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Luminescence of indirect excitons in high in-plane magnetic fields

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Abstract

We report on low-temperature magneto-luminescence measurements of biased $Ga_{1-x}Al_xAs/GaAs$ double quantum well structures. The luminescence of spatially indirect excitons (IX) is studied up to the magnetic field of 22 T. In contradiction to theoretical predictions and their several experimental confirmations, the IX line survives in PL spectra of our double quantum well structure up to high in-plane magnetic fields. We explain this difference by the IX localization which enables the relaxation of the IX in-plane momentum, whose conservation is responsible for the damping of the IX luminescence intensity observed by other groups. This localization is supported by a relatively weak non-radiative recombination in comparison to the radiative one observed in our double quantum well structure. The IX luminescence was studied under various excitation intensities to obtain deeper insight into the IX localization mechanism. This paper confirms and broadens our previously published results obtained from a double quantum well structure of other width.

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Keywords: Double quantum well; Indirect exciton; In-plane magnetic field

1. Introduction

A special feature of double quantum well (DQW) structures is the formation of a spatially indirect exciton (IX) under an applied electric field. This quasi-particle consists of an electron and a hole localized in neighboring quantum wells resulting in a small overlap of their wave functions. Therefore, IXs are characterized by a very long lifetimes, up to hundreds of nanoseconds, i.e. three orders of magnitude longer in comparison with spatially direct excitons (DX) in bulk or in a single quantum well [1]. Their extremely long lifetime, bosonic character and also low effective mass are key features for a potential Bose–Einstein condensation at liquid helium temperatures. This effect became a subject of an intensive research within recent years and has led to promising results published in Refs. [2,3].

A lot of attention has also been paid to IX properties in in-plane magnetic fields $B_\parallel$. Theoretical works, e.g. Ref. [4], predicted a gradual quenching of IX luminescence intensity with increasing magnetic field, accompanied by a quadratic increase of IX recombination energy. This was soon confirmed in photoluminescence (PL) experiments carried out independently by two groups [5–7]. The IX PL quenching is based on two features — on the shift of the IX in-plane dispersion minimum out from the zero point of the reciprocal space, proportional to the magnetic field $B_\parallel$ and on the IX in-plane momentum conservation in optical recombination [5,7]. A simple model was suggested and applied by Parlangeli et al. [7]. In this model, two main assumptions are made: the IX density is independent of the applied magnetic field and the IX gas obeys the Boltzmann statistics. The first assumption is fulfilled in samples with a strong non-radiative recombination that is independent of $B_\parallel$ and the second one is valid at low IX densities when Bose–Einstein statistics can be replaced by the Boltzmann distribution. Under these conditions, a Gaussian damping

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of IX PL intensity can be experimentally indicated by

$$I \propto \exp\left(-\frac{e^2 d^2 B_\parallel^2}{2 M k_B T}\right) \quad (1)$$

together with an increase of IX recombination energy by amount of $e^2 d^2 B_\parallel^2 / 2M$. Here, M and d represent the exciton mass and center-to-center distance of the wells in the DQW, respectively. T is the IX gas temperature.

In this paper, we deepen the study of the IX luminescence published in Ref. [8], where no damping of IX line intensity was observed up to high in-plane magnetic fields and where IX localization leading to the exciton momentum relaxation was discussed. Here, we present spectra measured on a DQW structure of a different well width that exhibits similar behavior. The PL is studied under various excitation intensities in order to gain more information about IX localization. We show that the simple model applied by Parlangeli et al. [7] is not adequate for our DQW structures.

2. Experiment

The PL measurements were carried out on a $Ga_{1-x}Al_xAs/GaAs$ sample schematically depicted in Fig. 1, grown by molecular beam epitaxy. The growth started on an n-doped substrate at a temperature of 600 °C with a 500 nm-wide n-doped GaAs region (Si, $1.4\times 10^{18}\,cm^{-3}$) followed by n-doped and intrinsic $Ga_{0.7}Al_{0.3}As$ layers with a thickness of 300 nm and 500 nm, respectively. The growth was continued with a 5 nm thin p-layer (C, $3\times 10^{17}\,cm^{-3}$) and 100 nm of an undoped region, both of $Ga_{0.7}Al_{0.3}As$. Afterwards, three symmetric GaAs DQWs, each separated by 100 nm of $Ga_{0.7}Al_{0.3}As$ layers were added. The DQWs consist of 4 ML (ML = atomic monolayer) AlAs central barrier separating two quantum wells of equal width of 35 (≈ 10 nm), 26 (≈ 7.5 nm) or 18 ML (≈ 5 nm), respectively. Further $Ga_{0.7}Al_{0.3}As$ layers were grown as follows: 100 nm intrinsic, 5 nm n-layer (C, $4\times 10^{17}\,cm^{-3}$), 500 nm intrinsic and 300 nm p-doped (C, $1.4\times 10^{18}\,cm^{-3}$). The structure was capped by a 20 nm-wide p-doped (C, $2\times 10^{18}\,cm^{-3}$) GaAs-layer. The sample was processed photolithographically by mesa etching, insulation, and selective contacting to the bottom n-region and to the top p-region. The DQWs can be tilted by the perpendicular electric field when a bias is applied to p–n contacts. Taking into account the distance of 1.45 μm between p- and n-contact, the bias change of $\Delta U_{pn} = 1\,V$ should correspond to a variation of the electric field of 6.9 kV/cm in the DQW. The thin n- and p-layers screen the built-in field and allow for a zero-field situation in the DQWs for a relatively small bias voltage.

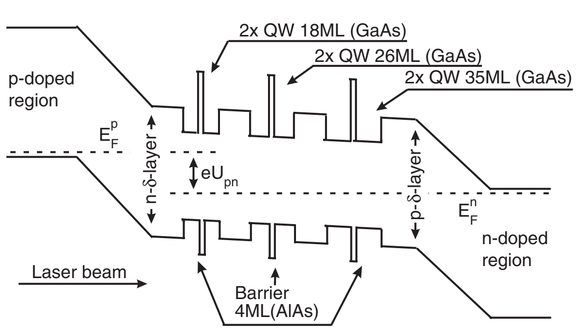

Fig. 1. Schematic bandstructure of the investigated sample. Symbols E_F^p and E_F^n denote the quasi-Fermi level in the p- and n-regions, respectively. Thicknesses of layers are not drawn to scale.

The sample was excited by a Ti:sapphire laser at a photon energy of 1.75 eV, i.e. below the band gap of $Ga_{0.7}Al_{0.3}As$ at low temperature. The standard intensity I_0 was about ~100 mW/cm^2. The PL signal was collected with an optical fiber, dispersed in a double-grating monochromator and detected by a cooled charge coupled camera. A helium bath cryostat was used to ensure a good temperature stability at 4.2 K. All measurements were performed in a resistive solenoid in the Voigt configuration up to a magnetic field of 22 T.

3. Results and discussion

In this paper, we focus our attention on IX PL gained from the 26-ML DQW in in-plane magnetic fields for various excitation intensities. All the results are discussed with respect to those published previously [8], where solely spectra from the 18-ML DQW were presented. Fig. 2 shows the PL spectra at $B_\parallel = 0\,T$ as a function of the applied voltage U_{pn}. We observe a typical shift of the IX peak to lower energies with increasing negative bias U_{pn}. As can be inferred from Fig. 2, the flat-band regime was achieved for small forward bias $U_{pn} = +0.5 - 1.0\,V$. The complex shape of the PL peak close to the flat-band regime is probably governed by effects due to the formation of charged excitons (trions) that will require a further study. The upper inset of Fig. 2 contains the integral PL intensities for 26-ML DQW, normalized to the value at $U_{pn} = 0.0\,V$. The IX peak related to 26-ML DQW overlaps with DX transitions in the 35-ML DQW for a bias voltage between $U_{pn} = -4.8$ and $-5.0\,V$. Therefore, the corresponding integral PL intensities are rough estimations there. The IX PL integral intensity remains close to unity also for higher negative bias U_{pn} where the IX radiative lifetime should be strongly enhanced. Hence, the radiative recombination dominates in this DQW while non-radiative channels are relatively weak. This is in agreement with our observations on the 18-ML DQW [8].

The luminescence spectra taken at the standard excitation intensity I_0 in the in-plane magnetic field for the bias voltage in the range from $U_{pn} = -4.0$ to $-4.9\,V$ are depicted in Fig. 3a–c. The spectra in Fig. 3a measured at $B_\parallel = 6.0\,T$ show a relatively narrow IX line (FWHM ≈ 3–4 meV), narrower than in zero magnetic field (cf. to Fig. 2). The magnetic field also partially suppresses the low-energy tail, which is well pronounced at zero magnetic field. No intensity decline comparing to $B_\parallel = 0\,T$ was noted. The IX PL is clearly observed also at $B_\parallel = 12.0$ and