Zeeman Effect in $Cd_{1-x}Mn_xTe$ Parabolic and Half-Parabolic Quantum Wells

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We have investigated the electronic structure of $Cd_{1-x}Mn_xTe$ parabolic quantum wells and half-parabolic quantum wells heterostructures in the envelope function approximation using the $\mathbf{k}\cdot\mathbf{p}$ method. We have considered an external magnetic field applied in two different configurations: in the plane of the layer and in the growth direction. The confined states have been calculated taking into account the effective mass dependence of the Mn concentration and the strain effects. In this work we analyze the giant Zeeman splitting due to applied magnetic fields and we have compared the energies of the excitonic transitions hh (lh) $\rightarrow$ el for the magnetic field in the two considered configurations. Comparison of our results for the half-parabolic quantum wells with available experimental data is made.

In the last few years the interest in the study of the optical properties of semiconductors heterostructures based on $Cd_{1-x}Mn_xTe$, the so-called diluted magnetic semiconductors (DMS), as the parabolic quantum wells (PQWs), have received much attention due to their uncommon spin behavior in the presence of an applied uniform magnetic field that leads to a giant Zeeman splitting. The potential technological applications of PQWs are for construction of high speed devices [1, 2] and infrared detectors with low leakage currents and low electric field sensitivity [3]. Particularly in these heterostructures the strain effects play a fundamental role in the electronic structure, since the lattice parameter is strongly dependent of the Mn concentration.

In this work we present a calculation of the electronic structure of a $Cd_{1-x}Mn_xTe$ PQW and half-parabolic quantum well (HPQW) in the envelope-function approximation within the $\mathbf{k}\cdot\mathbf{p}$ method [4, 5]. We have neglected the split-off band, resulting in a 6×6 Hamiltonian matrix with takes into account the valence-band–conduction-band coupling. The magnetic field is applied in two directions: parallel and perpendicular to the interfaces. Strain contributions due the misfit deformation are considered in the Pikus-Bir's model [6]. The exchange interaction between the carriers spin and the magnetic moments of Mn ions is treat following the Gaj's model [7]. A numerical method based on the finite differences technique and the inverse power method were employed to solve the effective mass equation to obtain the subband structure and wave functions for electrons and holes states. The energies of the excitonic transitions from heavy-hole (hh; $|\pm 3/2>$) and light-hole (lh; $|\pm 1/2>$) to electrons (el; $|\pm 1/2>$) are calculated for the two magnetic field configurations.

In Fig. 1, the results of the transition energies as a function of the magnetic field applied in the perpendicular direction to the interfaces are presented for a PQW. The sample is assumed to be grown in a InSb substrate. The quantum well width is 200 Å and the Mn concentration decreases from $x = 0.1$ at the barrier to $x = 0$ at the center of the parabolic quantum well. The dashed lines and the solid lines represents the results without an with the effective mass dependence of the Mn concentration and the strain effects. We can note that the effects of the strain and the dependence of the effective mass of the carrier with the Mn concentrations are more expressive for the excitonic transition

from heavy hole with spin down to electron with spin down ($|-3/2> \rightarrow |-1/2>$). For the two considered effects the strain is more important than effective mass dependence with Mn concentration and cannot be neglected.

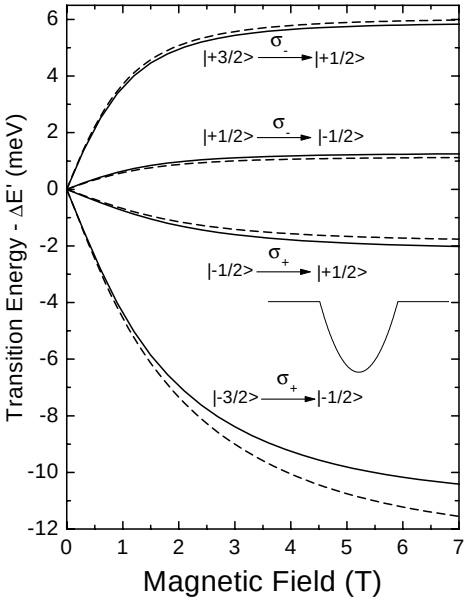

Figure 1. Transition energies versus an external magnetic field applied in the growth direction. In this figure $\Delta E'$ stands for $\Delta E' = E(B) - E(0)$.

Fig.2 shows the transition energies for two direction of the applied magnetic field, parallel (Fig. 2(a)) and perpendicular (Fig. 2(b)) to the interfaces. The strain effects and the dependence of the carrier mass of the Mn concentration are considered in this calculations. The solid (dashed) lines denotes the excitonic transitions energies between heavy-hole (light-hole) and electron states. We can see of this results that the change of the magnetic field direction leads to a strong anisotropy of the Zeeman splitting.

We also have investigated the $Cd_{1-x}Mn_xTe$ HPQWs. This system was studied for the first time by Kutrowski *et al.* [8]. In this kind of structure the energy levels are very sensitive to the valence band offset. The values of band offset that we have been used was $Q_c = 0.6$ and $Q_v = 0.4$. The appearance of "nondiagonals" ($\Delta n = n - n' \neq 0$, where n' are the quantum numbers of confined levels for electrons, el_n, and n are the quantum numbers of confined levels for heavy-holes, hh_n, or light-holes, lh_n) as well as "diagonal" ($\Delta n = 0$) transitions are expected to appear in HPQWs, whose confining potentials lack the reflection symmetry. This leads to an undetermined parity of the states and, as consequence, to relaxation of the parity-related selection rules for optical transitions.

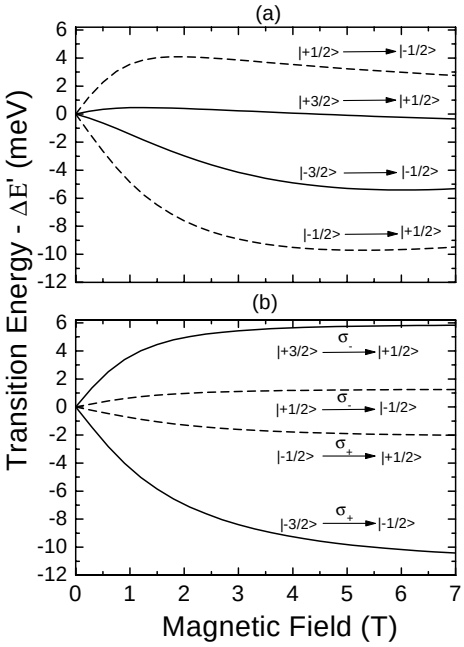

Figure 2. (a) Transition energies versus an external magnetic field applied in the plane of the layer. (b) Transition energies versus an external magnetic field applied in the growth direction.

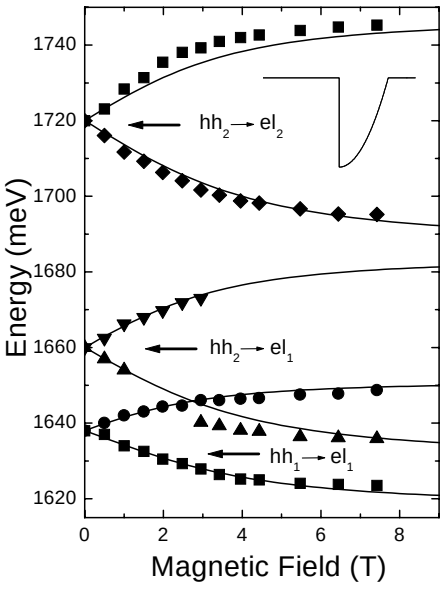

Figure 3. Transition energies concerning the half-parabolic quantum wells, when the magnetic field is applied in the growth direction. Experimental data are points and the lines come from $\mathbf{k} \cdot \mathbf{p}$ theory.

Fig. 3 shows such energies transitions versus the external magnetic field strength in a HPQW, with width of 259 Å (80 monolayers), and Mn concentration at

the barrier being $x = 0.5$ and the Mn concentration at the bottom of well being $x = 0$. This result has been obtained for magnetic field applied perpendicular to the interfaces. Comparison of our theoretical results (solid lines, where the strain effects and the dependence of the carrier mass of the Mn concentration has been considered) and the experimental data (points) shows good agreement between them. Recent $Cd_{1-x}Mn_xTe$ PQW heterostructures of high quality has been possible [9, 10]. Photoluminescense excitation technique has been used in the PQW structures where non-diagonal transitions can be observed [10]. However, only magnetic field applied perpendicular to the interfaces was considered. Concerning the PQW we don't have knowledge of any experimental results with a magnetic field applied parallel to the interfaces.

Acknowledgments

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