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Magneto-optical properties of diluted magnetic semiconductor quantum dots

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Abstract

The magnetoexciton polaron (MP) is investigated theoretically in a diluted magnetic semiconductor quantum dot (QD), with the Coulomb interaction and the sp–d exchange interaction included. The MP energy decreases rapidly with increasing magnetic field at low magnetic field and saturates at high magnetic field for small QDs, and the dependences of the MP energy on magnetic field are quite different for different QD radii due to the different carrier-induced magnetic fields B_{MP}. The competition between the sp–d exchange interaction and the band gap shrinkage results in there being a maximum exhibited by the MP energy with increasing temperature. Our numerical results are in good agreement with experiment (Maksimov A A, Bacher G, MacDonald A, Kulakovskii V D, Forchel A, Becker C R, Landwehr G and Molenkamp L W 2000 *Phys. Rev.* B **62** R7767).

The most striking properties of the diluted magnetic semiconductor (DMS) are the spin-dependent transport and optical properties. All of these novel properties arise from the strong sp–d exchange interaction between the carriers and the magnetic ions Mn^{2+} in DMS structures. Most of the previous investigations focused on the giant Zeeman effect, the giant Faraday rotation, the optically induced magnetization and the formation of the magnetoexciton polaron (MP) in two-dimensional DMS structures [1–5]. With the rapid progress in semiconductor growth techniques, it is now possible to fabricate various zero-dimensional DMS quantum dot (QD) structures. Unlike the case for two-dimensional MPs, only a small number of experimental [6–8] and theoretical [9] studies have been carried out on the zero-dimensional MP in a DMS QD which is synthesized chemically. Assuming a spherical hard-wall potential, Bhattacharjee *et al* studied the zero-dimensional MP in spherical DMS QDs within the framework of the effective-mass approximation, and found that the MP energy decreases with increases of the temperature and the dot size [9]. Very recently, the DMS QD was fabricated by the molecular beam epitaxy technique and the exciton photoluminescence proved that

zero-dimensional MP formation in a DMS QD is more pronounced due to the strong, three-dimensional confinement of the carriers [10–12]. These experiments clearly demonstrated that the existence of the zero-dimensional MP in DMS QD requires suppression of the nonradiative recombination process.

In this paper, we investigate theoretically the zero-dimensional MP in disc-like QDs in the DMS $Cd_{1-x}Mn_xTe/Cd_{0.6}Mg_{0.4}Te$ with a finite confining potential; the Coulomb interaction between the electron and the hole and the sp–d exchange interaction are included. We find that the energy of the σ^+ (σ^-) MP decreases (increases) rapidly with increasing magnetic field at low magnetic fields and saturates at high magnetic field for small QDs, but for large QDs the energy of the MP exhibits quite different behaviour with increasing magnetic field. The temperature dependence of the MP energy agrees well with experimental results [10] if the band gap shrinkage is taken into account. In [10] the authors fitted the experimental results by using the Brillouin function, but in this paper we solve the nonlinear Schrödinger equation numerically, including the Coulomb and exchange interaction.

We consider a DMS disc-like QD embedded in the nonmagnetic semiconductor material. The MP energy and wavefunction can be obtained from the Schrödinger equation $H_{MP}\Psi_{MP}(\boldsymbol{r}_e, \boldsymbol{r}_h) = E_{MP}\Psi_{MP}(\boldsymbol{r}_e, \boldsymbol{r}_h)$. Here the MP Hamiltonian H_{MP} in the DMS QD can be written as

$$H_{MP} = \frac{1}{2m_e^*}(\boldsymbol{p}_e + e\boldsymbol{A}(\boldsymbol{r}_e))^2 + V_e(\rho, z) + g_e^*\mu_B B + \frac{1}{2m_h^*}(\boldsymbol{p}_h - e\boldsymbol{A}(\boldsymbol{r}_h))^2 + V_h(\rho, z) + g_h^*\mu_B B + V_{exch} - \frac{e^2}{\epsilon|\boldsymbol{r}|}, \tag{1}$$

where $\boldsymbol{r} = \boldsymbol{r}_e - \boldsymbol{r}_h = (\rho, z)$ denotes the electron–hole relative coordinates and m_e (m_h) the effective mass of the electron (hole). The band mixing is neglected due to the strong confinement along the growth direction. $-e^2/\epsilon r$ is the Coulomb interaction between the electron and hole, ϵ the dielectric constant. V_e (V_h) is the confining potential of the electron (hole) in the QD, i.e., $V_{e,h}(z_{e,h}) = 0$ inside the QD and $V_{e,h}(z_{e,h}) = V_{e,h}$ otherwise. g_e^* (g_h^*) is the effective Landé g-factor of the electron (hole). The exchange interaction term V_{exch} describes the sp–d exchange interaction between the carriers and the magnetic ion Mn^{2+}:

$$V_{exch} = V_{exch}^e + V_{exch}^h = J_{\mathrm{s-d}}\langle S_z\rangle\sigma_z + J_{\mathrm{p-d}}\langle S_z\rangle\mu_z, \tag{2}$$

where $J_{\mathrm{s-d}} = -N_0\alpha x_{eff}$, $J_{\mathrm{p-d}} = -N_0\beta x_{eff}/3$ and $\langle S_z\rangle = S_0 B_J(Sg_{\mathrm{Mn}}\mu_B B/k_B(T + T_0))$; $S = 5/2$ corresponds to the spins of the localized $3d^5$ electrons of the Mn^{2+} ions. $B_J(x)$ is the Brillouin function, N_0 is the number of cations per unit volume, the phenomenological parameters x_{eff} (reduced effective concentration of Mn) and T_0 account for the reduced single-ion contribution due to the antiferromagnetic Mn–Mn coupling, k_B is the Boltzmann constant, μ_B is the Bohr magneton, $g_{\mathrm{Mn}} = 2$ is the g-factor of the Mn^{2+} ion and $\sigma_z = \pm 1/2$ ($\mu_z = \pm 1/2, \pm 3/2$) is the electron (hole) spin.

$$B = B_{ex} \pm B_{MP}, \tag{3}$$

where B_{ex} is the external magnetic field, and the carrier-induced exchange field inside the MP is proportional to the squared wavefunction of the carriers, i.e., $B_{MP} \approx (1/3\mu_B g_{\mathrm{Mn}})\beta\mu_z|\phi_h(r)|^2$ [9, 10]. The MP wavefunction with the total angular momentum L is constructed as a linear combination of the single-particle eigenstates $\Psi_{ex}^L(\boldsymbol{r}_e, \boldsymbol{r}_h) = \sum_{nkl_1l_2, l_1+l_2=L} a_{nk}^l\phi_{n,l_1}^e(\rho_e, z_e)\phi_{k,l_2}^h(\rho_h, z_h)$ where the subscripts n and k correspond to the single-particle eigenstates of the electron and hole. The single-particle eigenstates of the electron ($\phi_{n,l_1}^e(\rho_e, z_e)$) and the hole ($\phi_{k,l_2}^h(\rho_h, z_h)$) are obtained by the finite-difference method [13]. The transition energy of the MP for σ^+ and σ^- excitation is $E = E_g(T) + E_{MP}^{\pm}$, where

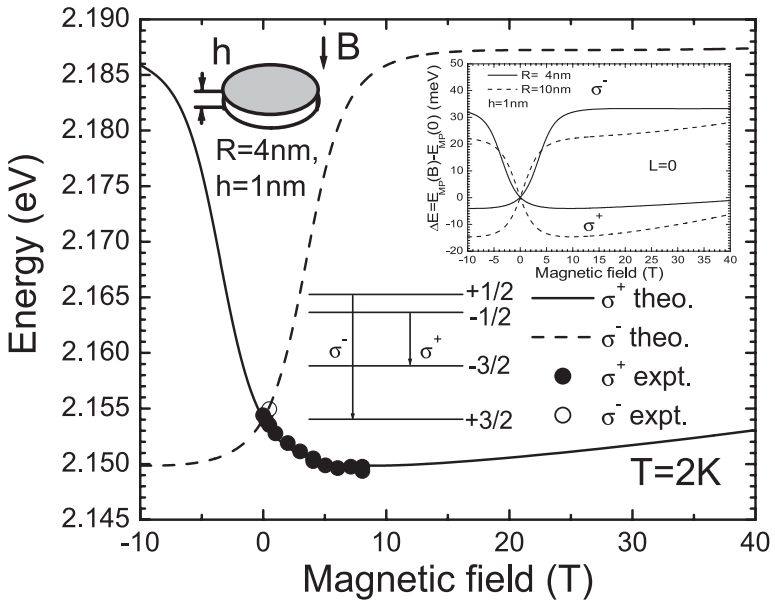

Figure 1. The MP transition energy versus magnetic field in the $Cd_{0.93}Mn_{0.07}Te/Cd_{0.6}Mg_{0.4}Te$ DMS QD for both σ^+ and σ^- transitions. Here $R \approx 4$ nm is the QD radius, $h = 1$ nm is the QD thickness, $T = 2$ K. The theoretical results (solid and dashed curves) are compared with the experimental measurements (solid and open symbols) ([10]). The inset shows how the difference of the MP energy varies with magnetic field for different QD radii.

$E_g(T) = E_g(0) - aT^2/(b+T)$ is the semiconductor band gap which depends on the temperature and the parameters $a = 0.346$ and $b = 15.059$ are obtained by fitting the band gap $E_g(T)$ at low temperature; $\mathrm{d}E_g(T)/\mathrm{d}T$ obtained from these parameters at $T = 77$ K agrees well with the previous experimental results (see [14]; $\mathrm{d}E_g(T)/\mathrm{d}T \approx -3 \times 10^{-4}$ eV K^{-1}). E^+_{MP} (E^-_{MP}) is the MP energy for the σ^+ (σ^-) transition.

The parameters used in our calculations are $m^*_e = 0.096\, m_0$, $m_h = 0.6\, m_0$, where m_0 is the free electron mass. $x_{eff} = 0.045$, $g_{\mathrm{Mn}} = 2$, $N_0\alpha = 0.22$ eV, $N_0\beta = -0.88$ eV, $S_0 = 1.32$, $T_0 = 3.1$ K [10], $g^*_e = -0.7$, $g^*_h = 0.3$, $\epsilon = 10.6$; $E_g = 1.586$ eV for CdTe [14], $E_g = (1.586 + 1.51x)$ eV for $Cd_{1-x}Mn_xTe$, $E_g = (1.586 + 1.705y)$ eV for $Cd_{1-y}Mg_yTe$ [15].

Figure 1 shows the $L = 0$ MP transition energies in a $Cd_{0.93}Mn_{0.07}Te/Cd_{0.6}Mg_{0.4}Te$ DMS QD which is shown schematically in the inset as a function of the external magnetic field B_{ex} for both σ^+ and σ^- excitation. With increasing magnetic field, the energy of the σ^+ (σ^-) MP decreases (increases) rapidly for small magnetic field, and saturates for strong magnetic field. From this figure, we can see that our calculation is in good agreement with experiment results [10], but we should point out that the QD radius is used as a fitting parameter due to the lack of more detailed description of the experimental samples. At low magnetic fields, the magnetic length $l_B = \sqrt{\hbar/eB}$ is much larger than the QD radius; the MP transition energies exhibit the behaviour of the Brillouin function since the sp–d exchange interaction is the dominant factor. At high magnetic fields, the magnetic length l_B is comparable to the QD radius for large QDs; thus the MP energies increase with increasing magnetic field. Due to the strong sp–d exchange interaction, therefore, the intrinsic Zeeman effect cannot be found at low magnetic fields since it is much smaller than the effect of the sp–d exchange interaction. Notice that the energy dependence for the MP changes significantly with changing QD radius

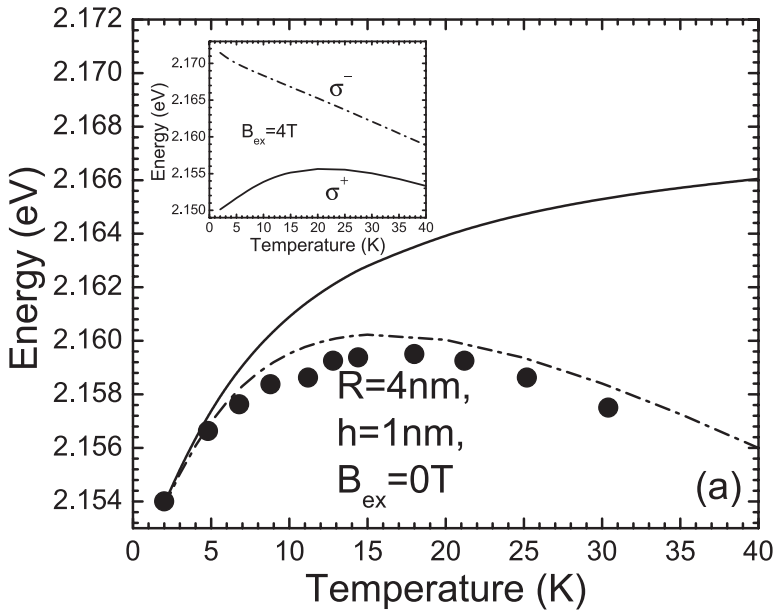

Figure 2. The σ^+ MP energy in the DMS QD versus the temperature. The solid symbols denote the experimental results; the solid curve (the dash–dotted curve) denotes the MP energy without (with) the band gap shrinkage effect. The inset shows the temperature dependence of the MP energy with the band gap shrinkage in the presence of the external magnetic field $B_{ex} = 4$ T.

(see the inset of figure 1). This is because the total magnetic field B is determined by the external magnetic field B_{ex} and the carrier-induced magnetic field B_{MP} (see equation (3)). The carrier-induced magnetic field B_{MP} decreases with increasing QD radius. In [10], the authors fitted the experimental results by using the Brillouin function, neglecting the quantum confinement effect and the Coulomb interaction.

In figure 2 we plot the energy of the σ^+ MP versus the temperature with and without band gap shrinkage. The MP energy without band gap shrinkage (the solid line) increases rapidly with increase of the temperature at low temperature and saturates at higher temperature. This behaviour can be understood on the basis of the temperature dependence of the sp–d exchange interaction. The temperature dependence of the exchange interaction is determined by the average spin of the magnetic ion $\langle S_z \rangle$, which shows the behaviour of the Brillouin function (see equation (3)). Note that this behaviour does not agree with the experimental results, which show a decrease when the temperature is higher than a certain value. Our calculation shows that this phenomenon could arise from the shrinkage of the band gap with increasing temperature, since the band gap decreases with increasing temperature, i.e., $E_g(T) = E_g(0) - aT^2/(b+T)$. Thus the competition between the sp–d exchange interaction and the shrinkage of the band gap leads to a maximum of the σ^+ transition of the MP being exhibited with increasing temperature. The inset shows the temperature dependence of the σ^+ and σ^- transitions in the presence of the external magnetic field. From this inset, one can see that the behaviour of the σ^- transition is qualitatively different from that of the σ^+ transition especially at low temperature. This phenomenon arises from the fact that both the sp–d exchange interaction for the σ^- transition and the band gap shrinkage decrease with increasing temperature. In [10], the authors did not fit their experimental results. Our theoretical results agree well with the experimental results.

In summary, we have investigated the MP energy in a DMS QD as a function of the magnetic field and the temperature. The variations of the σ^+ and σ^+ transition energies with

magnetic fields are quite different for different QD radii. The σ^+ transition energy exhibits a maximum with increasing temperature. Our theoretical calculation is in good agreement with recent experimental results. The exchange interaction in the DMS QD provides us with a novel freedom to tailor the electronic structure of a semiconductor QD. Such systems are extremely attractive from the point of view of both basic research and technological applications.

Acknowledgments

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