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Photoluminescence Studies of P-type Modulation Doped GaAs/AlGaAs Quantum Wells in the High Doping Regime

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Abstract

The influence of high Be-acceptor doping on the modulation-doped $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells structures has been optically studied by using the low-temperature photoluminescence (PL) and photoluminescence excitation (PLE) techniques.The modulation doped samples were grown by the molecular-beam epitaxy technique with a varying Be acceptor concentration ranging from 1×10^{18} to $8 \times 10^{18}\,cm^{-3}$. Several novels physical effects were observed. The main effect is a significant shift of the main emission towards lower energies as the doping concentrations increase. There are two contradictory mechanisms, which determine the peak energy of the main emission; the shrinkage of the effective bandgap due to many body effects and the reduction of the exciton binding energy due to the carrier screening effect. We conclude that the first one is the dominating effect. At a sufficiently high doping concentration (roughly $2 \times 10^{18}\,cm^{-3}$), the lineshape of the main PL emission is modified, and a new feature, the so called Fermi-edge singularity (FES), appears on the high energy side of the PL emission and exhibits a blue-shift as a function of doping concentration. This feature has been found to be very sensitive to a temperature change, already in the range of 4.4–50 K. In addition, PLE spectra with a suitable detection energy show that the absorption edge is blue-shifted with respect to the PL main emission. The resulting Stoke shift is due to phase-space-filling of the carriers, in agreement with the FES interpretation. Finally, we have found from the PLE spectra that the exciton quenching is initiated in the same doping regime. Compared to the exciton quenching in other p-type structures, the critical acceptor concentration required to quench the excitons is significantly lower than in the case of 2D structures with acceptor doping within the well, but larger than in the case of 3D bulk.

1. Introduction

The optical properties of semiconductors are strongly determined by the dopant impurities. When the density of the dopants becomes sufficiently high, the situation becomes more complicated. The single particle interaction picture is not sufficient to describe such a system but many-body effects instead become important. The exchange and correlation interactions induced by the high carrier concentration give rise to a shrinkage of the fundamental band gap and the higher subbands, the so-called Band-Gap Renormalization (BGR). Furthermore, the interaction between the carriers in the Fermi sea and the photogenerated carriers can enhance the Fermi Edge Singularity (FES). One possible mechanism that promotes the FES recombination is a localization of the photogenerated carriers as proposed by Skolnick *et al.* [1]. Another mechanism is to induce the interaction between the carriers at the Fermi edge and at the next unoccupied subband as proposed by Chen *et al.* [2, 3]. The doped quantum well (QW), either modulation doped (MDQW) or well doped quantum well (WDQW) is an advantageous system to study such effects. While most work has been focused on n-type doped structures up to now, less attention has been paid on the p-type structures. This is based on two reasons. First, it is well known that the heavy hole mass can be 5–8 times larger than the electron mass, and accordingly the Fermi energy of an electron gas will be 5–8 times higher than the corresponding hole gas of the same density. Due to this fact the effect is more pronounced and more easily observed in n-type system. The second reason is based on the strong nonparabolicity of the valence band.

In this work, we present the effects of high acceptor concentration in the MDQW structure on their optical properties.

2. Samples and experimental technique

The samples used in our study were grown by molecular beam epitaxy. These samples are double-side modulation doped multiple quantum wells. The structures were grown on semi-insulating GaAs substrates in the following sequence: 150 Å thick GaAs buffer layer, 50 periods of undoped GaAs wells of 150 Å nominal width separated by 150 Å thick $Al_xGa_{1-x}As$ barriers with the composition of $x = 0.3$ with a 50 Å Be-doped layer in the center of the barrier. Four samples were grown with the following acceptor concentration: 1×10^{18}, 2×10^{18}, 4×10^{18} and $8 \times 10^{18}\,cm^{-3}$ (labeled #193, #194, #195, #196) with a corresponding hole sheet density of 4.1×10^{11}, 1.3×10^{12}, 2.2×10^{12} and $3.1 \times 10^{12}\,cm^{-2}$, respectively, with the assumption that all acceptors are ionized. The structures are finally capped by an undoped GaAs layer of a thickness of 150 Å. All four samples were optically investigated together with an intentionally undoped reference sample (labeled #Ref).

The standard photoluminescence (PL) and photoluminescence excitation (PLE) techniques are employed to characterize the samples together with a polarization-dependence setup to identify the light hole transition in the PLE spectrum. The measurements were performed in a liquid helium-cooled Oxford cryostat pumped below the λ-point. The excitation source was provided from a tunable Ti-doped sapphire laser pumped by an Ar^+ ion laser. The luminescence from the samples was dispersed and analyzed by a 1-m double-grating monochromator with a GaAs photomultiplier detector and a lock-in detection system. For the polarization dependent PLE measurements, the technique of using a photoelastic modulator (PEM) was applied. The

laser beam was modulated by a 50 kHz PEM to have circularly polarised (σ^+ and σ^-) components to illuminate the sample perpendicularly. The net circularly polarized light (σ^+–σ^-) from the sample was detected by a quarter-wave plate and a Glan–Thompson polarizer, prior to dispersion in the monochromator.

3. Experiment results

The evolution of PL spectra observed as a function of acceptor concentration is displayed in Fig. 1. All spectra were taken at a constant laser excitation energy of 1.631 eV and a temperature below 2.2 K. The predominant peak observed in every sample is interpreted as the recombination between electrons from the lowest occupied conduction band and holes from the highest occupied 2D heavy hole subbands. This emission peak is obviously strongly dependent on the acceptor concentration. As the acceptor concentration increases, a significant red-shift and asymmetric broadening towards higher energy is observed. The corresponding shift with respect to the reference sample is about 10 and 20 meV for the sample with low (#193) and high (#196) acceptor doping, respectively. The major mechanism behind this red-shift is the BGR due to the many-body interaction. This red-shift is reduced due to a decreasing excitonic effect in PL band as the doping increases. The high energy tail of the main emission can be associated with phase space filling in the hole subband. The recombination of a localized electron in the well can recombine with a hole at any energy up to the Fermi level [4]. When the acceptor concentration is substantially higher, we are able to resolve a new feature appearing on the high energy tail. The development of this structure into the separate well-defined peak which we assign as a FES can be seen already in sample #195 and is clearly seen in sample #196. In order to understand the mechanism of this FES, the temperature dependence of the FES was observed in sample #196. As shown in Fig. 2, the thermal energy in the range of 4.4–50 K has a strong effect on the quenching of the FES compared to the main PL peak, as can be expected for the FES. The emission peaks observed at lower energy labeled A and B, are assigned to the impurity related recombination which will be excluded from the scope of our analysis.

The further investigations were based on PLE or absorption spectra corresponding to the same conditions as in Fig. 1. All PLE spectra were taken with a detection energy at the low energy tail of the main emission of the corresponding samples. In Fig. 3, it can be seen that the excitonic enhancement clearly appears at every energy step in the PLE spectrum of the reference sample. As the acceptor concentration increases, striking effects were observed. The whole spectrum shifts down in energy similar to the PL spectra and the sharp absorption peaks are smeared out and only step-like features remain. The excitonic feature is weakly resolved only in sample #193 and completely quenched in the others. The negative differential signal of the polarization (σ^+–σ^-) corresponding to the light hole transition tends to broaden and slightly red shift with increasing carrier concentration. It is important to point out that the light hole

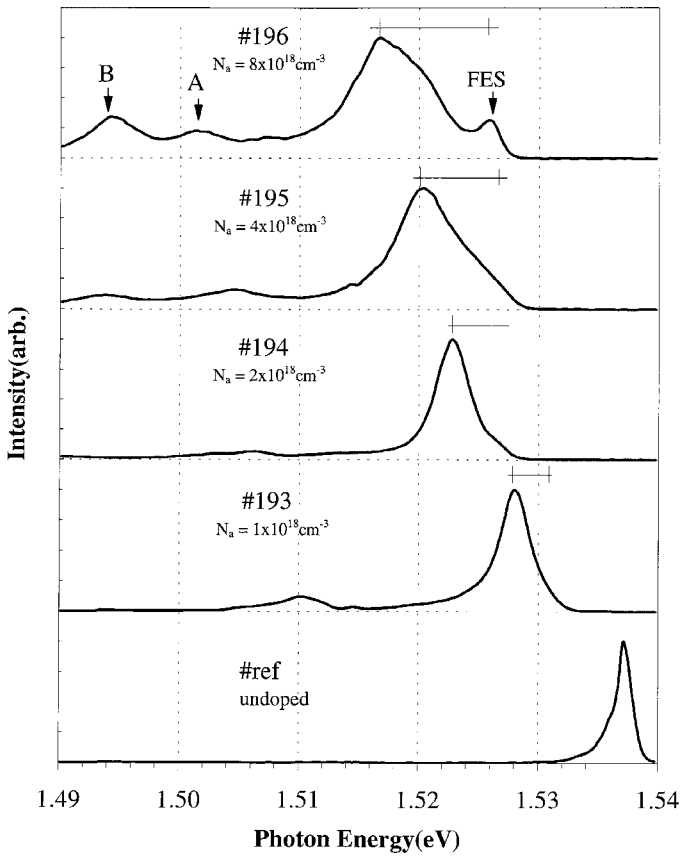

Fig. 1. The evolution of PL spectral measured at 2 K as a function of acceptor concentration with an excitation energy of 1.631 eV.

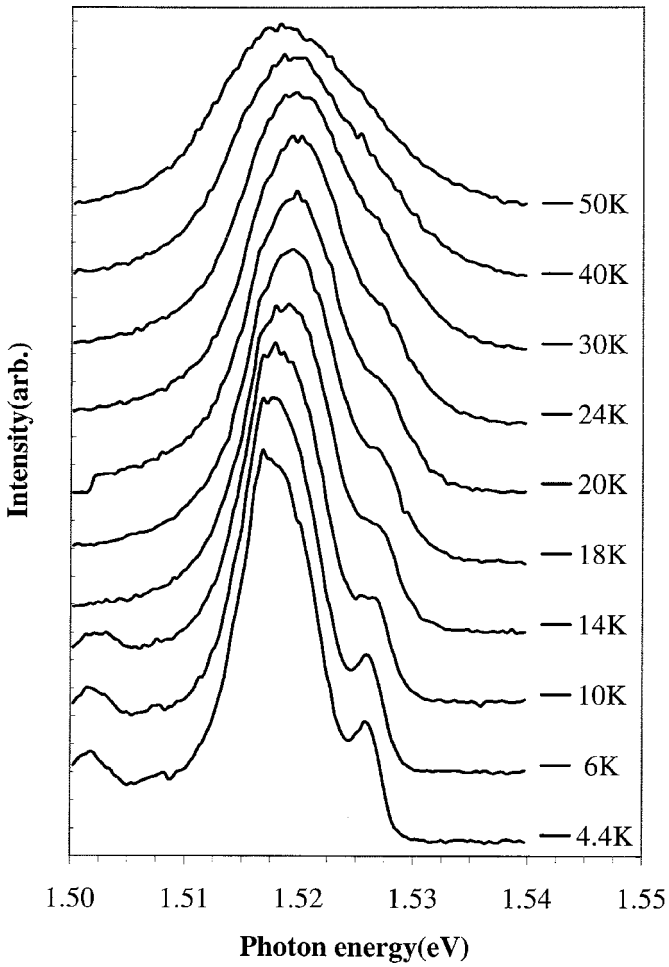

Fig. 2. The temperature dependence of PL spectra for sample #196 illustrating the thermal quenching of FES.

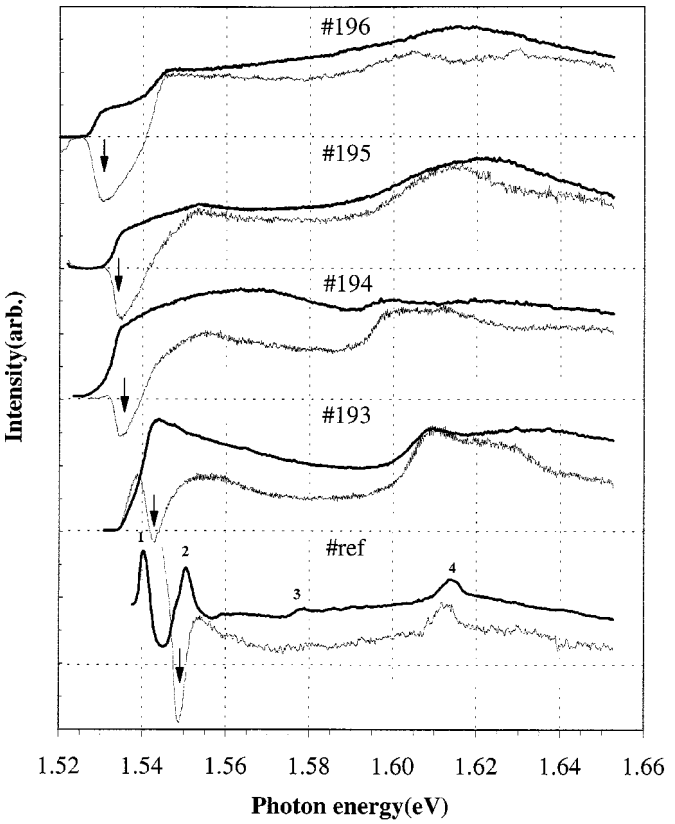

Fig. 3. PLE spectra at different acceptor concentrations. The thin lines represent the differential polarization ($\sigma^+ - \sigma^-$) curve. The numbers 1–4 denote the e1–hh1, e1–lh1, e1–hh3 and e2–hh2 related transitions. The arrows show an evolution of the e1–lh1 related transition as a function of doping concentration.

transition is present in every PLE spectrum. This fact implies that only the first heavy hole band is populated. The sharp cut-off on the low energy side of the PLE spectra weakly shifts in energy position. The cut-off region is associated with the phase space filling. The absorption of free carriers is forbidden up to E_F and therefore the laser excitation in this region does not result in any luminescence. The separation between the main PL peak and the absorption edge, the so-called Burstein–Moss shift, increases gradually from sample #193 to #196. The hole concentration can be roughly determined from this Burstein–Moss shift.

4. Discussion

As the acceptor concentration increases, the red shift of the PL peak becomes more pronounced, there are two mechanisms responsible for the PL peak shift: a) the reduction in exciton binding energy which results in an increasing exciton recombination energy b) BGR due to the exchange and correlation energy of free carriers. The first mechanism is significantly smaller than the second. In a similar case for a 100 Å MDQW [5], the oscillator strength of the exciton drops off rapidly as well as the exciton binding energy, as the concentration exceeds $4.1 \times 10^{11}\,cm^{-2}$. It is reasonable that the excitonic effect is mostly washed out from the contribution to the main PL starting already from sample #194, for which only the BGR remains effective even for the higher subbands. From the PLE spectra (Fig. 3), it is obvious from the red shift of the absorption edge that the BGR exhibits a stronger effect than the phase space filling. This is in contrast to n-type structures. This difference is attributed to the different effective mass for the electron and hole.

The mechanism behind the FES enhancement may be explained in two possible ways as mentioned in the introduction part: The localization of free photogenerated carriers and the carrier scattering between the Fermi edge and the next unoccupied subband. The first phenomenon is important in the systems with strong disorder due to alloy fluctuations or interface roughness. In general, the GaAs/AlGaAs system provides a smoother system with less disorder carrier localization. Therefore we can discard the FES caused by the localization mechanism. Instead, we assign the FES enhancement to scattering via the light hole band.

Generally, the quenching of the exciton is due to three mechanisms: Phase space filling, exchange interaction and coulombic screening. For our system, the heavy hole related exciton is completely quenched for the acceptor concentrations higher than $1 \times 10^{18}\,cm^{-3}$ ($4.1 \times 10^{11}\,cm^{-2}$) which is similar to what was reported by D. Haung *et al*, [5] for both n and p-type MDQW structures. In comparison to WDQWs structures, this seems to be similar to what has been observed in n-type structure [6] but it is about one order of magnitude lower than for p-type structures [7]. The quenching of the heavy hole exciton is mainly due to the phase space filling effect, which is effective only for filled bands [5]. Thus as long as the light hole subband is not populated, the light hole related exciton should be less sensitive to the doping concentration than the heavy hole exciton.

5. Conclusion

We have investigated the p-type modulation doped quantum wells for the doping concentrations up to $8 \times 10^{18}\,cm^{-3}$. The survival of heavy hole and light hole related excitons with increasing of acceptor concentration has been studied. Furthermore, the bandgap renormalization effect has been studied as a function of doping. Finally, we report on the first observation of the Fermi edge singularity in p-type quantum wells.

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