measured and formulated for $Zn_{0.3}Cd_{0.7}Se$ and are found to be very different from those of $Al_{0.3}Ga_{0.7}As$, which has been attributed to the existence of potential fluctuations in II-VI semiconductor alloys caused by compositional fluctuations. The excitation photon flux dependence of the PPC saturation level I_{max} and the decay parameter associated with the PPC buildup process α have also been measured

for both $Al_{0.3}Ga_{0.7}As$ and $Zn_{0.3}Cd_{0.7}Se$ and they are found in good agreement with calculations. The photoionization cross section of DX centers in $Al_{0.3}Ga_{0.7}As$, σ_{DX}, has also been obtained from the PPC buildup transient measurements and is consistent with the value obtained by other experimental techniques. It is shown that the PPC buildup transient not only contains information about electron excitation, it also contains information about electron relaxation. Our experimental results indicate that the transport properties in $Al_{0.3}Ga_{0.7}As$ are controlled by DX centers as expected, but in II-VI semiconductor alloys in the low electron concentration region they are governed nonetheless by tail states induced by compositional fluctuations.

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