Magnetoexcitons in type-II quantum dots

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The ground state of a spatially indirect exciton in type-II quantum dots with a short-range potential acquires nonzero angular momentum in the presence of a magnetic field oriented perpendicular to the plane of the system. The critical magnetic field of the transition to a ground state with nonzero angular momentum depends on the radius of the quantum dot. Such a transition can be observed as quenching of luminescence by a magnetic field in quantum dots of the GaSb/GaAs system, for example. © *1998 American Institute of Physics.*
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Type-II quantum dots are formed in the GaSb/GaAs system.[1] In such quantum dots a three-dimensional quantum well exists only for holes, while a potential barrier exists for electrons. Spatially indirect excitons localized near quantum dots exist in this system.[1] The indirect excitons were observed in the luminescence spectra.[1]

The ground state of an exciton in two-dimensional quantum wells[2] and in type-I quantum dots with cylindrical symmetry[3] possesses zero angular momentum for any value of the magnetic field. Exciton localization in microstructures with a complicated geometry can lead to interesting effects.[4,5] For example, the energy of an exciton in a quantum ring oscillates as the magnetic field increases.[5]

In the present letter we investigate excitons localized near a type-II quantum dot. We show that the angular momentum of such an exciton in the ground state varies as a function of the magnetic field. This effect can be observed as quenching of luminescence. We note that in most cases a magnetic field increases the probability of an interband transition (see, for example, Refs. 2 and 3), and it intensifies the luminescence on account of compression of the wave function. The change in the ground state can be demonstrated in the model shown in Fig. 1. The system consists of a two-dimensional AlGaAs/GaAs/AlGaAs quantum well containing a built-in quantum dot in the form of a GaSb cylinder of radius r_0 and height L. The band diagram is shown in Fig. 1b. Similar systems have been investigated experimentally in Ref. 1.

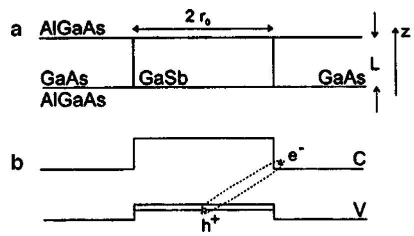

FIG. 1. Structure and band diagram for a GaSb–GaAs type quantum dot.

The motion of particles in such a system is assumed to be two-dimensional. The penetration of particles into the AlGaAs barriers will be neglected. The electron (hole) wave functions can be written in the form

$$\Psi_{e(h)}(\rho,\phi,z)=e^{il_{e(h)}\phi}R_{e(h)}(\rho)\psi(z), \tag{1}$$

where $(\rho,\phi)=\mathbf{r}$ are the coordinates in the plane of the system, $l_{e(h)}$ are the angular momenta, $R_{e(h)}(\rho)$ are the radial wave functions, and $\psi(z)$ is the size-quantization wave function in a square quantum well. An electron is localized near the quantum dot on account of attraction to the hole and moves in the potential shown in the inset in Fig. 2.

The probability of deexcitation of an exciton is determined by the integral

$$I=\int \Psi_e(\mathbf{R})\Psi_h(\mathbf{R})\,d\mathbf{R}=\int e^{i(l_e+l_h)\phi}\,d\phi\left[\int R_e(\rho)R_h(\rho)\rho\,d\rho\right]\int \psi^2(z)\,dz, \tag{2}$$

where $\mathbf{R}=(\mathbf{r},z)$.

The overlap integral $I_\rho=\int R_e(\rho)R_h(\rho)\rho d\rho$ of the radial wave functions is comparatively small because of the high potential barriers between GaAs and GaSb and varies smoothly as the magnetic field $\mathbf{B}\parallel\mathbf{z}$ increases. The factor that can change abruptly as a

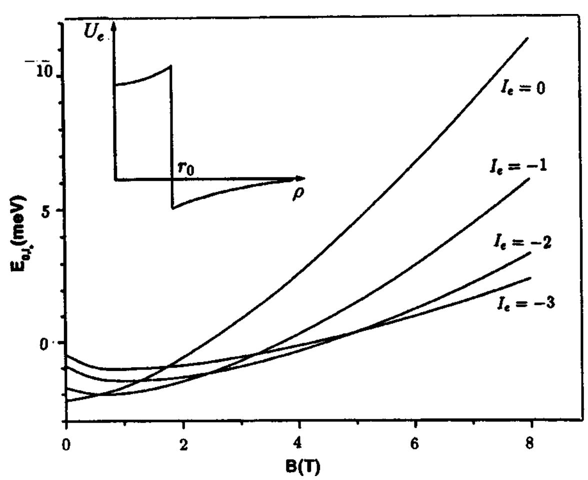

FIG. 2. Electron energy E_{0,l_e} versus the magnetic field for a quantum dot with $r_0=100$ Å and $L=70$ Å; $M_e=0.067m_0$. Inset: U_e versus ρ.

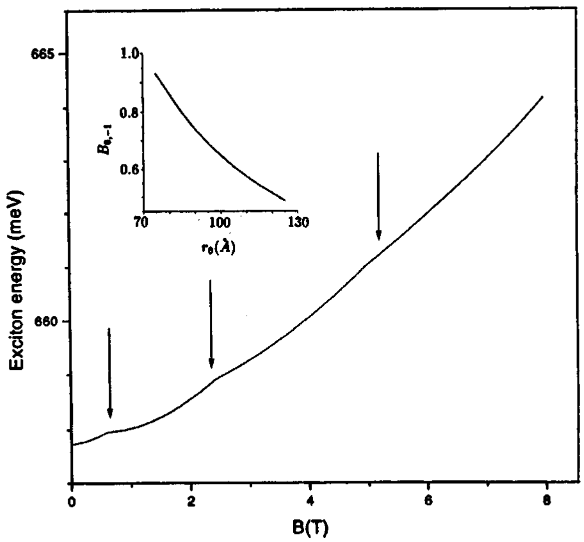

FIG. 3. Ground-state energy of an interband indirect exciton as a function of the magnetic field for a quantum dot with $r_0 = 100$ Å and $L = 70$ Å; hole mass $M_h = 0.3m_0$. The arrows show the change in angular momentum. Inset: Magnetic field $B_{0,-1}$ versus r_0.

function of B is the integral $I_\phi = \int e^{i(l_e+l_h)\phi} d\phi = 2\pi\delta_{l_e+l_h}$, where $l_{e(h)}$ is the angular momentum of the ground state. If the total angular momentum of an exciton in the ground state is $l_e + l_h \neq 0$, then it does not contribute to luminescence. In the presence of rapid energy relaxation of excitons into the ground state at low temperature, the appearance of a situation with $l_e + l_h \neq 0$ signifies quenching of luminescence.

To demonstrate this effect we shall assume, to simplify the calculations, that particles do not penetrate through the GaSb–GaAs heterointerface, i.e., $R_{e(h)}(r_0) = 0$. Since the penetration is small, this will not change the spectrum of the exciton much.[b)] Our estimates show that for dots of radius $r_0 \sim 100$ Å the hole quantization can be assumed to be quite strong and the effect of the Coulomb interaction with an electron on the hole spectrum can be neglected. The wave function of the ground state of a hole with a flat bottom and impenetrable walls can be easily found, and for it $l_h = 0$ for any B. The potential for an electron in the region $\rho > r_0$ is determined by the attraction to a hole:

$$U_e(\rho_e) = -\frac{e^2}{\epsilon}\int \frac{\psi^2(z_e)\psi^2(z_h)\,dz_e\,dz_h}{\sqrt{(\mathbf{r}_e-\mathbf{r}_h)^2+(\mathbf{z}_e-\mathbf{z}_h)^2}} R_h^2(\rho_h)\,d\mathbf{r}_h\,, \tag{3}$$

(see inset in Fig. 2). The quantization equation for $R_e(\rho)$ has the standard form

$$-\frac{\hbar^2}{2M_e}\left[R_e'' + \frac{R_e'}{\rho} - \frac{l_e^2}{\rho^2}R_e\right] + \left(\frac{\hbar\omega_c}{2}l_e + \frac{M_e\omega_c^2}{8}\rho^2 + U_e(\rho)\right)R_e = ER_e\,, \tag{4}$$

where ω_c is the electron cyclotron frequency and M_e is the electron effective mass. The spectrum has two quantum numbers n and l_e. In the ground state $n = 0$ always. Figure 2 shows the numerical results for E_{0,l_e}. One can see that the angular momentum of the ground state varies with the magnetic field. The magnetic field $B_{0,-1}$ at which the changeover $l_e=0\rightarrow l_e=-1$ of the ground-state angular momentum occurs depends on r_0 (see inset in Fig. 3). The ground-state energy of an exciton is displayed in Fig. 3 and has a kink on account of the change in the angular momentum. The energy of the exciton was calculated for a quantum dot with a sharp GaSb–GaAs heterointerface. In the experiments of Ref. 1 the energies of indirect excitons lie much higher (~ 1 eV) on account of diffusion of Sb into GaAs. The angular momentum of the ground state changes from l_e to l_e-1 when $r_0^2/l_c^2\sim l_e$, where l_c is the magnetic length. This follows from an analysis of the character of the wave function in a magnetic field. The changeover of the ground state is analogous to the appearance of a nondecaying current in the ground state in rings carrying electrons[6] and charged excitons.[7] The present letter is concerned with the case of a quasiparticle which is neutral as a whole but is polarized by the potential of the quantum dot. This polarization leads to the nondecaying current in the ground state. We note that the possibility of a situation where excitons would be optically inactive in the ground state was discussed in Ref. 8. In Ref. 8 excitons in crossed magnetic and electric fields were studied. It is easy to calculate the spectrum of an exciton for a finite barrier between GaAs and GaSb. In this case the character of the spectrum remains the same (see Fig. 2).

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[b]Obviously, the penetration of the particles must be taken into account in the calculation of the intensity of an interband transition.

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