Extreme In-Plane Anisotropy of the Heavy-Hole g Factor in (001)-CdTe/CdMnTe Quantum Wells

Yu. G. Kusrayev, A. V. Koudinov, I. G. Aksyanov, and B. P. Zakharchenya
A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

T. Wojtowicz, G. Karczewski, and J. Kossut
Institute of Physics, Polish Academy of Sciences, 02-668 Warsaw, Poland
(Received 9 October 1998)

A paradoxical behavior of the linear polarization of luminescence has been observed in CdTe/CdMnTe quantum wells. Although the polarization is induced by a magnetic field, neither the magnitude of the polarization nor the orientation of its plane vary when the field is rotated in the quantum well plane. An analysis shows that this can be accounted for by a low-symmetry perturbation of the crystal lattice that gives rise to a mixing of the valence subbands leading, in turn, to an anisotropy of the in-plane heavy-hole g factor. [S0031-9007(99)08866-3]

PACS numbers: 78.66.Hf, 75.50.Pp, 78.55.–m

In diamond and zinc blende semiconductors, such as Si, GaAs, or CdTe, the valence-band states are fourfold degenerate at the Brillouin zone center Γ. The top of the valence band consists of the heavy- and light-hole subbands, each twofold degenerate in angular-momentum projection. The heavy-hole subband states are characterized by the angular momentum projections of $\pm 3/2$, and the light-hole subband states, by $\pm 1/2$.

A biaxial strain usually present in quantum-well (QW) structures, as well as the difference between the light and heavy-hole effective masses result in a partial lifting of valence band degeneracy. Unless there is a strong tensile in-plane strain of the QW, the states which are higher in energy are those of the heavy-hole subband, and it is these states that determine properties of the recombination radiation emitted from QWs. The spin-orbit interaction results in a strong anisotropy of the Zeeman splitting of the hole states [1,2]. In an ideal QW having D_{2d} symmetry, only the longitudinal component of the heavy-hole g-factor tensor g_{zz} is appreciable. The in-plane, or transverse components are determined by the Luttinger parameter q which describes cubic corrections to the spin Hamiltonian and which is small in value.

Let us note that the transverse g factor is connected with the spin relaxation efficiency. A vanishing transverse g factor would suppress the most effective channels of the hole spin relaxation, contrary to numerous optical pumping experiments performed on low-dimensional systems which evidence a fairly high efficiency of this process [3]. Smallness of $g_\perp$ in QWs made of diluted magnetic semiconductors, where the anisotropy of the hole exchange field gives rise to an anisotropic spin structure of the magnetic polaron state [4,5] and an unusual spin dynamics [6–9], has even more specific consequences.

The present Letter reports observation of a strong dependence of the linear polarization of the photoluminescence in (001)-CdTe/CdMnTe quantum wells on the direction of an in-plane magnetic field. We show that the anisotropy of the hole ground state g factor manifests itself not only as a difference between g_{zz} and small $g_\perp$; in fact, the transverse g factor is found to be also essentially anisotropic, $g_{xx} \neq g_{yy}$. This anisotropy may range from moderate, $|g_{xx}| > |g_{yy}|$, to ultimately strong, $g_{xx} = -g_{yy}$, depending on the QW width and/or the barrier height. All the results can be understood assuming that the electron g factor is isotropic. In the case of narrow QWs, however, where the magnetic polaron effect is significant, one has to take into account a correlation between the electron and hole magnetic moments.

The experiments were performed on CdTe/CdMnTe structures grown by molecular-beam epitaxy (MBE) on (001) GaAs substrates with 2° miscut to [110]. First 0.2 μm ZnTe, 0.8 μm CdTe, and 2 μm $Cd_{1-x}Mn_xTe$ buffers were deposited. Structure I contained four CdTe QWs 20, 40, 60, and 100 Å wide, separated by 500-Å-thick $Cd_{1-x}Mn_xTe$ barriers with $x = 0.3$. Structure II consisted of three QWs 40, 60, and 100 Å wide; the barriers were made of $x = 0.1$ material. The magnetoluminescence measurements were carried out at 2 K. An external magnetic field was oriented in the plane of the structures. The luminescence, excited by a helium-neon or argon laser of about 1 W/cm^2 power, was detected along the growth axis z. *The pump light polarization did not affect in any way the polarization of the luminescence in our experiments.*

To characterize fully the linear polarization of the light, one has to measure two quantities. In the experiments, we measured the parameters ρ_0 and ρ_{45} defined as

$$\rho_0 = \frac{I_\alpha - I_\beta}{I_\alpha + I_\beta}, \qquad \rho_{45} = \frac{I_{\alpha'} - I_{\beta'}}{I_{\alpha'} + I_{\beta'}}, \tag{1}$$

where the directions α and β in the QW plane are perpendicular and parallel to the magnetic field, respectively, the directions α' and β' are rotated relative to α and β by 45° about the z axis, I_s denote the intensities of the radiation polarized along the corresponding directions.

Figure 1a displays the spectra of the luminescence and of its linear polarization for 60 Å wide QW in structure I. Here we shall focus on the polarization of the luminescence lines which in analogous structures were identified [10] as due to recombination of quantum-confined heavy hole excitons. In the absence of the field, the amount of linear polarization in the luminescence does not exceed 2%. In a magnetic field of about 1 T, the polarization is by an order of magnitude greater, with ρ_0 and ρ_{45} increasing with the field first quadratically, and after that, linearly (Fig. 1b). By fixing the field and rotating the crystal, we were able to obtain angular scans of ρ_0 and ρ_{45} for different QWs. The three qualitatively different types of these relations are shown in Figs. 2a, 3a, and 3b. Let us note that in all the cases the observed anisotropy is quite strong. It is remarkable that applying the field along [110] and $[1\bar{1}0]$ one obtains different results, while for an ideal structure with D_{2d} symmetry these axes are equivalent. It should be pointed out that the nonequivalence of [110] and $[1\bar{1}0]$ directions in low-dimensional systems based on GaAs/AlAs (manifesting itself in the fine structure of the exciton spectrum) has recently been revealed in ODMR [11] and optical orientation [12] experiments. In our case, however, manifestation of the exciton fine structure can hardly be expected, because the corresponding splittings are usually of the order of tens of μeV, whereas the interaction energy of localized carriers with magnetic fluctuations in semimagnetic semiconductors is estimated to be a few meV [13].

It is convenient to start the analysis of the angular relations with symmetry considerations. The linear polarization of light is described by the symmetric part of the polarization tensor, $\langle E_\alpha E_\beta \rangle$. Limiting oneself to the weak magnetic-field domain, where the field-induced variations of the tensor components are bilinear in the field,

$$\langle E_\alpha E_\beta \rangle^{\mathrm{symm}} = A^0_{\alpha\beta} + A_{\alpha\beta\gamma\delta} B_\gamma B_\delta \,, \qquad (2)$$

one finds that the angular dependence of ρ_0 in an ideal QW with D_{2d} symmetry can contain only the zeroth and fourth harmonics (and that of ρ_{45}—only the fourth harmonic). As we have seen, none of the QWs studied by us exhibits a relation of this kind. If we assume, however, that the symmetry of the system is lowered for some reason from D_{2d} to C_{2v}, the minimum distortion making the [110] and $[1\bar{1}0]$ axes nonequivalent, then the result is expected to be different. For the sake of convenience, we shall first write it in the parameter system related to the crystal reference frame:

$$\rho'_0 = DB^2[a + b\cos 2\varphi] \,, \qquad (3)$$

$$\rho'_{45} = cDB^2 \sin 2\varphi \,, \qquad (4)$$

to be later transformed to the magnetic field reference frame, i.e., to the directly measured parameters:

$$\rho_0 = DB^2\left(\frac{b + c}{2} + a\cos 2\varphi + \frac{b - c}{2}\cos 4\varphi\right), \qquad (5)$$

$$\rho_{45} = DB^2\left(a\sin 2\varphi + \frac{b - c}{2}\sin 4\varphi\right). \qquad (6)$$

φ in Eqs. (3)–(6) is the angle between the [110] axis and the magnetic field, $a = A_{11} - A_{21} - A_{22} + A_{12}$, $b = A_{11} - A_{21} + A_{22} - A_{12}$, $c = 4A_{66}$, where indices 1, 2, and 6 are used to replace pairs xx, yy, and xy (x and y being along [110] and $[1\bar{1}0]$), D is proportional to the inverced luminescence intensity and depends on φ weakly. Parameters ρ'_0 and ρ'_{45} in Eqs. (3) and (4) are defined similarly to Eq. (1), but for the light polarized along [110], $[1\bar{1}0]$ and [100], [010], respectively. Presenting results in the form given by Eqs. (3) and (4) will prove

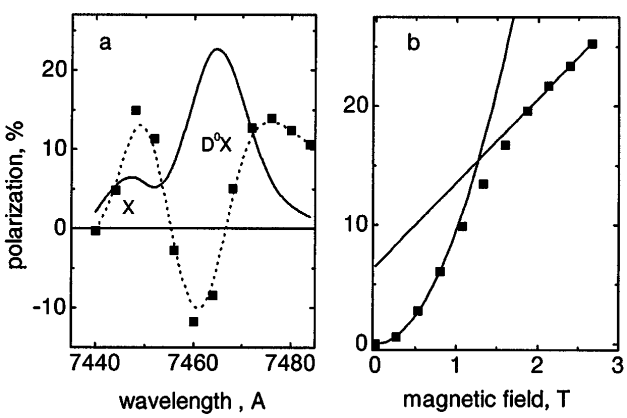

FIG. 1. (a) Spectra of intensity (solid line) and degree of linear polarization (squares) of the radiation emitted by 60-Å-thick QW in structure I, and (b) field dependence of the degree of polarization (40-Å-thick QW, structure I). The luminescence lines visible in (a) are due to recombination of heavy hole excitons localized by QW thickness fluctuations (X) and bound to neutral donors (D^0X).

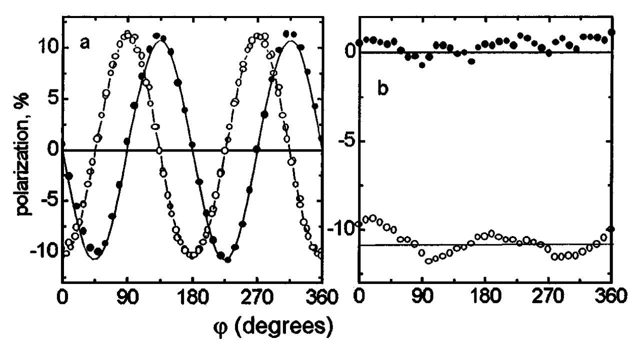

FIG. 2. Luminescence polarization degrees ρ_0 (open circles) and ρ_{45} (closed circles) vs angle φ between the in-plane magnetic field $B = 2.6T$ and [110] crystal axis (60-Å QW in structure I): (a) direct measurements; and (b) data obtained by reduction to crystal-axis-related parameters. The solid lines in (a) are fits of the data according to Eqs. (5) and (6) with $aD = 0.016T^{-2}$, $b = c = 0$.

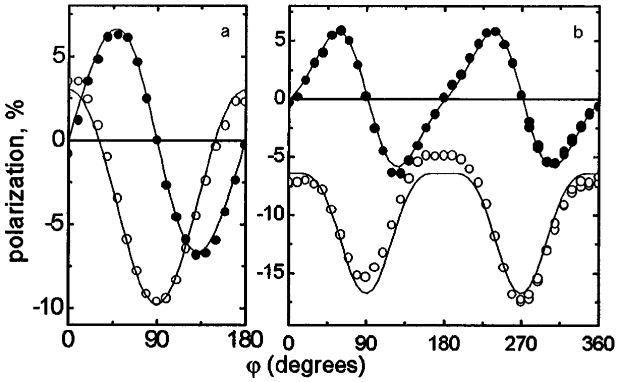

FIG. 3. Same as in Fig. 2a but for the 40-Å QW in structure II (a) and for the 20-Å QW in structure I (b). Fitting parameters (in T^{-2}): (a) $aD = 0.10$, $bD = cD = -0.05$; (b) $aD = 0.008$, $bD = -0.008$, $cD = -0.006$.

convenient later. Equations (5) and (6) can be directly compared with the angular relations displayed in Figs. 2a and 3.

As seen from Eqs. (5) and (6), C_{2v} symmetry allows the zeroth, second, and fourth harmonics to appear in the angular dependence $\rho_0(\varphi)$ [and, accordingly, the second and fourth harmonics in $\rho_{45}(\varphi)$]. The form of the coefficient a multiplying the second harmonic implies that it does not vanish for this symmetry because the x and y directions are not equivalent. Formal description of our experimental data by means of Eqs. (5) and (6) using a, b, and c as fitting parameters gives a good agreement in all different types of behavior. This argues for the above suggestion concerning the real symmetry of the structures, while not revealing how the angular relations transform from one type to another.

We take the $\rho_0(\varphi)$ relations to analyze the results of the fit. The second harmonic in Eq. (5) alone was sufficient to fit the results presented in Fig. 2a. For the 40-Å QW in structure II (Fig. 3a), the coefficients of the zeroth and second harmonics are found to differ from zero. Finally, all three harmonics allowed by C_{2v} symmetry are required to describe the behavior of the thinnest QW (Fig. 3b). This holds also for $\rho_{45}(\varphi)$ dependencies, the only difference being that neither the theory nor the experiment contain the zeroth harmonic in this case.

The case of the first 60 Å wide QW is of particular interest. Its essence can be most clearly conceived if one transforms the experimental angular dependencies $\rho_0(\varphi)$ and $\rho_{45}(\varphi)$ to the $\rho_0'(\varphi)$, $\rho_{45}'(\varphi)$ system related to the crystal axes (Fig. 2b). We obtain that $\rho_0'(\varphi)$ and $\rho_{45}'(\varphi)$ are practically independent of φ, i.e., the coefficients b and c in Eqs. (3) and (4) are zero. This leads to the following paradoxical conclusion: *the magnetic field induces a linear polarization of the luminescence, but neither the magnitude of this polarization nor its orientation in the crystal depend on the magnetic field direction.* In order to understand this result we carried out the calculation presented below, based on the heavy hole pseudospin formalism. We shall see that the behavior of the linear polarization under crystal rotation is naturally related to the in-plane anisotropy of the heavy-hole g factor.

The spin splitting of the hole subbands, $J_z = \pm 3/2$ and $J_z = \pm 1/2$, is much smaller in our case than the subbands separation. This permits us to relate the Kramers doublet $\pm 3/2$ to states of a particle with a pseudospin $j = 1/2$ and an anisotropic g factor, $J_\alpha = g_{\alpha\beta} j_\beta$, in a standard way [14]. To write out the tensor $g_{\alpha\beta}$, we use the Hamiltonian of heavy holes in a magnetic field $\mathbf{B} = (B_x, B_y, 0)$ derived [15,16] for a QW having C_{2v} symmetry. After transforming this Hamiltonian to the basis $x = [110]$ and $y = [1\bar{1}0]$, it takes the form

$$H = 2\mu_B[(q_1 + q_2)J_x^3 \tilde{B}_x + (q_1 - q_2)J_y^3 \tilde{B}_y], \qquad (7)$$

where we account for the exchange-induced enhancement of the field acting on holes [17] by replacing B with an "exchange field" $\tilde{B}$. The coefficients q_1 and q_2 determine heavy-hole g factor, with q_2 being C_{2v} invariant. As is evident from Eq. (7), the g factor is diagonal in this basis, and its components can be expressed by q_1 and q_2: $g_{xx} = 3(q_1 + q_2)$, $g_{yy} = 3(q_1 - q_2)$.

Let us calculate now the matrix element of the optical transition. The pseudospin formalism allows one to present the spin wave functions of the electron and the hole oriented at angles φ_e and φ_h, respectively, relative to x axis in a unified form [4]

$$|\psi_p\rangle = \frac{1}{\sqrt{2}}\left(\left|+\frac{1}{2}, p\right\rangle e^{-i\varphi_p/2} + \left|-\frac{1}{2}, p\right\rangle e^{i\varphi_p/2}\right) \qquad (8)$$

($p = e$ or h), and then one readily finds the transition matrix element

$$V_{eh} \propto (\mathrm{e}_x + i\mathrm{e}_y)e^{i(\varphi_h + \varphi_e/2)} + (\mathrm{e}_x - i\mathrm{e}_y)e^{-i(\varphi_h + \varphi_e/2)}. \qquad (9)$$

Here e_x and e_y are unit vectors along x and y. As seen from Eq. (9), radiation propagating normal to the QW plane is linearly polarized, and the plane of polarization is at an angle $(\varphi_h + \varphi_e)/2$ to the x axis. The final expressions for ρ_0' and ρ_{45}' are determined by the product of the mean values of electron spin $\langle s\rangle_\alpha = A_e\beta_e\mu_B g_e B_\alpha$ and hole pseudospin $\langle j\rangle_\alpha = A_h\beta_h\mu_B g_{\alpha\alpha} B_\alpha$, $\alpha = x$ or y:

$$\rho_0' = kg_eB^2[(g_{xx} - g_{yy}) + (g_{xx} + g_{yy})\cos 2\varphi], \quad (10)$$

$$\rho_{45}' = kg_eB^2(g_{xx} + g_{yy})\sin 2\varphi, \qquad (11)$$

where $k = A_eA_h\beta_e\beta_h\mu_B^2$. The factors A_e and A_h are the coefficients describing the enhancement of the spin splitting due to the exchange interaction with localized magnetic moments in diluted magnetic semiconductors [17], the coefficients β_e and β_h are related to the mechanism of spin polarization in a magnetic field [in the simplest case, they have the meaning of $(k_BT)^{-1}$]. Equations (10) and (11) differ from the symmetry expressions (3) and (4) in that the coefficients of the second harmonics [b and c in Eqs. (3) and (4)] are the same in Eqs. (10) and (11). This means that the present model does not yield symmetry-allowed fourth harmonics in the angular dependencies of ρ_0 and ρ_{45} [see Eqs. (5) and (6)]. The "remarkable" result presented in Figs. 2a and 2b corresponds to an extreme anisotropy of the g factor, $g_{xx} = -g_{yy}$ ($q_1 \ll q_2$, i.e., the in-plane hole g factor is governed by C_{2v} perturbation), and the result in Fig. 3a, to a moderate anisotropy, $|g_{xx}| > |g_{yy}|$ ($q_1 \sim q_2$).

The presence of the fourth harmonic in the angular relations for narrow QWs (Fig. 3b) remains so far unexplained. However, one has to remember that in narrow CdTe/CdMnTe QWs the magnetic polaron effect is significant [18]. When heavy hole forms a polaron, the magnetic moment of Mn ions deviates from the direction of the external field, and the electron spin will no longer align with magnetic field even if its g factor is isotropic [4]. This fact can be taken into account and, indeed, in this way one can obtain angular relations containing the fourth harmonic [19]. Let us note that a similar result is obtained if the electron g factor becomes anisotropic in narrow QWs for some reason.

Consider once more the results displayed in Fig. 1. As seen in Fig. 1a, the polarization reverses its sign within the D^0X band. This observation can be explained as follows. The ground state of the two-electron D^0X complex is the spin singlet. The energy of the photon emitted when hole recombines with one of the electrons in a magnetic field depends on the Zeeman energy of the remaining electron. This results in a splitting of the recombination line into two lines, with the long- (short-)wavelength component corresponding to annihilation of the electron with spin along (opposite to) the magnetic field. The magnitude of φ_e of these two electrons differs by π, but one can readily see from Eq. (9) that a replacement of φ_e with $\varphi_e + \pi$ turns the plane of polarization by $\pi/2$, and therefore the linear polarization of the Zeeman components of the luminescence differs in sign. Spectrum exhibit the sum of two shifted and oppositely polarized lines, which accounts for the polarization sign reversal.

One can now readily explain the crossover from the quadratic to linear field dependence of the degree of polarization (Fig. 1b). It is associated with a small value of the in-plane g factor of holes compared to that of electrons. In low fields, $\langle j \rangle_\alpha$ and $\langle s \rangle_\alpha$ ($\alpha = x, y$) vary linearly with the field, whence the quadratic growth of the polarization, but subsequently $\langle s \rangle_\alpha$ saturate to make polarization linearly dependent of the field.

In summary, our experimental results allow a straightforward interpretation if one assumes the existence of a low-symmetry perturbation mixing the heavy- and light-hole states in a QW. Symmetry considerations suggest as candidates for this perturbation uniaxial in-plane strain in the QW [12], interface anisotropy [20], or anisotropy of the hole in-plane localization potential. The first possibility seems to us the most likely. Recent extensive x-ray diffraction studies of MBE grown films [21,22] in fact revealed C_{2v}-symmetric distortions and related their occurrence to differences of dislocation mobilities along [110] and [$1\bar{1}0$] directions. Note that our model takes into account the semimagnetic feature of the structures through a trivial magnetic-field renormalization, so that the results obtained here should be valid, after inessential corrections, for nonmagnetic QWs. We believe that optical studies of the hole g-factor anisotropy may become a tool for probing the true QW symmetry.

Sincere thanks are due to E. L. Ivchenko and K. V. Kavokin for fruitful ideas and for a careful reading of the manuscript. Partial support of the Russian Basic Research Foundation (Grants No. 96-02-16887 and No. 98-02-18213) is gratefully acknowledged. Work in Poland was partially supported by the State Committee for Scientific Research under Grant No. PBZ 28.11.

[1] B. Kuhn-Heinrich *et al.*, Solid State Commun. **91**, 413 (1994).
[2] P. Peyla *et al.*, Phys. Rev. B **47**, 3783 (1993).
[3] T. C. Damen *et al.*, Phys. Rev. Lett. **67**, 3432 (1991); T. Amand *et al.*, in *Proceedings of the 22nd International Conference on the Physics of Semiconductors* (World Scientific, Singapore, 1995), p. 1139.
[4] I. A. Merkulov and K. V. Kavokin, Phys. Rev. B **52**, 1751 (1995).
[5] D. R. Yakovlev, J. Phys. IV (France) **3**, C5-67 (1993).
[6] J. Stühler *et al.*, Phys. Rev. Lett. **74**, 13 (1995); **74**, 2567 (1995).
[7] S. A. Crooker *et al.*, Phys. Rev. Lett. **77**, 2814 (1996).
[8] Yu. G. Kusrayev *et al.*, in *Proceedings of the 23rd International Conference on the Physics of Semiconductors* (World Scientific, Singapore, 1997), p. 2459.
[9] D. R. Yakovlev *et al.*, Phys. Rev. B **56**, 9782 (1997).
[10] M. Kutrowski *et al.*, Thin Solid Films **267**, 64 (1995).
[11] H. W. van Kesteren *et al.*, Phys. Rev. B **41**, 5283 (1990).
[12] C. Gourdon and P. Lavallard, Phys. Rev. B **46**, 4644 (1992).
[13] J. Warnock *et al.*, J. Lumin. **34**, 25 (1985).
[14] A. Abragam and B. Bleaney, *Electron Paramagnetic Resonance of Transition Ions* (Clarendon, Oxford, 1970).
[15] G. E. Pikus and F. G. Pikus, Solid State Commun. **89**, 319 (1994).
[16] E. L. Ivchenko and G. E. Pikus, *Superlattices and Other Heterostructures: Symmetry and Optical Phenomena* (Springer-Verlag, New York, 1995).
[17] J. K. Furdyna, J. Appl. Phys. **64**, R29 (1988).
[18] D. R. Yakovlev *et al.*, Solid State Commun. **82**, 29 (1992).
[19] Yu. G. Kusrayev *et al.* (to be published).
[20] I. L. Aleiner and E. L. Ivchenko, Pis'ma Zh. Eksp. Teor. Fiz. **55**, 662 (1992) [JETP Lett. **55**, 692 (1992)]; E. L. Ivchenko, A. Yu. Kaminskii and I. L. Aleiner, Zh. Eksp. Teor. Fiz. **104**, 3401 (1993) [Sov. Phys. JETP **77**, 609 (1993)].
[21] H. Heinke *et al.*, J. Cryst. Growth **135**, 53 (1994).
[22] J. Domagala *et al.*, Phys. Status Solidi (b) (to be published).