

# Time-resolved photoluminescence spectra of $\text{Ga}_x\text{In}_{1-x}\text{P}$ under picosecond-laser-pulse excitation measured by a streak camera

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We have measured the time-resolved photoluminescence spectra of  $\text{Ga}_x\text{In}_{1-x}\text{P}$  ( $x=0.56$ ) with 10-ps time resolution using a streak camera. From the theoretical fitting of photoluminescence spectra we determine the time evolution of the carrier density and carrier temperature. We find the carrier-energy-loss rate to be slower than predicted from a simple model if we assume a Maxwell-Boltzmann distribution function. This is attributed to the screening of the hot-carrier energy relaxation under high-carrier densities. Integro-differential equations describing the time dependence of the carrier temperature are solved, and the results are compared with the experimental data.

## INTRODUCTION

Over the past decade a great deal of effort has been devoted to research on III-V ternary semiconductors. The efficient conversion of electrical energy to optical energy in GaAs has long been realized. Partial substitution of P for As or Al for Ga results in the fabrication of  $\text{GaAs}_{1-x}\text{P}_x$  and  $\text{Ga}_{1-x}\text{Al}_x\text{As}$  semiconductor alloy systems with adjustable band gaps depend on the degree of substitution. One of the important semiconductor alloy systems is  $\text{Ga}_x\text{In}_{1-x}\text{P}$  which has interesting optical and electrical properties. The band gap of this ternary semiconductor increases from 1.351 ( $x=0$ , direct) to 2.78 eV ( $x=1$ , indirect) and at  $x=0.73$  the direct-indirect crossover occurs.<sup>1</sup>

Information about the dynamics of hot-carrier energy relaxation in highly excited semiconductors is important and fundamental in the design and fabrication of high-speed devices. Time-resolved absorption and luminescence spectroscopy of semiconductors provide direct information about the evolution of the carrier density as well as on the distribution function.<sup>2</sup> To study the ultrafast processes in semiconductors there are a variety of direct and indirect techniques: pump and probe,<sup>3</sup> optical Kerr gate,<sup>4</sup> up-conversion gate,<sup>5</sup> and streak camera.<sup>6</sup> The energy relaxation of low-density carriers in GaAs has been studied by Ulbrich by measuring the photoluminescence spectra under nanosecond-laser-pulse excitation.<sup>7</sup> From the results of picosecond reflection measurements Shank *et al.*<sup>8</sup> concluded that in GaAs carriers with initial energies of 0.6 eV lose their energy and thermalize with the lattice in about 2 ps. At high photogenerated carrier density, the screening of the electron-phonon interaction<sup>9</sup> and nonequilibrium optical-phonon buildup can occur.<sup>10</sup> Shah *et al.*<sup>11</sup> observed a moderate decrease in the carrier cooling rate at high excitation power in GaAs. Seymour, Junnarkar, and Alfano<sup>6</sup> and Yao and Alfano,<sup>12</sup> using the streak-camera technique, observed a pronounced reduction in the cooling rate of photogenerated carriers in GaAs and GaSe, respectively. In these cases, the reduction of the cooling rate of the photogenerated carriers were either attributed to the screening of the carrier-

phonon interaction or to the nonequilibrium phonon population. Recently using the up-conversion-gate technique, Kash and Shah<sup>13</sup> studied the cooling rate of carriers in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ . They found the cooling rate to be insensitive to the density of photogenerated carriers. This was in contrast to the measurements of the carrier cooling rate in GaAs and GaSe. In most of the experiments done to date, the semiconductor samples were excited at low temperatures. There has not been that much information available in the literature about carrier-energy relaxation at room temperature even though most of the electronic and optical devices fabricated from semiconductors are used at room temperature.

In this paper, we report on measurements of the time-resolved spectra of  $\text{Ga}_x\text{In}_{1-x}\text{P}$  ( $x=0.56$ ) at room temperature using a streak camera as the detection system. The photoluminescence spectra at various times were fitted to the theoretical expression for direct transitions. From the fitting, the time evolution of the photogenerated carrier density, temperature, and distribution function have been determined.

## EXPERIMENTAL METHODS

The experimental setup used in this research has been describe in detail elsewhere.<sup>14</sup> A second harmonic (527 nm) of a Nd-glass laser pulse of 8 ps duration was used to excite the sample of  $\text{Ga}_x\text{In}_{1-x}\text{P}$  ( $x=0.56$ ) on the front surface. The excitation area was measured to be approximately  $8 \times 10^{-3} \text{ cm}^2$ . The sample was 1.5  $\mu\text{m}$  thick, moderately pure ( $10^{16} \text{ cm}^{-3}$ ) and was grown by vapor-phase epitaxy (VPE) on a GaAs substrate. The composition of the sample was determined from the calibration of the band gap versus composition.<sup>1</sup> The band gap of the sample was determined to be 1.903 eV at room temperature from the relationship

$$E_g = h\nu_p - \frac{1}{2}k_B T,$$

where  $h\nu_p$  is the peak energy in the low-power steady-state photoluminescence spectra and  $\frac{1}{2}k_B T$  accounts for the direct transition of the carriers. The photolumines-

cence of the sample was collected by a combination of lenses and imaged into a 30- $\mu\text{m}$  slit of a Hamamatsu streak camera. The output was detected by a temporal analyzer and computer for data analysis. The time resolution of the detection system was approximately 10 ps. Various narrow-band filters centered at different energies were placed in front of the streak camera to select different spectral regions of the photoluminescence spectra corresponding to carriers with different energies.

### EXPERIMENTAL RESULTS

Time-resolved photoluminescence profiles at different energies are shown in Fig. 1 for an excitation pulse of 60  $\mu\text{J}$ . We used

$$N(E,t) = A \left[ \exp\left(\frac{-t}{\tau_d(E)}\right) - \exp\left(\frac{-t}{\tau_r(E)}\right) \right]$$

to fit the experimental time-resolved profiles of Fig. 1 in order to determine rise and decay times of the emission at different energies. In the above equation,  $N(E,t)$  is the number of photons detected at energy  $E$ , where  $E$  is the central energy of the narrow-band filter,  $\tau_d(E)$  and  $\tau_r(E)$  are the decay and rise time of the time-resolved profiles at energy  $E$ , and  $A$  is the proportionality constant. The vertical scale of the time-resolved profile at  $E = 1.981$  eV has been normalized to 1000 counts and the rest of the vertical scales are relative to  $E = 1.981$  eV for comparison. All the time-resolved profiles shown in Fig. 1 are corrected for nonlinearity of the detection system, streak-camera-tube spectral response, and the transmission of the narrow-band filters. Each time-resolved profile shown in Fig. 1 was repeated several times and the deviation in the vertical scale was less than 5%.

The salient features of the time-resolved profiles shown in Fig. 1 are as follows: The rise time  $\tau_r(E)$  of the emission increased moderately from 10 ps at  $E = 2.107$  eV [Fig. 1(a)] to 18 ps at  $E = 1.919$  eV [Fig. 1(f)]. The decay time of the emission  $\tau_d(E)$  increased from 47 ps at  $E = 2.107$  eV [Fig. 1(a)] to 310 ps at  $E = 1.919$  eV near the band edge [Fig. 1(f)]. Figure 2 shows the plot of the rise time of the emission versus energy. The variation of the decay time with respect to energy is shown in Fig. 3. Since the number of photons detected [ $N(E)dE$ ] at different energies decayed with different decay time, we have plotted  $N(E,t)$  versus  $E$  to obtain the photoluminescence spectra at different times. Figure 4 shows the photoluminescence spectra at  $t = 0, 25, 50, 100, 150,$  and  $200$  ps. The circles are the experimental results and the solid lines are the theoretical line shapes assuming direct transitions of the carriers with  $k$  conservation. Theoretical fitting will be discussed in the next section. The photoluminescence spectrum at  $t = 0$  ps [Fig. 4(a)] is a very broad full-width at half-maximum (FWHM) of  $\sim 200$  meV. At longer times the spectra become narrower and the maximum shifts to lower energies. The slope of the high-energy tail becomes steeper, reflecting the cooling of the carriers. At  $t = 200$  ps [Fig. 4(f)] the peak of the spectrum is around 635 nm with a FWHM of  $\sim 100$  meV. The decrease in the FWHM of the spectra with time is due to the reduction of the photogenerated carrier density

by recombination and possibly plasma expansion.<sup>15</sup> Comparing the spectra at  $t = 0$  and  $t = 200$  ps shows that the intensity of the photoluminescence around the band edge (645 nm) increased with time.

### THEORETICAL FITTING

In order to determine the carrier temperature and the photogenerated carrier density at different times, the photoluminescence spectra of Fig. 4 were fitted to the theoretical expression of line shape assuming direct transitions. The photoluminescence spectra neglecting the effect of the reabsorption of the emitted photons through the epilayer can be described by<sup>16</sup>

$$N(E)dE \sim E^2(E - \hat{E}_g)^{1/2} f_e \left[ \frac{m_e}{m_e + m_h} (E - \hat{E}_g), \mu_e \right] \times f_h \left[ \frac{m_h}{m_h + m_e} (E - \hat{E}_g), \mu_h \right] dE, \quad (1)$$

where  $N(E)dE$  is the number of photons detected within energy  $dE$  of energy  $E$ ,  $\hat{E}_g$  is the reduced band gap, and  $f_e$  and  $f_h$  are the electron- and hole-occupation probabilities which are given by

$$f_i(\epsilon, \mu_i) = \left[ 1 + \exp\left(\frac{\epsilon - \mu_i}{k_B T_i}\right) \right]^{-1} \quad \text{for } i = e, h, \quad (2)$$

where  $T_i$  is the carrier temperature. In Eq. (1) the recombination matrix element is assumed to be independent of the carrier energy. The carrier density for a degenerate distribution is given by

$$n = N_c F_{1/2}(\eta_i) \quad \text{for } i = e, h, \quad (3)$$

where

$$N_c = 2 \left[ \frac{2\pi m_i^* k_B T_i}{h^2} \right]^{3/2} \quad \text{and} \quad \eta_i = \frac{\mu_i}{k_B T_i}.$$

The  $F_{1/2}(\eta_i)$  is the Fermi integral and is given by<sup>17</sup>

$$F_j(\eta_i) = \frac{1}{\Gamma(j+1)} \int_0^\infty \frac{x^j}{1 + \exp(x - \eta_i)} dx. \quad (4)$$

Since  $\mu_e$  and  $\mu_h$  are related to carrier temperature by Eq. (3) through the Fermi integral we used the approximate analytical expression for  $\eta$  given by<sup>18</sup>

$$\eta = \ln \left[ \frac{n}{N_c} \right] + 0.353 \left[ \frac{n}{N_c} \right] - 4.95 \times 10^{-3} \left[ \frac{n}{N_c} \right]^2 + 1.48 \times 10^{-4} \left[ \frac{n}{N_c} \right]^3 - 4.42 \times 10^{-6} \left[ \frac{n}{N_c} \right]^4 + \dots \quad (5)$$

for simplifying the fitting procedure. Equation (5) is accurate at low carrier densities  $n/N_c \leq 1$  and at high carrier densities  $n/N_c \sim 15$  there is less than 5% error in calculation of Fermi levels.

To determine the carrier density ( $n$ ), reduced band gap ( $\hat{E}_g$ ), and carrier temperature ( $T_c$ ), we have fitted the

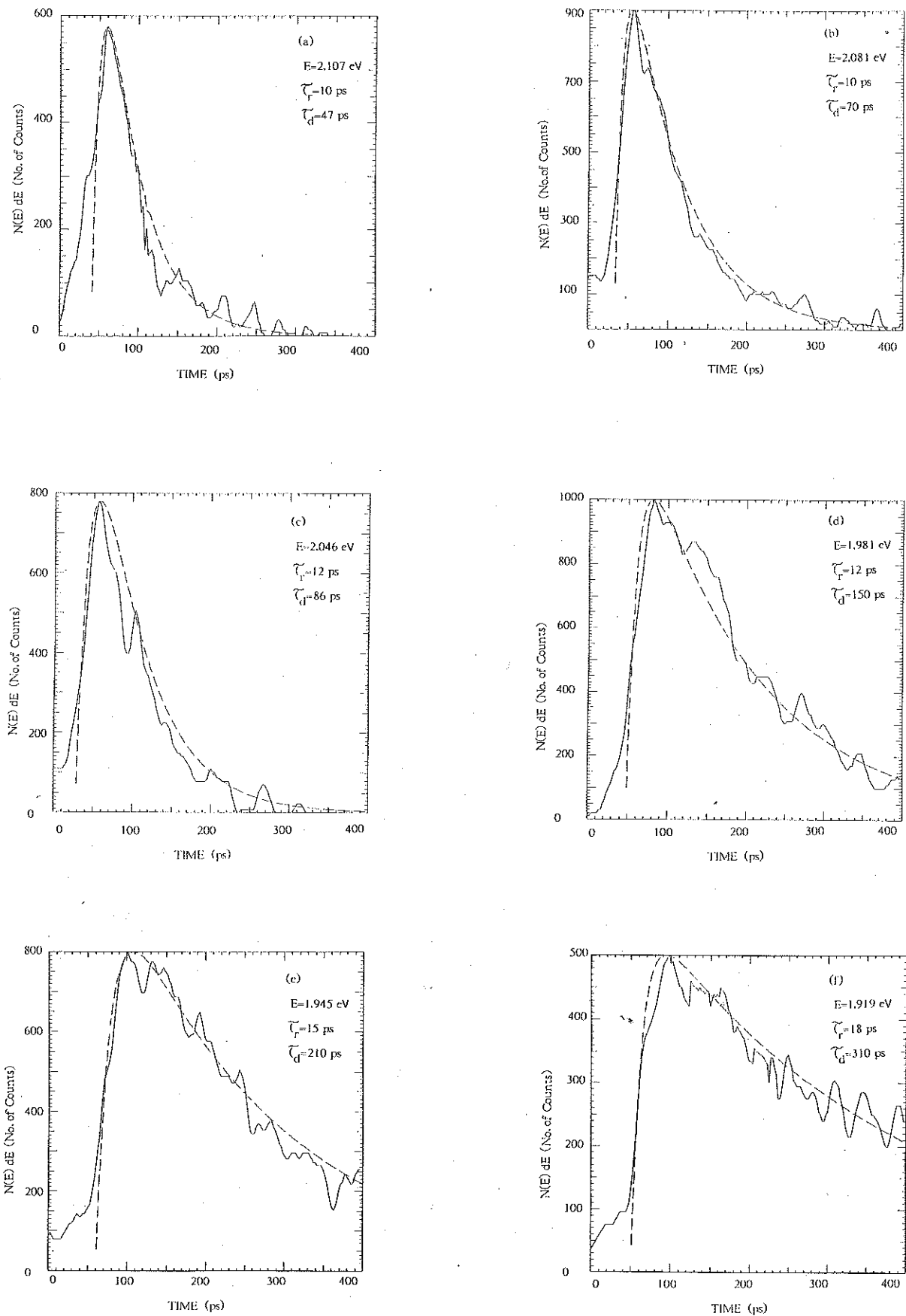


FIG. 1. (a)–(f) Time-resolved photoluminescence profiles of Ga<sub>0.56</sub>In<sub>0.44</sub>P at different energies under picosecond-laser-pulse excitation of 60- $\mu$ J energy. The solid lines are the experimental data and the broken lines are the theoretical fit.

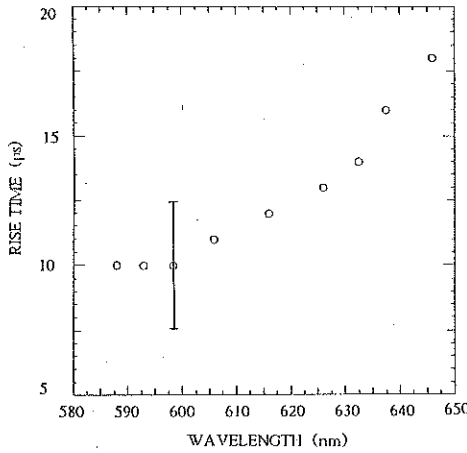


FIG. 2. Rise time of the emission as a function of the energy.

time-resolved photoluminescence spectra to Eq. (1) assuming electrons and holes have the same temperature. The main objective of the fitting was to obtain the best fit on the high-energy side of the photoluminescence spectra where the effect of the band-gap renormalization and band filling is not important.

At  $t=200$  ps [Fig. 4(f)] the carrier temperature was assumed to be the same as room temperature, namely,  $T_c=300$  K, and  $\hat{E}_g$  and  $n$  were treated as parameters to obtain the best fit between the experimental photoluminescence spectrum and the theoretical line shape given by Eq. (1). The best fit was obtained when  $E_g=1.913$  eV and  $n=3.4 \times 10^{18}$  cm $^{-3}$ . The reduced band gap obtained from the fitting of the spectrum at  $t=200$  ps is lower than the band gap by  $\sim 10$  meV as a result of band-gap renormalization at high carrier densities.<sup>19,20</sup> The fact that we assume that the carriers are in thermal equilibrium with the lattice at  $t=200$  ps is justified by the fact that the carrier temperature drops at the rate of  $\approx 1000$  K/ps assuming a Maxwell-Boltzmann distribution function.<sup>21</sup> For the rest of the photoluminescence spectra we used the value of  $\hat{E}=1.913$  eV as a fixed parameter and carrier temperature ( $T_c$ ) and carrier density

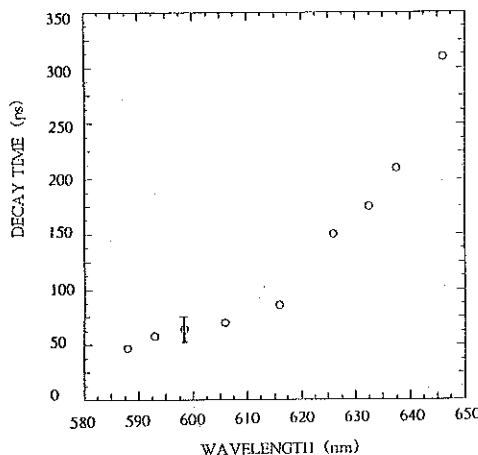


FIG. 3. Decay time of the emission as a function of the energy.

( $n$ ) as dynamical variables. The best fit of the experimental data of Fig. 4 to Eq. (1) was when  $n=6.6 \times 10^{18}$  cm $^{-3}$ ,  $T_c=725$  K for  $t=0$  ps spectra [Fig. 4(a)];  $n=6.1 \times 10^{18}$  cm $^{-3}$ ,  $T_c=540$  K for  $t=25$  ps [Fig. 4(b)];  $n=5.6 \times 10^{18}$  cm $^{-3}$ ,  $T_c=445$  K for  $t=50$  ps spectra [Fig. 4(c)];  $n=4.7 \times 10^{18}$  cm $^{-3}$ ,  $T_c=325$  K for  $t=100$  ps spectra [Fig. 4(d)];  $n=4.2 \times 10^{18}$  cm $^{-3}$ ,  $T_c=310$  K for  $t=150$  ps spectra [Fig. 4(e), and  $n=3.4 \times 10^{18}$  cm $^{-3}$  and  $T_c=300$  for  $t=200$  ps spectra [Fig. 4(d)].

The time dependence of the photogenerated carrier density as determined from the above fitting is shown in Fig. 5. The experimental points of  $n(t)$  in Fig. 5 were fitted to the equation

$$n_e(t) = n_e(0) \exp\left[-\frac{t}{\tau}\right] \quad (6)$$

to determine the carrier lifetime ( $\tau$ ), where  $\tau$  is the time where the carrier density drops to  $1/e$  of its initial value. The best fit was obtained when  $\tau=290 \pm 10$  ps. Note that this value is very close to the decay time of the time-resolved profile near the band edge [see Fig. 1(f)]. The deduced carrier temperature determined from the above fitting as a function of time is shown in Fig. 6 by open circles.

## DISCUSSION

Excitation of Ga $_{0.56}$ In $_{0.44}$ P ( $E_g=1.903$  eV) by a 527-nm (2.34 eV) ps laser pulse creates electrons with initial energy of

$$\frac{m_h}{m_e + m_h} (h\nu_L - E_g) = 0.35 \text{ eV}$$

in the conduction band and holes with excess energy of

$$\frac{m_e}{m_e + m_h} (h\nu_L - E_g) = 0.09 \text{ eV}$$

in the valence band. The photogenerated carriers lose their energy by interaction with LO phonons as long as their temperature is above 40 K. The average rate of energy loss due to carrier LO phonon interaction for a Maxwell-Boltzmann distribution is given by<sup>21</sup>

$$\left\langle \frac{d\epsilon}{dt} \right\rangle = -P_0 \left[ \frac{e^{x_0 - x_c} - 1}{e^{x_0} - 1} \right] \times \left[ \frac{(x_c/2)^{1/2} e^{x_c/2} K_0(x_c/2)}{(\pi/2)^{1/2}} \right], \quad (7)$$

where  $P_0$  is a parameter (in units of eV/sec) independent of carrier temperature and is given by

$$P_0 = 3.54 \times 10^{11} [\hbar\omega_{LO}(\text{meV})]^{3/2} \left[ \frac{m_e^*}{m} \right]^{1/2} \left[ \frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_s} \right]. \quad (8)$$

In Eq. (7),  $x_0 = \hbar\omega_{LO}/k_B T_L$ ,  $x_c = \hbar\omega_{LO}/k_B T_c$ , and  $K_0(x)$  is the modified Bessel function of zero order; the rest of

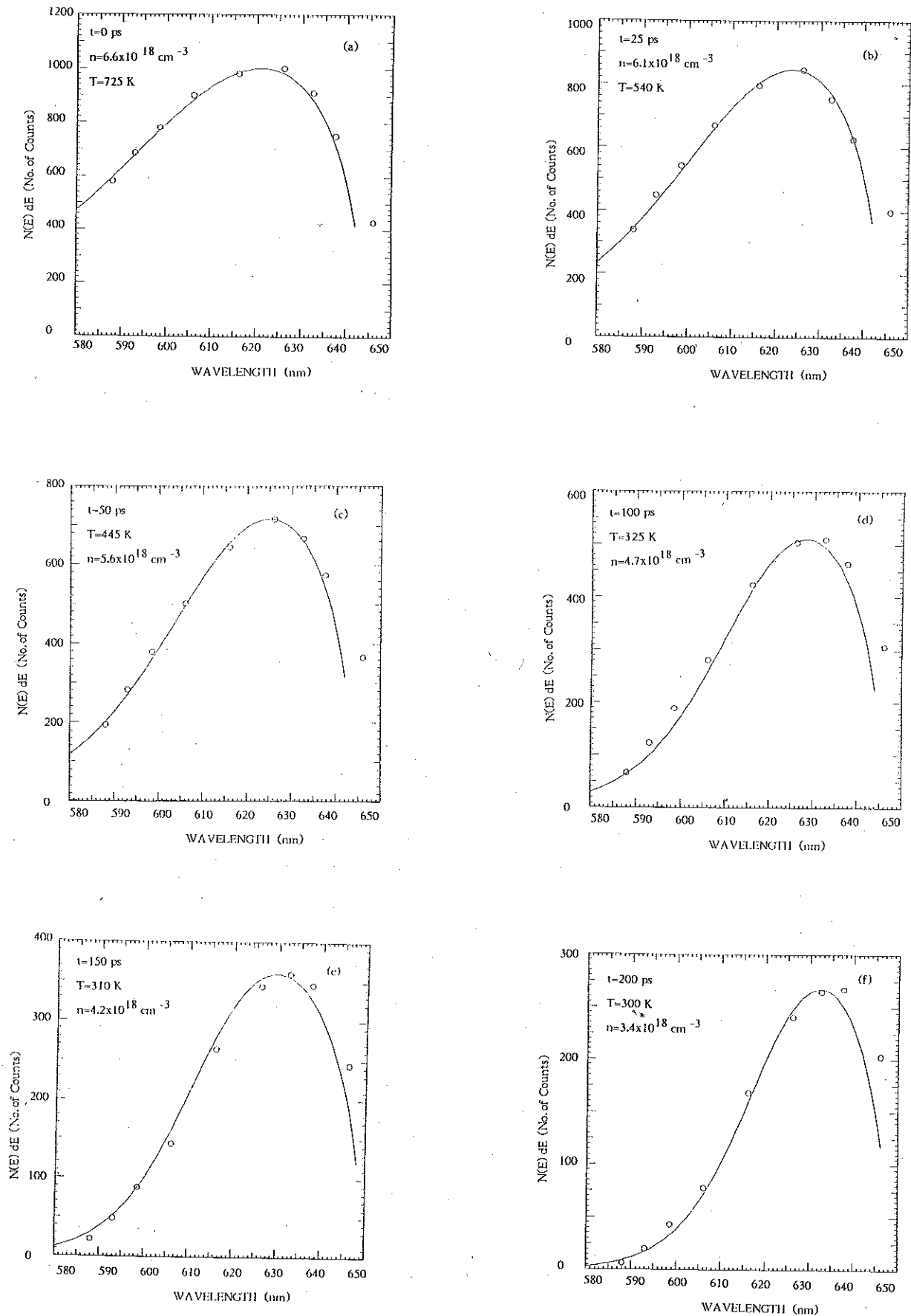


FIG. 4. (a)–(f) Time-resolved photoluminescence spectra of  $\text{Ga}_{0.56}\text{In}_{0.44}\text{P}$  at  $t=0, 25, 50, 100, 150,$  and  $200$  ps. The circles are experimental data and solid lines are the theoretical fit assuming direct transition of carriers with  $k$ -selection rule.

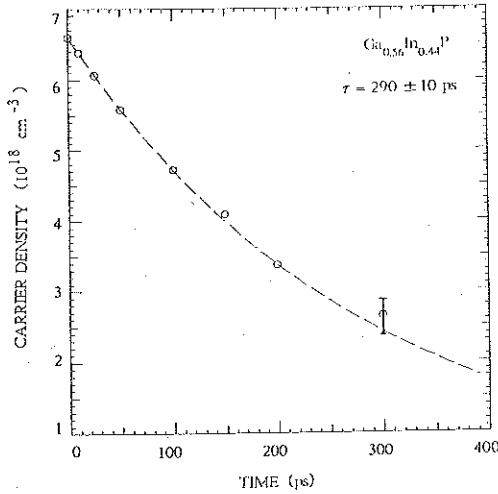


FIG. 5. Density of photogenerated carriers vs time. The circles are determined from the time-resolved spectra and the broken line is the fit assuming exponential decay.

the parameters have their usual meanings. Since electrons in conduction bands are Fermi gas, the average energy  $\langle \epsilon \rangle$  of electrons is  $\frac{3}{2}kT_c$ . Therefore the left-hand side of Eq. (7) may be replaced with  $\frac{3}{2}k_B dT_c/dt$  to obtain the differential equation describing the time evolution of carrier temperature. For  $\text{Ga}_{0.50}\text{In}_{0.44}\text{P}$  this equation simplifies to (in units of K/ps)

$$\frac{dT_c}{dt} = -8 \times 10^3 \left[ \frac{e^{x_0 - x_c} - 1}{e^{x_0} - 1} \right] \times \left[ \frac{(x_c/2)^{1/2} e^{x_c/2} K_0(x_c/2)}{(\pi/2)^{1/2}} \right] \quad (9)$$

To determine  $T_c$  vs  $t$  from Eq. (9) we used the value of  $m_e = 0.094$  for the electron effective mass,<sup>22</sup>  $\epsilon_\infty = 11.6$  for the optical dielectric constants,  $\epsilon_s = 9.1$  for the static

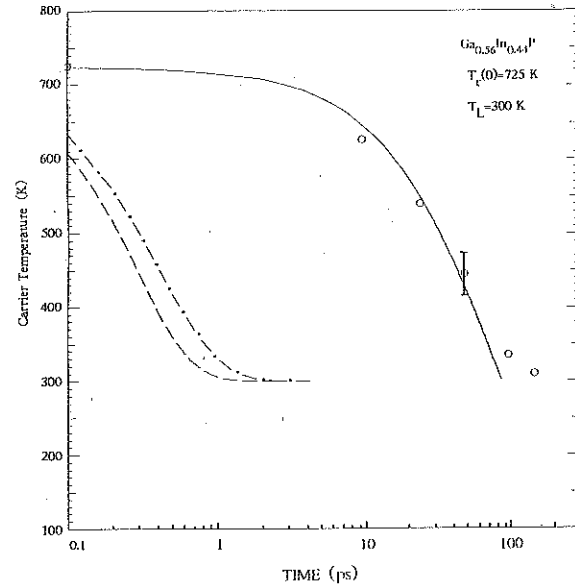


FIG. 6. Time dependence of carrier temperature. The circles are the experimental data, the dashed curve is calculated for a MB distribution, the dashed-dotted curve is calculated for a FD distribution, and the solid curve is calculated in the presence of screening.

dielectric constant, and 48 meV for the LO phonon energy.<sup>23</sup> Equation (9) has been solved numerically by computer to obtain the time dependence of the carrier temperature. This is shown in Fig. 6 by a dashed curve and it shows that in the case of a Maxwell-Boltzmann distribution ( $\eta < 0$ ) the carriers are thermalized with the lattice temperature in less than  $\sim 2$  ps for the initial temperature of 725 K. In  $\text{Ga}_{0.56}\text{In}_{0.44}\text{P}$  the distribution of electrons is degenerate when  $n > 3.5 \times 10^{17} \text{ cm}^{-3}$  and one has to consider the Fermi-Dirac (FD) distribution function. The cooling rate in the case of FD distribution is calculated by Bauer and Kahlert and is given by<sup>24</sup>

$$\left\langle \frac{d\epsilon}{dt} \right\rangle = -P_0 x_c^{1/2} \left[ \frac{2}{\sqrt{\pi}} \right] \frac{1}{F_{1/2}(\eta)} \left[ N_q \int_0^\infty f(\epsilon) [1 - f(\epsilon + x_c)] \sinh^{-1} \left[ \frac{\epsilon}{x_c} \right]^{1/2} d\epsilon - (N_q + 1) \int_0^\infty f(\epsilon + x_c) [1 - f(\epsilon)] \sinh^{-1} \left[ \frac{\epsilon}{x_c} \right]^{1/2} d\epsilon \right], \quad (10)$$

where

$$N_q = 1 / [\exp(\hbar\omega_{\text{LO}}/k_B T) - 1]$$

is the occupation probability of phonons. In the case of FD distribution the changes in carrier temperature are given by<sup>25</sup>

$$\left\langle \frac{d\epsilon}{dt} \right\rangle = \frac{3}{2} k \left[ \frac{\frac{5}{2} F_{3/2}(\eta)}{F_{1/2}(\eta)} - \frac{\frac{3}{2} F_{1/2}(\eta)}{F_{-1/2}(\eta)} \right] \frac{dT}{dt}, \quad (11)$$

where  $F_j$  is the Fermi integral of order  $j$  and  $\eta = \mu_i/kT_c$ . When ( $\eta < 2$ ) the bracket in Eq. (11) is close to unity. Equations (6), (10), and (11) together give a complete description of the time evolution of carrier temperature in

the case of a FD distribution and they have to be solved together to yield the time dependence of the carrier temperature. Note that carrier temperature and carrier density are both dynamical variables and change with time. The time evolution of carrier temperature in the case of the FD distribution which is given by Eq. (10) has been solved numerically, assuming the initial carrier temperature to be 725 K. The result is shown in Fig. 6 by a dashed-dotted line and it shows even in the case of a FD distribution the carriers are thermalized with lattice in

$$\begin{aligned} \left\langle \frac{d\epsilon}{dt} \right\rangle = & \frac{-m_e^* e^2 (\omega_{LO})^2}{2\pi^2 \bar{\epsilon}} [N_{LO}(T_c) - N_{LO}(T_L)] \int_0^\infty k dk \left[ f \left[ \frac{\epsilon_k}{k_B T_c} \right] - f \left[ \frac{\epsilon_k + \hbar \omega_{LO}}{k_B T_c} \right] \right] \\ & \times \left[ \ln \frac{[k + (k^2 + 2m_e \omega_{LO}/\hbar)^{1/2}]^2 + Q^2}{[k - (k^2 + 2m_e \omega_{LO}/\hbar)^{1/2}]^2 + Q^2} \right. \\ & \left. - \frac{Q^2}{[k - (k^2 + 2m_e \omega_{LO}/\hbar)^{1/2}]^2 + Q^2} \right. \\ & \left. + \frac{Q^2}{[k + (k^2 + 2m_e \omega_{LO}/\hbar)^{1/2}]^2 + Q^2} \right], \end{aligned} \quad (12)$$

where  $N(T_c) - N(T_L)$  is the difference in phonon occupation at the carrier temperature and lattice temperature, and is equal to

$$N(T_c) - N(T_L) = \frac{1}{\exp \left[ \frac{\hbar \omega_{LO}}{k_B T_c} \right] - 1} - \frac{1}{\exp \left[ \frac{\hbar \omega_{LO}}{k_B T_L} \right] - 1}, \quad (13)$$

where  $Q$  is the Debye screening wave vector and is given by<sup>27</sup>

$$Q = \left[ \frac{32\pi e^2 n}{\epsilon_0 k_B T_c} \right]^{1/2}. \quad (14)$$

In Eq. (12) the value of  $\bar{\epsilon}$  is given by

$$\frac{1}{\bar{\epsilon}} = \frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_s}, \quad (15)$$

where  $\epsilon_\infty$  and  $\epsilon_s$  are the optical and static dielectric constants. At low carrier densities where screening is not important  $Q \rightarrow 0$  and in addition the Maxwell-Boltzmann (MB) statistics can apply, then the electron distribution becomes

$$\begin{aligned} f \left[ \frac{\epsilon_k}{k_B T_c} \right] &= \exp \left[ \eta_e - \frac{\epsilon_k}{k_B T_c} \right] \\ &= \frac{n_e}{2} \left[ \frac{h^2}{2\pi m_e k_B T_c} \right]^{3/2} \exp \left[ \frac{-\hbar^2 k^2}{2m_e k_B T_c} \right]. \end{aligned} \quad (16)$$

Under these conditions, the integral in Eq. (12) can be performed analytically to give the equation

less than  $\sim 3$  ps. The temperature of carriers determined from the fitting even at  $t = 50$  ps is around 450 K and shows that the carriers are not thermalized with the lattice.

In order to calculate the changes in carrier temperature at high carrier densities one has to take into account the effect of the screening of the carriers. The equation describing the rate of energy loss of carriers in the presence of screening is given by<sup>26</sup>

$$\left\langle \frac{d\epsilon}{dt} \right\rangle = n_e \left\langle \frac{d\epsilon}{dt} \right\rangle_{MB}, \quad (17)$$

where  $\langle d\epsilon/dt \rangle_{MB}$  is given by Eq. (7).

To obtain the time evolution of carrier temperature in the presence of screening we solved Eq. (12) numerically considering the fact that carrier density is a dynamical variable and its time dependence is given by Eq. (6). The result is shown in Fig. 6 by a solid line. The cooling curve fits the experimental data well when screening is included. This curve shows that carriers with initial temperature of  $725 \pm 25$  K lose their energy and reach the temperature of  $325 \pm 25$  K in about 100 ps. This implies that cooling rate has been reduced by a factor of 50. This reduction factor is calculated by comparing the cooling rate in the case of MB distribution  $\Delta T_c / \Delta t = (725 - 325) / 2 = 200$  K/ps with the result of cooling rate in the presence of screening  $\Delta T_c / \Delta t = (725 - 325) / 100 = 4$  K/ps. This reduction is comparable to the rate observed by Seymour, Junnarkar, and Alfano<sup>6</sup> in GaAs at high excitation power.

Reduction of cooling rate in semiconductors as a result of the screening of carrier phonon interaction has been calculated by Yoffa.<sup>9</sup> According to her calculations, in a polar semiconductor when density of photogenerated carriers exceeds a critical value of  $n_c$ , the phonon-emission frequency by hot carriers reduces by a factor of  $1 + (n_e/n_c)^2$  where  $n_e$  is the carrier density and  $n_c$  is the critical carrier density which is equal to

$$n_c = \frac{\epsilon_0 \hbar}{8\pi e^2 \sqrt{27}} \left[ \frac{m^*}{k_B T_c} \right] \omega^3, \quad (18)$$

where  $\omega$  is the phonon frequency and the rest of the terms have their usual meanings. By using the parameters of  $\text{Ga}_{0.56}\text{In}_{0.44}\text{P}$  and  $T_c = 725$  K a value of  $n_c = 2.37 \times 10^{17} \text{ cm}^{-3}$  is obtained. This implies a reduction of  $1 + (6.6 \times 10^{18} / 2.37 \times 10^{17})^2 = 775$  in the phonon-emission

rate. The difference between the experimentally observed reduction of cooling rate and the theoretical calculations based on Yoffa's theory may be due to the fact that Yoffa's calculations were carried out for a nondegenerate electron distribution.<sup>13</sup> The theoretical cooling rate for a degenerate carrier distribution including the effects of screening given by Eq. (12) fits the experimental data well. One of the reasons that the theoretically calculated cooling curve is slightly off from the fit to the experimental data beyond 100 ps is the fact that one has to consider other factors such as energy loss to coupled-plasmon phonon modes,<sup>28</sup> the population of nonequilibrium phonons,<sup>10</sup> and plasma expansion due to Fermi pressure.<sup>29</sup>

### CONCLUSION

In conclusion, we have measured time-resolved photoluminescence spectra of  $\text{Ga}_{0.56}\text{In}_{0.44}\text{P}$  with 10-ps resolution. From the theoretical fitting of the photolumines-

cence spectra we have obtained the time dependence of the carrier temperature. The observed spectra show the presence of a hot-carrier distribution following the exciting picosecond laser pulse. The theoretical time dependence of the carrier temperature in the presence of screening has been calculated and compared with experimental data. It is found that the electron-phonon interaction is reduced as a result of the screening of the carriers. The high-density hot-carriers lose their initial energy to the lattice by phonon emission at a reduced rate of  $\sim 4$  K/ps in contrast to the low-density carrier rapid rate of  $\approx 200$  K/ps.

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