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Direct and indirect excitons in diluted magnetic semiconductor double-quantum-well structures in external magnetic fields

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Abstract

Energy levels and optical transition intensities of direct and indirect excitons in diluted magnetic semiconductor double quantum wells were calculated as a function of the structure parameters and magnetic field. The effects arising from magnetic field induced crossing and repulsion of the exciton levels were investigated. Two structures were studied: (Zn, Mn)Se-based and (Cd, Mn)Te-based double quantum wells. In the (Zn, Mn)Se-based system, magnetic field induced level crossing of direct and indirect excitons was found. Above some magnetic field the indirect exciton becomes the lowest excited state of the system, which leads to an increase of the exciton lifetime by several orders of magnitude. In the (Cd, Mn)Te-based system, energy level crossing of excitons localized in the different wells of the structure was found. In this case magnetic field rise leads to transfer of the lowest exciton state from one well to another well of the system.

1. Introduction

The properties of indirect excitons with spatially separated electrons and holes in two-dimensional semiconductor structures have attracted considerable interest during the last few years. A particular feature of indirect excitons is a large lifetime due to the localization of the electron and the hole in different wells and consequently weak overlap of their wavefunctions. The latter allows one to get a high concentration of indirect excitons and to study collective exciton effects. Unusual and interesting new phenomena in systems with high concentrations of collectively interacting indirect excitons have been demonstrated in [1–4]. There is an important necessary condition for exciton accumulation in the structure, namely the energy levels of the indirect excitons must be lower than the levels of the other excited states of the

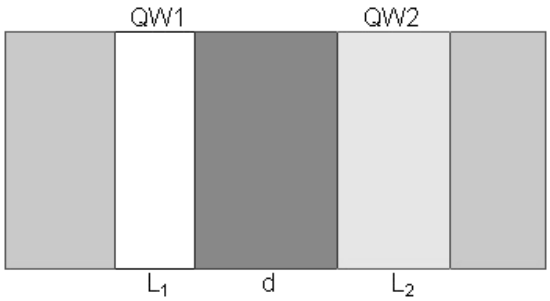

Figure 1. A schematic diagram of the heterostructure. The quantum wells are denoted as QW1 and QW2.

system. In the above mentioned works [1–4] an electric field has been used to lower the indirect exciton energy level, due to the large dipole momentum of these states.

In the present work another system with indirect lowest exciton energy states is proposed. We suggest using double quantum wells, on the basis of diluted magnetic semiconductors. In diluted magnetic semiconductors the strong exchange interaction between the carriers and the localized spins of magnetic ions leads to a strong dependence of the exciton levels on the external magnetic field intensity. A strong magnetic field dependence of the exciton spectra is one of the advantages of diluted magnetic semiconductor use in low-dimensional system study. The magnetic field dependence of the potential heights allows one to tune the carrier confinement in the same quantum well structure.

There is a rich collection of different states in crystals containing a double quantum well. Application of the external magnetic field allows one to tune the level position, to reach the level crossing and to have an essential influence on the exciton optical parameters. In the present paper two types of diluted magnetic semiconductor double-well structure were studied. In the first case the (Zn, Be, Mg)Se/ZnSe/(Zn, Be, Mg)Se/(Zn, Mn)Se/(Zn, Be, Mg)Se system was investigated. In the system studied, resonance between the direct and the indirect exciton states takes place at a certain value of the magnetic field and the indirect exciton energy level becomes the lowest one in a certain magnetic field intensity range. Calculations show that a specially chosen magnetic ion distribution allows us to get a structure with the lowest state corresponding to the indirect exciton, with a lifetime several orders of magnitude greater than the direct exciton lifetime. In the second structure ($Cd_{1-x}Mn_xTe/CdTe/Cd_{1-y}Mn_yTe/Cd_{1-z}Mn_zTe/Cd_{1-x}Mn_xTe$), resonance between the states of two direct excitons localized in the different wells of the structure as well as mixed states of such excitons were studied. The wavefunctions of the mixed states are symmetrical or asymmetrical with respect to simultaneous rearrangement of the electron and the hole (the exciton) between the wells. That essentially effects optical excitation intensities of the states.

One of the advantages of magnetic field application in comparison with electric field application is the absence of a photocurrent, which makes collective exciton phenomena interpretation difficult.

2. The method of calculation

In the present section a theoretical study of the direct and indirect exciton energies and lifetimes in the double-well structures, on the basis of diluted magnetic semiconductors, is presented. A schematic diagram of the heterostructure is shown in figure 1. We will study two double-

well structures based on two different semimagnetic materials: (Cd, Mn)Te and (Zn, Mn)Se. These systems will be described in detail later. In both systems one or several layers of the heterostructure contain magnetic impurities. Use of the semimagnetic layers provides the possibility of tuning the well depth for the electron and the hole with the external magnetic field due to the giant Zeeman splitting of the bands [5–9].

There is a translation symmetry in the system under study, so the exciton spectrum consists of bands whose state is described by the two-dimensional in-plane exciton centre of mass wavevector $\vec{K}$. In the case of normal light wave incidence (which is used in the overwhelming majority of experiments), the excitons with $\vec{K} = 0$ are excited due to the in-plane translation symmetry and by the momentum conservation law. So, in this case the exciton in-plane centre of mass kinetic energy is equal to zero. In zinc-blende semiconductors in a magnetic field applied along the crystal growth axis there is no mixing between heavy and light hole states [10]. So, the Hamiltonian of the heavy hole exciton in the double-well system can be written as

$$H = H_0\left(\vec{r}_\mathrm{e}, \vec{r}_\mathrm{h}\right) + H_\mathrm{field} + V_\mathrm{e}\left(x, z_\mathrm{e}, H, s_{\mathrm{e},z}\right) + V_\mathrm{h}\left(x, z_\mathrm{h}, H, s_{\mathrm{h},z}\right), \tag{1}$$

$$H_0 = E_\mathrm{g} - \frac{\hbar^2}{2\mu_\rho}\frac{1}{\rho}\frac{\partial}{\partial\rho}\rho\frac{\partial}{\partial\rho} - \frac{\hbar^2}{2m_\mathrm{e}}\frac{\partial^2}{\partial^2 z_\mathrm{e}} - \frac{\hbar^2}{2m_\mathrm{h}}\frac{\partial^2}{\partial^2 z_\mathrm{h}} - \frac{e^2}{4\pi\varepsilon_0\varepsilon}\frac{1}{\sqrt{\rho^2 + (z_\mathrm{e} - z_\mathrm{h})^2}} \tag{2}$$

and

$$H_\mathrm{field} = \frac{1}{8}\left(\frac{1}{m_\mathrm{e}} + \frac{1}{m_\mathrm{h}}\right)e^2\rho^2H^2 + g_\mathrm{e}\mu_\mathrm{B}s_{\mathrm{e},z}H + g_\mathrm{h}\mu_\mathrm{B}s_{\mathrm{h},z}H, \tag{3}$$

where H_0 is the Hamiltonian of the free exciton (see, for example, [8]), E_g is the band gap of the narrow-gap semiconductor layer, $\vec{r}_{\mathrm{e\,(h)}}$ is the coordinate of the electron (hole), z is the direction of crystal growth, $z_{\mathrm{e\,(h)}}$ is the electron (hole) position in the direction of the z-axis, $\rho = |\vec{\rho}_\mathrm{e} - \vec{\rho}_\mathrm{h}|$, $\rho_{\mathrm{e\,(h)}}$ is the electron (hole) position in the plane of the layer, x is the relative concentration of the impurity ions, $m_{\mathrm{e\,(h)}}$ is the effective mass of the electron (the heavy hole) in the growth direction, μ_ρ is the in-plane exciton reduced mass. The potentials of the double quantum well for the electron and the hole

$$V_\mathrm{e}(x, z_\mathrm{e}, H, s_{\mathrm{e},z}) = V_\mathrm{e}(z_\mathrm{e}) + \Delta V_\mathrm{e}(x, H, s_{\mathrm{e},z}), \tag{4}$$

$$V_\mathrm{h}(x, z_\mathrm{h}, H, s_{\mathrm{h},z}) = V_\mathrm{h}(z_\mathrm{h}) + \Delta V_\mathrm{h}(x, H, s_{\mathrm{h},z}) \tag{5}$$

each consist of two parts. The first part $V_{\mathrm{e\,(h)}}(z_\mathrm{e})$ arises from the electron density change and the crystal lattice deformation caused by the replacement of cations by magnetic impurity ions. It does not depend on the magnetic field. The second part $\Delta V_{\mathrm{e\,(h)}}$ describes the exchange interaction and depends on the magnetic field intensity H and the electron (hole) spin projection $s_{\mathrm{e},z}$ ($s_{\mathrm{h},z}$). As was mentioned above, the exchange interaction between the carriers and the localized spins of the magnetic ions leads to conduction and valence band splittings for the excitons with different spin directions. In the diluted magnetic layers the magnetic field applied along the crystal growth axis changes the band offsets as follows:

$$\Delta V_\mathrm{e}(x, H, s_{\mathrm{e},z}) = -xN_0\alpha\overline{S}_{\mathrm{Mn},z}(H)s_{\mathrm{e},z}, \tag{6}$$

$$\Delta V_\mathrm{h}(x, H, s_{\mathrm{h},z}) = -\tfrac{1}{3}xN_0\beta\overline{S}_{\mathrm{Mn},z}(H)s_{\mathrm{h},z}. \tag{7}$$

Here $N_0\alpha$ and $N_0\beta$ are the exchange integrals, $\overline{S}_{\mathrm{Mn},z}(H)$ is the average spin of the impurity ions.

The last term H_field in the Hamiltonian (1) describes the non-exchange interaction of the exciton with the magnetic field. This interaction includes the diamagnetic shift and the linear Zeeman effects for the electron and for the hole respectively (here $g_{\mathrm{e\,(h)}}$ is the g-factor for the electron (hole), μ_B is the Bohr magneton). The exciton level shift is significantly smaller than

the exchange splitting in the diluted magnetic systems in weak magnetic fields $H < 5$ T but the diamagnetic shift was taken into account in our calculations.

Let us introduce the following designations for the potentials in different layers of the structure:

$$V_{\mathrm{e\,(h)}}\left(x, z_{\mathrm{e\,(h)}}, H, s_{\mathrm{e\,(h)},z}\right) = \begin{cases} V_1, & z \leqslant 0, \\ 0, & 0 < z \leqslant a, \\ V_2, & a < z \leqslant b, \\ V_3, & b < z \leqslant c, \\ V_4, & c < z \leqslant \infty. \end{cases} \tag{8}$$

Here $a = L_1$, $b = L_1 + d$, $c = L_1 + d + L_2$, where L_1, L_2 and d are the widths of the quantum wells and the barrier layer; the potentials V_i will be determined later for the two structures under study. In the semimagnetic layers these potentials depend on the magnetic field intensity and the carrier spin orientations and therefore they are different for the σ^--component of the exciton transition ($s_{\mathrm{e},z} = \frac{1}{2}$ and $s_{\mathrm{h},z} = \frac{3}{2}$) and the σ^+-component of the exciton transition ($s_{\mathrm{e},z} = -\frac{1}{2}$ and $s_{\mathrm{h},z} = -\frac{3}{2}$). In the systems studied in the present paper the exciton binding energy is less than the distance between the one-particle levels in every single well. Thus only the lowest quantum dimensional levels have been taken into account for the electron and the hole in each of the wells (but the distance between the levels of the different wells may be less than the exciton binding energy).

The following method was used for the exciton energy calculation in the double-well system. As a basis of wavefunctions a set of wavefunctions with a certain localization of the electron and the hole was chosen. Let $\varphi_i(z_\mathrm{e})$, $i = 1, 2$, be the one-particle wavefunctions of the electron in the single well i (i.e. without the presence of another well of the double-well system). Thus, for example, $\varphi_1(z_\mathrm{e})$ is the wavefunction of the electron localized in the well QW1 in the case when the well QW2 is absent. Correspondingly, for the hole in the valence band we will denote the one-particle function by $\psi_i(z_\mathrm{h})$. Then the following functions were chosen as the basis functions for the 1S exciton states:

$$\Psi_{ij}\left(\rho, z_\mathrm{e}, z_\mathrm{h}\right) = \varphi_i\left(z_\mathrm{e}\right)\psi_j\left(z_\mathrm{h}\right)\sqrt{\frac{2}{\pi}}\frac{1}{\lambda_{ij}}\exp\left(-\frac{\rho}{\lambda_{ij}}\right), \tag{9}$$

where λ_{ij} is the variational parameter which is determined by minimizing the system energy with the Hamiltonian (1) using the wavefunctions (9). In (9) we suppose the in-plane centre of mass wavevector $\vec{K} = 0$. The separable wavefunctions (9) with decoupled motions in the quantum well plane and along the growth directions can be used for well widths not exceeding the exciton Bohr radius (see [11, 12] and references therein). In this range of the well widths the calculations with separable and more complicated non-separable trial wavefunctions lead to only a small difference in results, within the limits of the optical bandwidths (several millielectronvolts).

The functions (9) describe the state of the system in which the electron is localized in the well i, and the hole is localized in the well j. The positions of the electron and the hole for four wavefunctions (9) are schematically presented in figure 2. The functions (9) do not take into account the carrier transfer between the wells. The general exciton wavefunctions for the Hamiltonian (1) are presented as superpositions of the functions (9) [13]

$$\Psi = \sum_{i,j} a_{ij}\Psi_{ij}. \tag{10}$$

The coefficients a_{ij} are the amplitudes of the probability of finding the electron in the well i and the hole in the well j. The coefficients a_{ij} and the exciton energies E are determined after

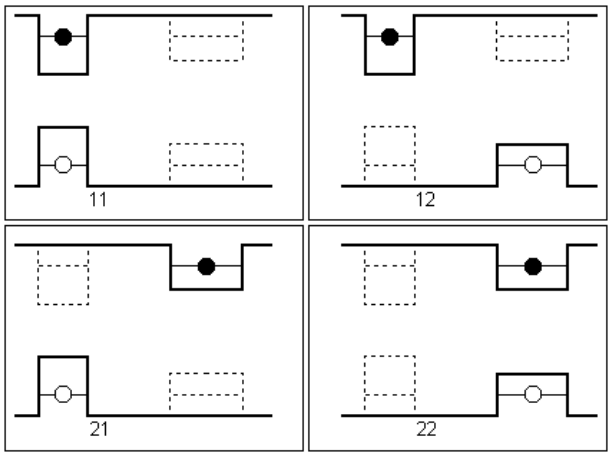

Figure 2. The schematic location of the electron and the hole for four basic wavefunctions.

solving the following equations:

$$\det |\langle ij|H|km\rangle - E\langle ij|km\rangle| = 0. \tag{11}$$

Hereinafter the enumeration of levels E_ν starts from the lowest one; $\nu = 1, \ldots, 4$. The exciton radiation lifetime is inversely proportional to the overlap integral

$$I = \left| \int \Psi\,(0, z, z) \right|^2, \tag{12}$$

which was calculated for each of the exciton states in the double-well structure. Using the value of this integral we can calculate different optical properties of the system: reflection spectra, absorption and transmission spectra and so on. The related formulae are presented for example in [14].

3. Results and discussion

3.1. (Zn, Mn)Se-based heterostructure; direct and indirect exciton level crossing

Heterostructures based on ZnMnSe such as ZnMnSe/ZnSe have been investigated intensively during the last few decades as materials for spin superlattices with spatially separated carriers with different spin projections [15, 16]. To provide a strong confinement of the carriers in ZnSe-based structures, the four-component alloy (Zn, Be, Mg)Se can be used as a barrier material [17].

We will consider the (Zn, Be, Mg)Se/ZnSe/(Zn, Be, Mg)Se/(Zn, Mn)Se/(Zn, Be, Mg)Se structure. It consists of two coupled quantum wells: one made of non-magnetic semiconductor and the other made of the diluted magnetic semiconductor (figure 1). The wells are separated by a non-magnetic potential barrier. In figure 3 a schematic band diagram of the structure is shown.

For the σ^+-component of the exciton transition the magnetic well depth increases as the magnetic field intensity rises (see figure 3(b)), while for the σ^--transition the well depth decreases. For a relative concentration of magnetic impurities Mn^{2+} of 5% in the semimagnetic layer, the well depth for the hole increases by about 40 meV for the magnetic field intensity $H = 3$ T and temperature $T = 1.6$ K in comparison with that for the initial depth for $H = 0$.

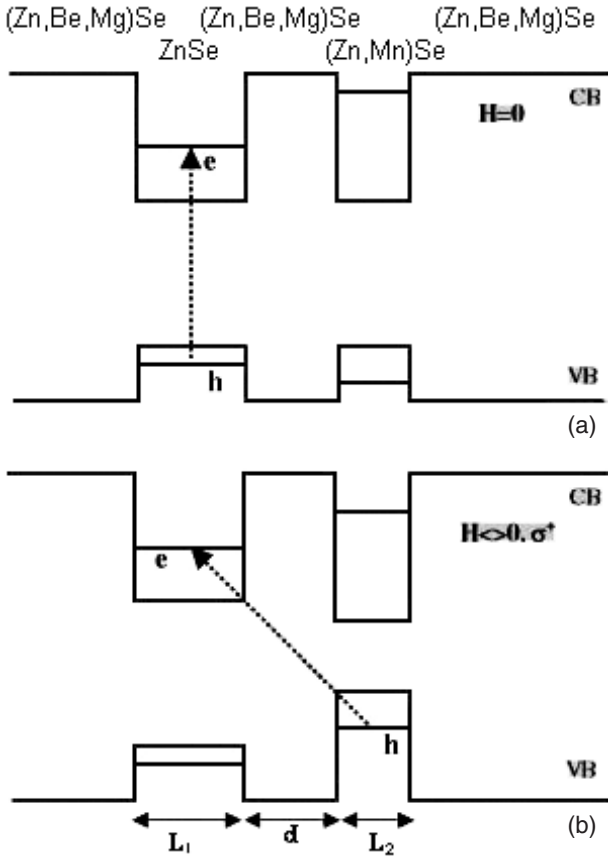

Figure 3. Schematic representations of band profiles (a) in zero magnetic field and (b) in a magnetic field. Arrows show direct (a) and indirect (b) exciton transitions.

This magnetic well depth change leads to a considerable shift of the one-particle energy levels of the electron and the hole in the magnetic well. In contrast, in the non-magnetic well, the magnetic field dependence of the one-particle levels is very weak (this dependence is caused by coupling with the magnetic well). Therefore, in the system under study the well depth and the energy levels of the carriers in one of the wells are tunable by an external magnetic field, which leads us to expect creation of an indirect exciton with an energy level lower than the level of the direct exciton. Calculations were performed for the double-well structure $Zn_{0.76}Be_{0.08}Mg_{0.16}Se/ZnSe/Zn_{0.76}Be_{0.08}Mg_{0.16}Se/Zn_{0.95}Mn_{0.05}Se/Zn_{0.76}Be_{0.08}Mg_{0.16}Se$.

To calculate the potential barrier heights we assumed [16–18] that the band gap of the barrier material $Zn_{0.76}Be_{0.08}Mg_{0.16}Se$ is equal to $E_g^{bar} = 3.2$ eV [17], the band gap of ZnSe is $E_g^{ZnSe} = 2.822$ eV, the band gap of $Zn_{1-x}Mn_xSe$ is equal to $E_g^{ZnMnSe} = 2.822$ eV for $x < 0.065$ and $E_g^{ZnMnSe} = (2.822 + 0.4141x)$ eV for $x \geqslant 0.065$ [16], where x is the relative concentration of Mn. So, the double-well potential (8) for the electron can be written as

$$\begin{aligned} V_1 &= (1 - Q_V)(E_g^{bar} - E_g^{ZnSe}), \\ V_2 &= V_1, \\ V_3 &= (1 - Q_V)(E_g^{ZnMnSe} - E_g^{ZnSe}) + \Delta V_e(x, H, s_{e,z}), \\ V_4 &= V_1. \end{aligned} \tag{13}$$

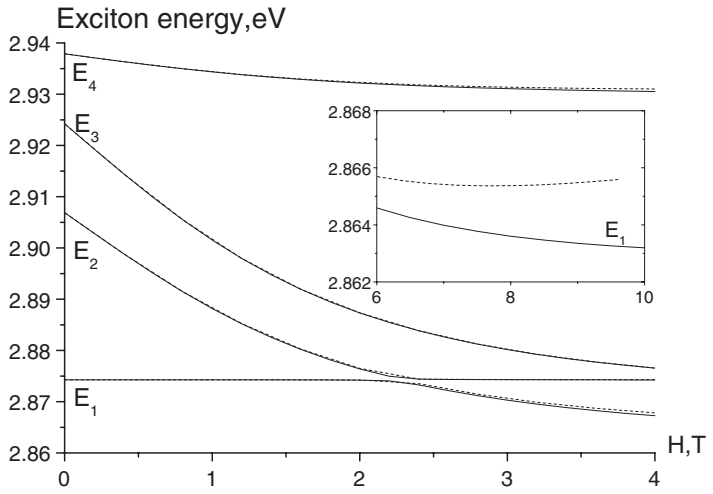

Figure 4. Magnetic field dependences of the exciton energy levels in the (ZnMn)Se-based double-well structure with (dashed curve) and without (solid curve) the diamagnetic shift of the exciton levels taken into account.

For the hole,

$$\begin{aligned} V_1 &= Q_V(E_g^{\text{bar}} - E_g^{\text{ZnSe}}),\\ V_2 &= V_1,\\ V_3 &= Q_V(E_g^{\text{ZnMnSe}} - E_g^{\text{ZnSe}}) + \Delta V_h(x, H, s_{h,z}),\\ V_4 &= V_1. \end{aligned} \tag{14}$$

Here parameter Q_V determines the ratio of the potential barrier heights for the electron and the hole. The exchange integrals are equal to $N_0\alpha = 0.26$ eV, $N_0\beta = -1.31$ eV; $Q_V = 0.22$ [17].

The thermal average value of the Mn spin along the direction of the magnetic field H was calculated as $\overline{S}_{\text{Mn},z}(H) = S_{\text{eff}} B_{\frac{5}{2}}\left(\frac{5g\mu_B H}{2k_B(T+T_{\text{eff}})}\right)$, where $B_{\frac{5}{2}}$ is the Brillouin function, $g = 2$, μ_B and k_B are the Bohr magneton and the Boltzmann constant respectively. The alloy-dependent phenomenological parameters for the effective spin S_{eff} and temperature T_{eff} are equal to $S_{\text{eff}} = 1.5$ and $T_{\text{eff}} = 1.7$ K for $x = 0.05$ [18]. The effective mass of the electron is equal to $m_e = 0.16m_0$; for the heavy hole in the growth direction $m_{\text{hh},\perp} = 0.74m_0$, while the heavy hole in-plane mass is equal to $m_{\text{hh},\parallel} = 0.28m_0$ [17], where m_0 is the mass of the free electron; the dielectric constant $\varepsilon = 9$ [17].

The calculated magnetic field dependences of the exciton energy in the double-well structure with the well widths $L_1 = 40$ Å for the non-magnetic well, $L_2 = 27$ Å for the magnetic one, the barrier width $d = 30$ Å and the impurity concentration $x = 0.05$ are depicted in figure 4 for the σ^+-component of the exciton transition. Four curves in this picture correspond to possible 1S exciton states. The state E_3 corresponds to the direct exciton with the electron and the hole placed in the diluted magnetic layer. The state E_4 is the second indirect exciton (the hole is in the non-magnetic layer and the electron is in the magnetic one). The spatial characteristics of the lowest E_1 and E_2 will be described below.

Let us denote the magnetic field value for which the lowest energy levels E_1 and E_2 come maximally close by H_1 (see figure 4). For $H < H_1$ the lowest state E_1 corresponds to the exciton with the electron and the hole confined in the same layer (in the non-magnetic well QW1). The higher state E_2 corresponds to the indirect exciton state with the hole in the semimagnetic layer and the electron in the non-magnetic layer. For the σ^+-polarization the

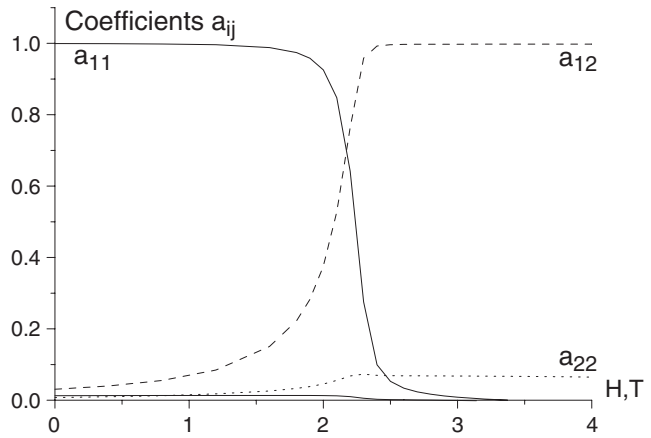

Figure 5. The magnetic field dependence of the coefficients a_{ij} of the lowest energy level.

quantum well depth increases as the magnetic field rises; moreover, for the heavy hole it rises more rapidly than for the electron by reason of the larger exchange integral value. Calculations show that transition to the indirect exciton state becomes profitable in magnetic fields $H > H_1$. The whole energy of the indirect exciton for $H > H_1$ becomes lowest (see figure 4), though the binding energy of this state is small in absolute value. So, the magnetic field increase leads to a change of the lowest exciton state spatial characteristic of the wavefunction at $H = H_1$ and resonance between the direct and indirect states takes place. To demonstrate this transition, the values of the coefficients a_{ij} in (10) for the lowest exciton state wavefunction are depicted in figure 5 as the function of the magnetic field. These coefficients determine the probability of finding the electron and the hole in a certain well. It can be seen that for $H < H_1$ the coefficient a_{11} is the largest one, so both the electron and the hole are localized in the QW1. For $H > H_1$ the coefficient a_{12} becomes the largest and, consequently, the lowest exciton state becomes indirect: the electron is localized in QW1 and the hole in QW2.

For the lowest states E_1, E_2, E_3 and E_4 in (figure 6) the corresponding overlap integrals denoted by 1, 2, 3 and 4 are shown (the overlap integral for state 4 is small and it is not visible in figure 6, like that for state 2 for $H < H_1$). As was mentioned above, the overlap integral is proportional to the oscillator strength of the exciton transition and inversely proportional to the exciton lifetime.

The overlap integral value is determined first of all by the spatial position of the carriers; therefore at $H < H_1$ the overlap integral for the lowest direct state considerably exceeds the overlap integral for the indirect one, with the electron and the hole spatially separated (it can be seen in figure 6 that $I_1 > I_2$ in this field region). A step-like decrease of the lowest state overlap integral (and, correspondingly, the step-like increase of the exciton lifetime) takes place near $H = H_1$ because the lowest state becomes indirect. Quantitatively, the overlap integral value depends on the system parameters. The indirect exciton lifetime increases strongly with barrier width increase. So, for the structure described above with the barrier width $d = 40$ Å, the indirect exciton lifetime is an order of magnitude greater than the direct one for $H > 3$ T. For the same structure with $d = 60$ Å this difference reaches four orders. The values of the overlap integral of the exciton transition with different barrier widths d and $T = 4$ K are shown in figure 7. Since the indirect state is the lowest one for $H > H_1$, the creation of a high concentration of excitons is possible in the system under study. It should be mentioned that the indirect exciton state can become the lowest state in such systems only if certain requirements

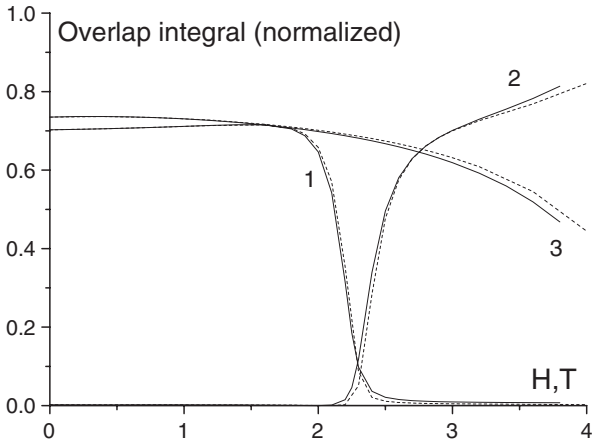

Figure 6. The value of the overlap integral of the exciton transition as a function of an external magnetic field in a (ZnMn)Se-based double-well structure with (dashed curve) and without (solid curve) the diamagnetic shift of the exciton levels taken into account.

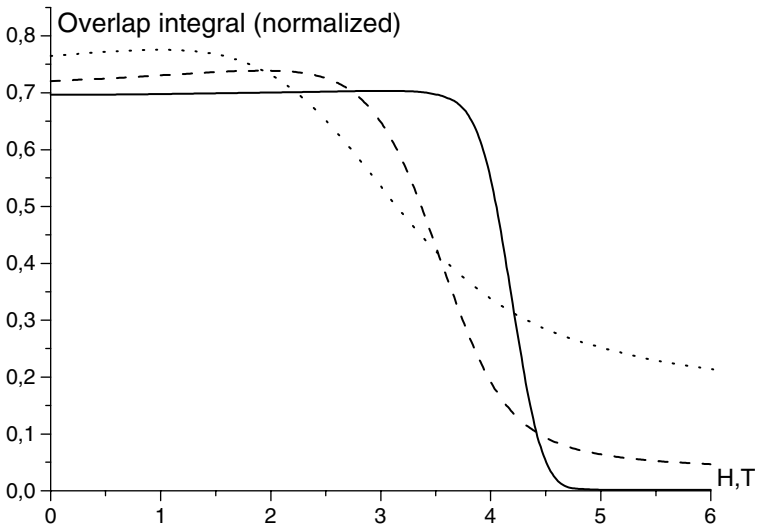

Figure 7. The value of the overlap integral of the exciton transition as a function of an external magnetic field in a (ZnMn)Se-based double-well structure with the barrier width $d = 60$ Å (solid curve), $d = 40$ Å (dashed curve) and $d = 30$ Å (dotted curve).

for the structure are fulfilled. The ranges of the well widths L_1 and L_2 for which the indirect excitons are the states with the lowest energy are shown in figure 8 for the relative concentration of the magnetic ions $x = 0.1$ and for different values of the magnetic field. With increasing magnetic field the region of appropriate parameters becomes wider. The calculations show that the region of acceptable values of the well widths L_1, L_2 is much larger for $x = 0.1$ than for $x = 0.05$ because increase in the concentration of the magnetic ions makes the wells more sensitive to the field. Calculations show that the diamagnetic shift makes a negligible contribution to the exciton energy and to the oscillator strength in weak magnetic fields up to 4–5 T (see figures 4, 6).

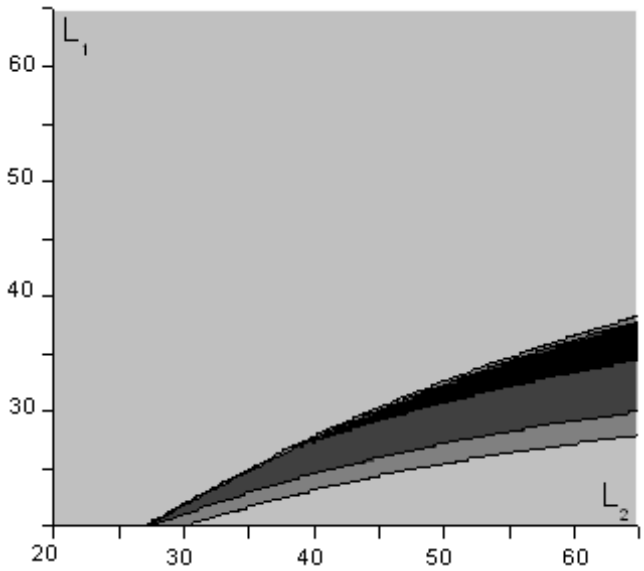

Figure 8. The range of well widths in which the lowest state is an indirect exciton in a (Zn, Mn)Se-based double-well structure for $x = 0.1$. The black region is the appropriate region in a magnetic field $H = 3$ T, in a magnetic field of 4 T the region of appropriate parameters extends to include the dark grey region, in a field of 5 T the appropriate region covers three segments: black, dark grey and light grey.

3.2. (CdMn)Te-based double-well structure; exciton transfer between two layers

The second structure under study consists of the CdTe layer non-magnetic quantum well (QW1), the $Cd_{1-z}Mn_zTe$ magnetic quantum well (QW2) and the $Cd_{1-x}Mn_xTe$ barrier layers (where $x > z$). To investigate strong confinement of the carriers in the quantum wells and increased indirect exciton lifetimes, we studied the case where the concentration of the impurity in the barrier between the wells is higher than in the external barriers, $V_2 > V_1$. In such a system the external magnetic field not only changes the depth of QW2, as in the previous case; it also changes the barrier heights. For the σ^+-component of the exciton transition the barrier decreases as the magnetic field intensity rises, while for the σ^--transition the barrier rises.

Calculations were performed for the double-well structure $Cd_{1-x}Mn_xTe/CdTe/Cd_{1-y}Mn_yTe/Cd_{1-z}Mn_zTe/Cd_{1-x}Mn_xTe$. The following parameters were used: the effective mass of the electron is equal to $m_e = 0.096\ m_0$, the heavy hole mass is equal to $m_{hh,\|} = 0.64\ m_0$; the dielectric constant $\varepsilon = 9.7$ [19]. The exchange integrals are equal to $N_0\alpha = 0.22$ eV, $N_0\beta = -0.88$ eV, $Q_V = 0.4$ [19]. For the calculation of the total energy band gap discontinuity and the average spin projection $\overline{S}_{Mn,z}(H)$ for $T = 1.6$ K, empirical expressions were used [20]. The band gap of the non-magnetic well material CdTe is $E_g^{CdTe} = 1.606$ eV. When the magnetic field is absent the band gap of the magnetic materials $E_g^{Cd_{1-x}Mn_xTe} = E_g^{CdTe} + x\,dE_g$, where x is the relative concentration of Mn, $dE_g = 1.592$ eV is an empirical coefficient. So, the potential for an electron in a magnetic field can be written as

$$V_i = (1 - Q_V)\left(E_g^{Cd_{1-x_i}Mn_{x_i}Te} - E_g^{CdTe}\right) + \Delta V_e\left(x_i, H, s_{e,z}\right) \tag{15}$$

and for the hole

$$V_i = Q_V\left(E_g^{Cd_{1-x_i}Mn_{x_i}Te} - E_g^{CdTe}\right) + \Delta V_e\left(x_i, H, s_{e,z}\right). \tag{16}$$

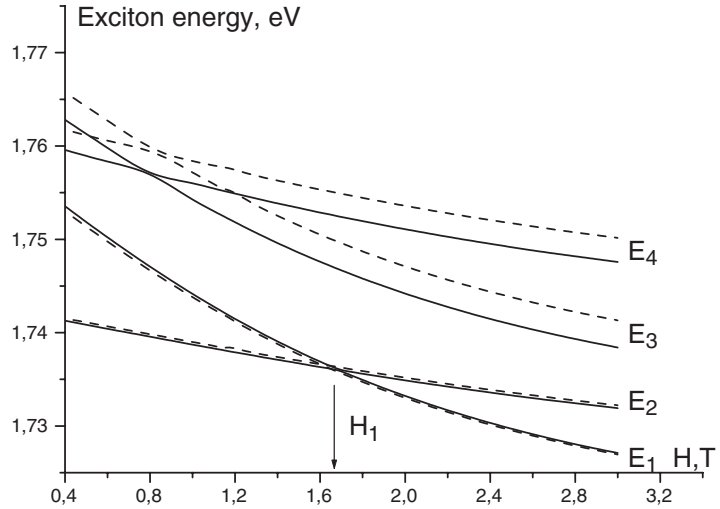

Figure 9. The magnetic field dependence of the exciton energy levels in the (CdMn)Te-based double-well structure.

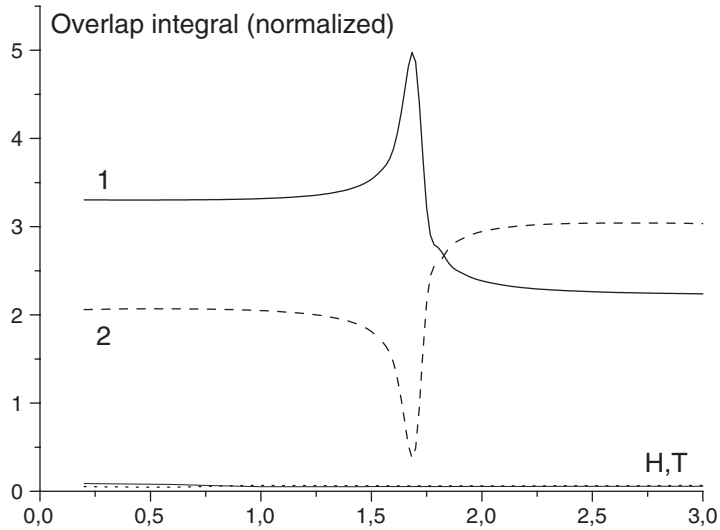

Figure 10. The value of overlap integral of the exciton transition as a function of an external magnetic field in a (CdMn)Se-based double-well structure.

In figure 9 the magnetic field dependences of the exciton energy in the double-well structure with the well widths $L_1 = 22$ Å for the non-magnetic well and $L_2 = 32$ Å for the magnetic one, the barrier width $d = 50$ Å and impurity concentrations $x = 0.15$, $y = 0.2$, $z = 0.05$ are presented for the σ^+-component of the exciton transition. The corresponding overlap integrals are shown in figure 10.

All symbols in figures 9 and 10 coincide with ones described in section 3.1 in relation to figures 4 and 6. As in the previous system, the magnetic field value for which the lowest energy levels E_1 and E_2 come maximally close is denoted as H_1. Levels E_1 and E_2 both correspond to direct excitons but these excitons have different spatial localization. For $H < H_1$, E_1 belongs

to the exciton with the carriers placed in the non-magnetic well (QW1), E_2 belongs to the exciton with the electron and the hole localized in QW2, while for $H > H_1$, E_1 corresponds to the exciton in QW2, E_2 to the exciton in QW1. In other words, for $H < H_1$ the exciton in QW1 has the lowest energy, but for $H > H_1$ the energy for the exciton from QW2 becomes lowest and, as seen from figure 10, the value of the overlap integral becomes a little smaller for such fields. When the field value H is close to H_1, mixed states are created with wavefunctions symmetric and asymmetric with respect to the simultaneous rearrangement of the excitons between the wells. As a result a peak and a dip in the corresponding curves of the overlap integrals are observed (see figure 10). In the case considered, resonance between the energy levels is observed for the excitons placed in different quantum wells. At $H = H_1$ we obtain a collective exciton state delocalized over the wells. In the case considered, the repulsion of the levels at the point of resonance of the two direct exciton levels is much less than in the case of the resonance of the direct and indirect excitons studied in section 3.1 (see figures 4 and 8). This is explained by the feature that in the case of indirect and direct exciton resonance the states differ by the localization of only one particle. In the case of direct two-exciton resonance the states have different localizations of two particles and the tunnelling integral is much less.

4. Conclusions

The dependences of the exciton levels and the intensity of the optical transitions in the semimagnetic double quantum well on an external magnetic field have been studied. It was shown that resonances between the different exciton levels take place in a certain magnetic field intensity range. These resonances have a strong influence on the optical properties of the system. In some magnetic fields the lowest exciton state can be transformed from a direct to an indirect state, which leads to an increase of the exciton lifetime by several orders of magnitude. Thus on changing the magnetic field and parameters of the system, the kinetic characteristics of excitons can be affected significantly.

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