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Magnetic field tuning of the effective *g* factor in a diluted magnetic semiconductor quantum dot

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The spin interaction and the effective g factor of a magnetic exciton (ME) are investigated theoretically in a diluted magnetic semiconductor (DMS) quantum dot (QD), including the Coulomb interaction and the $sp-d$ exchange interaction. At low magnetic field, the ME energy decreases rapidly with increasing magnetic field and saturates at high magnetic field for high Mn concentration. The ground state of the ME exhibits an interesting crossing behavior between σ^+-ME and σ^--ME for low Mn concentration. The g_{ex} factor of the ME in a DMS QD displays a monotonic decrease with increasing magnetic field and can be tuned to zero by an external magnetic field. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1568825]

The spin of carriers in semiconductor nanostructures has attracted recently considerable interest because of its importance for basic physics as well as for its potential application in spintronic devices. Recently, several quantum computational approaches[1,2] based on semiconductor quantum dot systems were proposed due to the long spin-coherence time in semiconductors.[3] Electron-hole entanglement involving two magnetoexciton states was recently identified experimentally in a single GaAs quantum dot (QD).[4] The photon polarization and the spin of carriers in semiconductors are suitable candidates for quantum information storage and processing. The coherent transfer of quantum information among the different physical systems requires a quantum device, e.g. a photodetector, which can preserve the entanglement while the quantum information is transferred from the photon polarization to the exciton spin in the semiconductor. In order to maintain the entanglement, the quantum device should absorb equally into up (σ^+) and down (σ^-) exciton spin states, therefore the effective g_{ex} factor of the exciton in the semiconductor has to be zero which should be realized by adjusting the parameters of the physical system.

The g factor is important in understanding the spin-dependent optical and transport properties in semiconductor nanostructures. Since the Coulomb interaction,[5] the quantum confinement effect,[6] spin-orbit coupling,[7] electron-hole exchange interaction,[8] and hyperfine interaction[9,10] can influence the spin splitting, therefore the g factor of the electron, the hole and the exciton will provide us with insights in the spin relaxation and coherence in semiconductors. In a nonmagnetic semiconductor, the exchange interaction between the carriers and the nuclei of the host semiconductor material has been demonstrated experimentally although its strength is rather weak ($\sim\mu$eV).[9,10] In the diluted magnetic semiconductors (DMS) the $sp-d$ exchange interaction between the carriers and the magnetic impurities is strong which leads to a giant spin splitting, and spin-dependent transport, and optical properties.[11–15] Very recently, a DMS QD was fabricated, using molecular beam epitaxy techniques, which was found to be more robust against thermal fluctuations. Photoluminescence experiments[16–18] clearly demonstrated that the formation of a zero-dimensional magnetic exciton (ME) in the DMS QD leads to a suppression of the nonradiative recombination process.

In this work we investigate theoretically the g_{ex} factor and the energy of the zero-dimensional ME in $Cd_{1-x}Mn_xTe/Cd_{1-y}Mg_yTe$ DMS QDs, including the contribution of the Coulomb interaction and the $sp-d$ exchange interaction. We show how the effective g_{ex} factor of the ME in the DMS QD can be engineered by using the fact that for low Mn concentration, the spin splitting caused by the $sp-d$ interaction is comparable to the intrinsic Zeeman splitting. For low Mn concentration the g_{ex} factor of the ME decreases rapidly with increasing magnetic field at low magnetic fields and saturates at high magnetic field. The most interesting phenomenon is that the effective g_{ex} factor of the ME can be tuned to zero by changing the magnetic field. This is extremely interesting for practical realization of, e.g., quantum information transfer from a photon system to excitons in a semiconductor system.

The effective g_{ex} factor is determined by the spin splitting between the σ^+ and σ^- polarized transition in DMS QDs:

$$g_{\mathrm{ex}}=\Delta E_{\mathrm{ME}}/\mu_B B=g_{\mathrm{ex}}^0+g_{\mathrm{ex}}^{sp-d}, \tag{1}$$

where the Zeeman splitting $\Delta E_{\mathrm{ME}}=E_{\mathrm{ME}}(\sigma^+)-E_{\mathrm{ME}}(\sigma^-)=\Delta E_{sp-d}^{\pm}+\Delta E_{\mathrm{Zeeman}}^{\pm}$ denotes the total spin splitting caused by the intrinsic Zeeman effect and the $sp-d$ exchange inter-

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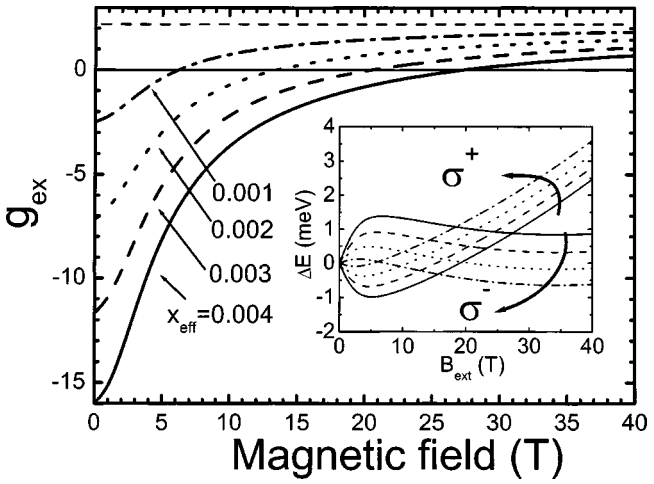

FIG. 1. The effective g_{ex} factor and the ME energy (inset, the same line conventions are used as in the main figure) vs magnetic fields for low Mn concentrations. The quantum disk has $R=4$ nm, $h=1$ nm, and the results are shown for $T=2$ K. The magnetic field where $g_{\mathrm{ex}}=0$ defines the critical magnetic field B_c.

action for spin-up or spin-down ME, where $E_{\mathrm{ME}}(\sigma^{\pm})$ is the energy of the spin-up or spin-down ME, i.e., two possible transitions with different circular polarization (see lower inset of Fig. 1). g_{ex}^0 is the intrinsic g factor, and g_{ex}^{sp-d} the g factor induced by the $sp-d$ exchange interaction. The energy of the zero-dimensional ME in a DMS disk-like quantum dot embedded in a nonmagnetic semiconductor material can be obtained from the Schrödinger equation $H_{\mathrm{ME}}\Psi_{\mathrm{ME}}(\mathbf{r}_e,\mathbf{r}_h)=E_{\mathrm{ME}}\Psi_{\mathrm{ME}}(\mathbf{r}_e,\mathbf{r}_h)$. Here, the stationary ME Hamiltonian $H_{\mathrm{ME}}^{\sigma\pm}$ for the $\sigma^{\pm}$ ME in the DMS QD is

$$H_{\mathrm{ME}}^{\pm}=\frac{1}{2m_e^*}[\mathbf{p}_e+e\mathbf{A}(\mathbf{r}_e)]^2+V_e(\rho_e,z_e)+g_e^*\mu_B B\sigma_z + \frac{1}{2m_h^*}[\mathbf{p}_h-e\mathbf{A}(\mathbf{r}_h)]^2+V_h(\rho_h,z_h)+g_h^*\mu_B B j_z + V_{\mathrm{exch}}-\frac{e^2}{\epsilon|\mathbf{r}|}, \tag{2}$$

where $\mathbf{r}=\mathbf{r}_e-\mathbf{r}_h=(\rho,z)$ denotes the electron-hole relative coordinates, $m_e(m_h)$ is the effective mass of electron (hole), ϵ is the dielectric constant and $\sigma_z=\pm 1/2$ ($j_z=\pm 1/2,\ \pm 3/2$) is the electron (hole) spin. The band mixing is neglected due to the strong confinement along the growth direction. $V_e(V_h)$ is the confining potential of 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 Landè g factor of electron (hole). The $sp-d$ exchange interaction term V_{exch} between the carriers and the magnetic ion Mn^{2+} is treated in a mean-field approximation[11]

$$V_{\mathrm{exch}}=J_{s-d}\langle S_z\rangle\sigma_z+J_{p-d}\langle S_z\rangle j_z, \tag{3}$$

where $J_{s-d}=-N_0\alpha x_{\mathrm{eff}}$, $J_{p-d}=-N_0\beta x_{\mathrm{eff}}/3$, and $\langle S_z\rangle=S_0B_J[Sg_{\mathrm{Mn}}\mu_B B/k_B(T+T_0)]$, $S=5/2$ 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 reduced effective concentration of Mn is given by the phenomenological parameter x_{eff}, and T_0 accounts 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. The total magnetic field is

$$B=B_{\mathrm{ME}}\pm B_{\mathrm{ext}}, \tag{4}$$

where B_{ext} is the external magnetic field, and the carrier-induced exchange field[16] inside ME is proportional to the squared wave function of the carriers, i.e., $B_{\mathrm{ME}}\approx(1/3\mu_B g_{\mathrm{Mn}})\beta j_z|\phi_h(r)|^2$. The ME wave function with total angular momentum L is constructed as a linear combination of the single particle eigenstates

$$\Psi_{\mathrm{ex}}^L(\mathbf{r}_e,\mathbf{r}_h)=\sum_{n,k,l_1,l_2,l_1+l_2=L} a_{nk}^l\phi_{n,l_1}^e(\rho_e,z_e)\phi_{k,l_2}^h(\rho_h,z_h). \tag{5}$$

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 solving the stationary Schrödinger equation using the finite difference method.[19] More detailed information about the nonuniform space grid can be found in Ref. 19. In our calculation, the QD is modeled as a disk (see the left upper inset in Fig. 1) and we take $n=10$ and $k=10$ [see Eq. (5)] which leads to an accuracy for the ground state energy better than 1%. The transition energy of ME for both σ^+ and σ^- excitation is $E=E_g(T)+E_{\mathrm{ME}}^{\pm}$, where $E_g(T)=E_g(0)-aT^2/(b+T)$ is the semiconductor band gap which depends on the temperature, the parameters $a=0.346$ and $b=15.059$ are obtained by fitting the band gap $E_g(T)$ at low temperature, and $dE_g(T)/dT$ is obtained from these parameters at $T=77$ K, which agrees well with the previous experimental results (see Ref. 20), $dE_g(T)/dT\approx-3\times10^{-4}$ eV/K). $E_{\mathrm{ME}}^+(E_{\mathrm{ME}}^-)$ is the ME energy for the $\sigma^+(\sigma^-)$ transition, respectively. The parameters used in our calculations are $m_e^*=0.096m_0$, $m_h=0.6m_0$, m_0 is the free electron mass. $x_{\mathrm{eff}}=0.045$, $g_{\mathrm{Mn}}=2$, $N_0\alpha=0.22$ eV, $N_0\beta=-0.88$ eV, $S_0=1.32$, $T_0=3.1$ K,[16] $g_e^*=-1.47$, $g_h^*=-0.24$,[21] $g_{\mathrm{ex}}^0=(g_e^*+3g_h^*)\approx2.2$, $\epsilon=10.6$, $E_g=1.586+1.51x$ (eV) for $Cd_{1-x}Mn_xTe$, and $E_g=1.586+1.705y$ (eV) for $Cd_{1-y}Mg_yTe$.[22]

Figure 1 depicts the variation of the g_{ex} factor and the energy (the inset of Fig. 2) of the ME with magnetic field for low Mn concentrations. The g_{ex} factor shows a monotonic increase with increasing magnetic field for different Mn concentrations. It is important to notice that the g_{ex} factor can be tuned to zero by changing the magnetic field, i.e., the energies of $\sigma^{\pm}$ ME become degenerate at these magnetic fields B_c. This behavior can be understood from the inset which shows the ME energy as a function of magnetic field. From the inset, one finds that the variation of the ME energy versus magnetic field is different from that in DMS QD with high Mn concentration (see Ref. 16). For the DMS QD with low Mn concentration, the spin splitting ΔE_{sp-d} induced by the $sp-d$ interaction is comparable to the intrinsic Zeeman splitting $\Delta E_{\mathrm{Zeeman}}$. Due to the competition between these interactions, the ground state of the ME energy changes from σ^+ ME to σ^- ME, i.e., the polarization of the emission light changes from σ^+ circular polarization to σ^- circular polarization with increasing magnetic field. This interesting crossing behavior is only possible when the sign of the spin splitting ΔE_{sp-d} is opposite to the intrinsic Zeeman splitting $\Delta E_{\mathrm{Zeeman}}$. The significant variation of the g_{ex} factor with

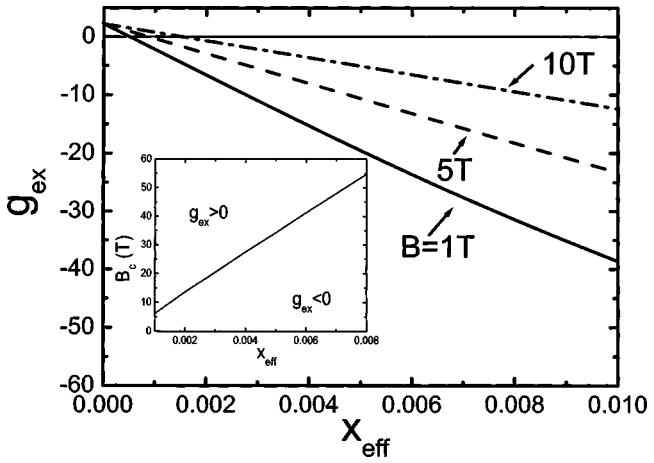

FIG. 2. The effective g_{ex} factor and the critical magnetic field B_c (inset) vs the effective Mn concentration for a quantum disk with $R=4$ nm, $h=1$ nm at a temperature $T=2$ K.

magnetic field provides us with a freedom to tailor the ME transition energies, and its polarization, in semiconductors.

In Fig. 2 we plot the g_{ex} factor as a function of the effective Mn concentration x_{eff} in a DMS QD for different magnetic fields. Two characteristics can be found in this figure: (i) the g_{ex} factor of ME is initially equal to $g_{\mathrm{ex}}^0=2.2$, i.e., the intrinsic g_{ex} factor, decreases almost linearly with increasing Mn concentration, and (ii) decreases with increasing magnetic field. The first characteristic arises from the fact that the spin splitting induced by the $sp-d$ exchange interaction increases linearly with increasing effective Mn concentration [see Eq. (3)]. The second characteristic can be understood from the dependence of the ME energy on the magnetic field (see Fig. 1). Because of the competition between the intrinsic Zeeman effect and the $sp-d$ exchange interaction a crossing occurs between the σ^+ ME and the σ^- ME, i.e., the spin splitting of the $\sigma^{\pm}$ ME decreases with increasing magnetic field. The inset shows the critical magnetic field B_c versus the effective Mn concentration x_{eff}. The line indicates the zero g_{ex} factor at critical magnetic fields, below the line $g_{\mathrm{ex}}<0$ and above the line $g_{\mathrm{ex}}>0$.

Recent experiments have shown that a magnetic field parallel to the hole quantization axis (Faraday geometry) suppresses strongly the magnetic fluctuations in DMS QD.[23] Therefore, the mean-field approximation adopted in our calculation[11] in which the fluctuation effect of the magnetic ions is neglected, is expected to be a good first-order approximation. The effect of fluctuation will be enhanced for low Mn concentration and higher temperature, which well lead to a higher critical magnetic field B_c. Nevertheless the underlying physics picture of the magnetic field tuning of g_{ex} will stay valid.

In summary, we investigated the spin interaction and the effective g_{ex} factor of a ME in a DMS QD for different magnetic fields and Mn concentrations. The effective g_{ex} factor of the ME in a DMS QD can be tuned to zero by a magnetic field for low Mn concentration. The variation of g_{ex} and the $\sigma^{\pm}$ ME energy with magnetic field are quite different for different Mn concentrations. The exchange interaction in the DMS QD provides us with a freedom to tailor the spin interaction and the effective g_{ex} factor of the semiconductor quantum dot by varying the external magnetic field and the Mn concentration.

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