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Magnetic-field-induced localization effects on radiative recombination in GaAs/Al$_x$Ga$_{1-x}$As heterostructures

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The influence of localization effects on the radiative recombination of two-dimensional confined electrons and holes in single-side modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructures is investigated by magneto-optical measurements. The results show a rapid decrease of photoluminescence (PL) intensity with increasing temperature and a striking increase of PL intensity when a weak magnetic field is applied. This is explained as an enhancement of hole localization caused by an inhomogenous distribution of background impurities. The effective thermal-activation energy of the hole localization potential is found to vary from about 0.6 to 1.7 meV with increasing magnetic field from 0 to 4.5 T, respectively.

INTRODUCTION

The power of photoluminescence (PL) related methods as a means of studying the electronic properties of modulation-doped III-V heterostructures has been demonstrated in a number of recent investigations of GaAs/Al$_x$Ga$_{1-x}$As,[1-9] as well as of InP/In$_x$Ga$_{1-x}$As heterostructures.[10-13] The broad PL emission bands related to confined two-dimensional (2D) carriers occur close to the band-gap energy of GaAs in n-type modulation-doped GaAs/Al$_x$Ga$_{1-x}$As structures with at least one heterointerface. Properties such as the spectral shape, PL energy position,[2-4] decay time,[6,8] and many-body effects (such as the Fermi-edge singularity) (Refs. 7, 9, and 10) have been reported. Those properties are strongly dependent on the detailed materials-related properties of the samples and also on excitation intensities. Since the electrons involved in the PL emissions are confined at the heterointerface and are the majority carriers, the photoexcited holes play a crucial role in determining the optical properties in the structures.

Localization effects are suggested to be important in InP/In$_x$Ga$_{1-x}$As based heterostructures,[10] but believed to play a minor role in the GaAs/Al$_x$Ga$_{1-x}$As system, where the interface roughness is the dominant cause of localization potentials for quantum well (QW) structures.[14] For wider heterostructures, as shown in this work, the contribution from interface roughness is negligible, but localization effects might arise from the occurrence of an inhomogeneous distribution of dopants or defects in the active layer.

In this paper, we present a magneto-optical study on n-type modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructures. The influence of the localization of photocreated holes on the radiative recombination is investigated by PL measurements in the presence of an applied magnetic field. The results show a strong influence on the 2D related PL emission band, the so-called HB1 band, by a weak magnetic field. This strong influence can be understood in terms of localization effects of holes, caused by potential fluctuations induced by the irregular distribution of residual background impurities. An applied magnetic field will enhance these impurity-related localization effects. The effective thermal-activation energy characteristic of the induced potentials can be estimated from the PL measurements.

EXPERIMENT

The samples used in this study were grown by molecular-beam epitaxy (MBE) on a semi-insulating GaAs substrate. On top of the substrate followed a ten-period GaAs/AlAs (20 Å/20 Å) superlattice (SL), a 500-Å-thick GaAs layer, an undoped 200-Å Al$_{0.35}$ Ga$_{0.65}$As spacer layer, an 800-Å n-type Si-doped Al$_{0.35}$Ga$_{0.65}$As layer with a doping concentration of 10^{18} cm^{-3}, and finally a 50-Å undoped GaAs cap layer. The interface potential containing the 2D electron gas is formed between the Al$_{0.35}$Ga$_{0.65}$As spacer layer and the active GaAs layer. Both the superlattice and the active GaAs layer were slightly p type from an unintentional p-type background doping ($p \approx 10^{15}$ cm^{-3} in the GaAs layer). The 2D electron concentration is estimated to be about 2×10^{11} cm^{-2} under dark conditions, from Shubnikov–de Haas experiments performed separately.

Photoluminescence from the samples was dispersed by a double-grating monochromator and detected with a GaAs photomultiplier detector. A tunable sapphire:Ti solid-state laser was used as the excitation source. The typical laser excitation intensity is about 10^{-3} W/cm^2. The samples were mounted in a 16-T magnet. The laser light was coupled to the samples via optical fibers, and the emission from the sample was collected through the same fiber into the monochromator. The temperature of the sample can be controlled in the range 1.5–300 K.

A schematic picture of the potential across the structures is shown in Fig. 1. The transition HB1 is also indicated in this figure. The shape and spectral position of the HB1 emission are strongly dependent on the excitation intensity and the excitation photon energy.[2,4] In our previous studies on n-type modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterostructures, it is concluded that

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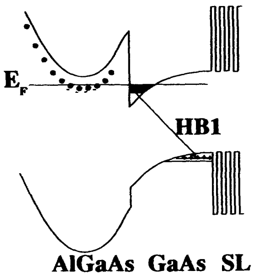

FIG. 1. Schematic diagram of the potential for an asymmetric *n*-type modulation-doped heterostructure used in this work.

the HB1 emission is due to the recombination between the confined 2D electrons and 2D holes in the valence band at the other interface of the active 500-Å GaAs layer,[4,5] in agreement with earlier reports.[2,3]

RESULTS AND DISCUSSION

Figure 2 shows two sets of PL spectra for the HB1 transition near the bulk GaAs band-gap region in the presence of an applied magnetic field at two different temperatures 2.0 and 15 K. The results show a strong increase of the HB1 PL intensity with increasing magnetic fields, especially at the higher temperature. There is no significant energy shift of the HB1 peak position. The observed effect is therefore either an enhancement of the radiative recombination probability, or a decrease in competing nonradiative processes. Since the radiative recombination probability of a band to band transition will not significantly change by applying a small magnetic field as used in Fig. 2, the integrated PL intensity is not expected to change. The peak at the energy 1.515 eV (denoted *F*) in the PL spectra is due to two overlapping emissions, the Fermi-edge singularity[7] (FES) and the exciton related to the $n=2$ electron subband. It should be noted that the FES dominates at low temperature, since there is no electron population in the $n=2$ electron subband. With increasing temperature there may be a thermal population in the $n=2$ electron subband. In that situation the PL intensity of the excitons related to the $n=2$ electron subband becomes stronger. There is no corresponding enhancement of the PL intensity related to the *F* emissions in the presence of a small magnetic field. The difference between the HB1 and the *F* emissions is that the HB1 originates from a band to band transition, while the *F* emission is of excitonic character. The radiative recombination decay time of the *F* band (the FES and the $n=2$ excitons) is much faster [sub ns (Ref. 15)] than the HB1 emission (~ 100 ns).[6]

Figure 3 shows the temperature dependence of the HB1 PL spectra at two different magnetic fields, 0 and 4.5 T. The results clearly show that the HB1 PL intensity decreases much faster with temperature for 0 than for 4.5 T magnetic field. The HB1 and the *F* emissions exhibit different temperature dependencies in Fig. 3. The intensity of the *F* band increases with increasing temperatures at both 0 and 4.5 T. For the case of 4.5 T the HB1 PL emission survives to temperatures higher than 15 K. For temperatures higher than 15 K, the *F* band intensity grows more rapidly and the energy peak position of the *F* band shifts to lower energy with increasing temperatures. The increased intensity of the *F* band is due to an increased thermal population of the $n=2$ electron subband with increasing temperature. It is also consistent with

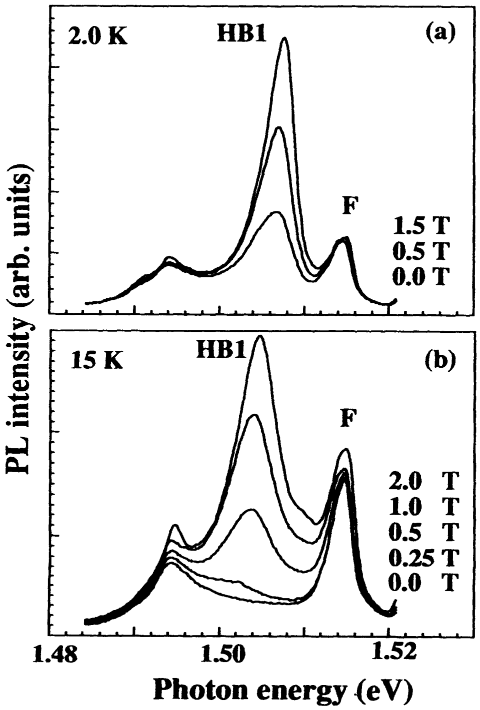

FIG. 2. The magnetic-field dependence of the HB1 recombination at two different temperatures, (a) 2.0 K and (b) 15 K.

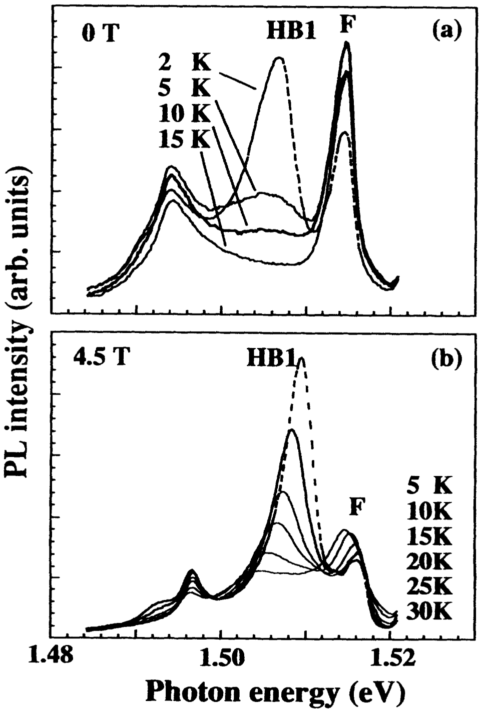

FIG. 3. The temperature dependence of the HB1 recombination at two different magnetic fields, (a) 0 T and (b) 4.5 T.

the fact that the redshift of the F band peak position with temperature correlates with the energy shift of the HB1.

The effective thermal activation energies deduced from the temperature dependence of the HB1 emission are plotted in Fig. 4. The results show that the activation energy increases from about 0.6 to 1.7 meV when the magnetic field varies from 0 to 4.5 T. Both the magnetic field dependence and the temperature dependence of the HB1 PL intensity indicate that the holes involved in the recombination are to a large extent localized at the lowest temperatures. The absence of resolved electron Landau level splitting in the PL spectra is also consistent with a broadening of the HB1 emission due to potential fluctuations caused by a random distribution of Coulomb charges in the active GaAs layer. The interface roughness in such 500-Å-wide heterostructures will introduce negligibly weak localization potentials for holes (<10 μeV). We propose that the hole localization potentials in our samples are due to the inhomogenous distribution of negatively charged residual acceptors (IDRA) in the active GaAs layer. In our samples the unintentional background doping in the GaAs layer is about 10^{15} cm^{-3} C acceptors, which is sufficient to introduce potential fluctuations which are of the same order as observed in our experiments, i.e., a few meV.[16,17]

With a magnetic field applied along the growth direction of the structures (denoted as the z direction), the motion of the charged carriers in the xy plane will be restricted due to the Lorenz force. The localization length L_b of free carriers at a given magnetic field is equal to $\sqrt{\hbar/eB}$. The magnetic-field dependence of the PL intensity in Fig. 2 is consistently explained in terms of a localization at impurity-induced potentials enhanced by the magnetic-field localization, in the presence of a strong nonradiative channel from hole traps at the SL/GaAs interface. If the holes escape from the potentials induced by IDRA, there is an increasing probability that the holes instead are captured by nonradiative traps, resulting in a decreasing intensity of the HB1 emission. When a magnetic field is applied, the hole motion perpendicular to the magnetic field is restricted, and the holes become more strongly localized in the potential introduced by IDRA. This increasing localization will increase the probability for the holes to recombine radiatively with the 2D electrons, and accordingly the radiative recombination channel HB1 increases in intensity.

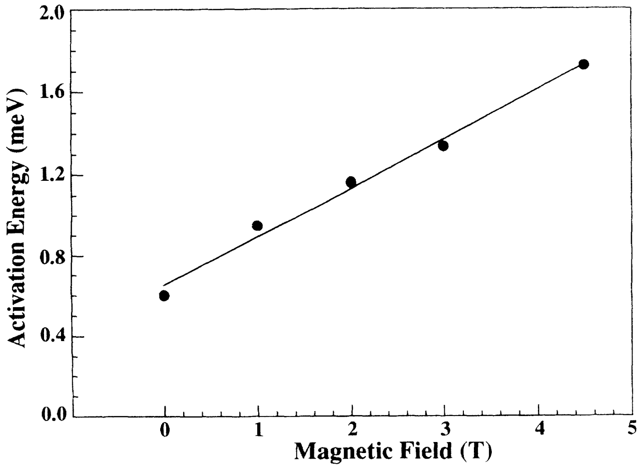

FIG. 4. The effective thermal activation energy associated with the hole localization vs magnetic field.

On the other hand, the temperature dependence of the PL integrated intensity of emission related to 2D electrons in Fig. 3 shows a decrease with increasing temperatures. This is also consistent with the above localization model. Since increasing temperatures results in an increase of the thermal energy of the holes, the holes will escape more easily from the potential induced by IDRA and become trapped at nonradiative interface states, and the HB1 intensity will accordingly decrease. The F band does not show a strong influence by the hole localization. This can be understood by considering the relative time scale between the recombination time of the F band and the capture time of holes at the nonradiative traps. The nonradiative traps will not have any significant influence on the radiative recombination channel if the latter has a faster recombination time. It has been shown that the FES as well as the second subband excitons have a fast radiative recombination time, typically <1 ns at low temperatures.[15]

The characteristic energy shift of the HB1 emission with temperature observed in a magnetic field [Fig. 3(b)] can also be understood in this localization model. The low-energy part of the HB1 peak is redshifted by about 5 meV when the temperature increases from 5 to 30 K. We suggest that this effect reflects the hole distribution. The weakly localized holes are thermally released and suffer nonradiative recombination, while the more strongly localized holes survive at higher temperature, and the resulting HB1 emission is accordingly redshifted. Since the electrons in the notch potential will also experience a similar impurity-induced localization as the holes, the energy shift of HB1 may be expected to be about the sum of the localization energies for electrons and holes at each temperature. The F emission, on the other hand, is associated with the higher electron subband at higher temperatures (above 15 K). Due to the more extended electron wave function in the second subband, the F band shift would only be mainly due to the hole localization. The downshift of the F peak in Fig. 3(b) is observed to be about 2 meV when the temperature increases from 15 to 30 K.

Localization effects for holes will profoundly affect the appearance of PL spectra. The disappearance of resolved Landau level splitting for samples with higher background impurity concentration ($>10^{15}$ cm^{-3}) in the active GaAs layer is one striking effect discussed above. Also the PL line shape differs dramatically between different reports,[2-4] a fact which has not been properly explained in the literature. For high-purity samples ($<10^{14}$ cm^{-3} background impurities in the GaAs layer) with perfect interfaces (i.e., no nonradiative traps), the emission related to the 2D electrons can be observed[3] even at very low laser excitation intensity (10^{-5} W/cm^2), and the PL line shape for HB1 reflects the 2D density of states. This is consistent with a complete relaxation of the momentum conservation in the radiative process.

This can be understood if the holes are completely localized at the low excitation level. In other cases,[2,4] as well as in this work, a relatively high excitation intensity (10^{-3} W/cm^2) must be used in order to observe the HB1 recombination due to a higher background impurity concentration and the existence of nonradiative hole traps. The line shape is far from flat in these cases. The broadening of the HB1 emission due to potential fluctuation is one factor, and it also appears that the momentum conservation is partly retained, since the high-energy part of the HB1 emission is quenched. Since a relatively high excitation intensity was used in this work, compared to Ref. 3, a large fraction of quasifree or only weakly localized holes participates in the PL process, giving a strong preference to the low electron energy ($k_{\parallel}$ close to 0) part of the HB1 spectra. From a detailed inspection of Fig. 3(b), we can see that at high temperatures the line shape shows a stronger relaxation of the momentum conservation in the radiative process, since more strongly localized holes are involved in this recombination, in agreement with the above discussion.

SUMMARY

Magnetoluminescence investigations on *n*-type modulation-doped heterostructures have been presented. The results show a striking increase of PL intensity related to the 2D electrons when a weak magnetic field is applied, and a rapid decrease with increasing temperature. This strong influence can be understood in terms of magnetic-field-enhanced localization effects of holes, primarily caused by potential fluctuations induced by the irregular distribution of residual background impurities, in the presence of nonradiative interface hole traps. The effective thermal activation energy of the localized potential is found to vary from about 0.6 to 1.7 meV with increasing magnetic field from 0 to 4.5 T, respectively. A coherent picture of the various spectral line shapes observed in literature for the PL spectra related to the 2D electron gas in GaAs/Al$_x$Ga$_{1-x}$As heterostructures is provided, in terms of hole localization.

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