

## Optical orientation of electron spins by linearly polarized light

S. A. Tarasenko

*A.F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia*

(Received 6 July 2005; published 6 September 2005)

Absorption of circularly polarized light in semiconductors is known to result in optical orientation of electron and hole spins. It has been shown here that in semiconductor quantum well structures spin orientation of carriers can be achieved by linearly or even unpolarized light. Moreover, the sign and magnitude of the spin orientation can be varied by rotating the polarization plane of incidence light. The effect under study is related to reduced symmetry of the quantum wells as compared to bulk materials and, microscopically, caused by zero-field spin splitting of electron and hole states.

DOI: [10.1103/PhysRevB.72.113302](https://doi.org/10.1103/PhysRevB.72.113302)

PACS number(s): 72.25.Fe, 72.25.Dc, 72.25.Rb, 78.67.De

Spin-dependent phenomena in semiconductor structures are the subject of extensive ongoing research. One of the most widespread and powerful methods for creating spin polarization and investigating kinetics of spin-polarized carriers is optical orientation of electron and nuclear spins by circularly polarized light.<sup>1-5</sup> This effect can be interpreted as a transfer of the photon angular momenta to free carriers. Under interband excitation by circularly polarized light, direct optical transitions from the valence band to the conduction band can occur only if the electron angular momentum is changed by  $\pm 1$ . These selection rules lead to the spin orientation of photoexcited carriers, with degree and sign of spin orientation depending on the light helicity.

In the present paper we show that in low-dimensional semiconductor systems spin orientation of carriers can be achieved by linearly or even unpolarized light. The effect under consideration is related to reduced symmetry of the low-dimensional structures as compared to bulk compounds and is forbidden in bulk cubic semiconductors. Microscopically, it is caused by asymmetrical photoexcitation of carriers in spin subbands followed by spin precession in an effective magnetic field induced by the Rashba or Dresselhaus spin-orbit coupling.<sup>6</sup>

The effect is most easily conceivable for direct transitions between the heavy-hole valence subband  $hh1$  and the conduction subband  $e1$  in quantum well (QW) structures of the  $C_s$  point symmetry, e.g., in (113)- or (110)-grown QWs based on zinc-blende-lattice compounds. In such structures the spin component along the QW normal  $z$  is coupled with the in-plane electron wave vector. This leads to  $k$ -linear spin-orbit splitting of the energy spectrum as sketched in Fig. 1, where the heavy-hole subband  $hh1$  is split into two spin branches  $\pm 3/2$  shifted relative to each other in the  $k$  space. Due to the selection rules the allowed optical transitions from the valence subband  $hh1$  to the conduction subband  $e1$  are  $|+3/2\rangle \rightarrow |+1/2\rangle$  and  $|-3/2\rangle \rightarrow |-1/2\rangle$ , as illustrated in Fig. 1 by dashed vertical lines. Under excitation with linearly polarized or unpolarized light the rates of both transitions coincide. In the presence of the spin splitting, the optical transitions induced by photons of the fixed energy  $\hbar\omega$  occur in the opposite points of the  $k$  space for the electron spin states  $\pm 1/2$ . Such an asymmetry of photoexcitation results in nonequilibrium distribution where electrons with spin  $+1/2$  propagate mainly in one direction, e.g.,  $k_x > 0$ , and those

with the spin  $-1/2$  propagate in the opposite direction,  $k_x < 0$  (Refs. 7 and 8). This state represents a pure spin current, while the average electron spin is still zero. To obtain a net spin orientation one should take into account spin-orbit coupling in the conduction subband. The spin-orbit coupling can be considered as an effective magnetic field  $\mathbf{B}_k$  acting on electron spins, with the field direction depending on the electron wave vector  $\mathbf{k}$  and its strength being proportional to  $|\mathbf{k}|$  (Refs. 9–11). Spin-dependent asymmetry of photoexcitation considered above is caused by spin-orbit interaction in both the valence and conduction subbands and, in general, does not correspond to the eigenstate of the spin-orbit coupling in the subband  $e1$ . Therefore, electron spins originally directed, according to the selection rules, along or opposite to the QW normal will precess in the effective magnetic field  $\mathbf{B}_k$  (Ref. 12), which has a nonzero in-plane component, as shown in Fig. 1. Electrons with the initial spin  $+1/2$  and wave vector  $k_x > 0$  are affected by effective field with the Larmor frequency  $\Omega_k$ , while carriers with the opposite spin,  $-1/2$ , and opposite wave vector,  $-k_x$ , are affected by field with the frequency  $\Omega_{-k}$ . Since in QW structures the effective magnetic

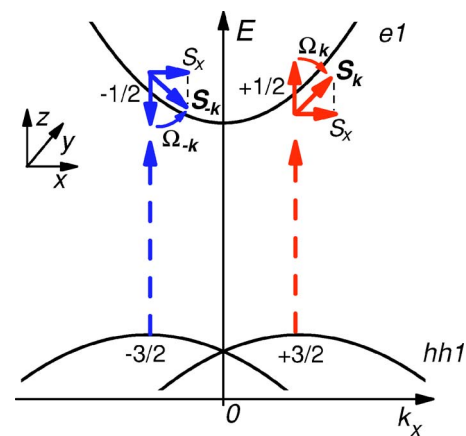


FIG. 1. (Color online) Microscopic origin of the optical orientation of electrons spins by linearly polarized light. Asymmetry of photoexcitation followed by spin precession leads to appearance of the average electron spin. The vertical dashed lines show the possible optical transitions. Spin-orbit coupling in the conduction subband is taken into account here as an effective magnetic field acting on electron spins.

field caused by spin-orbit coupling is linear in the wave vector, then  $\Omega_{-k} = -\Omega_k$  and the rotation axes are opposite for carriers with the initial spins  $\pm 1/2$ . As a result, the precession leads to an appearance of spin component  $S_x > 0$  for carriers with both positive and negative  $k_x$  as shown in Fig. 1. The value of the generated electron spin is determined by the average angle of spin rotation. Thus, interband absorption of unpolarized light in QW structures of low-symmetry results in spin orientation of photoinduced carriers. The spin polarization of electron gas disappears after photoexcitation with the conventional spin-relaxation time.

Generally, direction of the optically oriented electron spins is determined by light polarization and explicit form of spin-orbit interaction in both the conduction and valence bands. The latter is governed by the QW symmetry and can be varied. In QWs based on zinc-blende-type semiconductors and grown along the crystallographic direction  $z \parallel [110]$ , absorption of unpolarized light leads to orientation of electron spins in the QW plane, along  $x \parallel [1\bar{1}0]$ . We assume the relaxation time of the asymmetrical electron distribution  $\tau_e$  to be shorter than the Larmor precession period,  $\Omega_k \tau_e \ll 1$ . Then, the generation rate of the spin component determined by the average angle of electron spin rotation can be estimated as

$$\dot{S}_x = \frac{1}{2} \tau_e \Omega_{y, k_0} \dot{N}, \quad (1)$$

where  $\Omega_y$  is the  $y$  component of the Larmor frequency of the effective magnetic field,  $y \parallel [001]$ ,  $k_0$  is the average wave vector of electrons with the spin projection  $+1/2$  along the QW normal in the moment of photoexcitation, and  $\dot{N}$  is generation rate of electrons in the subband  $e1$ . Taking into account the explicit form of the spin-orbit interaction in (110)-grown QWs of the  $C_s$  point-group symmetry, one derives

$$\dot{S}_x = \gamma_{yx}^{(e1)} \gamma_{zx}^{(hh1)} \frac{\mu_{e,hh} \tau_e}{\hbar^3} \dot{N}. \quad (2)$$

Here  $\gamma_{\alpha\beta}^{(\nu)}$  ( $\nu = e1, hh1$ ) are the constants describing linear in the wave-vector coupling between the  $\alpha$  component of the electron angular momentum and  $\beta$  component of the wave vector in the subbands  $e1$  and  $hh1$ , respectively,  $\alpha$  and  $\beta$  are the Cartesian coordinates,  $\mu_{e,hh} = m_e m_{hh}^{\parallel} / (m_e + m_{hh}^{\parallel})$  is the reduced mass, and  $m_e$  and  $m_{hh}^{\parallel}$  are the electron and heavy-hole effective masses in the QW plane, respectively.

The possibility to achieve optical orientation by linearly polarized light in various low-dimensional structures follows also from symmetry analysis. Phenomenologically, spin generation by light is described by

$$\dot{S}_\alpha = I \sum_{\beta\gamma} \chi_{\alpha\beta\gamma} \frac{e_\beta e_\gamma^* + e_\gamma e_\beta^*}{2} + I \sum_{\beta} \phi_{\alpha\beta} i [e \times e^*]_\beta, \quad (3)$$

where  $\dot{S}_\alpha$  are the generation rates of the spin components,  $I$  is the light intensity,  $e$  is the (complex) unit vector of the light polarization,  $e^*$  is the complex conjugate vector to  $e$ . The pseudotensor  $\phi_{\alpha\beta}$  describes ‘‘conventional’’ optical orientation by circularly polarized light since the vector product  $i[e \times e^*]$  is proportional to the light helicity and vanishes for

linearly polarized light. In contrast, the symmetrized product  $(e_\beta e_\gamma^* + e_\gamma e_\beta^*)/2$  is insensitive to the light helicity for elliptically polarized radiation and reaches maximum for linear polarization. Thus, the third-rank tensor  $\chi_{\alpha\beta\gamma}$  symmetrical in the last two indices,  $\chi_{\alpha\beta\gamma} = \chi_{\alpha\gamma\beta}$ , describes spin orientation by linearly polarized light. In what follows we consider this effect and assume the polarization vector  $e$  to be real.

Symmetry analysis shows that in zinc-blende- or diamond-type bulk crystals,  $T_d$  and  $O_h$  point groups, respectively, all components of  $\chi_{\alpha\beta\gamma}$  vanish, and optical orientation of electron and hole spins can be achieved by circularly polarized light only. In contrast, in low-dimensional systems grown on the basis of cubic semiconductors, nonzero components of  $\chi_{\alpha\beta\gamma}$  do exist, allowing for spin orientation by light of zero helicity. In particular, in QWs of the  $C_s$  symmetry the tensor  $\chi_{\alpha\beta\gamma}$  contains eight independent constants, and spin orientation can be achieved even under excitation with unpolarized light as was demonstrated above.

In (001)-grown QWs spin orientation cannot be achieved by unpolarized light, but is allowed under excitation with linearly polarized light. Asymmetrical (001)-grown structures, such as single heterojunctions or QWs with nonequivalent normal and inverted interfaces, belong to the  $C_{2v}$  point-group symmetry, and optical orientation by linearly polarized light is described here by three independent constants  $A$ ,  $B$ , and  $C$  as follows:

$$\dot{S}_{z'} = A e_{x'} e_{y'}, \quad \dot{S}_{x'} = B e_{y'} e_{z'}, \quad \dot{S}_{y'} = C e_{x'} e_{z'}, \quad (4)$$

where  $z' \parallel [001]$  is the QW normal,  $x' \parallel [1\bar{1}0]$ , and  $y' \parallel [110]$ . One can see that excitation with linearly polarized light under normal incidence may result in orientation of electron spins along the QW normal, with the sign and magnitude depending on the light polarization. The point-group symmetry of (001)-grown QWs with equivalent interfaces is enhanced to  $D_{2d}$ , which allows only one linearly independent constant:  $A=0$ ,  $B=-C$ . Particularly, it follows that in such structures excitation with linearly polarized light in the geometry of normal incidence does not lead to spin orientation. In the other limiting case, when the spin-orbit coupling is determined only by the structure inversion asymmetry unrelated to the crystal lattice, as it can happen in QWs grown of centrosymmetrical semiconductor compounds like SiGe, the symmetry of the structure is effectively increased to  $C_{\infty v}$  and the relations  $A=0$ ,  $B=-C$  retain. Thus, generation of electron spins along the QW normal is possible in asymmetrical (001)-grown QWs, but vanishes for symmetrical structures of the  $D_{2d}$  point group as well as for uniaxial structures of the  $C_{\infty v}$  symmetry.

A consistent theory of the spin orientation by linearly polarized light is conveniently developed by using the spin-density-matrix technique. The dynamics of the density matrix  $\rho$  of photoexcited electrons in the subband  $e1$  is described by the equation<sup>1</sup>

$$\frac{\partial \rho}{\partial t} + \frac{\rho}{\tau_0} + \frac{i}{\hbar} [H_{so}^{(e1)}, \rho] = G + S_I \rho. \quad (5)$$

Here  $\tau_0$  is the lifetime of photoelectrons,  $H_{so}^{(e1)}$  is the spin-orbit contribution to the Hamiltonian,

$$H_{so}^{(e1)} = \frac{\hbar}{2} (\mathbf{\Omega}_k^{(e1)} \cdot \boldsymbol{\sigma}), \quad (6)$$

$\mathbf{\Omega}_k^{(e1)}$  is the Larmor frequency of the spin-orbit coupling-induced effective magnetic field,  $\boldsymbol{\sigma}$  is the vector composed of the Pauli matrices  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_z$ ,  $G$  is the matrix of electron photogeneration, and  $S_I \rho$  is the collision integral that describes electron scattering by phonons, static defects, charge carriers, etc., leading to equilibration. It is convenient to expand the density matrix  $\rho$  and the matrix of photogeneration  $G$  into diagonal and spin components as follows:

$$\rho = f_0 I + (\mathbf{S}_k \cdot \boldsymbol{\sigma}),$$

$$G = g_0 I + (\mathbf{g}_k \cdot \boldsymbol{\sigma}),$$

where  $f_0 = \text{Tr} \rho / 2$  is the distribution function of electrons,  $\mathbf{S}_k = \text{Tr}(\boldsymbol{\sigma} \rho) / 2$  is the total spin of electrons with the wave vector  $\mathbf{k}$ ,  $2g_0$  is the rate of carrier photogeneration,  $\mathbf{g}_k$  is the rate of spin photogeneration into the state with the wave vector  $\mathbf{k}$ , and  $I$  is the  $2 \times 2$  unit matrix. Then, for the steady-state regime, the equation for the spin density  $\mathbf{S}_k$  in the relaxation-time approximation and neglecting spin-flip scattering has the form

$$\frac{\mathbf{S}_k}{\tau_0} + [\mathbf{S}_k \times \mathbf{\Omega}_k^{(e1)}] = \mathbf{g}_k - \frac{\mathbf{S}_k - \bar{\mathbf{S}}_k}{\tau_e}, \quad (7)$$

where  $\bar{\mathbf{S}}_k$  is  $\mathbf{S}_k$  averaged over directions of the wave vector  $\mathbf{k}$ ,  $\tau_e$  is the isotropization time of the spin density  $\mathbf{S}_k$ . In the case of elastic scattering by static defects in two-dimensional structures, the time  $\tau_e$  coincides with the conventional momentum relaxation time that governs the electron mobility. However, we note that electron-electron collisions between particles of opposite spins, which do not affect the mobility, can contribute to relaxation of the asymmetrical spin-dependent distribution and decrease the time  $\tau_e$ , as it happens, e.g., in spin relaxation.<sup>13</sup> Assuming the value  $\tau_e \mathbf{\Omega}_k^{(e1)}$  to be a small parameter, the solution of Eq. (7) for the spin density  $\bar{\mathbf{S}}_k$  to the second order in  $\mathbf{\Omega}_k^{(e1)}$  has the form

$$\frac{\bar{\mathbf{S}}_k}{\tau_0} + \overline{\tau_e [\mathbf{\Omega}_k^{(e1)} \times (\bar{\mathbf{S}}_k \times \mathbf{\Omega}_k^{(e1)})]} = \bar{\mathbf{g}}_k + \tau_e \overline{[\mathbf{\Omega}_k^{(e1)} \times \mathbf{g}_k]}, \quad (8)$$

where the overline means averaging over directions of the wave vector. The first term in the left-hand side of Eq. (8) describes disappearance of the total electron spin due to recombination. The second term in the left-hand side is responsible for the D'yakonov-Perel' spin-relaxation mechanism.<sup>9,10</sup> The right-hand side of Eq. (8) describes orientation of electron spins. The first term is responsible for "conventional" optical orientation by circularly polarized light, while the second term describes spin generation caused by asymmetric photoexcitation  $\mathbf{g}_k$  followed by spin precession in effective magnetic field with the Larmor frequency  $\mathbf{\Omega}_k$ . Under illumination with linearly polarized or unpolarized light  $\bar{\mathbf{g}}_k$  is zero, and the spin generation is given by the second term. Then, the total spin generation rate in the subband  $e1$  has the form

$$\dot{\mathbf{S}} = \sum_k \tau_e [\mathbf{\Omega}_k^{(e1)} \times \mathbf{g}_k]. \quad (9)$$

As an example, let us consider optical orientation of electron spins in (001)-grown QWs under normal incidence of linearly polarized light. In contrast to the energy spectrum in low-symmetry structures sketched in Fig. 1, in (001) QWs the  $\mathbf{k}$ -linear spin splitting of the  $hh1$  valence subband is depressed and here, for the sake of simplicity, we consider optical transitions between the light-hole subband  $lh1$  and the conduction subband  $e1$ . Calculations show that in this particular case the dependence of the photogeneration matrix components on the polarization vector  $\mathbf{e}$  to the first order in the spin-orbit interaction has the form

$$\mathbf{g}_k = [\mathbf{\Omega}_k^{(e1)} + 2\mathbf{e}(\mathbf{\Omega}_k^{(lh1)} \cdot \mathbf{e}) - \mathbf{\Omega}_k^{(lh1)}] \frac{\hbar}{2} \frac{\partial g_0}{\partial \varepsilon_k},$$

$$g_0 = \frac{\pi}{3\hbar} \left( \frac{eA}{cm_0} \right)^2 |P_{cv}|^2 \delta(E_{e1, lh1} + \varepsilon_k - \hbar\omega). \quad (10)$$

Here  $e$  is the electron charge,  $A$  is the amplitude of the vector potential of the light wave,  $c$  is the light velocity,  $m_0$  is the free-electron mass,  $P_{cv} = \langle S | \hat{p}_z | Z \rangle$  is the interband matrix element of the momentum operator,  $E_{e1, lh1}$  is the energy gap between the subbands  $lh1$  and  $e1$ ,  $\varepsilon_k = \hbar^2 k^2 / 2\mu_{e, lh}$ , and  $\mu_{e, lh} = m_e m_{lh}^{\parallel} / (m_e + m_{lh}^{\parallel})$  is the reduced mass for the in-plane motion.

In (001)-grown structures the vectors  $\mathbf{\Omega}_k^{(v)}$  have the form

$$\mathbf{\Omega}_k^{(v)} = \frac{2}{\hbar} (\gamma_{x'y'}^{(v)} k_{y'}, \gamma_{y'x'}^{(v)} k_{x'}, 0),$$

where  $\nu = e1, lh1$  is the subband index. Then, substituting Eq. (10) into Eq. (9), one derives the spin generation rate in the subband  $e1$ ,

$$\dot{S}_z' = 2e_{x'} e_{y'} (\gamma_{y'x'}^{(e1)} \gamma_{y'y'}^{(lh1)} - \gamma_{x'y'}^{(e1)} \gamma_{x'y'}^{(lh1)}) \frac{\mu_{e, lh} \tau_e}{\hbar^3} \dot{N}. \quad (11)$$

Optical orientation of electron spins by linearly polarized light can be observed and studied with a conventional technique for the detection of spin orientation, e.g., by analyzing circular polarization of luminescence under electron-hole radiative recombination. Moreover, the dependence of  $\dot{S}_z'$  on polarization of the incident light given by Eq. (11) allows one to separate the effect under study from possible experimental background noise. Indeed, the spin generation  $\dot{S}_z'$  is of opposite sign for the exciting light polarized along the  $[100]$  and  $[010]$  crystallographic axes and vanishes for the light polarized along the  $[1\bar{1}0]$  or  $[110]$  axes. Generally, the dependence of the spin orientation on the light polarization is given by  $\dot{S}_z' \propto 2e_{x'} e_{y'} = \sin 2\varphi$ , where  $\varphi$  is the angle between the light polarization plane and the  $[1\bar{1}0]$  axis.

The spin generation rate given by Eq. (11) is proportional to constants of the spin-orbit coupling in both  $e1$  and  $lh1$  subbands and vanishes if the product  $\gamma_{y'x'}^{(e1)} \gamma_{y'y'}^{(lh1)}$  equals to  $\gamma_{x'y'}^{(e1)} \gamma_{x'y'}^{(lh1)}$ . The appearance of the  $\mathbf{k}$ -linear terms is connected with the reduction of the system symmetry as compared to

bulk materials. In (001)-grown QWs based on zinc-blende-lattice semiconductors, there are two types of the  $\mathbf{k}$ -linear contributions to the effective Hamiltonians of electron and light-hole subbands.<sup>6,11</sup> The contributions can originate from the lack of an inversion center in the bulk compositional semiconductors and/or from anisotropy of chemical bonds at the interfaces (so-called Dresselhaus term),<sup>10</sup> and can be induced by the heterostructure asymmetry unrelated to the crystal lattice (Rashba term).<sup>14</sup> The constants describing  $\mathbf{k}$ -linear spin splitting in the subbands  $e1$  and  $lh1$  are related to the corresponding Dresselhaus and Rashba constants by

$$\begin{aligned}\gamma_{x'y'}^{(\nu)} &= \gamma_D^{(\nu)} + \gamma_R^{(\nu)}, \\ \gamma_{y'x'}^{(\nu)} &= \gamma_D^{(\nu)} - \gamma_R^{(\nu)}.\end{aligned}\quad (12)$$

In symmetrical (001)-grown QWs, the spin-orbit coupling is given by the Dresselhaus term only, while the Rashba term vanishes. In this case the constants  $\gamma_{x'y'}^{(\nu)}$  and  $\gamma_{y'x'}^{(\nu)}$  are equal and, hence, the expression in the parenthesis in Eq. (11) is zero and the spin orientation does not occur. In the other limiting case, if the Rashba coupling dominates and the Dresselhaus term is negligible, the constants are related by  $\gamma_{x'y'}^{(\nu)} = -\gamma_{y'x'}^{(\nu)}$ , and the effect vanishes as well. Thus, only in QWs with both the Rashba and the Dresselhaus spin-orbit couplings can one induce orientation of electron spins by normally incident linearly polarized light. This result is in

full agreement with the symmetry analysis presented above. The spin orientation along the QW normal by linearly polarized light is possible for asymmetrical (001)-grown QWs, but vanishes for symmetrical structures of the  $D_{2d}$  class as well as for uniaxial structures of the  $C_{\infty v}$  symmetry.

The constants of spin-orbit coupling and the relaxation time can be estimated as  $\gamma/\hbar \sim 10^5$  cm/s,  $\tau_e \sim 10^{-11}$  s. Then, an estimation for electron spin generated under absorption of one photon following Eq. (11) gives  $\dot{S}/\dot{N} \sim 10^{-2}$  (or 1%).

Spin orientation of carriers, caused by asymmetrical photoexcitation followed by spin precession in the effective magnetic field, can be achieved not only under interband optical transitions, but also under intersubband and intrasubband (Drude-like) photoexcitation in QW structures. In the latter case it can be considered as a nonlinear effect of generation of spin polarization by ac electric field.

It should be noted that circular polarization of luminescence under excitation with linearly polarized light in zero magnetic field was observed under study of excitons localized on anisotropic islands in QWs (Ref. 15). This effect is caused by optical alignment of exciton dipoles followed by dipole oscillations in anisotropic media and, generally speaking, can be observed in spinless systems.

The author acknowledges helpful discussions with E.L. Ivchenko. This work was supported by the RFBR, programs of the RAS and St. Petersburg government, and Foundation “Dynasty”—ICFPM.

<sup>1</sup>*Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (Elsevier Science, Amsterdam, 1984).

<sup>2</sup>E. L. Ivchenko and S. A. Tarasenko, Zh. Eksp. Teor. Fiz. **126**, 426 (2004) [JETP **99**, 379 (2004)].

<sup>3</sup>S. Pfalz, R. Winkler, T. Nowitzki, D. Reuter, A. D. Wieck, D. Hagele, and M. Oestreich, Phys. Rev. B **71**, 165305 (2005).

<sup>4</sup>H. Sanada, S. Matsuzaka, K. Morita, C. Y. Hu, Y. Ohno, and H. Ohno, Phys. Rev. Lett. **94**, 097601 (2005).

<sup>5</sup>P.-F. Braun, X. Marie, L. Lombez, B. Urbaszek, T. Amand, P. Renucci, V. K. Kalevich, K. V. Kavokin, O. Krebs, P. Voisin, and Y. Masumoto, Phys. Rev. Lett. **94**, 116601 (2005).

<sup>6</sup>S. D. Ganichev, V. V. Bel'kov, L. E. Golub, E. L. Ivchenko, Petra Schneider, S. Giglberger, J. Eroms, J. De Boeck, G. Borghs, W. Wegscheider, D. Weiss, and W. Prettl, Phys. Rev. Lett. **92**, 256601 (2004).

<sup>7</sup>S. A. Tarasenko and E. L. Ivchenko, Pis'ma Zh. Eksp. Teor. Fiz. **81**, 292 (2005) [JETP Lett. **81**, 231 (2005)].

<sup>8</sup>E. Ya. Sherman, A. Najmaie, and J. E. Sipe, Appl. Phys. Lett. **86**, 122103 (2005).

<sup>9</sup>M. I. D'yakonov and V. I. Perel', Fiz. Tverd. Tela (Leningrad) **13**, 3581 (1971) [Sov. Phys. Solid State **13**, 3023 (1971)].

<sup>10</sup>M. I. D'yakonov and V. Yu. Kachorovskii, Fiz. Tekh. Poluprovodn. (S.-Peterburg) **20**, 178 (1986) [Sov. Phys. Semicond. **20**, 110 (1986)].

<sup>11</sup>N. S. Averkiev, L. E. Golub, and M. Willander, J. Phys.: Condens. Matter **14**, R271 (2002).

<sup>12</sup>V. K. Kalevich, V. L. Korenev, and I. A. Merkulov, Solid State Commun. **91**, 669 (1994).

<sup>13</sup>M. M. Glazov and E. L. Ivchenko, Pis'ma Zh. Eksp. Teor. Fiz. **75**, 476 (2002) [JETP Lett. **75**, 403 (2002)].

<sup>14</sup>Yu. A. Bychkov and É. I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 66 (1984) [JETP Lett. **39**, 78 (1984)].

<sup>15</sup>W. A. J. A. van der Poel, A. L. G. J. Severens, and C. T. Foxon, Opt. Commun. **76**, 116 (1990).