Enhancement of the free-to-bound transition in narrow GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells via a possible excitonic Auger mechanism

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The recombination of an $n=1$ quantized electron with a hole bound at an acceptor in a so-called free-to-bound (FB) transition has been observed in GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells with a rather low p-type doping level ($<1\times10^{17}$ cm^{-3}) in selective photoluminescence (SPL) upon excitation in the vicinity of the free exciton (FE). This is in contrast to the photoluminescence (PL) measurements with above-band-gap excitation, where the FB band is not seen. This FB transition is strikingly enhanced at excitation resonant with the heavy-hole (hh) or light-hole (lh) state of the FE. The peak intensity of the FB reaches about 8% of the corresponding FE intensity at resonant excitation in the investigated sample. The intensity correlation between the FE and FB is also observed in the PL-excitation measurements and in the temperature dependence of the SPL spectra. The observed results are tentatively explained in terms of a multistep excitonic Auger mechanism where the hole of the FE is attracted and captured by an ionized acceptor. The excess energy is transferred to the electron, which is then excited into the continuum. In the final step a "free" electron recombines with a hole from the neutral acceptor in a FB transition. The free carriers created by this process have also been detected by photoconductivity measurements upon excitation resonant with the exciton states, which is consistent with the proposed excitonic Auger recombination model.

INTRODUCTION

The photoluminescence (PL) spectrum of an intentionally undoped quantum well (QW), and also of a QW doped up to a fairly high impurity concentration, is usually dominated by the intrinsic free-exciton (FE) transitions. This is in sharp contrast with bulk material, for which impurity-induced recombinations dominate the PL spectra even in the purest material available. For QW's, the probability of recombination via intrinsic transitions has been shown to increase relative to the capture by impurities[1] due to reduced radiative lifetimes with decreasing QW width.[2] Thus, the electron-hole pair will recombine as a FE before getting captured by impurities. Fairly high impurity concentrations are required in the case of QW's in order to get equal probability for the carriers to be captured by an impurity as for recombining via an intrinsic exciton. For instance, this "critical" impurity concentration is for a 50-Å-wide GaAs/$Al_xGa_{1-x}As$ QW found to be at $p=2\times10^{17}$ cm^{-3}.[3]

In the present paper we have studied QW's with impurity concentrations below the above-mentioned "critical" limit, which accordingly do not show any extrinsic luminescence with above-band-gap excitation. However, upon excitation close to any of the intrinsic FE states, including either the heavy-hole (hh) or the light-hole (lh) states, we are able to observe the extrinsic PL originating from the free-to-bound (FB) transition. When any of these FE states are resonantly excited, a striking enhancement of the FB transition is observed. The efficiency of this process can be illustrated by a 70-Å-wide QW with p-type doping ($p=3\times10^{16}$ cm^{-3}) well below the "critical" limit (thus showing no FB transition in PL at above-band-gap excitation), where the intensity of the extrinsic FB luminescence is about 8% of the intrinsic FE luminescence, when any of the FE states are selectively excited. The mechanism giving rise to this striking enhancement of the extrinsic PL is tentatively interpreted as an excitonic Auger recombination. A theoretical investigation of this capture process was recently reported for the case of a deep impurity in bulk material.[4] The same kind of capture mechanism is suggested to apply for a QW with a significant transition probability due to strong localization effects in QW's.

EXPERIMENT

The GaAs/$Al_xGa_{1-x}As$ QW's used in this investigation were grown by molecular-beam epitaxy (MBE) in a Varian Gen II system. The layers were deposited at a temperature of nominally 680 °C on a semi-insulating (100) GaAs substrate with a 0.5-μm undoped GaAs buffer layer. Four different samples were used for this study. Two of them, A and B, contained a single QW (SQW) with a width of approximately 70 Å confined by $Al_{0.3}Ga_{0.7}As$ barrier layers. The samples were doped in the central 25% of the QW with a Be concentration of 3×10^{16} cm^{-3} for sample A and 1×10^{17} cm^{-3} for sample B. Most of the spectra shown in this paper are for sample A, but it should be pointed out that the corresponding spectra for sample B are very similar. Two additional samples, C and D, were used in this study. These samples

were multiple QW (MQW) structures, consisting of 50 GaAs wells of width 100 and 150 Å, respectively, separated by 200-Å $Al_{0.3}Ga_{0.7}As$ barriers and doped in the central 25% at a Be level of 1×10^{17} cm^{-3} in the same way as samples *A* and *B*.

The samples were excited with an Ar-ion laser ($\lambda=5145$ Å) for the above-band-gap measurements. For the selective PL (SPL) and PL excitation (PLE) measurements, tunable cw dye lasers (with LD-700 or Styryl-8 dye) were used. The samples were mounted in an exchange-gas-type cryostat, in which the temperature could be varied from 1.6 K to room temperature. The luminescence spectra were dispersed with a McPherson 1-m monochromator and detected with a dry-ice–cooled GaAs photomultiplier tube. For the photoconductivity (PC) experiments, two indium contacts separated by about 5 mm were deposited on top of sample *C* so that the PC was measured parallel to the QW layers. The bias was kept low, from zero bias to about 1 V, in order to minimize the effects of the electric field itself.

EXCITONIC AUGER RECOMBINATION

The basic idea of the model

The excitonic Auger capture is based on the idea that when the FE approaches an impurity, one of the electronic particles of the FE is attracted by the ionized impurity. If this electronic particle is captured by the impurity, the excess energy is transferred to the other particle of the FE, which then is excited into the continuum in an Auger-like process. This basic process is illustrated in Fig. 1 for the case of a FE interacting with an ionized acceptor. The hole of the FE is attracted by the ionized acceptor and is captured by this impurity. Due to the overlap of the electron and hole wave functions within the FE, the excess energy from the hole upon the capture is taken over by the electron, which is excited into the continuum.

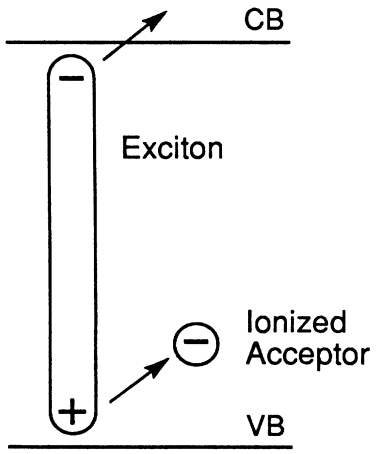

FIG. 1. Illustration of the excitonic Auger recombination. The hole of the exciton is attracted by the ionized acceptor and is captured by the impurity. The excess energy is taken over by the electron, which is excited into the continuum.

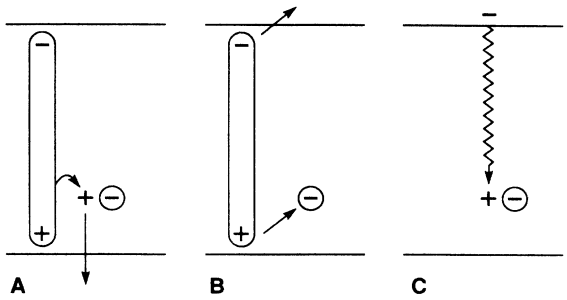

FIG. 2. Illustration of the proposed mechanism giving rise to the enhancement of the FB transition upon excitation resonant with the exciton via an excitonic Auger recombination. A more detailed description of this model is given in the text.

The excitonic Auger recombination requires, however, that the acceptor is ionized, which is not the case at the temperatures the measurements in this study have been performed. However, two-hole transitions (THT's) via the bound exciton (BE) have recently been observed in QW's upon resonant excitation.[5] It seems reasonable that the observed THT's, including hole transitions to different excited states in the SPL spectra, are just a minor part of the hole excitations. The dominant fraction of the holes will most likely be excited into the continuum, leaving the acceptor in an ionized state. The model we are proposing to explain the enhanced FB transition by resonant excitation of the FE is illustrated in Fig. 2 and can be shortly recapitulated in the following way: a neutral acceptor is ionized upon recombination of an exciton bound at the same acceptor via a THT (step *A*). Before the acceptor is neutralized by a hole from the continuum, another hole from a FE will be captured by the ionized acceptor. The excess energy is transferred to the electron, which is excited into the continuum (step *B*). Finally, the acceptor hole is radiatively recombining with a free electron in a FB transition (step *C*). It should also be added that the BE which causes the ionization of the acceptor is formed when a FE is captured by the neutral acceptor. This means that, in principle, two successive FE's can give rise to the observed enhancement of the FB via resonant excitation of the FE.

Alternatively, the acceptor can, after the FB transition (step *C*), while it is still in an ionized state, attract a second FE for another Auger recombination (step *B*). Thus, once this procedure is initialized, it can continue in a kind of chain reaction. The prerequisite for this reaction (and also for the process from step *A* to step *B*) is that the ionized acceptor should capture a FE hole (in a Auger process) instead of capturing a free hole (to become neutral).

Theoretical results for bulk and predictions for QW's

The theoretical investigation of the excitonic Auger mechanism has been reported elsewhere[4] for the case of bulk semiconductors. Corresponding calculations for QW's do not exist to the best of our knowledge, and at present we will simply give some general reflections on

what should be expected for the case of QW's based on the available theoretical results from the bulk material.

The prerequisite for excitonic Auger recombinations should be favorable in the case of a QW due to additional localization effects in comparison with bulk. The transition matrix element for the Auger capture contains impurity-related factors such as the trap depth and the impurity localization, but also the extension of the exciton wave function.[4] The usually widely spread FE wave function is found to be a limiting factor for these processes in bulk material. The transition probability depends on the overlap of the wave functions for the impurity and FE, respectively, and reaches a maximum, when they are of comparable extension. For our case with an acceptor confined in the center of a QW of 70 Å thickness, the acceptor envelope function has a radius of the order 10 Å.[6] The longitudinal and transverse Bohr radii for an exciton confined in a 70-Å-wide QW (with infinite wells) are found to be ≈ 15 and 120 Å, respectively,[7] to be compared with ≈ 100 Å for bulk.

RESULTS

The PL spectrum of sample *A* with a 70-Å-wide SQW, Be doped in the central 25% of the well, measured at 1.6 K with above-band-gap excitation (5145 Å) is shown in Fig. 3. This spectrum is dominated by the FE line at 1.576 eV. On the low-energy side of the FE, a second weak feature (at ≈ 1.571 eV) can be observed as a shoulder on the FE. This feature is interpreted as the exciton bound at the confined Be acceptor,[5] which thus has a BE binding energy of about 5 meV. It should be stressed that no further luminscence originating from this SQW can be observed even at the highest detection sensitivity.

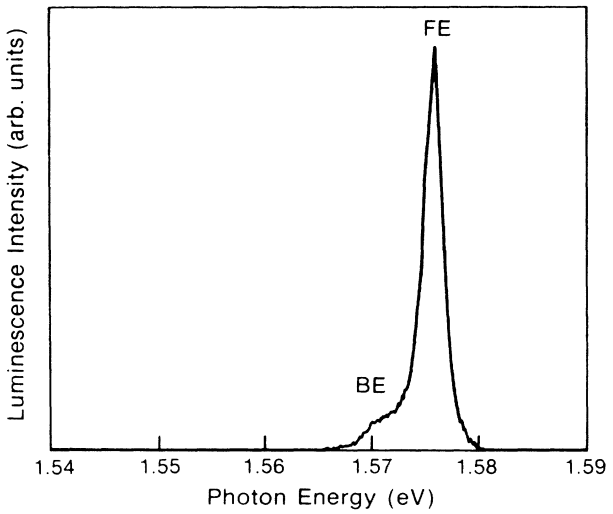

FIG. 3. PL spectrum of sample *A* measured at 1.6 K with above-band-gap excitation (5145 Å). This spectrum is dominated by the intrinsic FE line, and the exciton bound at the Be acceptor (BE) appears as a weak threshold on the low-energy side of the FE.

When the detection is resonant with either the FE or the BE in a PLE spectrum, only the FE-related states, principally the lowest hh and lh states, are observed in this sample [Figs. 4(a) and 4(b)]. It should again be pointed out that no structure of extrinsic origin can be observed in any of these PLE spectra.

When any of the FE states observed in PLE are excited resonantly in a selective PL (SPL) spectrum, the luminescence spectrum will differ quite drastically from the corresponding PL spectrum with above-band-gap excitation (Fig. 3). In each of Figs. 5 and 6 is shown a synopsis of SPL spectra for excitation resonant with or in the vicinity of the hh state (Fig. 5) and the lh state (Fig. 6), respectively. The most striking difference at resonant excitation compared with above-band-gap PL spectrum is the new

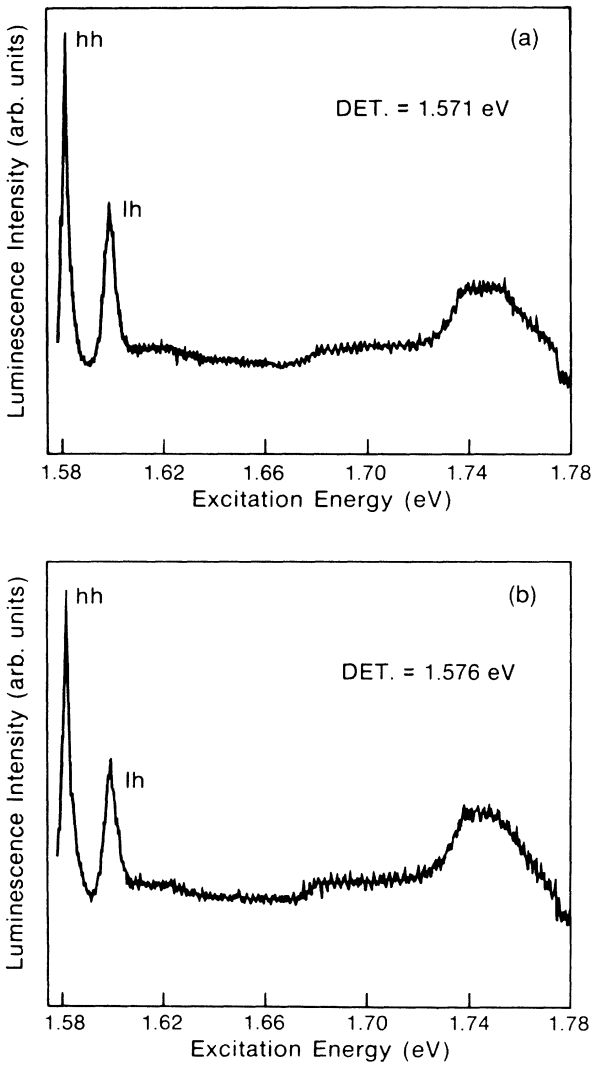

FIG. 4. PLE spectrum at 1.6 K of sample *A*, when (a) the FE and (b) the BE is detected. The two spectra are very similar and are both dominated by the hh and lh states of the FE. The structure at ≈ 1.74 eV originates from transitions to the excited $n=2$ electron state. No additional structure of extrinsic origin could be observed in this doped sample.

peak appearing at ≈ 1.55 eV, which is at the same position as has been observed in earlier reports[8,9] for the FB transition (recombination of an $n=1$ quantized electron with a hole from the confined neutral Be acceptor) in a similar QW, but at a higher Be-doping level. This interpretation of the luminescence peak is also consistent with theoretical predictions. The energy separation between the FE and FB is found to be ≈ 25 meV for the investigated sample. If the FE binding energy is assumed to be 11 meV,[10] the binding energy for the involved Be acceptor confined in a 70-Å QW can be estimated to be 36 meV. Theoretical calculations by Masselink *et al.*[11] predict a binding energy of 34 meV for an effective-mass-like acceptor confined in the central part of a 70-Å-wide QW. If the same central-cell correction (the energy difference between the ground states of the Be acceptor and an effective-mass-like acceptor) as for bulk GaAs (1 meV) is used, a predicted binding energy of 35 meV is provided, which thus is in good agreement with what is observed in the measurements. While the FB transition is not detectable at above-band-gap excitation (Fig. 3), the intensity of this band reaches about 8% of the intensity of the FE exciton peak upon excitation resonant with the hh or lh state as can be seen in Figs. 5 and 6. The intensity of the FB peak is then drastically reduced as the excitation is shifted off the resonance with the hh or lh state and has reached 50% of the intensity within a range of $\pm(1-1.5)$ meV from the resonance position. This width corresponds fairly well to the half-width of the FE peak at selective excitation. This fact, however, cannot be verified directly from this spectrum, since the FE and BE peaks are poorly resolved at selective excitation, but merge into a broader band. Nevertheless, at slightly elevated temperatures (20–30 K), when the BE is quenched and only the FE can be observed in the luminescence spectrum (Fig. 7), the half-width for the FE peak of about 2.2 meV can be confirmed. Furthermore, from a comparison with the PL spectrum (Fig. 3) and the

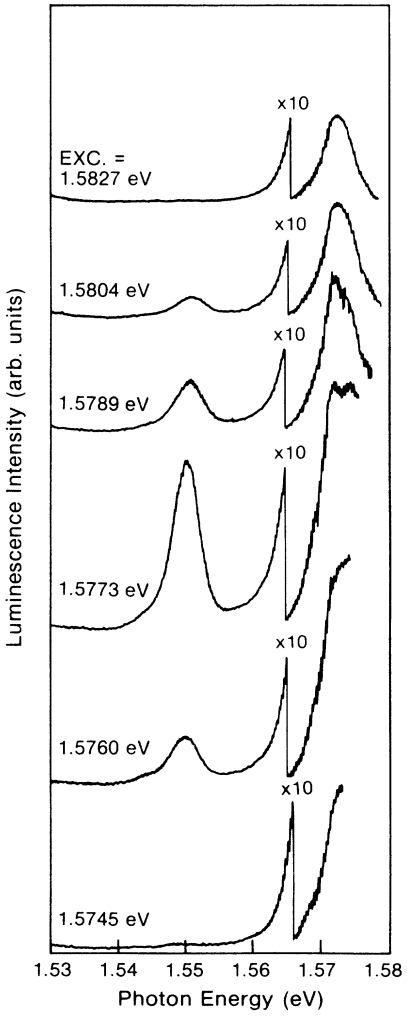

FIG. 5. SPL spectra of samples *A* measured at 1.6 K with the excitation energies close to or resonant with the hh state (at 1.577 eV) of the FE. All spectra are measured with the same detector sensitivity and excitation intensity (within ±2%).

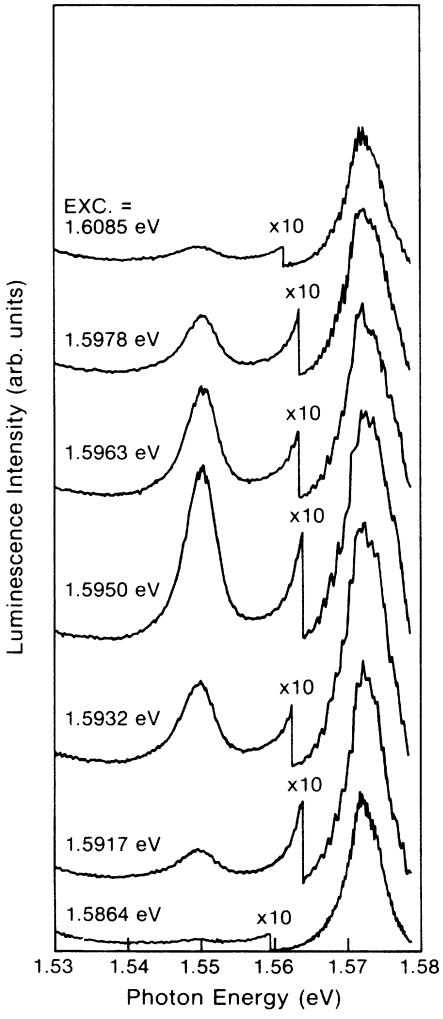

FIG. 6. A synopsis of SPL spectra corresponding to Fig. 5 but with the excitation energies close to or resonant with the lh state (at 1.595 eV) of the FE.

SPL spectra measured at elevated temperatures (Fig. 7), it is apparent that the joint exciton peak is fairly close to the position of the BE for most of the SPL spectra at the lowest temperature (Figs. 5 and 6) with the exception of the spectrum measured with resonant excitation with the hh state (the fourth spectrum from top of Fig. 5). At this excitation (1.5773 eV), there is a doublet exciton peak, which seems to be confirmed by a comparison with the SPL spectra excited at slightly higher energies, where the FE peak tends to increase in strength. No relevant conclusions can be drawn from SPL spectra excited at energies lower than 1.5773 eV, because the exciting laser line is getting too close to the detected FE energies. Thus, from these SPL spectra one can conclude that there is an intensity correlation between the FB and FE upon excitation resonant with the hh state. This effect is weaker for the corresponding resonant excitation with the lh state, but a broadening of the exciton peak on the high-energy side can be observed upon resonant excitation.

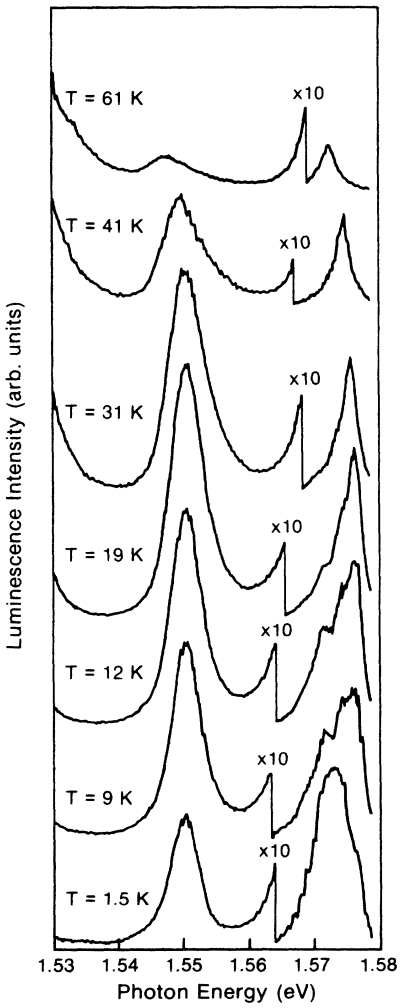

FIG. 7. SPL spectra of sample *A* measured at different temperatures with the excitation energy resonant with the lh state. All spectra are measured with the same detector sensitivity and excitation intensity (within ±2%).

In order to investigate the possibility that the observed enhancement of the FB transition upon excitation resonant with any of the FE states could be due to saturation of the FE, the SPL measurements were performed at different excitation intensity levels. With the excitation resonant with any of the FE states, the excitation intensity was reduced up to 2 orders of magnitude. The SPL spectra seem to remain almost unchanged at these lower excitation intensities. In fact, the intensity ratio between the FB and FE peaks increases slightly at lower excitation levels. This fact is contradictory to a model in which the saturation of the FE causes the enhancement of the FB.

The intensity ratios between the FB and the FE peaks were also established for two wider QW's. This ratio was found to decrease from ≈8% for the 70-Å SQW (sample *A*) investigated in this paper to ≈3% for a 100-Å MQW (sample *C*) and ≈1.5% for a 150-Å MQW (sample *D*). These two samples were identical with the 70-Å SQW with exception for the QW width and the number of QW's.

Figure 7 shows SPL spectra measured at several different temperatures up to ≈60 K, with the excitation energy consistently resonant with the lh state of the FE. From these spectra it is obvious that the BE dominates over the FE at lowest temperatures (up to about 7–9 K), while the FE gains in intensity and will dominate at higher temperatures. One can also see from the same plot that the FB peak has a temperature dependence which is very similar to the one observed for the FE. This fact is better illustrated in Fig. 8, which shows the normalized PL intensity of the three bands, FE, BE, and FB, for temperatures up to ≈80 K. The intensity of the BE drops off quite rapidly, as expected, and is completely quenched at ≈30 K. The activation energy for this process derived from an Arrhenius plot (inset in Fig. 8) is 3.7

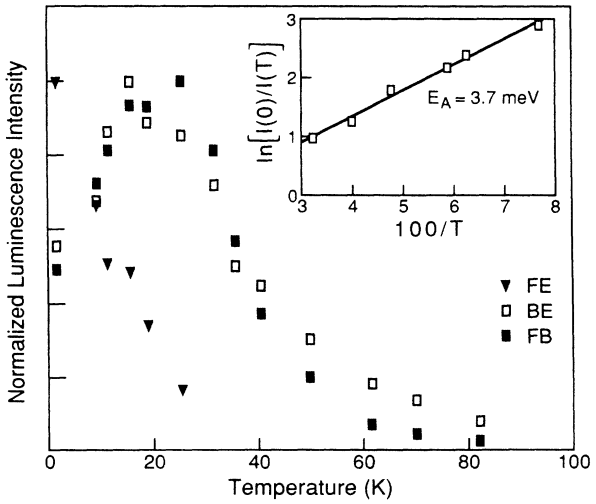

FIG. 8. The temperature dependence of the peak intensities for the FE, BE, and FB, respectively. The inset shows an Arrhenius plot for the thermal behavior of the BE, which gives an activation energy of 3.7 meV.

meV, which corresponds to the binding energy of the BE as observed from the energy separation (4.6 meV) between the FE and BE in the PL spectrum (Fig. 3) or SPL spectra measured at elevated temperatures (Fig. 7). The FE gains obviously intensity in the same temperature range (up to ≈ 20 K) as the BE intensity is reduced. The activation energy for the FE intensity gain is, however, not as well defined as for the case of the BE, which is probably due to the fact that two competing processes affect the intensity of the FE: the gradual quenching of the FE by itself gives rise to a reduction of the FE intensity with temperature, but the quenching of the BE's will at the same time increase the FE intensity. Up to a temperature of ≈ 20 K the latter process will apparently dominate, while at still higher temperatures most BE's are already quenched, and the first process will give rise to the overall reduction of the FE. Figure 8 shows clearly that the thermal behavior of the FB and FE are very similar, with the FB transition dropping off slightly faster than the FE. The similar temperature dependences for the FE and FB are consistent with the model suggested of the excitonic Auger recombination and will be further expounded in the discussion below.

The observed correlation between the FE and FB in the SPL spectra (Figs. 5 and 6) and in the temperature dependences (Figs. 7 and 8) is also obvious in the PLE spectra as shown in Fig. 9. When either the FE or BE emission is detected (Fig. 4), two lines originating from the hh and lh states of the FE will dominate the PLE spectrum, as expected. If, instead, the FB emission is detected (Fig. 9), the PLE spectrum will still be dominated by same FE-related peaks (hh and lh). However, it is important to note that one obtains enhanced luminescence intensity of these states, when the FB is detected, as can be observed in Figs. 4 and 9 by comparing the intensity ratio of the FE peaks with the background.

As a prerequisite for the proposed excitonic Auger mechanism, free carriers are created at different stages in the multistep process shown in Fig. 2. Carriers are formed at the first two steps: free holes at step *A* (when the acceptor is ionized) and free electrons at step *B* (the excitonic Auger mechanism). One way to detect the presence of these free carriers is to measure the photoconductivity (PC) of the sample upon optical excitation in the exciton range. Figure 10 shows the PC spectrum together with the corresponding PLE spectrum with excitation in the exciton range for sample *C* (doped 100-Å-wide MQW). The hh and lh states associated with the FE are observed in the PLE as well as in the PC spectra, consistent with the proposed model as described above. In addition, another peak can be observed at lower energy in both spectra (even if the PC spectrum does not have the same high resolution as the PLE spectrum). This peak is interpreted as the BE, which is observed in a PLE spectrum for the first time. Work is currently in progress to investigate its properties in more detail.[12] The fact that the BE can be observed also in the PC spectrum proves that free carriers are created also at excitation resonant with the BE, which is in agreement with the proposed excitonic Auger mechanism. It should also be mentioned that the PC spectrum has a strong background (about

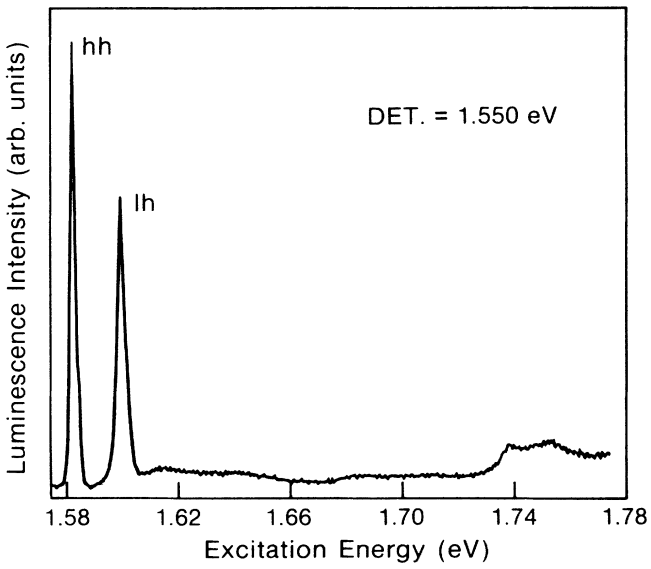

FIG. 9. PLE spectrum at 1.6 K of sample *A* with detection at the peak of the FB transition. In addition to the FE hh and lh states, one can also observe transitions to the $n=2$ electron state at ≈ 1.74 eV. This spectrum was measured on the same spot as used for the PLE spectra in Fig. 4 so the spectra could therefore be directly compared. As observed, the intensity ratio of the intrinsic FE structure vs the background is enhanced when the FB transition is detected.

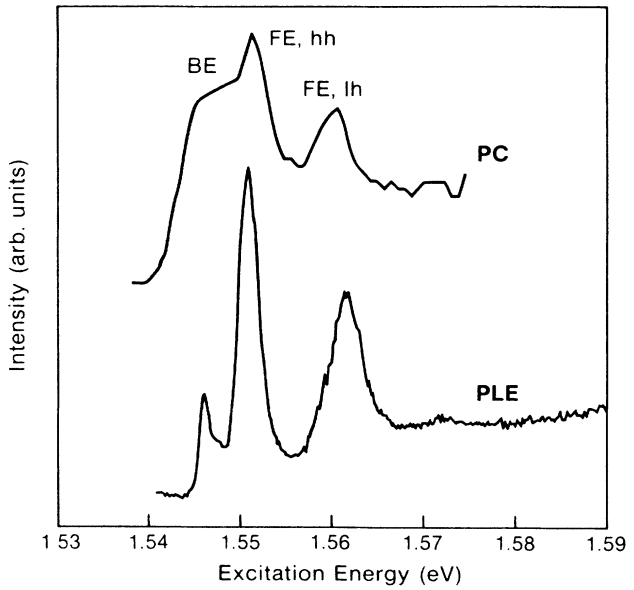

FIG 10. A comparison of the PC and PLE spectra for sample *C* (doped 100-Å MQW) measured at 1.6 K. The detection of the PLE spectrum is at ≈ 1.523 eV (corresponding to the position of an observed THT). It should also be pointed out that there is a strong background (about 80%) in the PC spectrum, most likely originating from the bulk GaAs. In both the PLE and the PC spectrum the FE states (hh and lh) as well as the BE are clearly observed.

80% of the signal), which most probably originates from the GaAs.

DISCUSSION

In this study we report on the observation of the FB transition upon excitation in the vicinity of the FE states and a striking intensity enhancement of this transition at excitation resonant with any of the FE states in QW structures with a fairly low level of Be doping. The experimental results from the SPL, where the excitation energy as well as the temperature has been varied, and PLE experiments show a conclusive intensity correlation between the FE and FB transitions. This observation is at first fairly surprising from our experience with bulk material, for which two "capture paths" dominate for radiative recombinations: (a) one (or two) free electronic particle(s) is (are) captured by an impurity (impurities) and will then, from this impurity level, recombine radiatively with an electronic particle of the opposite charge in a FB (donor-acceptor pair) transition. The second recombination path is the formation of an electron-hole pair (FE) by the mutual Coulomb attraction. This FE can migrate through the lattice until it possibly feels the potential from an impurity. The impurity, either a donor or acceptor or an isoelectronic center, might then trap the exciton to form a BE. These two radiative recombination paths are overwhelmingly dominating mechanisms in bulk material, at least for shallow impurities. Competing nonradiative transitions, e.g., multiphonon and other Auger-like processes, are commonly reported for bulk materials.[13–18] The probability for such transitions is, however, found to decrease with reduced localization of the impurity [e.g., $\tau \sim E_A^{-4}$ for acceptors in Si (Ref. 16)] and is fairly low for the case of shallow impurities in bulk. For the case of QW structures, our knowledge is much more limited and we are more obliged to resort to theoretical predictions than to experimental results. Calculations on phonon-assisted capture processes[19] show that the average capture time is found to display an oscillatory behavior due to the phonon interaction with a periodicity corresponding to the optical-phonon energy. For QW's of the thickness we have investigated in this study, a typical capture time is predicted to be of the order 0.5 ns.[19] This time should be compared with experimental results on the FE decay time, $\tau \leq 0.3$ ns, for samples similar to the investigated ones.[20]

The reported enhancement of the FB transition upon excitation resonant with the FE states is observed in the temperature range 1.6–80 K. Such an enhancement, which occurs also at the lowest temperatures, necessarily requires a multistep process. The prerequisites for the enhanced FB transition is a free electron and a hole bound at the acceptor (i.e., a neutral acceptor) and a strong resonant effect with the FE for the excitation. There are alternative possibilities to create a free electron given the above conditions, e.g., (a) direct photoexcitation of a donor electron, (b) two-electron transition (TET) of a donor BE (DBE) leaving the donor in an ionized state, (c) excitonic Auger recombination via capture of a FE by an acceptor as described above, and (d) process (c), but with a BE involved instead of the FE. Of these possibilities, only (c) fulfills the prerequisite of the observed FE resonance. The pronounced resonant effect observed in SPL (Figs. 5 and 6), in the temperature-dependent luminescence spectra (Fig. 7), as well as in PLE (Figs. 4 and 9) strongly favors alternative (c). The low donor concentration in the samples used ($n < 10^{15}$ cm^{-3}) makes alternatives (a) and (b) further unlikely (but not excluded).

The temperature dependence of the FB transition should, according to the described model, be given by the thermal behavior of the FE and an additional factor reflecting the ratio of ionized to neutral acceptors. The probability for step *C* (Fig. 2), the FB recombination, decreases with the ratio of ionized to neutral acceptors, since there is no bound hole to recombine with in the case of an ionized acceptor. [The intensity ratio of FB to FE could possibly be affected by the fact that step *B* can occur without the THT (step *A*) at increasing temperatures, if this is a limiting factor for the Auger recombination.] We have experimentally (Figs. 7 and 8) observed that the thermal behaviors of the FB and FE are similar, but with the FB intensity reduced somewhat faster than the FE at elevated temperatures (at which the accuracy of the measurements is deteriorating, however). If an Arrhenius plot is performed on the data of the normalized intensity ratio of FB to FE in Fig. 8 (in the range 30–70 K, where the experimental accuracy is satisfactory), an activation energy of the order 40 meV is provided, i.e., in reasonable agreement with the binding energy of the confined Be acceptor. The intensity ratio of FB to FE thus seems to correlate with the fraction of neutral acceptors with increasing temperatures, which indicates that the temperature dependence for the total PL intensity of the FB transition is determined by the thermal behavior of the FE and the fraction of neutral acceptors in step *C* (Fig. 2).

FE states have earlier been observed in PC measurements on QW's or superlattices,[21] but we do not have any detailed knowledge about the mechanism giving rise to the formation of free carriers at excitation resonant with any of the FE states, even if different suggestions have been made. The most common explanation is the electric field model, in which the excitons are quenched by the field. It should be pointed out that in our case both the FE and BE can be observed in the PC spectra even when the applied field is zero, i.e., there is a detectable photocurrent measured along the QW layers without any applied voltage. We believe that the suggested excitonic Auger mechanism is a reasonable explanation for this observation of the exciton states in the PC measurements. One could raise the concern that FE state have been also observed in undoped samples. However, we have used similar samples with different doping levels (3×10^{16} and 1×10^{17} cm^{-3}), which show the effect of FB transition enhancement upon resonant excitation with approximately the same efficiency (the FB peak intensity constitutes 8–9 % of the FE peak in these samples). This fact indicates (despite the limited number of samples investigated) that the efficiency of the proposed excitonic Auger recombination is saturated at relatively low doping levels. In a recent PL study on fairly low-doped ($n = 10^{16}$ cm^{-3})

material,[22] the FB transition as well as the exciton bound at the ionized donor are observed. The prerequisites for the proposed excitonic Auger recombination should be favorable in such a system. Even if the FB transition is not observed in nominally undoped samples (presumably limited by step *C* in Fig. 2), the background doping (of the order 10^{15} cm^{-3}) present in these samples might be sufficient to give rise to the excitonic Auger mechanism.

SUMMARY

Narrow QW's (70–150 Å) in the GaAs/$Al_{0.3}Ga_{0.7}As$ system have been investigated in this spectroscopic study. The *p*-type doping level in these samples has been below the critical limit ($<1\times10^{17}$ cm^{-3}), so that only the intrinsic FE emission is observed using above-band-gap cw excitation. At selective dye-laser excitation, on the other hand, the extrinsic FB transition (an $n=1$ quantized electron recombining with a hole from the neutral acceptor) appears, if the excitation is in the vicinity of the hh or lh states of the FE. Upon resonant excitation with any of these states, the intensity of the FB band is strikingly enhanced. The intensity correlation between the FE and the FB is also observed in the PLE spectra. Furthermore, the thermal behavior of the FE and the FB is found to be very similar, as established by SPL measurements with resonant excitation performed at different temperatures. The observed enhancement of the FB transition upon excitation resonant with any of the FE states is by necessity a multistep mechanism. This process is tentatively explained by an excitonic Auger recombination, where the exciton hole is attracted and captured by an ionized acceptor. The excess energy is transferred to the electron, which is excited into the continuum. In the last step, a free electron recombines with an acceptor hole in a FB transition. The formation of free carriers at excitation resonant with the excitons has been verified by PC measurements, consistent with the proposed model.

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