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MAGNETIC FIELD DEPENDENT COUPLING OF VALENCE BAND STATES IN ASYMMETRIC DOUBLE QUANTUM WELLS

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We discuss a theoretical model for the Zeeman splitting in dimension reduced structures consisting of semimagnetic semiconducting materials. The interplay of the magnetic field in different orientations with the confinement and strain induced symmetry reduction in quantum well structures is discussed. The coupling of valence band states of magnetic and nonmagnetic wells in asymmetric double quantum well structures is studied.

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1. Introduction

The unique properties of semimagnetic semiconductors have been studied for bulk material but their exceptional magnetic properties are even more pronounced in the combination with nonmagnetic materials in layered structures like superlattices (SL) or other quantum well (QW) structures [1,2]. Beside the giant Zeeman splitting due to the s–p, d exchange interaction between the localized spins of the Mn ions and the band electrons, two other effects are induced, the change of the lattice constant and the change of the band gap energy and, as a consequence, its modification and tuning by an external magnetic field.

For zero magnetic field the confinement potential is the same for all particles in the quantum well which results in a splitting of heavy hole and light hole states because of the different effective masses. Additionally, the strain induced splitting of opposite sign in different layers of the quantum well structure is caused by the lattice misfit due to different bulk lattice constants of the materials which allows the classification of the zero-field states for well and barrier transitions [2].

We will study the magnetic field correlated coupling of the states and the magnetic field induced confinement effects for asymmetric double quantum wells and compare the results with the splitting pattern observed for superlattices.

2. Theory

The material in the layers is described by an Kohn–Luttinger Hamiltonian [3]:

$$H = H_{kp} + H_{\text{strain}} + H_{\text{ex}}, \tag{1}$$

where H_{kp} describes the band structure, H_{strain} — the misfit induced deformation and H_{ex} — the exchange interaction present either in the well or in the barrier material. The magnetic field dependence is caused only by the third term. The confinement effects appearing in the structure are taken into consideration by adding a constant potential to the parts of the Hamiltonian which appear in the transfer matrix formalism. The transfer matrix formalism [4] includes automatically the modified periodicity in the layered structure by replacing the k_z component by the z-derivative of the envelope wave function $F(z)$ in the effective mass approximation. The equivalence of the x and y in-plane directions in the homogeneously deformed cubic material will be expressed by the representation of H_{kp} which reads

$$H^{\text{v}}_{\text{cryst}} = \begin{pmatrix} F & H & J & 0 \\ H^* & G & 0 & J \\ J^* & 0 & G & -H \\ 0 & J^* & -H^* & F \end{pmatrix}, \tag{2}$$

with

$$F = -\left(\gamma_1 + \frac{5}{2}\gamma_2\right) k^2 + \frac{3}{2}\gamma_2(k_x^2 + k_y^2 + 3k_z^2), \tag{3}$$

$$G = -\left(\gamma_1 + \frac{5}{2}\gamma_2\right) k^2 + \gamma_2 \left(\frac{7}{2}k_x^2 + \frac{7}{2}k_y^2 + \frac{1}{2}k_z^2\right), \tag{4}$$

$$H = 2\sqrt{2}\gamma_3(k_y\, k_z + \mathrm{i}k_x\, k_z), \tag{5}$$

$$J = \sqrt{3}\gamma_2(-k_x^2 + k_y^2) + 2\mathrm{i}\sqrt{3}\gamma_3 k_x k_y, \tag{6}$$

where γ_1, γ_2 and γ_3 are the Kohn–Luttinger parameters. In layered structures, we choose the z-direction parallel to the growth direction. For $k_x = k_y = 0$, the matrix (2) becomes diagonal. Hence, in the transfer matrix remain only diagonal elements for the calculation of the envelope wave function.

We will now discuss the specific features of the envelope wave function in 2D structures. Projecting onto the total momentum components of the valence band states, we may write the envelope function as linear combination

$$\begin{aligned} \Phi^j_{\Gamma_8}(z) &= F^j_{3/2}(z)|3/2\rangle + F^j_{1/2}(z)|1/2\rangle \\ &\quad + F^j_{-1/2}(z)|-1/2\rangle + F^j_{-3/2}(z)|-3/2\rangle, \end{aligned} \tag{7}$$

with $j = 1, 2, 3, 4$ indicating the envelope functions of the four observed energetically different states in the Zeeman pattern. In Faraday configuration where the magnetic field is oriented parallel to the growth direction the linear combination is reduced to one component belonging to each Kohn–Luttinger state. In Voigt configuration where the magnetic field is oriented perpendicular to the growth direction all four components contribute to the envelope function and the linear combination cannot be reduced to one or two contributions.

3. Results and discussion

The typical features of the magnetic field caused effects in dependence on the orientation will be discussed for asymmetric double quantum wells which consist of nonmagnetic and magnetic wells of different widths and depths. The wells are separated by nonmagnetic barriers whose widths will be varied. The whole structure is embedded in nonmagnetic material which is of the same type as the barrier material. The Zeeman splitting pattern of the valence band states will be investigated in dependence on the barrier width and the orientation of the magnetic field. The reduction of the barrier width leads in Faraday as well as in Voigt configuration to a decrease in the heavy hole and light hole splittings. In the following we denote the splitting pattern and the states according to their zero-field nature which remains valid for nonzero magnetic fields only in Faraday configuration. In Voigt configuration we have, according to Eq. (7), always states composed of heavy hole and light hole zone center states.

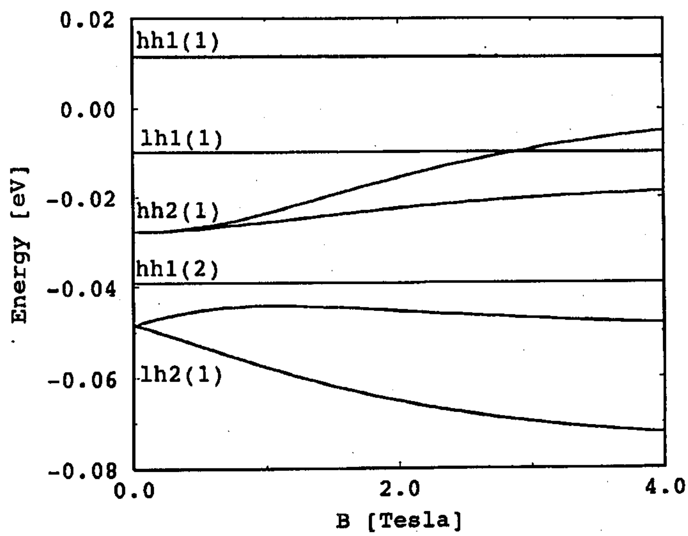

Fig. 1. Zeeman splitting pattern of an asymmetric double quantum well in Voigt configuration ($\boldsymbol{B} \parallel x$). Parameters of the structure: nonmagnetic well 1 — well width $L_{w1} = 30$ Å, nonmagnetic barrier — barrier width $L_b = 400$ Å, semimagnetic well 2 — well width $L_{w2} = 45$ Å, $x_{Mn} = 0.21$. Valence band offset: $\Delta E_{v1} = 110$ meV, $\Delta E_{v2} = 80$ meV. In the energy scale the shift of the states is scaled relative to the zero-field value of the bottom of well 2.

In Fig. 1 the splitting pattern in Voigt configuration for two wells separated by a large barrier of $L_w = 400$ Å is shown. We observe the typical anti-crossing of the curves belonging to the hh2(1) and lh2(1) zero-field states in the magnetic well which can be explained by the magnetic field induced coupling of the valence band states. Furthermore, the heavy hole splitting is smaller than the light hole splitting. The hh1(1), lh1(1) and hh1(2) states of the nonmagnetic well remain practically

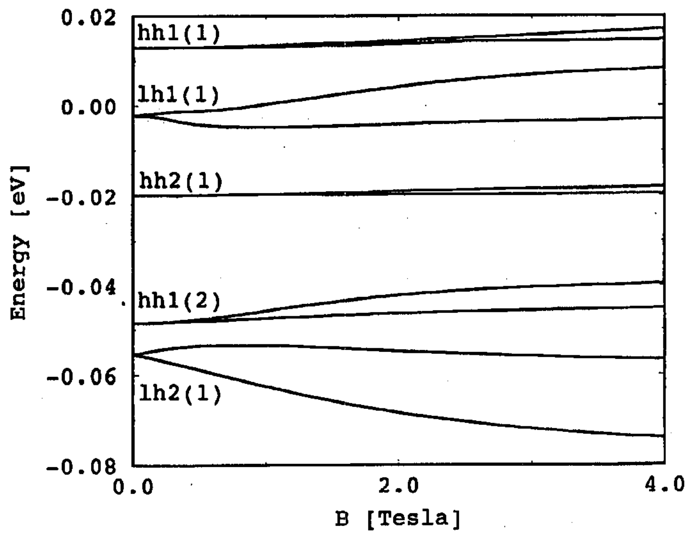

Fig. 2. Zeeman splitting pattern of an asymmetric double quantum well in Voigt configuration ($\boldsymbol{B}|\boldsymbol{x}$). The parameters are the same as in Fig. 1 except the barrier width: $L_b = 20$ Å.

degenerate because the influence of the magnetic field is drastically reduced by the broad barrier. In Faraday configuration (not shown here) the states are not coupled, the heavy hole splitting is larger than the light hole splitting and no anti-crossing of the curves is observed.

Increasing the coupling strength between the wells by diminishing the barrier width we observe two effects: (i) the splitting pattern of the well 2 states is modified and, (ii) the well 1 states hh1(1), lh1(1), and hh1(2) are split too, which is shown in Fig. 2. The light hole splitting is larger than any heavy hole splitting which can be observed for the hh1(1) as well as for the higher hh1(2) states in comparison to the lh1(1) state. Obviously, in coupled wells the splitting of the hh1 states is smaller than that of the hh2 states in uncoupled wells, because the latter are mainly influenced by the semimagnetic material whereas the others have only a reduced overlap with the magnetic layer and are mainly localized in the nonmagnetic material also in the case of a small barrier. The reduction of the hh2 splitting in coupled wells is explained by the interaction with the lh1 states (see Fig. 2), both lh1(1) and hh2(1) states show the typical anti-crossing features. This repulsion leads to a decrease in the hh2(1) splitting and can even result in larger values of hh1(1) and hh1(2) splitting in comparison to the values of the hh2(1) splitting.

The character of the states and the coupling mechanism which is responsible for the magnetic field dependence in Voigt configuration can be deduced from the slope of the curves in the limit $B \to 0$. The splitting of the states in the coupled wells follows the same classification scheme as in uncoupled magnetic well. The light hole splitting is linear in B whereas the heavy hole splitting shows a quadratic dependence on B, a linear term does not appear.

Analogous typical feature has been observed for different material combinations in SLs and QW structures like CdTe/CdMnTe [2, 5, 6], ZnSe/ZnMnSe [7], ZnCdMnSe/ZnSe [8] and CdMnTe/CdMgTe [9] reported in literature. Thus, we can conclude that the same coupling mechanism acts also in asymmetric double quantum well structures.

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