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Many-body effects as probe of defects presence in heavily doped AlGaAs/InGaAs/GaAs heterostructures

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Abstract. Strikingly strong many-body enhancement of the oscillator strength for interband transitions is observed in the photoluminescence (PL) of heavily doped pseudomorphic $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ heterostructures under condition of the $n = 2$ subband filling. The many-body excitations reveal a remarkable stability with respect to thermal and excitation density decay. Such behaviour is addressed the intersub-band coupling in high-density one-component plasma of InGaAs quantum well in the presence of defects localising the heavy holes.

1. Introduction

Modulation-doped pseudomorphic $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ heterostructures, besides the excellent transistor characteristics with respect to power gain, current, transconductance, and noise performance at high frequencies, occur to be ideally suited for the study of a number of effects fundamental for the semiconductor physics such as the Fermi edge singularity (FES). The defect presence is of extreme importance for the realization of the preferable conditions for the FES observation [1,2]. Thus, on the contrary, the FES origination can serve as a sensitive probe for the detection of the defects presence. Here we present the results of spectroscopic study of the interband optical transitions in a close vicinity of Fermi energy in the conduction band of $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ modulation-doped structures and their behavior under temperature and excitation density variation. The results give evidence of the many-body nature of a strong complementary PL stabilized by the defects.

2. Experimental details

Pseudomorphic modulation-doped $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ samples have been grown on semi-insulating (100)-oriented GaAs substrates in a Riber 32-P gas-source molecular-beam epitaxy (GSMBE) system. The $Al_xGa_{1-x}As$ and $In_yGa_{1-y}As$ layer compositions were intentionally held invariable at the level of $x \approx 0.20$ and $y \approx 0.1$, respectively. The Si-doping and the InGaAs quantum well (QW) width d_w were adjusted to meet requirements of second electronic subband ($n_e = 2$) filling. The set of samples with invariable Si doping and the d_w value changing within the range 18 nm < d_w < 27 nm has been grown. The PL was excited by the 514.5-nm line of a cw Ar laser. The excitation density was varied in the range 0.05÷20 W×cm^{-2}. The PL signal was dispersed through a 3/4-m Czerny-Turner scanning spectrometer, with a spectral resolution better than 0.1 meV. The samples were mounted in an Oxford Spectromag 4000 system, which allows measurements at temperatures from 1.7 to 300 K.

3. Results and Discussion

A principally new behaviour in PL of heavily doped pseudomorphic modulation–doped $Al_xGa_{1-x}As/In_yGa_{1-y}As/GaAs$ ($x = 0.2$, $y \leq 0.1$) heterostructures is detected in the case of occupied $n = 2$ electronic subband. Fig.1 depicts the low temperature spectra measured at low excitation density for the set of samples with varying quantum well width d_w (from 8 nm up to 27 nm) at invariable Si doping of supplier $Al_xGa_{1-x}As$ layer. The energy origin is placed at the maximum of the high-energy peak in each particular spectrum. The d_w variation allows to change the population of $n = 2$ electronic subband. The ratio ξ of magnitudes for the E_{21} and E_{11} peaks varying within the range 0.1 to 50 mirrors the change of $n = 2$ subband population. It is clearly seen that if the ξ value reaches nearly 20 a complementary feature A arises below E_{21} transition. This feature grows by intensity, exceeding even E_{11} transition, if ξ takes the value ≈ 30. In order to ascertain the nature of this complementary peak the temperature and excitation density elevation has been performed. Fig.2 depicts the modification in the PL spectrum of S7 sample with temperature increase. It occurs that the strength of A feature grows initially with

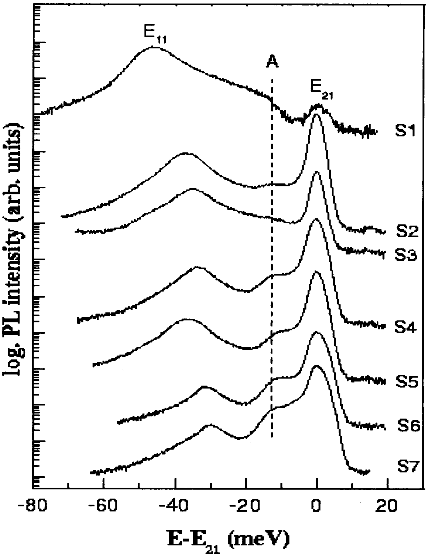

Figure 1. Low temperature PL spectra for samples with varying d_w value: S1 = 8 nm, S2 = 18.2 nm, S3 = 19.7 nm, S4 = 21.4 nm, S5 = 21.5 nm, S6 = 25.4 nm, S7 = 26.7 nm.

temperature increase and this peak becomes even more distinct. If temperature reaches 80 K the feature A decays completely revealing the binding energy the order of 7 meV. The similar behaviour is detected also at the excitation density elevation.

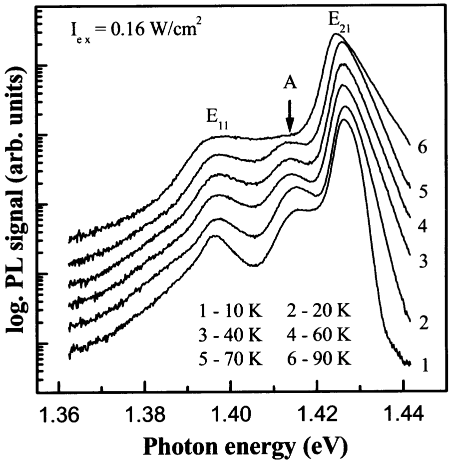

Figure 2. Temperature dependent spectra for sample S7.

Such behaviour of complementary feature A is observed for the first time. Indeed for the case of empty n = 2 electronic sub-band the PL study has shown convincingly that the carrier concentration and the excitation density strongly influence the additional feature appearance, immediately below the n = 2 bare exciton, in the presence of hole localization. This particular feature has been addressed to the FES manifestation. At least the FES evolves in PL spectra under appropriate light illumination being absent at the lowest excitation density. The FES excitation density dependence cannot be addressed to the presence of inner electric field and has to be bounced back to the properties of 2DEG unexplored. The model of Fano resonance between the many-body excitations of Fermi sea and the discrete excitonic state of n = 2 conduction sub-band is also not very plausible for the explanation of both the excitation density and temperature dependences of the feature observed experimentally.

An additional peak has been also detected earlier in the PL spectra of pseudomorphicGaAs/$\mathrm{In_{0.2}Ga_{0.8}As}$/$\mathrm{Al_{0.25}Ga_{0.75}As}$ modulation-doped single QW's [3]. It was ascribed to the strong coupling between the InGaAs QW and the potential well formed in the AlGaAs barrier due to planar doping. This coupling could produce the hybrid states in the conduction band giving rise to additional transitions in the emission spectrum. One of these transitions between hybrid electronic state and heavy-hole state could be responsible for the extra PL peak observed below the E_{21} transitions. The strongly nonmonotonic temperature dependence of the peak strength, however, makes such an assignment somewhat questionable. Indeed, the calculated electron-hole wave function overlaps exhibit no substantial variation within the investigated temperature range (2 K- 51 K), thus no reasonable explanations remain for the strong quenching of this peak at temperatures as high as 40 K.

Our novel findings concerning the spectroscopy of the Fermi edge states in pseudomorphic modulation-doped AlGaAs/InGaAs/GaAs heterostructures are as follows: i) The temperature behaviour of the E_{21} transition provides unequivocal evidence of the FES presence for the $n = 2$ electron subband. The E_{21} peak amplitude falls abruptly down under the temperature increase within the range of 20 K. Then it becomes weakly temperature dependent up to the temperature $T = 80$ K; ii) The large strength of the additional feature is observed even at the lowest temperatures. It can not be of impurity nature while the doping level in the AlGaAs supplier layer is held constant under variation of the InGaAs QW width; iii) The strength of additional PL feature is strongly dependent on the $n = 2$ subband filling. The 2DEG concentration was derived from the low temperature Hall measurements; iv) The high stability of the feature under the temperature and excitation density elevation allows to evaluate the binding energy. It is about of 7 meV; v) The A feature reveals the non-monotonous temperature and excitation density behaviour, non-typical to the well-known FES manifestations.

Nevertheles this feature can be related to the many-body effects. Energetically this feature can be addressed the transition from the Fermi edge states in the $n = 1$ electronic band to the localized state of heavy holes in the valence band. In this case the binding energy of localized hole can be directly estimated from the temperature dependent PL (see Fig.2). Indeed in the PL spectrum the corresponding FES features will arise at the E_{21} transition energy and at the energy, shifted toward lower energies by value of the localization energy for heavy holes, as follows from Fig.2. The energy by which the A feature is shifted with respect to the energy of the E_{21} transition is found to be 14 meV. We assume, that the temperature and excitation density dependences of the feature A observed from the samples under investigation, can be caused by a strong enhancement of the oscillator strength for the transitions at the Fermi edge in the E_1 band due to the inter-subband Coulomb scattering of electrons [4]. Besides the non-Coulomb scattering can also efficiently control the formation of FES in multi-subband heterostructures [5]. The alloy dependent inter-subband scattering may easily prevail over multiple diffusions from charged valence holes expected by many-body processes. The hole localization is of importance for several reasons. The localized hole states may be viewed as being constructed from states with a range of momenta and therefore allow the PL from the vicinity of the Fermi level to be observed. The heavy holes can be localized by a form of disorder, typically alloy fluctuations in InGaAs QW. The PL enhancement is due to the mixing of the subband states by the photoexcited hole and due to virtual excitations of electron-hole pairs involving the higher subbands.

So, the main points of novelty are: i) the FES enhancement from E_F of $n = 1$ electronic subband is observed under condition of the $n = 2$ subband population; ii) heavy hole localization energy is directly observed in the FES development; iii) the many-body enhancement is nonmonotonicly dependent on temperature and excitation intensity. The behavior observed is assigned to the inter-subband scattering in one-component plasma in the presence of strong electron-hole correlations. The defects localizing the heavy hole become reachable for investigation through the many-body effects.

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