In-Plane Optical Anisotropy of [001]-Oriented Asymmetrical Quantum Wells

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We consider polarization-sensitive optical effects in quantum wells grown from zinc blend semiconductor materials on the basis of an envelope-function approximation. Particular attention is paid to the case of normal incidence of linearly polarized light on a quantum well grown in the [001] crystallographic direction. We demonstrate that for the [001]-oriented quantum wells characterized by structure inversion asymmetry, in-plane optical anisotropy can be governed by a bulk-related microscopic mechanism. This intrinsic mechanism is due to the Γ_8 valence band interaction, which is linear in the hole momentum operator and is allowed for bulk cubic crystals lacking a space inversion center. Analytical results are obtained in the limiting case of a strong confinement regime. The resulting in-plane optical anisotropy and related effects can be detected in the vicinity of exciton resonances.

topics: quantum wells, optical-related phenomena, spin–orbit coupling

1. Introduction

The phenomenon of optical anisotropy (OA) in crystals — the dependence of optical properties on the polarization of light — has been well-known for a long time. Over the past decades, this topic was reopened due to intensive investigation of low-dimensional semiconductor structures. The study of optical effects in the low-dimensional structures provides insight into the fundamental properties of material systems and is also relevant for the creation of different optical devices. Since the dielectric tensor ε_{ij}, which describes the optical properties of crystal materials, is sensitive to electronic wave functions on the macroscopic scale [1], the OA effects of most crystals are due to the character of their structure. For example, bulk semiconductor materials belonging to the T_d point group symmetry do not show natural OA, at least without taking into account spatial dispersion effects [2]. On the other hand, for quantum wells (QWs) grown from cubic semiconductors, the violation of the translation symmetry in the growth direction leads to a reduction of lattice symmetry and induces a polarization dependence of optical properties†. Already in the case of the [001]-oriented QW, belonging to the D_{2d} point group symmetry, the near-band-gap optical transitions become different for light polarized along (TM mode) or perpendicular (TE mode) to the QW growth direction [3]. Furthermore, for QWs grown on low-symmetry planes, i.e., for structures oriented along directions with higher Miller indices, OA in the plane of QW also becomes typical. The reason of the in-plane OA is a further reduction of the QW symmetry from the D_{2d} point group in the [001]-oriented QW to, for example, the C_{2v} symmetry in QWs grown in the [110] crystallographic direction. Such an effect of natural in-plane OA in QWs grown on low-symmetry planes has been considered in a number of theoretical and experimental works [4]. The microscopic reason is, accordingly, due to the anisotropic character of the Γ_8 valence band dispersion law in cubic symmetry crystals [5]. Having in mind the QW structures grown in the [001] crystallographic direction, the in-plane OA here can be due to the structure inversion symmetry. Indeed, if for conventional QWs belonging to the D_{2d} symmetry group, in-plane polarization degeneracy is maintained, the symmetry reduction can originate, for example, from the C_{2v} symmetry of atomic structures at (001) interfaces [6]. In-plane OA in heterostructures without common cations and anions was predicted in [7] and observed in non-common atom (GaInAs)/InP QWs in [8]. For such an intra-cell effect of the composition discontinuity, the classical theory of envelope

†1This statement is true for QWs with a width much smaller than the wave length of the light. Note that in the visible spectral region the scale of the wave length is of the order of a few thousand Å, while the width of the studied QWs is usually of the order of a few tens Å.

function is not applicable, in contrast to the above case of QWs oriented along nonconventional directions. Note also that non-common atom quantum well systems exhibit in-plane OA, even if the potential barriers are identical [4]. This is not the case for common atom QWs grown in the [001] direction. Here, the in-plane optical anisotropy requires some structure asymmetry, e.g., due to the asymmetry of the potential barriers.

Below, to complete the picture, we consider the in-plane OA in the [001]-oriented *asymmetrical* QWs that are characterized by nonequivalent z and $-z$ directions. A rectangular QW with potential barriers of different heights can serve here as a simple example. As an intrinsic mechanism of in-plane OA in this case, we propose the valence band interaction of relativistic nature, which is linear in the hole momentum operator and is allowed already for bulk zinc blend crystals lacking a space inversion center [9]. For asymmetrical QWs oriented in the [001] crystallographic direction, this spin–orbit interaction leads to a mixing of the hh and lh states at the Γ point and contributes to in-plane OA at the normal incidence of light. The intrinsic mechanism of the in-plane OA proposed here has not yet been discussed in the literature to our knowledge.

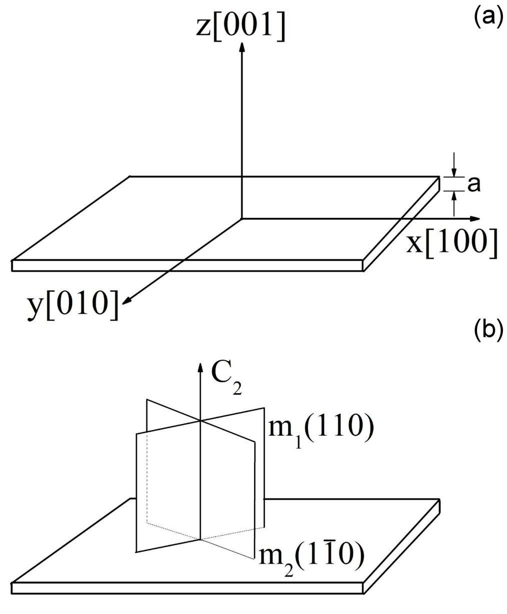

Fig. 1. (a) The coordinate system for QW grown in the [001] direction and belonging to the D_{2d} point group symmetry; a is the thickness of the well. (b) Symmetry elements of the C_{2v} point group: mirror planes $m_1(110)$ and $m_2(1\bar{1}0)$ and C_2-axis in QW grown along $z \parallel [001]$.

2. Description of optical anisotropy in [001]-oriented QW

We will start with a brief information on the phenomenological and microscopic description of OA in QWs. We mean the [001]-oriented QW, which is grown from zinc blend lattice semiconductors belonging to the T_d point group symmetry. Having in mind the macroscopic consideration of optical effects, the symmetry properties of the dielectric tensor $\varepsilon_{ij}(\omega, \boldsymbol{q})$ (with ω and $\boldsymbol{q}$ as light frequency and wave vector, respectively,) play a crucial role here. Ignoring the spatial dispersion effects ($\boldsymbol{q} \to 0$), the symmetry consideration leads to the following results. For symmetrical QWs belonging to the D_{2d} point group, the permittivity tensor ε_{ij} has a diagonal form with two independent components $\varepsilon_{xx} = \varepsilon_{yy}$ and ε_{zz} [10], where $x \parallel [100]$ and $y \parallel [010]$ are the axes in the QW plane and $z \parallel [001]$ is the growth direction, as shown in Fig. 1a. Hence, symmetrical [001]-oriented QWs show no in-plane OA. For asymmetrical QWs, the point symmetry group is lowered. The respective C_{2v} point group includes the symmetry axis C_2 parallel to the [001] growth direction and the two reflection planes $m_1(110)$ and $m_2(1\bar{1}0)$, as shown in Fig. 1b. The corresponding permittivity tensor is now characterized by three independent components $\varepsilon_{x'x'}$ ($x' \parallel [110]$), $\varepsilon_{y'y'}$ ($y' \parallel [1\bar{1}0]$), and ε_{zz} ($z \parallel [001]$) [10]. Consequently, the optical properties in the plane of the asymmetrical [001]-oriented QW can be different for the light polarizations $\boldsymbol{e} \parallel [110]$ and $\boldsymbol{e} \parallel [1\bar{1}0]$ so that in-plane optical anisotropy can manifest.

The microscopic description of the OA phenomenon is closely related to the concept of the optical matrix elements, which are fundamentally important for any optical process. Below we consider, for simplicity, narrow QWs belonging to a strong confinement regime. In other words, the well width a is supposed to be smaller than the exciton Bohr radius a_B, $a \ll a_B$. For example, in GaAs, the bulk exciton Bohr radius $a_B = 11.6$ nm. Besides, we assume that the size-quantized energy subbands of the strongly confined QW are described in the frame of an envelope-function approximation. We will concentrate on the fundamental optical transitions between the size-quantized lowest electron subband $1e$ and the ground $hh\,(lh)$-like subband $1v$. For linearly polarized light, the optical transitions $1e \leftrightarrow 1v$ of interest are governed (in dipole approximation) by the matrix elements of the momentum operator $\hat{\boldsymbol{p}} = -\mathrm{i}\hbar\nabla$ [4]. These are as follows

$$M_i^{J_z,s_z} = \Big\langle \Psi_{1e,s_z} \big| (\hat{p}_i e_i) \big| \Psi_{1v,J_z} \Big\rangle, \qquad (1)$$

where e_i ($i = x, y, z$) is the component of the polarization vector $\boldsymbol{e}$ and $s_z\,(J_z)$ are the projections of the electron (hole) total momentum. At the zero in-plane wave vector $\boldsymbol{k}_\parallel = \{k_x, k_y\} = 0$, the electron wave function in the $1e$ subband is given by $\Psi_{1e,s_z}(z) = \varphi_{1e}(z) S |s_z\rangle$ with $\varphi_{1e}(z)$ being the wave function of the confined conduction electron, S being the (s-type symmetry) orbital Bloch function, and $|s_z\rangle$ ($s_z = \pm 1/2$) — spin function. For the pure hh states ($v = hh$), the electron wave functions in the ground hh doublet $\Psi^0_{1hh,\pm3/2}(z) = \varphi_{1hh}(z)|\frac{3}{2},\pm\frac{3}{2}\rangle_e$ are determined by the size quantization function $\varphi_{1hh}(z)$ and the Bloch amplitudes $|\frac{3}{2},\pm\frac{3}{2}\rangle_e$. The latter are presented as linear combinations of the angular momentum $L = 1$ functions X, Y, Z, and the spin functions $|\uparrow\rangle(|\downarrow\rangle) = |\frac{1}{2}\rangle(|-\frac{1}{2}\rangle)$ (see, e.g., [4])

$$\left|\frac{3}{2},+\frac{3}{2}\right\rangle_e = -\frac{1}{\sqrt{2}}(X + \mathrm{i}Y)|\uparrow\rangle, \qquad (2)$$

$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle_e = +\frac{1}{\sqrt{2}}(X - \mathrm{i}Y)|\downarrow\rangle. \qquad (3)$$

The functions X, Y, Z transform under the operations of the T_d group as x, y, z ($x \parallel [100]$, $y \parallel [010]$, $z \parallel [001]$). Similarly, for the pure lh states ($v = lh$), the wave function is given by $\Psi^0_{nlh,\pm1/2}(z) = \varphi_{nlh}(z)|\frac{3}{2},\pm\frac{1}{2}\rangle_e$. Here, n is the subband number, $\varphi_{nlh}(z)$ is the wave function of the confined valence electron, and the Bloch amplitudes $|\frac{3}{2},\pm\frac{1}{2}\rangle_e$ are given by

$$\left|\frac{3}{2},+\frac{1}{2}\right\rangle_e = -\frac{1}{\sqrt{6}}(X+\mathrm{i}Y)|\downarrow\rangle + \sqrt{\frac{2}{3}}Z|\uparrow\rangle, \qquad (4)$$

$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle_e = +\frac{1}{\sqrt{6}}(X-\mathrm{i}Y)|\uparrow\rangle + \sqrt{\frac{2}{3}}Z|\downarrow\rangle. \qquad (5)$$

The Bloch amplitudes above are given in electron representation, the hole representation is obtained by the time inversion operation [9]. Note also that in the frame of the Luttinger–Kohn Hamiltonian, the pure hh and lh states in QWs refer to the Γ ($\boldsymbol{k}_\parallel = 0$) point.

The above microscopic description does not take into account the spatial dispersion effects. For QWs, this description is valid at the normal incidence of a light beam to the QW plane. The reason is that the translation invariancy in the growth direction of QW is violated, so that at the normal incidence the spatial dispersion effects are absent at all. As a result, the in-plane wave vector of the excited electron–hole pair $\boldsymbol{K}_\parallel = \boldsymbol{k}_{v\parallel} + \boldsymbol{k}_{e\parallel}$ can be equal to zero ($\boldsymbol{K}_\parallel = 0$) and direct interband optical transitions at the Γ point are possible. Note that the absence of any mixing between the states hh and lh, as is supposed above, leads to isotropic optical properties in the QW plane. Indeed, it is easy to check that for the *pure hh* doublet ($1v \equiv 1hh$), it follows from (1)–(2) that the $1e \leftrightarrow 1hh$ interband transitions at the Γ point have the same probability $|M_\xi|^2 = |M_\zeta|^2 = |\langle S|\hat{p_x}|X\rangle|^2$ for any two orthogonal polarizations ξ and ζ lying in the plane of the [001]-oriented QW. Similarly, for the *pure lh* doublet, the $1e \leftrightarrow 1lh$ interband transition is characterized by the probability $|M_\xi|^2 = |M_\zeta|^2 = \frac{1}{3}|\langle S|\hat{p_x}|X\rangle|^2$. Such a result, as follows from the phenomenological description presented above, is typical for symmetrical QWs belonging to the D_{2d} point group symmetry. Consequently, the expected in-plane OA in the asymmetrical [001]-oriented QWs requires some microscopic mechanism of the hh–lh mixing.

3. Heavy hole–light hole mixing

To introduce the mixing of the ground hh doublet with the underlying lh subbands at the Γ point in the [001]-oriented asymmetrical QW, we propose an intrinsic microscopic mechanism due to the bulk inversion asymmetry of the GaAs-like semiconductor crystals. Namely, we take into account that for the bulk cubic crystals without an inversion center, the spin-dependent part of the 4×4 effective Hamiltonian in the Γ_8 valence band expanding in powers of the wave vector $\boldsymbol{k}$ starts already with the first order term [9, 11]

$$\mathcal{H}_{lin} = \frac{4}{\sqrt{3}}\mathcal{K}_0\Big[k_x\,J_x(J_y^2 - J_z^2) + k_y\,J_x(J_z^2 - J_x^2) + k_z\,J_z(J_x^2 - J_y^2)\Big]. \qquad (6)$$

Here $k_i = -\mathrm{i}\partial/\partial r_i$ is the carrier wave vector operator; $r_i = x, y, z$ indicate the principal axes [100], [010] and [001], respectively; and J_i is the angular momentum $J = 3/2$ matrices. The constant $\mathcal{K}_0$ is relativistic in its origin and is due to the $\boldsymbol{k}-\boldsymbol{p}$ mixing with the remote states [11, 12]. For [001]-oriented QWs, this $\boldsymbol{k}$-linear interaction, according to (6), leads to a mixing of the hh and lh states at the Γ point, i.e., at $\boldsymbol{k}_\parallel = 0$. This means that the interaction $\mathcal{H}_{lin}$ can be responsible for the in-plane optical anisotropy of the [001] QWs already at the normal incidence of light. Obviously, such a conclusion is valid for asymmetrical QWs only, since the hh–lh mixing of interest arises from the third term in parenthesis, which is linear in the hole momentum k_z. For structure–symmetrical QWs, this term averaged over the size-quantized motion limits to zero, $\langle k_z\rangle = 0$. Note that for QWs, the bulk inversion asymmetry induces also another type of the $\boldsymbol{k}_\parallel$-linear interaction, which is commonly accepted in the literature. This interaction arises from the bulk $\boldsymbol{k}$-cubic spin–orbit interaction [12], acts as an effective magnetic field and is responsible for the optical activity of QWs [13].

Having in mind the asymmetrical [001]-oriented QW, taking in the Hamiltonian $\mathcal{H}_{lin}$ the in-plane wave vector $k_x = k_y = 0$ and treating the remaining term as a perturbation of pure hole states, for the Γ point wave function of the ground size-quantized subband $1hh$ one obtains

$$\Psi_{1hh,\pm3/2}(z) \cong \varphi_{1hh}(z)\left|\frac{3}{2},\pm\frac{3}{2}\right\rangle \pm \Phi_h(z)\left|\frac{3}{2},\mp\frac{1}{2}\right\rangle, \qquad (7)$$

where

$$\Phi_h(z) = 2\mathcal{K}_0\sum_m \frac{\langle mlh|\hat{k}_z|1hh\rangle}{E_{1hh} - E_{mlh}}\,\varphi_{mlh}(z) \qquad (8)$$

and $E_{1hh}\,(E_{mlh})$ is the $hh\,(lh)$ size quantized energy at $\boldsymbol{k}_\parallel = 0$. By inserting (7) into (1) and taking into account the above definitions of the basis functions, (2)–(3) and (4)–(5), for the matrix elements of the optical transitions between the highest hh-like valence subband and the lowest electron subband at the light polarization along $x' \parallel [110]$ and $y' \parallel [1\bar{1}0]$, respectively, one obtains

$$M_{110}^{3/2,1/2} = -\mathrm{i}\, M_{110}^{-3/2,-1/2} = -\frac{p_{cv}}{2} \langle 1e|1hh\rangle\, (1+\beta_h)(1+\mathrm{i}), \tag{9}$$

and

$$M_{\bar{1}10}^{3/2,1/2} = +\mathrm{i}\, M_{\bar{1}10}^{-3/2,-1/2} = +\frac{p_{cv}}{2} \langle 1e|1hh\rangle\, (1-\beta_h)(1-\mathrm{i}), \tag{10}$$

where $p_{cv} = \langle S|\hat{p_x}|X\rangle$ is the interband momentum matrix element (see Sect. 3), and the structure inversion asymmetry parameter is

$$\beta_h = \frac{2\mathcal{K}_0}{\sqrt{3}} \sum_m \frac{\langle mlh|\frac{\partial}{\partial z}|1hh\rangle}{E_{1hh} - E_{mlh}} \frac{\langle 1e|mlh\rangle}{\langle 1e|1hh\rangle}. \tag{11}$$

It follows from (9)–(10) that at $\beta_h \neq 0$ the probability of the considered optical transitions depends on the radiation polarization direction in the QW plane. Note also that similar results can be obtained for optical transitions from the first lh-like subband to the lowest electron subband with the change of the inversion asymmetry parameter β_h by the parameter

$$\beta_l = 2\mathcal{K}_0 \sum_m \frac{\langle mhh|\frac{\partial}{\partial z}|1lh\rangle}{E_{1lh} - E_{mhh}} \frac{\langle 1e|mhh\rangle}{\langle 1e|1lh\rangle}. \tag{12}$$

4. Discussion

In Sect. 3 above, it is shown that for asymmetrical [001]-oriented QWs, the valence band interaction $\mathcal{H}_{lin}$ (see (6)) leads to mixing between the hh and lh states at zero in-plane hole momentum $\boldsymbol{k}_\parallel = 0$. As a result, the matrix elements of the interband optical transitions become dependent on the light polarization direction in the QW plane. In particular, for the $1e \leftrightarrow 1hh$ and $1e \leftrightarrow 1lh$ transitions, the in-plane OA is set by the parameters β_h and β_l, respectively, see (11)–(12). As expected, both parameters limit to zero in the case of symmetrical QWs, $\beta_h = \beta_l = 0$. Indeed, for symmetrical QWs, the directions z and $-z$ are equivalent and therefore the electron (hole) size quantization wave functions $\varphi_{me}(\varphi_{mhh}, \varphi_{mlh})$ are even for odd $m = 1, 3, 5, \ldots$ and odd for even $m = 2, 4, \ldots$ relative to the QW's center. As a result, the momentum matrix element $\langle mlh|\frac{\partial}{\partial z}|1hh\rangle$ in (11) is zero for odd m, while for even m the overlap $\langle 1e|mlh\rangle$ of lh state and electron envelope functions is zero. Similarly, the momentum matrix element $\langle mhh|\frac{\partial}{\partial z}|1lh\rangle$ in (12) is zero for odd m, while for even m the overlap $\langle 1e|mhh\rangle$ is zero. For asymmetrical QWs, the parity restriction is removed and consequently the parameters β_h and β_l differ from zero; $\beta_h \neq 0$, $\beta_l \neq 0$.

According to (11)–(12), the structure inversion asymmetry parameters β_h and β_l can be estimated as $\beta_h \sim (\mathcal{K}_0 a/(\hbar^2\kappa))\zeta$ and $\beta_l \approx -\beta_h$. Here a is the well thickness, $\kappa = (m_{lh} - m_{hh})/(m_{lh} m_{hh})$ with

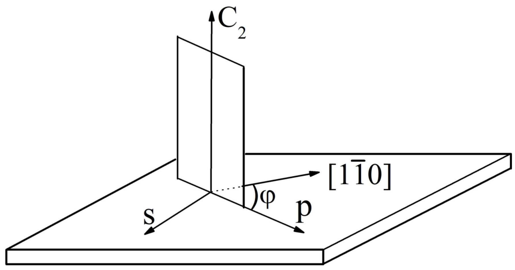

Fig. 2. Schematic representation of the incidence plane at the normal incidence of light linearly polarized in the plane of incidence (p polarization) or perpendicular to it (s polarization) for QW grown in the [001] direction.

m_{hh} (m_{lh}) the hh (lh) transverse effective mass, and $\zeta = z_{1lh,1hh}/a$ with the matrix element $z_{1lh,1hh} = \langle 1lh|z|1hh\rangle$. In terms of the Luttinger parameters γ_1 and γ_2, the transverse hole masses are given by $m_{hh} = m_0/(\gamma_1 - 2\gamma_2)$ and $m_{lh} = m_0/(\gamma_1 + 2\gamma_2)$ [9], so that the parameter $\kappa = -4\gamma_2/m_0$. The quantity $z_{1lh,1hh}/a$ differs from zero for QW structures showing inversion asymmetry caused by the difference in the left and right barrier materials. This potential difference results in a shift of the hole wave functions away from the point in the middle of QW and leads to a nonzero matrix element $z_{1lh,1hh}$. For symmetrical QWs characterized by symmetrical hole wave functions, the matrix element $z_{1lh,1hh}$ and therefore the parameter ζ are limited evidently to zero. A similar parameter was introduced in [14] where the experimentally observed magnetospatial dispersion was attributed to the inversion asymmetry of the studied semiconductor QW structures. For asymmetrical QWs, the nonzero parameters β_h and β_l are close in magnitude and opposite in sign. Also note that both parameters β_h and β_l show an approximately linear dependence on the width a of QW.

In the vicinity of the hh-like exciton resonance, the parameter β_h sets the degree of in-plane OA given, according to (9)–(10), by

$$\varrho_h = \frac{|M_{110}|^2 - |M_{\bar{1}10}|^2}{|M_{110}|^2} \cong 4\beta_h, \tag{13}$$

where $|M_i|^2 = |M_i^{+3/2,+1/2}|^2 + |M_i^{-3/2,-1/2}|^2$. Similar consideration is valid for the lh-like exciton. Here the degree of optical anisotropy ϱ_l is governed by the parameter β_l ($\varrho_l \simeq 4\beta_l$), and a more remarkable peculiarity is that the quantities ϱ_l and ϱ_h have opposite signs. It turns out that the polarizations of the peak values of the hh exciton and the lh exciton are opposite of each other in the optical spectra. One has to note that a similar peculiarity of in-plane OA was observed in semiconductor QWs grown on low-symmetry (11N) planes [5].

One of the manifestations of the OA phenomena is the conversion of the light polarization state [15] — an effect based on the transformation of a pure linearly or circularly polarized wave into elliptically polarized light. As a tool for studying this effect the phenomenon of light reflection can serve. Namely, for the incident light linearly polarized, e.g., in the plane of incidence (p polarization) or perpendicular to it (s polarization) (see Fig. 2), the reflected light will contain both components and thus becomes elliptically polarized. In Fig. 2 the incident plane, which contains the $C_2[001]$ axis, is presented for the quantum wells grown along $z \parallel [001]$. In terms of the reflection coefficient tensor $\mathbf{r}_{ij}$, and where $E_i^r = r_{ij}E_j^0$ $(i,j = s,p)$ with $\boldsymbol{E}^0\,(\boldsymbol{E}^r)$ being the light field of the incident (reflected) wave, the polarization conversion effect means that the off-diagonal components differ from zero, $r_{sp} = r_{ps} \neq 0$. For the hh-like exciton resonance, e.g., solving the problem of light reflection in QW following [4], at the normal incidence we obtain

$$r_{sp} = 4\beta_h r_{ss}\sin(2\varphi). \tag{14}$$

Here, φ is the angle between the incident plane and the axis $[1\bar{1}0]$, see Fig. 2. The reflection coefficient is given by

$$r_{ss} = \frac{\mathrm{i}\,\mathit{\Gamma}_0}{\omega_0 - \omega - \mathrm{i}\,\mathit{\Gamma}} \tag{15}$$

with ω_0 and $\mathit{\Gamma}$ being the hh exciton resonant frequency and the linewidth, respectively, and $\mathit{\Gamma}_0$ is the exciton oscillator strength. From (13)–(14) it follows that the polarization conversion coefficient $\mathcal{R} = r_{sp}/r_{ss}$ is proportional to the degree of in-plane optical anisotropy, $\mathcal{R} = \varrho_h\sin(2\varphi)$. No polarization conversion of the reflected light occurs, evidently, if the incident light is polarized along the $[1\bar{1}0]$ and $[110]$ symmetry axes, that is at $\varphi = 0, \pi/2$.

Below, we present some evaluations of the obtained results. First of all, note that the actual value of the structure inversion asymmetry parameter $\beta_h\,(\beta_l)$ is set by the constant $\mathcal{K}_0$. For various zinc blend semiconductors, this constant differs significantly in magnitude from a few meV Å in A_3B_5 compounds to several tens of meV Å in copper hallides [11]. To estimate the effects of optical anisotropy in [001]-oriented QWs, resulting from the mechanism proposed here, we will choose a set of relevant parameters. Considering a GaAs-based quantum well, we use the constant $\mathcal{K}_0 = -3.4$ meV Å [11] and the Luttinger parameter $\gamma_2 = 2$ [16]. Taking the well width $a = 10$ nm and the parameter $\zeta = 0.2$, we get the value $\beta_h\,(|\beta_l|) \sim 10^{-3}$. Note that the above-chosen value of the ζ parameter is rather realistic. For example, the authors of a recent paper [14], which is devoted to the magnetically induced polarization conversion effect in semiconductor QWs, report the growth of triangular GaAs/AlGaAs QW characterized by the parameter $\zeta = 0.2$. The obtained numerical estimate shows that in the region of the hh-like exciton the polarization conversion coefficient $\mathcal{R}$ does not exceed a few tenths of a percent, $\mathcal{R}_{\max} \approx \varrho_h \sim 4\times10^{-3}$, where $\varrho_h\,(|\varrho_l|)$ is the degree of in-plane OA. Hence, the bulk asymmetry related effect of in-plane OA in the [001]-oriented QWs is rather weak, at least for the GaAs-based QW structures. By comparison, interface-related OA of about a few percent was observed experimentally in non-common-atom (GaInAs)/InP semiconductor structures [7, 8], as well as in unconventionally [110]-oriented GaAs-based QW systems [17]. Note that the effect considered here may be one order of magnitude greater for QWs based on the A_2B_6 and A_2B_7 semiconductor compounds, which are characterized by a constant $\mathcal{K}_0$ about several tens of meV Å [11]. The in-plane optical anisotropy can reach in this case several percent.

With regards to experimental observations, the detection of in-plane OA of the [001]-oriented QWs at the normal incidence is reported in literature for different QW systems. Note that most observations refer to nonconventional QWs. For example, in [18], in-plane optical anisotropy of CdTe-based quantum wells with asymmetric barriers made of (Cd,Mg)Te or (Cd,Mn)Te ternary compounds was investigated. The authors observed a significant linear polarization, from a few tenths of a percent to a few percent, of the fundamental excitonic transitions along the ⟨110⟩ directions. The experimental results were discussed in terms of interface symmetry reduction. The authors developed an envelope function theory based on the methods proposed in [19] and [7]. In the frame of this theory, the boundary conditions for the envelopes are represented by δ-potentials at the interfaces, and the interface-related mixing between the heavy and light holes was calculated. Regarding the correspondence between theory and experiment, the authors concluded that a significant contribution of additional mechanisms may also be important. The bulk inversion asymmetry and the surface electric field were listed as supplemental sources of optical anisotropy. Using the results presented here for CdTe-based QWs with parameter $\zeta = 0.2$, linear constant $\mathcal{K}_0 = 34$ meV Å [11], and width $a = 10$ nm, we find the degree of in-plane OA due to the bulk inversion asymmetry of the order of $\varrho_h \sim 0.01$.

In [20], in-plane OA was investigated in the (100) GaAs/AlGaAs QWs by reflectance difference spectroscopy. Two types of samples were examined in this paper. Firstly, the QW structures where asymmetry was specially introduced by inserting of a monolayer of InAs or AlAs at the interfaces were studied. For excitonic transitions between the first subbands of the valence and conduction bands, the reported polarization degree is $\simeq 9\%$, which is comparable to the values typical for the QW systems with no common atom. The second type of systems investigated are conventional nominally symmetrical QWs. For such systems, the polarization degree of the order of 0.7% was measured, which is close to the estimations presented above for GaAs-based QW. The observed weak OA in [20] has been attributed to the residual QW asymmetry related to the anisotropic interface structures or the segregation effect, but the authors did not propose any relevant microscopic mechanism, as far as we understand. Note also that for asymmetrical nonconventional (001) GaAs-based QWs, similar investigations of the in-plane OA were performed in [21]. Regarding ordinary [001]-oriented QWs, experimental detection of in-plane OA at the normal incidence was reported in [13]. The polarization conversion effect due to the optical activity of a nominally symmetrical ZnSe-based QW grown in the [001] direction was investigated both experimentally and theoretically [13]. The weak signal detected at the normal incidence of light was attributed to the stress-induced reduction of the structure symmetry and the influence of in-plane deformation on the short-range exchange interaction in the exciton as well [13].

5. Conclusions

To summarize, we examine the in-plane OA of semiconductor [001]-oriented QWs in the spectral region of the $hh\,(lh)$-like exciton resonance on the basis of an envelope function approximation. We show that this optical effect can be observed in asymmetrical QWs, which are grown from the zinc blend semiconductors. The valence band interaction, linear in the hole momentum operator, can serve here as the intrinsic macroscopic mechanism of in-plane OA. A degree of the respective OA in the QW plane increases linearly with the well width. As an example, an order-of-magnitude estimation of in-plane OA in the quantum well of GaAs is given. For a reasonable degree of the structure inversion asymmetry of 20%, the degree of in-plane OA and the polarization conversion coefficient are on the order of 0.4% for a well width of about 10 nm. For asymmetrical QWs oriented in the [001] direction, experimental measurements of the optical anisotropy effects at the normal incidence can be helpful in determining the degree of the structure inversion asymmetry.

Acknowledgments

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