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Abstract : We present an experimental and theoretical investigation of the oscillator strength of E_1HH_1 excitonic transition in the presence of the external magnetic field in thick GaAlAs/GaAs quantum well. We observe a dramatic increase of the oscillator strength given by a factor 6 when the magnetic field increases from 0 to 8 Tesla. The variational calculation performed in models of exciton confinement as a whole particle, and independent electron and hole quantization demonstrates the substantial magnetic field induced squeezing of the exciton wave function in a QW plane, which causes an increase of the oscillaltor strength in good agreement with experimental data.

1. Introduction

The magnetic field tuning of excitonic parameters like binding energy and oscillator strength is a promising direction of the development in semiconductor science[1-5]. Rather well investigated theoretically is the case of strong magnetic field limit when the magnetic length $L = (c\hbar / eH)^{1/2}$ is much smaller than the exciton Bohr radius a_B. The bulk exciton becomes quasi-one-dimensional, and the quantum well exciton is zero-dimensional in this case[1-4]. It is however, difficult to reach the strong field limit in the most popular III-V and II-VI semiconductors, where the value of the exciton Bohr radius is about 100 Å.

That is why the actual problem consists in a description of the exciton behaviour in the range of intermediate fields, where L is of the same order as a_B. For the quantum well exciton problem there are three factors, which govern the shape of the exciton wave function : quantum confinement potential, magnetic potential and Coulombic potential of electron-hole interaction. The variational solution of the excitonic problem has been recently found[6] for thin GaAlAs/GaAs QWs. It is shown that the effect of magnetic field on the exciton binding energy is reduced in thin wells because of the strong Coulombic interaction between confined electron and hole. Nevertheless, for the excited states, this effect is shown to be stronger than for the ground exciton state since the Bohr radiuses of the former are larger.

In order to reveal a pronounced distorsion of the exciton wave function by the magnetic field we study in this paper the oscillator strength of E_1HH_1 excitonic transition in 500 Å thick GaAlAs/GaAs modulation doped quantum wells with and without δ doping in the well. By a porper-choice of electron density in the well we suppress all effect on the reflectivity spectra originated from the ground E_0HH_0 exciton state. That is why, analysing the reflectivity spectra in line with Refs. [5,7] we obtain directly the

E_1HH_1 exciton oscillator strength as a function of the magnetic field. It appears to increase drastically with the field enhancement.

In 500 Å thick QWs the criterion of exciton quantization as whole particle[8-9] seems to be just satisfied. This allows us to calculate variationnaly the dynamics of exciton Bohr radiuses, as a function of the field, in a model of the Coulombic centre in the anisotropic media[5] with an introduced magnetic potential. A good agreement between experiment and calculation allows to conclude that the exciton wave function distorsion changes its sign at the field H = 3T.

2. Experimental procedure

The investigated samples are $Ga_{1-x}Al_xAs$-GaAs assymmetric modulation doped QWs grown by MBE. The layer sequence starting from the (001) semi-insulating undoped GaAs substrate, comprises a 10-period GaAs-AlAs short period (2.5 nm) superlattice buffer to prevent propagation of dislocations from the substrate, followed by a 50 nm .thick undoped ($p \cong 2x10^{14}$ cm^{-3}) GaAs layer (QW), an undoped $Ga_{.7}Al_{.3}As$ spacer of 35 nm thickness, a Si-doped n type $Ga_{.7}Al_{.3}As$ layer of 70 nm thickness and finally an undoped GaAs cap layer of 8 nm thickness. For one sample a δ layer of donors (4.10^{10} cm^{-2} Si) had been positioned in the GaAs well at 18 nm from the QW-spacer interface.

We perfom measurements of luminescence and reflectivity in magnetic field up to 12T (T = 4.2K) (see Fig. 1). A compartive analysis of photoluminescence and reflectivity spectra is made to understand the reflectivity structure.

3.Theory

The Schroedinger equation for an exciton in a QW in the presence of the magnetic field H normal to the QW plane can be written in general form as follows [6] :

$$\left\{\hat{T}(R,r) + V_{QW}(R,r) - \frac{e^2}{\chi r} + \frac{\hbar^2\rho^2}{8\mu_\perp L^4}\right\}\psi_{exc}(R,r) = E\psi_{exc}(R,r) \qquad (1)$$

Here $\hat{T}$ is the kinetic energy operator, which describes both the exciton motion as a particle and relative motion of electron and hole, V_{QW} is the quantum well potential ; χ is the dielectric constant, $\mu_\perp$ is the reduced effective mass of in-plane relative motion of the exciton, R is the centre of mass coordinate, r, ρ are respectively the electron-hole motion coordinates in volume and in the QW plane.

One should separate now the cases of exciton quantization as a whole particle in the QW, and independent confinement of electron and hole. According to Refs. 8,9 the criterion for this separation is $L_z > 3\ a_B$, where L_z is the QW width. In the case of a whole exciton quantization one can represent the exciton envelope function as :

$$\psi_{exc}(R,r) = F(R)f(r) \qquad (2)$$

where F (R) describes exciton centre of mass motion, f (r) is a function of electron-hole relative motion. We shall neglect for simplicity the penetration of the exciton wave function into the barriers. In this case for E_1HH_1 exciton state $F\ (R) = \sqrt{\frac{2}{SL_z}}\sin\frac{2\pi Z}{L_z}$, where S is the area of the QW layer. Solving

variationally the Eq. (1) with a trial function $f(\rho) = \frac{1}{\sqrt{\pi a^3_\perp\sqrt{1+\alpha^2}}} e^{-\frac{1}{a_\perp}\sqrt{\rho^2+\frac{z^2}{1+\alpha^2}}}$ (3)

one can obtain the system of equations for $a_\perp$ and α :

$$\frac{1}{2}\left(\frac{a_\perp}{L}\right)^4 + \frac{\mathrm{Arcsh}\alpha}{\alpha}\frac{a_\perp}{a^\perp_B} - \frac{1}{3}\left(2 + \frac{\gamma}{1+\alpha^2}\right) = 0 \quad \text{(4a),}$$

$$\frac{a_\perp}{a_b^\perp} = \frac{\gamma\alpha^3}{3\left(1+\alpha^2\right)^{3/2}\left[\sqrt{1+\alpha^2}\,\mathrm{Arsch}\alpha - \alpha\right]} = 0 \quad \text{(4b)}$$

Here $a_B^\perp = \frac{a_B}{2} = \frac{\hbar^2\chi}{2\mu_\perp e^2}$, $\gamma = \frac{\mu_{//}}{\mu_\perp}$, and $\mu_{//}$ is the reduced *exciton mass in z-direction*.

The exciton oscillator strength in a QW can be written following Ref.5 as :

$$\omega_{LT}^{SQW} = \omega_{LT}\frac{\pi a_B^3}{L_z}\left[\int_{-\infty}^{\infty} dz\psi_{ex|r=0}\right]^2 \quad (5)$$

where ω_{LT} is the oscillator strength in bulk crystal. With ψ_{exc} (R,r) deduced from Eqs. 3 and 4 one obtains :

$$\omega_{LT}^{SQW} = \omega_{LT}\frac{8a_B^3}{\pi^2 a_\perp^3\sqrt{1+\alpha^2}} \quad (6)$$

On the other hand, if we suppose the electron and the hole to be quantized independently, which corresponds to the case $L_z < 3a_B$, one can represent the exciton wave function as :

$$\psi_{exc}(R,r) = \phi(R_\perp)U_e(z_e)U_h(z_h)f(\rho) \quad (7)$$

where $\phi(R_\perp)$ describes the exciton centre of mass in-plane motion, $U_e(z_e)$,$U_h(z_h)$ are electron and hole envelope functions in z-direction ; $f(\rho)$ is a function of electron-hole relative motion in the QW plane.

The variational solution of Eq. (1), in the approach of infinit barriers with a trial function $f(\rho) = \sqrt{\frac{2}{\pi}}\frac{1}{a_\perp}e^{-\frac{\rho}{a_\perp}}$ will give the equation for $a_\perp$ (see Ref.6) :

$$\frac{\hbar^2}{8\mu_\perp}\left[1 - 6\left(\frac{a_\perp}{2L}\right)^4\right] = \int \rho d\rho V(\rho)\left(1 - \frac{\rho}{a_\perp}\right)e^{-\frac{2\rho}{a_\perp}} \quad (8)$$

$$\text{where}\, V(\rho) = \frac{e^2}{\chi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dz_e dz_h \frac{U_e^2(z_e)U_h^2(z_h)}{\sqrt{\rho^2 + (z_e - z_h)^2}} \quad (9)$$

The formulation for ω_{LT}^{SQW} (5) now can be reduced to the form :

$$\omega_{LT}^{SQW} = \omega_{LT}\frac{a_B^3}{L_z a_\perp^2} \quad (10)$$

In this work we discuss the case of a QW of *thickness* L_z = 500 Å. This is slightly higher than $3a_B$ in GaAs, so that one should prefer the model of exciton confinement as whole particle. We shall plot, however, for comparison, a calculation in the model of independent electron and hole confinement. (Fig.2).

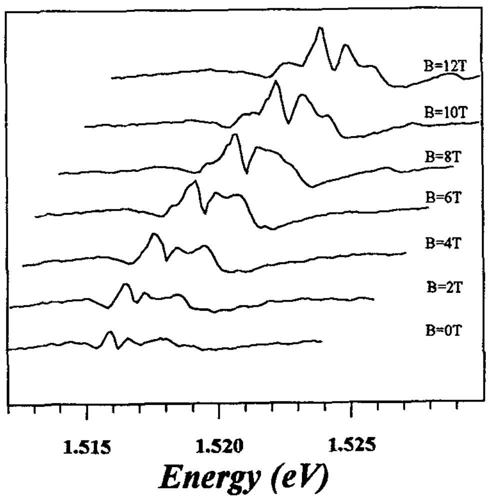

Fig.1 : Reflectivity spectra over magnetic field range 0-12T. The E1HH1 excitonic transition is observed at 1.5185eV in zero magnetic field.

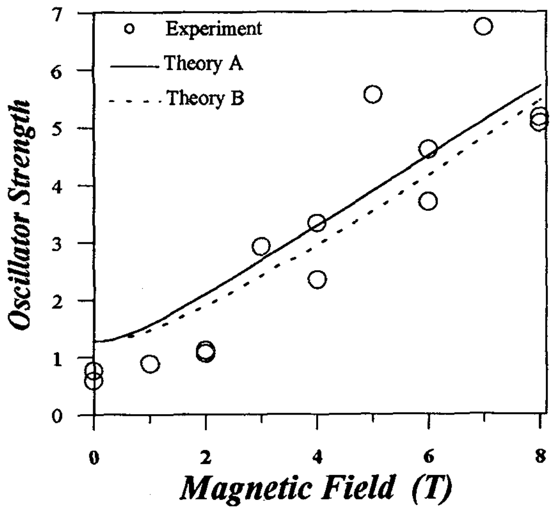

Fig. 2 : Oscillator strength of E1HH1 excitonic transition. Comparison between theory and experiment.

4. Results and discussion

Figure 1 shows reflectivity spectra for different magnetic fields, of a sample with Si δ-doping in the well. The density N_s of the 2D electrons is 1.9 x 10^{11} cm^{-2} in the dark and 2.8 x 10^{11} cm^{-2} under illumination. The E_1HH_1 excitonic transition is observed at 1.5185 eV in zero magnetic field and gives in photoluminescence a strong line which intensity progressively decreases when H increases.

On Figure 2 we have reported the oscillator strength for E_1HH_1 excitonic transition calculated in both models, as well as the experimental one, versus magnetic field up to 8T. Because of the non polarization of the light in reflectivity experiments, the accuracy of the experimental determination decreases in high field regime. Nevertheless the theory describes well the increase of the oscillator strength when H increases.

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