Interface states in two-dimensional electron systems with spin–orbital interaction

Aleksei A Sukhanov and Vladimir A Sablikov

V A Kotel’nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Fryazino, Moscow District, 141190, Russia

Received 20 April 2011, in final form 27 July 2011
Published 15 September 2011
Online at stacks.iop.org/JPhysCM/23/395601

Abstract
Interface states at a boundary between regions with different spin–orbit interactions (SOIs) in two-dimensional (2D) electron systems are investigated within the one-band effective mass method with generalized boundary conditions for envelope functions. We have found that the interface states unexpectedly exist even if the effective interface potential equals zero. Depending on the system parameters, the energy of these states can lie in either or both forbidden and conduction bands of bulk states. The interface states have chiral spin texture similar to that of the edge states in 2D topological insulators. However, their energy spectrum is more sensitive to the interfacial potential, the largest effect being produced by the spin-dependent component of the interfacial potential. We have also studied the size quantization of the interface states in a strip of 2D electron gas with SOI and found an unusual (non-monotonic) dependence of the quantization energy on the strip width.

1. Introduction
Spin–orbit interaction (SOI) produces plenty of fascinating effects in solids which provide broad possibilities for spin current generation and spin manipulation [1]. A noteworthy feature of these effects is that in many cases the SOI acting in the bulk of the sample gives rise to effects which manifest themselves near the boundaries and interfaces with other media. It is enough to mention the following phenomena: (i) the spin Hall effect [2–6], where the spin current produced by an electric current gives rise to spin accumulation at side boundaries; (ii) the anomalous Hall effect [7], where a transverse voltage is generated by electrical current in spin polarized medium in the absence of external magnetic field; (iii) the equilibrium edge spin currents in two-dimensional (2D) systems [8] and edge spin accumulation [9, 10]. The importance of the boundary effects has motivated us to study electronic states appearing at the heterointerfaces in the presence of SOIs.

The interface states in the systems without SOIs have been widely investigated using different approaches such as the envelope-function method, and tight-binding and first-principle calculations [11–13]. However, in the presence of SOIs the interface states are not well studied yet, though this issue is now attracting growing interest stimulated by the rapid progress in the studies of topological insulators. Topological insulators are considered to be a new state of solids with inverted conduction and valence bands and strong SOI [14]. The electron spectrum of topological insulators is characterized by the presence of edge or surface gapless states lying in the energy gap of bulk states. An essential property of the topological states is their chiral spin texture, due to which these states are protected against the scattering and robust to the variation of system parameters and boundary conditions.

The present paper aims to study the interface states in 2D electron systems with heterogeneous SOI, such as a contact of 2D regions with SOIs of different kinds or strengths. Specifically, we consider contacts of regions with the Rashba and Dresselhaus SOIs and contacts of 2D regions with SOI and the normal 2D electron gas without SOI. Interface states are studied within an envelope-function approach using generalized boundary conditions and an effective interface potential. We restrict ourselves by adopting a one-band model which is commonly used for 2D electron gas with SOI, in
contrast to the case of topological insulators where at least two bands are to be taken into account to describe the edge states. Nevertheless, we find that in this system, interface states exist which are similar to the edge states in 2D topological insulators as regards chiral spin texture, but they are more sensitive to boundary conditions.

Depending on the parameters (such as the ratio of effective masses in adjacent regions and the band-bottom offset at the interface) the energy of these states can lie either in the forbidden band or in the conduction band for bulk states or in both bands. An interesting result is that the interface states exist even if the interface potential equals zero. Having analyzed conditions under which the interface states exist, we conclude that in 2D systems with heterogeneous SOIs there are interface states that appear due to the bulk properties.

The dependence of the interface-state spectra on the parameters of the effective interfacial potential is studied within a model in which the potential contains two components: a spin-independent component and a component arising from the SOI at the interface. The first component is shown to produce an energy shift of the spin-split dispersion curves, while the SOI component considerably changes the dispersion-curve form and the spin polarization of the states.

We study also the interface states in a 2D strip of finite width and find that the spatial overlap between the interface states of opposite edges of the strip essentially affects the spectrum, in addition to the usual size quantization effect. As a consequence of this effect the interface-state spectrum splits into two bands, the bottom of the lower band changing non-monotonically with the strip width.

The paper is organized as follows. In section 2 the statement of the problem and basic equations are presented. In section 3 we consider in detail the interface states at the boundary between a region with the SOI and a normal electron gas without the SOI. Section 4 presents the spectra of the interface state at the contact of regions with SOIs of different kinds (Rashba and Dresselhaus SOIs). In section 5 the interface states in a strip are studied. We end with conclusions.

2. Approaches and basic equations

Consider a 2D electron system with a sharp heterointerface between two uniform regions with different SOIs. In each region the Hamiltonian for the one-band envelope function $\Psi$ is

$$H_i = \frac{p^2}{2m_i} + U_i + H_{R,D}^{(i)}$$

where $i = 1, 2$ is the index of adjacent regions, $m_i$ is the effective mass, $U_i$ is a potential energy, $H_{R,D}^{(i)}$ is the Hamiltonian for the Rashba (R) and Dresselhaus (D) SOIs:

$$H_{R}^{(i)} = \frac{\alpha_i}{\hbar} (p_x \sigma_x - p_y \sigma_y), \quad H_{D}^{(i)} = \frac{\beta_i}{\hbar} (p_y \sigma_y - p_x \sigma_x),$$

$\sigma_x$ and $\sigma_y$ are the Pauli matrices, and $\alpha_i$ and $\beta_i$ are SOI strengths.

Boundary conditions for the envelope spinor functions $\Psi^{(i)}$ at the contact ($x = 0$) are expressed via the transfer matrix used in the effective mass method [15, 16]:

$$\begin{pmatrix} \Psi^{(2)}(0+) \\ -i \tau_y \Psi^{(2)}(0+) \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} \Psi^{(1)}(0-) \\ -i \tau_y \Psi^{(1)}(0-) \end{pmatrix},$$

where matrices $T_{ij}$ are determined by the symmetry of the system and the specific structure of the interface.

The general solution of the Schrödinger equation in the $ith$ region reads

$$\Psi^{(i)}(k_x, k_y) = e^{i k_x y} \sum_{j=1}^{2} \sum_{s} \frac{1}{2} \chi^{(i)}_{j,s}(E) e^{i k_{j,s} x},$$

where $k_x$ is the tangential wavevector, $k_{j,s}$ is the $x$ component of the wavevector, defined by a characteristic equation of the Hamiltonian (1), $s$ stands for the spin index, $j$ numbers the solutions of the characteristic equation, and $\chi^{(i)}_{j,s}$ is the spin function.

Generally there is a set of four wavevectors $k_{j,s}^{(i)}$. For the SOI region they were described in detail in [17–19]. A short resume is as follows. The wavevectors $k_{j,s}^{(i)}$ are complex functions of the energy $E$ and the tangential momentum $k_y$. Two of them correspond to the states propagating or decreasing along the $x$ axis; the other two relate to the states propagating or decreasing in the opposite direction. In the energy range $E < U_i - E_{SO}$, all $k_{j,s}^{(i)}$ contain both real and imaginary parts which describe decaying and oscillating states; $E_{SO}$ is the characteristic energy of the SOI: $E_{SO} = m\alpha^2/(2\hbar^2)$ for the Rashba SOI and $E_{SO} = m\beta^2/(2\hbar^2)$ for the Dresselhaus SOI. When $E > U_i - E_{SO}$, the wavevectors $k_{j,s}^{(i)}$ are either purely real or purely imaginary depending on the relation between $E$ and $k_y$.

To clarify whether the interface states exist near the boundary $x = 0$ one needs to find the solutions satisfying the boundary conditions (3) and vanishing at infinity ($x \to \pm \infty$). Dropping the terms which do not vanish at infinity in equation (4), we arrive at a system of homogeneous equations from equation (3). The zeros of its determinant give equations for the interface-state spectrum.

The results obtained in such a way are very cumbersome since the $4 \times 4$ matrix $T$ contains too many elements in spite of the restrictions imposed by the time reversal symmetry and the Hermitian character of the matrix being taken into account. To simplify the problem we use hereafter the following model Hamiltonian of the interface:

$$H_0 = v_0 \delta(x) + \frac{\gamma}{\hbar} p_x \sigma_x \delta(x),$$

which is widely used to describe the Tamm-like surface states at heterointerfaces within the envelope-function approach [12, 13, 11].

This Hamiltonian arises naturally using the $k \cdot p$ approximation, where the crystal potential step at the interface is treated perturbatively [13] or is introduced phenomenologically [12]. Here the first term is a spin-independent effective potential at the interface. The second
In the case of the Dresselhaus SOI the results are similar. The RSOI region is located at \( x < 0 \) and the N region lies at \( x > 0 \). Let the potential energy in the SOI region be \( U_{so} = 0 \) and in the N region be \( U_N = -U \). The energy diagram is depicted in figure 1(a).

In the Rashba SOI region the wavefunction is

\[
\Psi^{(r)} = e^{ikx} \sum_{s=\pm} A_s \chi_s(k) e^{i\kappa_s x}, \tag{8}
\]

where \( \kappa_s = \kappa_1 + s\kappa_2 \).

\[
\kappa_{1,2} = \frac{1}{\sqrt{2}} \sqrt{-\zeta + k_d^2 - 2k_{so}^2 \pm \sqrt{(\zeta - k_d^2)^2 - 4k_{so}^2 k_0^2}}, \tag{9}
\]

\[
\chi_s = \frac{2k_{so}(k_y + k_x)}{\zeta - k_d^2 + k_0^2}, \tag{10}
\]

\[
\zeta = 2m_{so}E/h^2, \quad k_{so} = m_{so}/h^2, \quad \text{and} \quad m_{so} \quad \text{is the effective mass of electrons in the SOI region.}
\]

In the N region the wavefunction is

\[
\Psi^{(N)} = e^{ik_N y} \begin{bmatrix} t_1 & 1 \\ 0 & t_2 \end{bmatrix} e^{-g x}, \tag{11}
\]

where \( g = \sqrt{k_d^2 - (\zeta + u)/\mu}, \quad u = 2m_{so}U/h^2, \quad \mu = m_{so}/m_N, \)

\( m_N \) being the effective mass in the N region.

3. Interface states in the SOI/N contact

Consider a contact of the SOI region and normal 2D electron gas. To be specific, suppose that the SOI is of Rashba type

\[
[(\kappa_1 + \mu g + \bar{v}_0)^2 - \kappa_2^2 + \bar{v}_0^2 - (\bar{v} k_y)^2](\chi_+ - \chi_-) - 2\bar{v} k_x k_2(\chi_+ + \chi_-) + 2k_{so} k_2(1 + \chi_+ + \chi_-) = 0, \tag{12}
\]
where \( \bar{v}_0 = 2v_0 m_0/\hbar^2 \) and \( \bar{\gamma} = 2\gamma m_0/\hbar^2 \). In equation (12), \( g \) and \( k_{1,2} \) are the functions of \( \zeta \) and \( k_r \), defined such that

\[
\text{Re}g(\zeta, k_r) > 0, \quad \text{Re}k_{1,2}(\zeta, k_r) > 0.
\]

Equations (13) are additional conditions to equation (12).

Taking into account the explicit dependences of \( k_1, k_2, g \) and \( \chi_0 \) on \( \zeta \) and \( k_r \), (given by equations (9), (10) and (11)) and equation (12) we arrive at the interface-state spectrum:

\[
\zeta = \zeta_{ES}(k_r).
\]

This equation is rather cumbersome in the full form. To analyze it we first consider a simple case where the interface Hamiltonian (5) is absent. Assuming that \( \nu_0 = 0 \) and \( \gamma = 0 \), equation (12) is simplified to

\[
(k_1 + \mu g)^2 - k_r^2 - k_{so}^2 = 0.
\]

This equation describes the interface states which appear due to the SOI in the bulk. The analysis of equation (14) shows that the interface states in the forbidden band exist only if \( \mu < 1 \) and \( m_{so} < m_N \), and the potential of the N region is higher than \(-1.25E_{so}\). The interface-state spectra for a variety of values of \( \mu \) and \( U = E_{so} \) are presented in figure 1(b). All dispersion curves lie above the curve

\[
E_0(k_r) = \frac{\hbar^2}{2m_{so}} \left( k_r^2 - |k_{so}|\sqrt{k_r^2 + 4k_{so}^2} \right),
\]

which corresponds to the limiting case \( \mu \to 0 \). It is seen that the interface states exist below the conduction band bottom in the SOI region in the energy interval \(-1.25E_{so} \leq E \leq -E_{so}\).

At a given energy there are two pairs of interface states with different signs of the wavevector \( k_r \) and the group velocity.

The interface states exist also in the energy region above the conduction band bottom of the bulk states, \( E > \min[-E_{so}, -U] \). They form here two branches with \( k_r < 0 \) and \( k_r > 0 \). The shape of the dispersion curve in the conduction band depends on the potential step height \( U \) and the effective mass ratio \( \mu \). There are two kinds of dispersion curves demonstrated in figure 2.

Figure 2(a) shows the case where the dispersion curve in the conduction band continues the dispersion curve from the forbidden band up to the point of intersection with the boundary of the bulk-state continuum (figure 2(a)). At this point \( \text{Re}g = 0 \).

In figure 2(b) the other case is demonstrated, where the interface states in the forbidden band are absent, but in the conduction band the interface states exist. Their spectrum is presented by two curve segments arranged symmetrically in regions \( k_r < 0 \) and \( k_r > 0 \), as shown in figure 2(b). These states exist in the energy interval \( E_{cr1} < E < E_{cr2} \), with \( E_{cr1,2} \) being correspondingly the energies at which the interface-state spectrum intersects the boundaries of the bulk-state continuum in the N and SOI regions. An equation describing this spectrum is easily found in the case where \( \mu = 1 \):

\[
\zeta_{ES} = \left( \frac{U - k_{so}^2}{2k_{so}} \right)^2 - \frac{k_{so}^2 k_r^2}{k_r^2 - ((U - k_{so}^2)/2k_{so})^2},
\]

with additional conditions (equations (13)). The interface states are absent when these conditions are violated. The interface-state spectrum has two branches corresponding to waves propagating in opposite directions. They are shown in figure 2(b) for the potential step \( U = 1.5E_{so} \) at the interface. The interface states occupy a finite energy layer and a finite interval of \( k_r \). The lower and upper edges of these intervals are determined by the intersection points of the interface-state spectrum with the boundaries of the bulk-state continua in the N and SOI regions.

The lower energy \( E_b \) of the interface-state band depends on the potential step \( U \) at the interface. The function \( E_b(U) \) is easy to find from equation (14) and the condition \( g(\zeta, k_r) = 0 \):

\[
E_b = -U + \frac{U^2 - E_{so}^2}{4E_{so}^2}.
\]
The interface-state formation can be interpreted as a result of the lowering of the electron energy near the interface because of the mutual penetration of electrons from one contacting region to another. Electrons penetrating from the N region into the SOI region gain energy since they undergo SOI action. In contrast, the electrons of the SOI region lose energy while penetrating into the N region since they do not feel the SOI there. If $m_{\text{so}} \ll m_{\text{N}}$, the electrons penetrate into the SOI region much more deeply than into the N region. Hence, the gain in the energy is larger than its loss and a state localized near the interface can appear with energy lower than the conduction band bottom.

3.2. The spin texture

The spin texture of the interface states is rigidly connected with the wavevector $k_y$ directed parallel to the boundary. In the case of the Rashba SOI the spin density vector $\vec{S}(x)$ is directed normally to $k_y$, its direction being reversed upon changing the sign of $k_y$. The case of the Dresselhaus SOI is similar, but the spin vector lies in the plane $(y, z)$.

Below we restrict ourselves to the RSOI case and consider the spatial distribution of the spin density components $S_x$ and $S_z$. Typical dependences of the spin density components $S_x(x)$ and $S_z(x)$ and the total spin density $\vec{S}(x)$ on the distance from the boundary are presented in figure 3 for the interface states in the forbidden band whose spectrum is shown in figure 2. At a given energy there are two states with different $k_y$. They are characterized by a qualitatively different dependence of $\vec{S}$ on $x$ in the RSOI region. In the states with lower $k_y$, the spin components $S_x$ and $S_z$ oscillate when decaying into the RSOI region. This means that $\vec{S}$ rotates in the $(x, z)$ plane. In contrast, the spin density in the states with higher $k_y$ decays without oscillations.

Since the spin in the interface states is uniquely connected with the wavevector $k_y$, they transfer a spin current even under the equilibrium conditions, the total spin current of all occupied states being polarized in the $(x, z)$ plane.

3.3. The interface potential effect

Now turn to effects produced by the interface Hamiltonian (5). The effect of the spin-independent component of the interface potential $v_0$ consists in shifting the interface-state energy up (when $v_0 > 0$) or down (when $v_0 < 0$). Specific calculations carried out in the case of $\mu = 0.1$ and $U = E_{\text{so}}$ show that (i) the increase in the repulsive potential leads to an increase in the energy of the interface states and finally results in their disappearance at $v_0 = 0.7 k_{\text{so}}$, (ii) the increase in the attractive potential results in shifting the interface-state energy down at such a rate that the energy doubles when $v_0 = -0.3 k_{\text{so}}$. This shift of the dispersion curves is accompanied by only a small change in their shape because the potential $v_0$ does not depend on $k_y$.

In contrast, the spin-dependent component of the interface potential ($\gamma x\sigma, k_y$ in equation (5)) affects the interface-state spectrum essentially. This effect is demonstrated in figure 4 where the interface-state spectra are presented for a variety of $\gamma$. When $\gamma > 0$, the increase in $\gamma$ results in lowering the energy of the interface states down to the forbidden band, the energy decrease being stronger for larger $|k_y|$. Negative $\gamma$ produces a more complicated effect. When $|\gamma| \ll 1$, the increase in $|\gamma|$ leads to growth of the interface-state energies.

However, in both cases there is a critical value of $|\gamma|$ above which the energy goes unboundedly to $-\infty$ with increasing $|k_y|$. This means that the states are radically restructured and a many-band consideration is required.

The spin-dependent component of the interface potential also changes the spin texture of the interface states. With increasing $\gamma$ the interface states become more localized near the boundary, the $z$ component of the spin density $S_z$ increases and the component $S_x$ decreases.

4. Interface states in an RSOI/DSOI contact

Another 2D system in which we demonstrate the existence of the interface states in the forbidden band is a contact of regions with the Rashba and Dresselhaus SOIs (RSOI/DSOI structure). The interface states are studied by solving
equations (3) and (4) in the same manner as was described above.

In the Rashba region \((x < 0)\) the wavefunction is given by equation (8) with the wavevectors and spin functions defined by equations (9) and (10). The counterparts for the Dresselhaus region \((x > 0)\) are easily obtained from corresponding expressions for the Rashba region via a unitary transformation [17].

The electron wavefunction in the DSOI region is

\[
\Psi^{(D)} = e^{i\kappa y} \sum_{s=\pm 1} B_s \left( \chi_s^{(D)}(\vec{k}) \right) e^{i \kappa_s^{(D)} x},
\]

where \(\kappa_s^{(D)} = \kappa_1^{(D)} + s \kappa_2^{(D)}\),

\[
\kappa_{1,2}^{(D)} = \frac{1}{\sqrt{2}} \left\{ k_y^2 - \frac{\zeta + \mu}{\mu} - 2k_D \right\}^{1/2} \pm \sqrt{\left( \frac{\zeta + \mu}{\mu} - k_y^2 \right) - 4k_D^2 k_y^2},
\]

\[
\chi_s^{(D)} = \frac{-2ik_D(k_y + \kappa_s^{(D)})}{\zeta + \mu - k_y^2 + \kappa_s^{(D)}^2}.
\]

The interface-state spectrum is calculated ignoring the interface potential. The results are presented in figure 5 for two different potential steps at the boundary.

The interface states are seen to exist in the forbidden band even if the effective masses in the contacting regions are equal, in contrast to the case for the SOI/N system. But the energy interval where the interface states are located and a general view of the spectra are quite similar to those shown in figure 2 for the SOI/N structure. The origin of the interface states can be interpreted as a result of the mutual action of the SOIs in the two contacting regions.

The electron and spin densities in the interface states are localized near the boundary at a distance of the order of the characteristic SOI length. It is worth noting that the \(S_x\) component of the spin density is concentrated in the RSOI region whereas the \(S_y\) component is located mainly in the DSOI region (figure 5(b)). The spin direction is reversed when
the sign of $k_y$ is changed. Therefore the interface states are of chiral nature. In addition, the interface states carry a spin current under thermal equilibrium. Under the nonequilibrium conditions appearing when a particle current flows parallel to the boundary, the spin density accumulates in the interface states.

5. Quantization of the interface states in a strip structure, DSOI/RSOI/DSOI

In a strip of electron gas with SOI the interface states exist near both opposed boundaries. In this section we study quantum states in the case where the strip width is of the order of their localization length. Under such conditions two effects are important: the size quantization of the interface states and the overlap between the states located near the opposite sides.

We have considered strip structures of two types: the strip of the 2D electron gas with the Rashba SOI bounded laterally by regions with the Dresselhaus SOI (DSOI/RSOI/DSOI structure) and the RSOI strip bounded by the normal electron gas (N/RSOI/N structure). In the case of strip structures the calculations are more cumbersome than above since the wavefunctions are to be found in three regions, using two boundary conditions of the form of equation (3). We have solved these problems numerically and present below the results only for the DSOI/RSOI/DSOI structure. In the case of the N/RSOI/N structure the results are similar.

The main difference between the spectra of the interface states in the strip structures and in the single RSOI/DSOI contact lies in the splitting of the interface-state band into two subbands with different distributions of the electron density across the strip. This is demonstrated in figure 6 where the energies $E_{b1}$ and $E_{b2}$ of the interface-state band bottoms are drawn as functions of the strip width $w$ in the case where $\alpha = \beta$, $m_R = m_D$, and $U_D = U_R$. In this case the SOI wavevectors in all regions are equal, $k_R = k_D = k_{so}$.

It is interesting that the quantization energy depends on the width in an unusual manner. The lower subband bottom $E_{b1}$ decreases with increasing $w$ until $w k_{so} \lesssim 1.5$. This is trivially explained by the decrease of the kinetic energy. However, $E_{b1}$ unexpectedly grows as $w k_{so} > 1.5$.

To interpret such a behavior of the quantized energy let us take into consideration the fact that the electron density is redistributed across the strip with increasing $w$ as shown in the insets of figure 6. The electron density in the lower subband is redistributed from the center to the edges. As has been discussed above, electrons gain energy near the interface because of the mutual action of the SOIs in the two regions. In the case of the strip, there is an additional energy gain caused by the joint effect of two interfaces. This energy gain decreases with increasing $w$ because the interface states overlap less. It is for that reason that $E_{b1}$ grows with $w$. In the case of the upper subband this effect is much smaller since the electron density in these states is always concentrated closer to the edges.

It is worth noting that this effect results in essential lowering of the interface-state energy down to the forbidden band as compared with the case of a single interface. This unusual behavior of the quantization energy can manifest itself in the formation of localized states in quantum constrictions whose width varies slowly with the longitudinal distance.

6. Concluding remarks

In this paper we have shown that interface states exist at a boundary between regions with different SOIs in 2D electron systems and studied their spectra and spin texture. Depending on the system parameters, the energy of these states can lie either in the forbidden or the conduction band, or in both bands. An unexpected result is that the interface states arise even if the effective potential of the interface equals zero. The interface states are similar to the edge states in 2D topological insulators since they have chiral spin texture and are determined by the bulk properties of materials, such as the SOI strengths and the effective mass ratio.

In view of the interest in the robustness of the topological edge states, the persistence of the interface states found here within a one-band model for variation of the boundary conditions has been explored.

We have studied the effect of the interfacial potential, which has two components: spin-dependent and spin-independent ones. The latter component does not qualitatively affect the interface-state spectrum, while the spin-dependent component changes the states essentially as this potential exceeds a critical value.

The persistence of the interface states for smoothing of the boundary was also investigated. We studied the system in which the SOI strength changes smoothly in the transition layer between the regions with different SOIs and found that the interface states survive if the transition layer width $L$ is small compared to the characteristic length of the SOI.
$L_{k_0} < 1$. With increasing layer width the energy interval where the interface states are located diminishes and finally the states disappear.

Thus, we conclude that the interface states in the system with heterogeneous SOI are less robust than the edge states in 2D topological insulators. In addition, their spectrum contains four states in the forbidden band at a given energy and hence there are more possibilities for scattering.

In realistic systems the SOIs of the Rashba and Dresselhaus types often act simultaneously and therefore it is expedient to explore this situation. When both types of the SOI are present the electron spectrum becomes anisotropic in the wavevector space, giving rise to interesting effects [22]. In particular, in the case where $\alpha = \beta$, the SOI is effectively suppressed for electrons moving along the [110] direction in a zinc-blende crystal. The detailed study of the interface states in 2D systems with both SOIs is beyond the scope of the present publication. Here we restrict ourselves to a brief discussion of results obtained for the contact of the (R + D)SOI region with normal electron gas. The joint action of the Rashba and Dresselhaus SOIs turns out to always reduce the energy depth of the interface states below the bottom of the bulk continuum states, the effects of the Rashba and Dresselhaus SOIs being not completely balanced at any ratio of $\alpha$ and $\beta$. The interface-state energy depends on the orientation of the interface line. The maximum energy depth of the interface states is reached when the boundary is parallel to the [110] direction. For any orientation of the boundary, there is such a ratio of $\alpha$ to $\beta$ at which the interface-state energy intersects the conduction band bottom. In the particular case where $\alpha = \beta$, below the conduction band bottom the interface states are absent.

There is another effect close to that considered in this paper. It consists in the existence of the edge spin currents in 2D systems with heterogeneous SOI. The mechanism of the edge spin currents is caused by the spin-dependent scattering of bulk electrons on the interface [8]. These currents also exist under the equilibrium. The estimations show that the spin current of the interface states studied here is small compared to the scattering spin current if the Fermi energy lies higher than $E_{so}$ above the conduction band bottom. In the opposite case, the interface-state spin current is prevailing, especially when the Fermi level lies in the forbidden band.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (project No 11-02-00337) and the Russian Academy of Sciences (programs ‘Basic research in nanotechnology and nanomaterials’ and ‘Strongly correlated electrons in solids and structures’).

References

[1] Dyakonov M I (ed) 2008 Spin Physics in Semiconductors (Springer Series in Solid-State Sciences vol 157) (Berlin: Springer)
[2] Dyakonov M I and Perel V I 1971 Phys. Lett. A 35 459
[3] Hirsch J E 1999 Phys. Rev. Lett. 83 1834
[4] Murakami S, Nagaosa N and Zhang S C 2003 Science 301 1348
[5] Wunderlich J, Kaestner B, Sinova J and Jungwirth T 2005 Phys. Rev. Lett. 94 047204
[6] Kato Y K, Myers R C, Gossard A C and Awschalom D D 2004 Science 306 1910
[7] Nagaosa N, Sinova J, Onoda S, MacDonald A H and Ong N P 2010 Rev. Mod. Phys. 82 1539
[8] Sablikov V A, Sukhanov A A and Tkach Yu Ya 2008 Phys. Rev. B 78 153302
[9] Usaj G and Balseiro C A 2005 Europhys. Lett. 72 631
[10] Sonin E B 2010 Phys. Rev. B 81 113304
[11] For a review see Foreman B A 2005 Phys. Rev. B 72 165345
[12] Ivchenko E L, Kaminski A Yu and Rüssler U 1996 Phys. Rev. B 54 5852
[13] Takhtamirov E E and Volkov V A 1999 Zh. Eksp. Teor. Fiz. 116 1843
[14] Hasan M Z and Kane C L 2010 Rev. Mod. Phys. 82 3045
[15] Ando T and Mori S 1982 Surf. Sci. 113 124
[16] For a review see Tokatly I V, Tisbizov A G and Gorbatevich A V 2002 Phys. Rev. B 65 165328
[17] Sablikov V A and Tkach Yu Ya 2007 Phys. Rev. B 76 245321
[18] Tkach Yu Ya, Sablikov V A and Sukhanov A A 2009 J. Phys.: Condens. Matter 21 125801
[19] Sukhanov A A, Sablikov V A and Tkach Yu Ya 2009 J. Phys.: Condens. Matter 21 375801
[20] Vasko F T and Kuznetsov A V 1999 Electronic States and Optical Transitions in Semiconductor Heterostructures (New York: Springer)
[21] Ast C R, Henk J, Ernst A, Moreschini L, Falub M C, Pacile D, Bruno P, Kern K and Grioni M 2007 Phys. Rev. Lett. 98 186807
[22] Averkiev N S, Golub L E and Willander M 2002 J. Phys.: Condens. Matter 14 R271