Exciton dynamics in $GaAs/Al_xGa_{1-x}As$ doped quantum wells

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The interaction of excitons with impurities in an intentionally doped $GaAs/Al_xGa_{1-x}As$ quantum well has been studied using picosecond time-resolved photoluminescence employing resonant excitation. The dominance of exciton recombination in a quantum structure allows a detailed analysis of the interaction kinetics, not previously possible in bulk GaAs. The recombination kinetics on a picosecond time scale are found to be strongly dependent upon the doping level, temperature, and well width. The contribution of these terms to the balance of the population between free excitons and impurity-bound excitons is investigated. A numerical solution of the associated differential equations allows a quantitative evaluation of the parameters describing this interaction (for a 100-Å acceptor-doped QW at 5 K we obtain the exciton lifetime $\tau_{FE} \sim 180$ ps, the bound exciton lifetime $\tau_{BE} \sim 450$ ps, and the capture rate for free excitons to neutral acceptors $C_{FE} \sim 2$ cm^2 s^{-1}). A consistent picture of the capture and thermal emission processes for excitons at neutral acceptors and their effect on the observed quantum-well recombination transient emerges from this analysis.

I. INTRODUCTION

The predominance of exciton recombination within the low temperature radiative emission of quantum wells is well known.[1] The observed strength of this transition is generally understood in terms of the increased binding energy and the associated shrinkage of the Bohr radius of the exciton due to confinement. In addition to the overall prominence of the free exciton (FE) recombination, it is interesting to note the relatively weaker contribution of the bound exciton (BE) spectra at low temperatures in comparison to the bulk GaAs behavior. The bulk photoluminescence (PL) signal is, in contrast, dominated by the bound exciton component and the polaritonlike free exciton is found to be extremely weak in all but the highest purity samples.[2] By way of comparison, the estimated impurity concentration for which there remains a strong free exciton component in bulk material is by conservative estimate $\sim 10^{13}$ cm^{-3}. On the other hand, we show in this work that the free exciton component in the confined $Al_xGa_{1-x}As$/ GaAs QW system is typically the stronger emission up to levels of 10^{16} cm^{-3} and above. The relative strength of the free exciton recombination as compared to the bound exciton has been associated with the absence of strong polariton character under quantum confinement. The contribution of the exciton-impurity interaction kinetics to this problem has not been investigated to date and has been the motivation for the study presented here.

There are a number of important factors which will determine the interaction of free excitons and impurities. In this work, we use picosecond time-resolved photoluminescence to study the interaction of the free and bound exciton states. In particular, the process of capture and thermal emission for excitons at neutral impurities are studied and their role in determining the observed luminescence decay time discussed. The interdependence of these mechamisms implies that an analysis can only be made if one takes into account the proper coupled rate equations. Using such a calculation, we are able to discuss the relative importance of the different processes in determining the overall temporal development.

The photoluminescence spectra observed at short times following pulsed excitation can appear distinctly different from those observed under cw excitation. This difference is due to the fact that we resolve the short time-

scale interactions, while in a cw experiment the observed signal is an ensemble of time averaged components. In this paper, we discuss the relatively low excitation intensity case for which we assume many-body related effects to be negligible.[3] Preliminary results from parts of this work have been presented at recent conferences.[4–6]

II. EXPERIMENTAL PROCEDURE

The interaction of excitons with impurities is, in general, found to take place on a picosecond and longer time scale. Photoluminescent transients in this range are ideally suited to measurements using a streak camera. Such a system has allowed us to achieve a temporal resolution of approximately 20 ps over a period of 1.8 ns; in most cases this is sufficient to trace the most relevant part of the decay in the radiative transition at low temperatures. The luminescence signal is excited using a tunable dye laser synchronously pumped with a mode-locked argon laser to give a pulse length of approximately 5 ps. Excitation resonant with the free or bound exciton has been used throughout this work in an attempt to exclude any luminescence or interaction due to free carriers. In addition, the contribution of relaxation mechanisms to the observed decay time is largely removed using such a resonant excitation technique.[7]

The samples used in this study have been prepared using molecular beam epitaxy on a semi-insulating GaAs substrate at a growth temperature of 680 °C. The layer sequence has included an undoped GaAs buffer layer and a short period superlattice to reduce the background impurity level in the doped MQW sequence. The structure in each case consists of a 50 period GaAs-$Al_{0.34}Ga_{0.66}As$ multiple quantum well with 150-Å barriers, a well width of either 50 Å, 100 Å, or 150 Å and doped in the central 20% of the well with either Si or Be. The measurement temperature has been varied in the range 5 K to 50 K.

III. RESULTS AND DISCUSSION

A. Photoluminescence spectra

Figure 1 shows PL spectra taken for a series of 150-Å samples doped with Be acceptors at various bulk concentrations from 3×10^{16} to 5×10^{17} cm^{-3} [corresponding to a two-dimensional (2D) density of approximately 6×10^{9} to 1×10^{11} cm^{-2}]. The spectra are for resonant excitation in the FE and show a time window approximately 36 ps after the center of the laser pulse. In all cases, the luminescence peaks are relatively broad, indicating the importance of localization effects and also the impurity interaction. The FE line is only slightly broadened with increasing impurity concentration, indicating that the linewidth is probably dominated by interface roughness.[8] The neutral acceptor BE (A^0), on the other hand, demonstrates a more dramatic dependence on doping concentration and appears as a narrow peak comparable to the FE only at low dopant concentrations. The peak intensity of the BE increases strongly in ratio to the FE with increasing concentration. At higher concentrations the acceptors strongly interact, and the BE recombination becomes extremely broad. This same behavior has been observed in bulk material and has been discussed in terms of localization of the exciton in environments of different impurity concentration, where the interaction of impurities determines the local potential.[9]

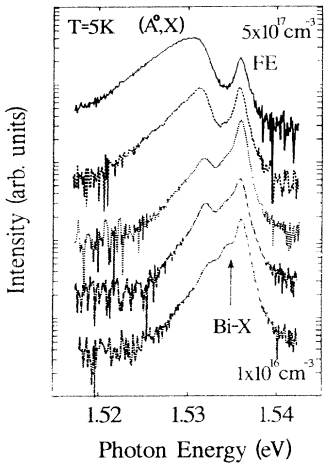

FIG. 1. Dependence of PL spectra on doping density; the illustrated spectra are for a time window 36 ps after the center of the laser pulse.

The low doping concentration data also show the presence of a third peak between the free and bound acceptor exciton transitions. A possible explanation of this peak would be an exciton bound to residual ionized donors in the system; however, this is inconsistent with why the peak should be lost at higher acceptor concentrations. The presence of a third peak has not been observed in any of the samples with narrower well widths, irrespective of dopant concentration, this further indicates a nonextrinsic origin. The binding energy of this component relative to the free exciton is also relatively small (1.4 meV); we, therefore, believe the most likely identity of this transition is the formation of a biexciton.[10,11] The occurrence and dynamics of biexcitons in doped QW's is discussed in Ref. 12.

B. Capture and thermal emission of excitons at acceptor sites

The importance of exciton capture at impurities has already been illustrated in Fig. 1. Despite this importance, capture processes for excitons have, in general, received relatively little attention in bulk material, most of which has largely been concentrated on Si.[13] The process of capture of a free exciton by an impurity site to form a bound exciton can be characterized by a capture cross section. In modeling the capture mechanism the simplest approach is to consider a single-level system, i.e., the particle is either bound or free. The analysis of the decay transient then requires a single rate equation for the bound state. The predominant capture process is assumed to occur via a cascade capture mechanism as the particle relaxes through the bound excited states

by successive phonon emission.[14] A series of shallow excited states are known to exist in the case of an exciton bound at a neutral impurity.[15] We assume that the relaxation from excited states following capture is rapid in comparison to the decay time and hence the bound exciton population resides predominantly in the ground state. The occupancy of excited states is important in determining the thermal emission or release from bound to free states, which in turn will define the temperature dependence of the overall capture mechanism.

The binding energy of a bound exciton state in a QW is enhanced by confinement. For the neutral acceptor this varies from approximately 6.5 meV at L_z=50 Å to approximately 3.5 meV at L_z=150 Å.[16] These values are large in comparison to k_BT at 5 K, and we, therefore, expect the thermal emission to be a relatively weak effect. The exciton to donor binding energy in comparison is smaller, and the effect of thermal emission is expected, therefore, to be correspondingly larger at 5 K. Figure 2 illustrates the time dependence of the FE emission for the same set of acceptor samples as Fig. 1. Excitation is again resonant with the FE. The use of crossed polarizers allows us to remove the majority of the scattered laser light from the measured signal. Due to the difference in scattered laser light between samples, the inital rise should, however, not be compared. The initial rate of decay of the FE peak is found to increase with doping density, in addition, the total loss in FE population is also increased.

The initial decay of the FE is clearly associated with the capture of free excitons at the acceptor state, the rate of capture being proportional to the concentration of available sites:

$$\frac{dN_{\mathrm{BE}}}{dt} = C_{\mathrm{FE}} \times N_{\mathrm{FE}} \times (A_0 - N_{\mathrm{BE}}) \ , \qquad (1)$$

where C_{FE} is the capture rate, A_0 the neutral acceptor concentration, and N_{FE}, N_{BE} the concentrations of free and bound excitons, respectively. The relatively low denisty of excitons excited ($\sim 10^9$ cm^{-2}, estimated from a detailed calibration of the spot size and an assumed absorption strength) allows us to exclude saturation effects in interpreting the observed exciton decay data.

Figure 3 shows the equivalent dependence on doping for excitation resonant with the bound exciton. In contrast to the FE, the decay is not significantly changed by increasing doping level. The onset shows a rapid population of the BE during the laser pulse. It should be again noted that the rise time inevitably contains a contribution from scattered laser light, hence we make no attempt to distinguish a difference in rise time with doping density. The bound exciton decay is a well defined exponential, as expected for a system where the rate of decay is simply proportional to the remaining population, this indicates that the BE system is decoupled from the free exciton, i.e., no significant thermalization occurs. The highest doped sample shows a slightly faster rate of decay than the more lightly doped; this is, however, probably an artifact of the way the transient is extracted from the experimental data. In deducing these transients the signal is integrated over a spectral width typically slightly larger than the full width at half maximum. Providing there is no spectral dependence to the decay, as is true for the lower doped samples, the chosen width is not important. For the high doping densities there is, however, some diffusion of excitons to lower energy sites. As a result of this diffusion, the decay of the high energy components is significantly faster than the low energy transitions, which are fed by diffusion. Provided the transient is integrated over sufficient spectral width, the cumulative effect of diffusion will average out, the faster and slower components balancing, as confirmed by the absence of any difference in decay for all but the highest doped sample.

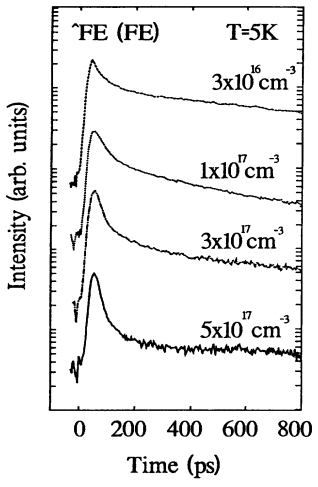

FIG. 2. Dependence of radiative decay of FE on acceptor-doping density. Both the initial rapid decay and the subsequent slower radiative emission rate are seen to be strongly dependent on doping density.

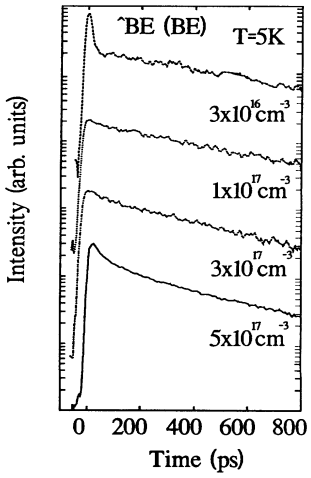

FIG. 3. Doping dependence of BE decay following resonant excitation in BE. In contrast to the FE, the BE decay is found to be essentially independent of doping density

C. Temperature dependence

The temperature dependence of the exciton decay is illustrated in Fig. 4(a)–(c), again results for excitation resonant in both the free (a),(c) and bound (b) excitons are shown. The sample in this case is a 100-Å MQW

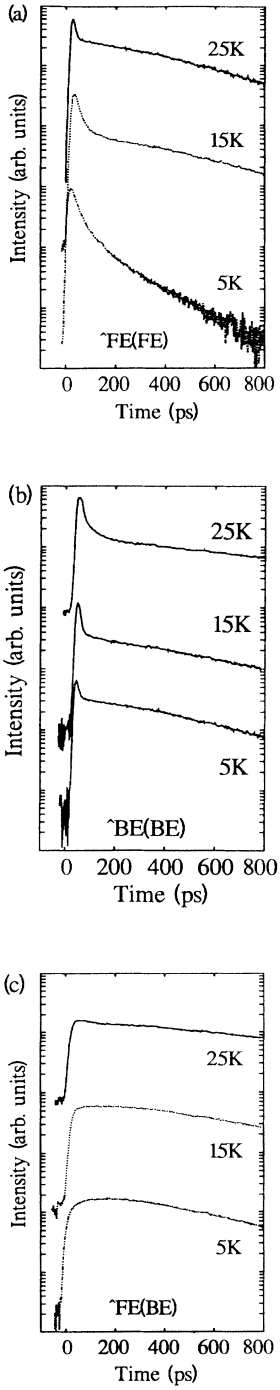

FIG. 4. Comparison of the temperature dependence of the radiative decay of excitons for a 100-Å acceptor doped QW. Transients for both FE (a) and BE (b), (c) are shown with resonant excitation in the FE (a),(c) and BE (b).

center doped at the 10^{16} cm^{-3} level with Be. For the 150-Å quantum well, the effects of thermalization are found to be already strong at 5 K such that the temperature dependence is less well illustrated. At 5 K the FE decay is dominated by capture at the bound site as shown in Fig. 4(a). As the temperature is increased, the long-time behavior is dramatically altered. The determining influence of the capture on the decay is reduced, and the FE population is sustained by the thermal release of bound excitons. The processes of capture and emission, therefore, begin to balance at higher temperatures and the populations of free and bound excitons are coupled. The relation between capture and emission rates can be expressed using the principle of detailed balance, which states that for a system in thermal equilibrium the rate of a process and its inverse are equal.[18] Assuming non-degenerate statistics we obtain the result:[19]

$$\frac{e_{\mathrm{BE}}}{C_{\mathrm{FE}}} = 4\pi m^* k_B T \hbar^2 g_{\mathrm{FE}} g_{\mathrm{BE}} e^{\frac{-E_{\mathrm{BE}}}{k_B T}} , \tag{2}$$

where e_{BE} and C_{FE} are the rates corresponding to the release and capture processes, respectively, g_{FE} and g_{BE} are the degeneracy ratios of the free and bound exciton (g_{FE}=4, g_{BE}=2), and E_{BE} is the binding energy of the exciton to the acceptor. This result is used later as a guideline to estimate the parameters required to model the temporal development of the population of free and bound excitons in a series of coupled differential equations (see Sec. III E). The observed decay time at 15 K and 25 K is larger than that measured at 5 K, as expected due to the increased scattering of excitons away from $\vec{K}$=0 ($\vec{K}_x, \vec{K}_y = 0$), whereby most of these excitons are scattered to sufficiently large $\vec{K}$ so that they are no longer radiative.[17] The BE result clearly follows the behavior of that of the FE for resonant excitation in the BE [Fig. 4(b)]. At higher temperatures the BE lifetime couples with that of the FE and at 25 K they have a common decay.

Figure 4(c) illustrates the same temperature series but for detection in the BE while resonantly exciting in the free exciton. The onset of the decay is determined by the capture rate of the exciton at the impurity. The data illustrate a surprising effect, the capture rate is actually increased with temperature, such behavior is contrary to the model previously discussed where capture efficiency is determined by the ratio of thermal ejection to relaxation through excited states. We instead interpret the apparent increase in capture of the BE at acceptor sites with temperature as a higher mobility of the free exciton due to the absence of weak localization at interface roughness potentials. If an exciton becomes localized at low temperature further capture to an impurity can occur only to those impurities within the localization volume.[20] For a given localization energy, a limited proportion of the impurity population is, therefore, open to capture. As a result, impurity capture is found to be extremely inefficient at low temperatures. This is an important mechanism for the continuing domination of the "free" (in fact weakly localized) exciton in narrow quantum wells even at relatively high doping densities.[21,22] At higher temperatures,

the exciton is not localized and is able to be captured at any available impurity site. Although the capture coefficient per impurity is decreased, the sites available to each exciton are increased. In the temperature range studied, the latter effect is suggested to dominate.

Figure 5 illustrates the dependence on well width of the FE recombination for samples with similar doping densities (excitation resonant with FE). It confirms the ideas presented so far on the dependence of the thermalization and capture process upon the binding energy. The binding energy of the exciton to the acceptor is increased for decreasing well width. As a result, we would expect the contribution of thermal release from the bound exciton to decrease with well width, exactly this behavior is observed in Fig. 5. For the 150-Å sample the thermal emission is relatively strong and the long-time decay rate is correspondingly slow. For the 50-Å sample the capture of the FE is found to be very strong, while the contribution of thermal emission is negligible.

D. Comparison with donor doped samples

The binding energy of the donor bound exciton complex is significantly smaller than that of the acceptor, approximately 2.2 meV for L_z=100 Å in comparison to 4.5 meV for the acceptor. As a result, the kinetics will be significantly different for the donor interaction and the free and bound exciton populations are strongly thermalized even at 5 K. A direct comparison of the decay transients for 100-Å QW's with acceptor or donor doping is shown in Fig. 6. Excitation is resonant with the free exciton for (a) and (b) and with the bound exciton in (c). In each case, the differences observed are consistent with the difference in exciton binding energy to the impurity center. Figure 6(a) illustrates the maintained population of the free exciton via thermal emission from the donor

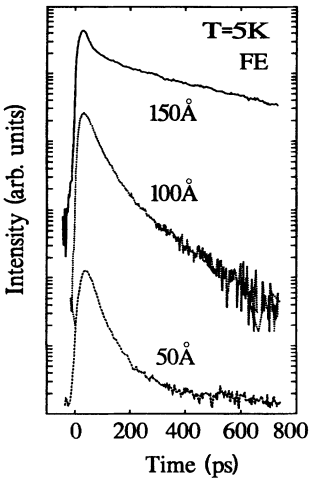

FIG. 5. Dependence of FE recombination upon width of acceptor-doped well for samples with similar doping concentrations. The difference in contribution of excitons thermalized from the BE in maintaining the free exciton population is shown.

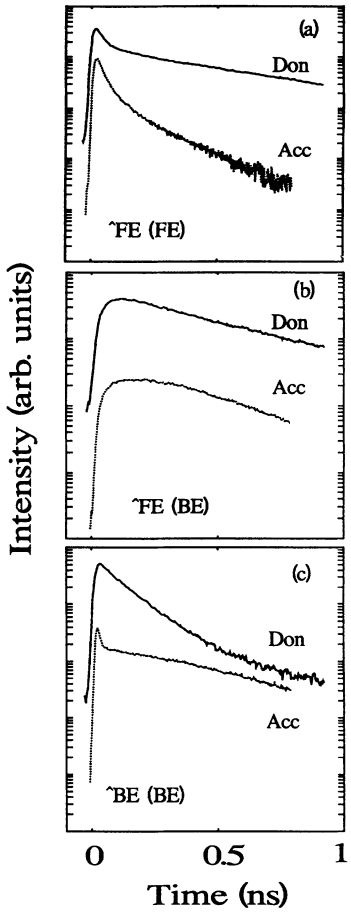

FIG. 6. Comparison of transients for donor and acceptor bound excitons for samples with comparable well widths and doping concentrations.

bound exciton. The acceptor-doped sample in contrast shows a free exciton decay dominated by the capture process. The opposite situation is clear from 6(c), where for resonant excitation in the acceptor bound exciton it is essentially uncoupled from the free and demonstrates an exponential decay at long times. On the other hand, the donor result illustrates the strong loss in population due to thermal release to the free exciton. The results for detection in the bound exciton while exciting in the free exciton [Fig. 6(b)] are perhaps less clear, since here we have the coupled effects of capture at and emission from the bound site. As expected, the long-time decay can be compared to case (a) for the donor and to case (c) for the acceptor.

E. Modeling of free-bound exciton kinetics

The discussion of the preceding sections has highlighted the complexity of the interaction between free and bound excitons. In this section, we consider how the kinetics can be modeled using a series of coupled rate equations, and from a simple fitting procedure the relevant parameters such as radiative lifetime for free (τ_{FE})

and bound exciton (τ_{BE}), and exciton capture rate (C_{FE}) can be found. In order to have a manageable number of terms, we make a number of basic assumptions regarding the interaction mechanisms, in particular, we restrict the terms to those describing simple capture and emission of excitons and the effective radiative recombination lifetime for each channel (i.e., free and bound exciton). Within the temperature range of the experiment, we assume the contribution of nonradiative recombination to be negligible.[23] This gives for the case of free exciton resonant excitation:

$$\frac{dN_{FE}}{dt} = G(t) - N_{FE}\tau_{FE} - C_{FE}N_{FE}(N_{i0} - N_{BE}) + e_{BE}N_{BE} , \tag{3}$$

$$\frac{dN_{BE}}{dt} = -N_{BE}\tau_{BE} + C_{FE}N_{FE}(N_{i0} - N_{BE}) - e_{BE}N_{BE} , \tag{4}$$

where $G(t)$ is the generation rate of free excitons during the short laser pulse. N_{FE}, N_{BE} are the number of free and bound excitons, respectively, and τ_{FE}, τ_{BE} are the associated lifetimes. N_{i0} is the density of neutral impurities. C_{FE} is the capture rate for a free exciton to a bound site, e_{BE} is the reverse process of thermal emission from the bound site to become a free exciton. For resonant excitation in the BE the relevant equations are identical except that the generation term $G(t)$ now instead appears in the BE equation. As discussed earlier, the capture and emission terms can be related when in thermal equilibrium through the principle of detailed balance [Eq. (3)]; this places some restriction on our choice of parameters. In particular, at low temperatures the exciton system is clearly not in thermal equilibrium and the emission rate will, therefore, be relatively low in comparison to a value calculated from detailed balance. As an initial estimate of the lifetimes for free and bound excitons a value taken from the long-time slope of the decay is used. Given these starting conditions the fitting procedure is a simple iterative process. For the simplest model this involves the four parameters (τ_{FE}, τ_{BE}, e_{BE}, C_{FE}) that are to be determined. Note that since we take no account of phonon interaction, the lifetimes derived are those thermalized to the lattice temperature (i.e., >5 K). As already pointed out, this analysis takes no account of the distribution of states within the inhomogeneous linewidth for both free and bound excitons but instead considers a two state model. The parameters derived are naturally influenced by this assumption since they represent an average over possible states. The model remains valid as long as low temperatures and low excitation conditions are employed such that there is a limited distribution of occupied states. Higher temperatures and, in particular, high excitation densities can still be approximated by including additional terms which describe the influence of states at higher energy.

Figure 7 illustrates the modeling of the observed transients for the decay of the free and bound excitons for a 100-Å QW doped with acceptors to a level of 5×10^9 cm^{-2}. The solid line superimposed on each curve is the result of the discussed fitting procedure, the parameters for which are given in Table I. For the BE, the fit achieved is extremely good both in the rise time and the decay. The line fit to the initial behavior of the BE is particularly sensitive to the choice of capture rate; we can, therefore, place a confidence interval of better than +/−10% on the value of 2 $cm^2\,s^{-1}$ derived. The capture also depends directly on the density of possible bound sites, any uncertainty in this constant is, therefore, also reflected in the accuracy of the capture rate value. There unfortunately exists only a limited discussion in the literature of exciton capture rates at impurities in bulk material, and that almost exclusively in Si. The capture rate in Si is found to depend strongly on the type of impurity. As a comparison, we take the In acceptor for which a value of 5×10^{-6} $cm^3\,s^{-1}$ at 5 K can be calculated from the literature.[24] The value for the quantum well is renormalized from the 2D case to give an equivalent 3D value of 4×10^{-7} $cm^3\,s^{-1}$. The 2D system, therefore, results in a significantly smaller value for the capture rate, as suggested by our earlier discussion. The topic of exciton capture in 2D is discussed in Ref. 21.

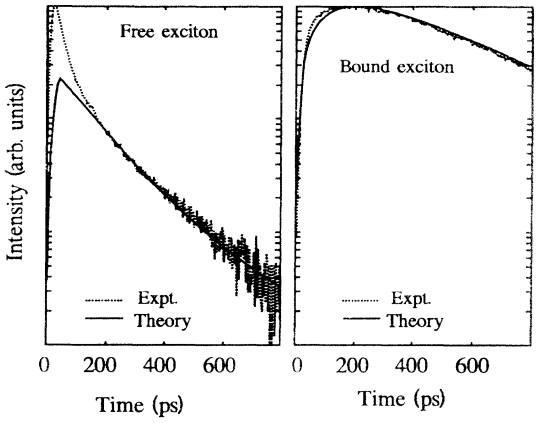

FIG. 7. Fit to experimental data for 100-Å acceptor-doped quantum well using simulation of decay based on series of coupled diffferential equations. The quality of the fit is excellent except for the initial decay of the FE, which is not reproduced by the simple model.

The long-time decay for both the FE and the BE is mainly determined by the remaining three variables, the respective lifetimes (τ_{FE}, τ_{BE}) and the thermal emission rate e_{BE}. In making a fit to the experimental data a balance between these terms is required which is made difficult by their interdependence. For example, we have shown that the lifetime of the free exciton appears artificially long in the experimental decay curves due to the effect of thermal emission from the bound exciton, as a result we realistically assign significant error limits to the parameters derived. The determined BE lifetime of

TABLE I. Parameters for simple fit to low intensity data.

	τ_{BE}	τ_{FE} (ps)	e_{BE} (ps)	C_{FE} ($cm^2\,s^{-1}$)
Value	450	180	1×10^9	2

450 ps has an estimated error of around ± 50 ps and is consistent with previous studies.[19] The free exciton lifetime is found to be significantly shorter, around 180 ps ± 50 ps at 5 K. This is also shorter than a value found by a simple exponential fit to the experimental data. Much of the data previously reported in the literature also suggests a longer decay time for the free exciton at this temperature.[25,26] The theoretical treatment of this problem predicts lifetimes which are considerably shorter than those measured,[27] but suggest that the differences observed are due to localization of the free exciton. A good indication of this viewpoint is the work by Deveaud *et al.*[28] using samples grown by the interrupted growth technique which is known to produce extremely smooth interfaces and minimal localization. This work reports a lifetime of 40 ps at 2 K, a value close to the theoretical value predicted. The model applied here assumes a free (mobile) exciton, although to account for the temperature dependence of the capture, this is clearly not strictly the case. The lifetime parameter for the free exciton, which would be expected to be short, is forced to be longer in the fitting procedure to take account of the exciton localization present in system.

The fit to the FE at longer times is good; however, there is clearly a component in the initial decay that is not reproduced in the simple model. This problem has already been partially discussed, due to the resonant excitation the exciton population is created "cold" and, therefore, takes a certain time to thermalize to the lattice temperature. As thermalization occurs there is a decrease in the population able to recombine (due to momentum conservation restrictions), corresponding to the behavior observed. The scattering of part of the free exciton population away from $\vec{K}=0$ requires the interaction of the exciton with a phonon. In addition to those phonons provided by the ambient lattice temperature, there are also those phonons emitted during the capture of an exciton at an impurity to form the bound exciton. At high densities, this secondary phonon population can make a significant contribution to the scattering away from $\vec{K}=0$, in effect the initial temperature of the system is hotter than the ambient lattice temperature. This mechanism is well illustrated in Fig. 8, where we compare the free exciton decay under nominally identical conditions but an order of magnitude difference in excitation densities. The initial decay of the free exciton is remarkably different in the two cases; at higher densities the decay is, as suggested, considerably faster.

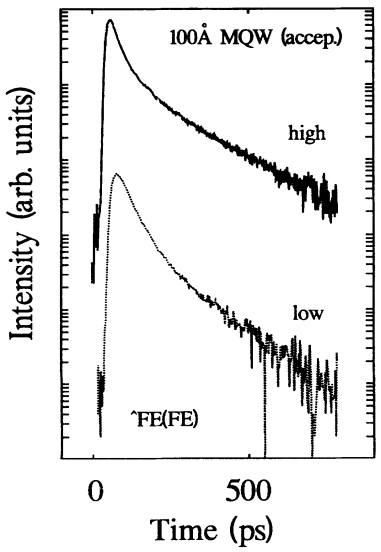

FIG. 8. Excitation density dependence of free exciton decay rate. The increased initial decay in population is due to the excess phonon population created by capture at impurities.

IV. CONCLUSIONS

The interaction of free excitons with impurities in GaAs-$Al_xGa_{1-x}As$ quantum wells has been studied using a time-resolved photoluminescence technique. The exchange between free and bound exciton populations is found to determine the observed recombination rate. Furthermore, this interaction is shown to be strongly dependent on doping concentration, well width, and temperature. The strong capture of excitons at impurities dominates the initial decay of the free exciton population with FE excitation. In addition, the thermal release from this same bound exciton state maintains the free exciton population at longer times and hence also influences the final decay rate. The processes of capture from and emission to the free exciton population is clearly strongly dependent on the impurity-binding energy; this results in significant differences in the recombination kinetics of acceptor bound excitons in comparison to donor bound excitons. The importance of the free exciton localization due to well width fluctuations is well illustrated by the increase in capture efficiency with increasing temperature observed up to 25 K. This is a clear indication of a mechanism contributing to the dominance of the "free" exciton in comparison to the bound exciton which is seen in steady state photoluminescence spectra for quantum wells but not in bulk GaAs.

In order to make a realistic estimate of the parameters which describe the observed rate of decay of emission, it is necessary to solve the associated differential equations for excitation resonant in either the free or bound exciton, respectively. An analysis of results for a 100-Å acceptor doped quantum well indicates a radiative lifetime at 5 K for the free exciton of 180 ps, while that of the bound exciton is equal to 450 ps. Under low intensity resonant excitation conditions, a simple fitting procedure using a small number of terms thus provides an accurate determination of the physical parameters. In particular, the qualitative dependence on the basic parameters of doping concentration, well width, and temperature are well understood from our model of the exciton interaction.

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