Manifestation of spin-orbit interaction in tunneling between two-dimensional electron layers

I. V. Rozhansky* and N. S. Averkiev
A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia
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An influence of spin-orbit interaction on the tunneling between two two-dimensional electron layers is considered. Particular attention is addressed to the relation between the contribution of Rashba and Dresselhaus types. It is shown that without scattering of the electrons, the tunneling conductance can either exhibit resonances at certain voltage values or be substantially suppressed over the whole voltage range. The dependence of the conductance on voltage turns out to be very sensitive to the relation between Rashba and Dresselhaus contributions even in the absence of magnetic field. The elastic scattering broadens the resonances in the first case and restores the conductance to a larger magnitude in the latter one. These effects open the possibility to determine the parameters of spin-orbit interaction and electron scattering time in tunneling experiments with no necessity of external magnetic field.

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I. INTRODUCTION

Spin-orbit interaction (SOI) plays an important role in the widely studied spin-related effects and spintronic devices. In the latter, it can be either directly utilized to create spatial separation of the spin-polarized charge carriers or indirectly influence the device performance through spin-decoherence time. In two-dimensional (2D) structures, two kinds of SOI are known to be of the most importance, namely, Rashba and Dresselhaus mechanisms. The first one, characterized by parameter α, originates from the structure inversion asymmetry, while the second one characterized by β is due to the bulk inversion asymmetry. Most importantly, both of the contributions reveal themselves when the values of α and β are comparable. In this case, a number of interesting effects occur: The electron energy spectrum becomes strongly anisotropic,[1] the electron spin relaxation rate becomes dependent on the spin orientation in the plane of the quantum well,[2] a magnetic breakdown should be observed in the Shubnikov–de Haas effect.[3] The energy spectra splitting due to SOI can be observed in rather well-developed experiments as that based on Shubnikov–de Haas effect. However, these experiments can hardly tell about the partial contributions of the two mechanisms, leaving the determination of the relation between α and β to be a more challenging task. At the same time, in some important cases spin relaxation time τ_s and spin polarization strongly depend on the $\frac{\alpha}{\beta}$ ratio. In this paper, we consider the tunneling between 2D electron layers, which turns out to be sensitive to the relation between Rashba and Dresselhaus contributions. The specific feature of the tunneling in the system under consideration is that the energy and in-plane momentum conservation put tight restrictions on the tunneling. Without SOI, the tunneling conductance exhibits a delta-function-like maximum at zero bias broadened by elastic scattering in the layers[4] and fluctuations of the layer width.[5] Such a behavior was indeed observed in a number of experiments.[6–8] Spin-orbit interaction splits the electron spectra into two subbands in each layer. Energy and momentum conservation can be fulfilled for the tunneling between opposite subbands of the layers at a finite voltage corresponding to the subbands splitting. However, if the parameters of SOI are equal for the left and right layers, the tunneling remains prohibited due to orthogonality of the appropriate spinor eigenstates. In Ref. 9, it was pointed out that this restriction can also be eliminated if Rashba parameters are different for the two layers. A structure design was proposed[10] where exactly opposite values of the Rashba parameters result from the builtin electric field in the left layer being opposite to that in the right layer. Because the SOI of Rashba type is proportional to the electric field, this would result in $\alpha^R=-\alpha^L$, where α^L and α^R are the Rashba parameters for the left and right layers, respectively. In this case, the peak of the conductance is expected at the voltage U_0 corresponding to the energy of SOI: $eU_0=\pm 2\alpha k_F$, where k_F is the Fermi wave vector. In this paper, we consider arbitrary Rashba and Dresselhaus contributions in the 2D layers and obtain a general expression for dc tunneling current. We show that different relations between Rashba and Dresselhaus contributions correspond to different shapes of current-voltage characteristic. Special attention is focused on particular but the most typical case of both contributions with the same order of magnitude.[11,12] In this case, the structure of the electron eigenstates should even suppress the tunneling at any voltage. At that, the scattering at impurities becomes very important because it restores the features of current-voltage characteristic containing information about SOI parameters. Finally, we show that the parameters α and β can reveal themselves in a tunneling experiment which, unlike other spin-related experiments, requires neither magnetic field nor polarized light.

II. CALCULATIONS

The system under study consists of 2D electron layers separated by a potential barrier (see Fig. 1). We consider zero temperature, only one level of size quantization, and a not too narrow barrier so that the electron wave functions in the left and right layers overlap weakly. Bardeen's tunneling Hamiltonian[4,5,13] can be written as

$$H = H_0^L + H_0^R + H_T, \tag{1}$$

where H_0^L and H_0^R are the partial Hamiltonians for the left and right layers, respectively, and H_T is the tunneling term. Tak-

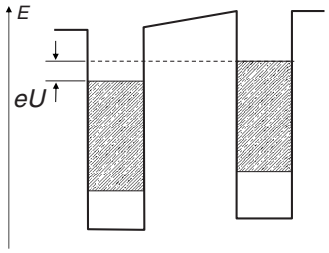

FIG. 1. Energy diagram of two 2D electron layers.

ing account of the elastic scattering and SOI in the layers, these terms have the following form:

$$H_0^l = \sum_{k,\sigma} \varepsilon_k^l c_{k\sigma}^{l+} c_{k\sigma}^l + \sum_{k,k',\sigma} V_{kk'}^l c_{k\sigma}^{l+} c_{k'\sigma}^l + H_{SO}^l,$$

$$H_T = \sum_{k,k',\sigma,\sigma'} T_{kk'\sigma\sigma'} (c_{k\sigma}^{L+} c_{k'\sigma'}^R + c_{k'\sigma'}^{R+} c_{k\sigma}^L), \tag{2}$$

Here, index l is used for the layer designation, $l=R$ for the right layer and $l=L$ for the left layer. k here and further throughout the paper denotes the wave vector parallel to the layer planes, σ is the spin polarization taking the values $\sigma = \pm 1/2$ and ε_k^l is the energy of an electron in the layer l having in-plane wave vector k. It can be expressed as

$$\varepsilon_k^l = \varepsilon + \varepsilon_0^l + \Delta^l, \tag{3}$$

where $\varepsilon = \frac{\hbar^2 k^2}{2m}$, m being the electron's effective mass, ε_0^l is the size quantization energy, and Δ^l is the energy shift due to the external voltage applied to the layer l. We shall also use the value $\Delta^{ll'}$ defined as $\Delta^{ll'} = (\Delta^l - \Delta^{l'}) + (\varepsilon_0^l - \varepsilon_0^{l'})$. The second term in the Hamiltonian [Eq. (2)] $V_{kk'}^l$ is the matrix element of the scattering operator. We consider only elastic scattering. The tunneling constant $T_{kk'\sigma\sigma'}$ in Eq. (2) denotes size quantization level splitting caused by the wave function overlap. By lowercase t, we shall denote the overlap integral itself. Parametrically, $T \sim t\varepsilon_F$, where ε_F is the electron Fermi energy. The term H_{SO}^l describes the spin-orbit part of the Hamiltonian,

$$\hat{H}_{SO}^l = \alpha^l \sum_k (k_y - ik_x) c_{k\sigma}^{l+} c_{k\sigma'}^l + (k_y + ik_x) c_{k\sigma'}^{l+} c_{k,\sigma}^l + \beta^l \sum_k (k_x - ik_y) c_{k\sigma}^{l+} c_{k\sigma'}^l + (k_x + ik_y) c_{k\sigma'}^{l+} c_{k\sigma}^l. \tag{4}$$

The tunneling current is given by[4]

$$I = \frac{ie}{\hbar} T \int dk \, \mathrm{Tr}(\langle \hat{\rho}_{kk'\sigma\sigma'}^{RL} \rangle - \langle \hat{\rho}_{kk'\sigma\sigma'}^{LR} \rangle) \delta_{kk'}, \tag{5}$$

where $\hat{\rho}_{kk'\sigma\sigma'}^{ll'} = c_{k,\sigma}^{l+} c_{k',\sigma'}^{l'}$, $\langle\,\rangle$ denotes the expectation value in the quantum-mechanical sense, δ is the Kronecker symbol, and trace refers to the spin indices. For further calculations, it is convenient to introduce four-dimensional vector operator $\hat{S}_{kk'}^{ll'}$, whose components are given by

$$(\hat{S}_{kk'}^{ll'})_{\nu=0,1,2,3} = \mathrm{Tr}(\sigma_\nu \hat{\rho}_{kk'\sigma\sigma'}^{ll'}),$$

where σ_ν are the Pauli matrices, including identity matrix σ_0. This vector operator fully determines the current. Its time evolution is governed by

$$\frac{d\hat{S}_{kk'}^{ll'}}{dt} = \frac{i}{\hbar}[H, \hat{S}_{kk'}^{ll'}]. \tag{6}$$

In the standard way of reasoning,[14] Eq. (6) turns into

$$(\hat{S}_{kk'}^{ll'} - \hat{S}_{kk'}^{(0)ll'}) w = \frac{i}{\hbar}[H, \hat{S}_{kk'}^{ll'}]. \tag{7}$$

Here, $\hat{S}_{kk'}^{(0)ll'}$ represents the stationary solution of Eq. (6) without interaction (i.e., tunneling and scattering by impurities) and w^{-1} is the time of adiabatic turn-on of the interaction. $\hat{S}_{kk'}^{(0)ll'}$ has the diagonal form

$$\hat{S}_{kk'}^{(0)ll'} = \hat{S}_k^{(0)l} \delta_{kk'} \delta_{ll'}. \tag{8}$$

Here and further, we avoid duplications of the indices, i.e., use l instead of ll and k instead of kk. The calculations performed in a way similar to Ref. 14 bring us to the following system of equations with respect to $\hat{S}_k^{ll'}$:

$$0 = (\Delta^{ll'} + i\hbar w)\hat{S}_k^{ll'} + T(\hat{S}_k^{l'} - \hat{S}_k^l) + \boldsymbol{M}(k)\hat{S}_k^{ll'} - \sum_{k'} \left(\frac{A_{kk'}^l \hat{S}_k^{ll'} - B_{kk'}^{ll'} \hat{S}_{k'}^{ll'}}{\varepsilon' - \varepsilon - \Delta^{ll'} + i\hbar w} + \frac{B_{kk'}^{ll'} \hat{S}_k^{ll'} - A_{kk'}^{l'} \hat{S}_{k'}^{ll'}}{\varepsilon - \varepsilon' - \Delta^{ll'} + i\hbar w} \right), \tag{9}$$

$$i\hbar w(\hat{S}_k^{(0)l} - \hat{S}_k^l) = T(\hat{S}_k^{l'l} - \hat{S}_k^{ll'}) + \boldsymbol{M}(k)\hat{S}_k^l + \sum_{k'} \frac{2i\hbar w A_{kk'}^l (\hat{S}_k^l - \hat{S}_{k'}^{l'})}{(\varepsilon' - \varepsilon)^2 + (\hbar w)^2}, \tag{10}$$

where $\boldsymbol{M}$ is a known matrix, depending on k and parameters of SOI. Here, the quadratic forms of the impurities potential matrix elements are

$$A_{kk'}^l \equiv |V_{k'k}^l|^2,$$

$$B_{kk'}^{ll'} \equiv V_{k'k}^l V_{kk'}^{l'}. \tag{11}$$

As Eqs. (9) and (10) comprise system of linear integral equations, $A_{kk'}^l$ and $B_{kk'}^{ll'}$ enter Eq. (5) linearly and can be themselves averaged over a spatial distribution of the impurities. We assume a short range potential of impurities and introduce $A \equiv \langle A_{kk'}^l \rangle$ and $B \equiv \langle B_{kk'}^{ll'} \rangle$ averaged over their spatial distribution. Here, we took $\langle A^l \rangle = \langle A^{l'} \rangle$ for brevity and omitted the index l. (As for B, the index is omitted because $B_{kk'}^{ll'} = B_{kk'}^{l'l}$.) According to Eq. (11), A denotes inverse electron's scattering time,

$$\frac{1}{\tau} = \frac{2\pi}{\hbar}\nu\langle|V_{kk'}|^2\rangle = \frac{2\pi}{\hbar}\nu A, \tag{12}$$

where ν is the 2D density of states. We note that the averaged correlators A and B have different parametrical dependences on the tunneling transparency t,

$$\frac{B}{A} \sim t^2 \sim T^2. \tag{13}$$

This result holds both for noncorrelated and strongly correlated arrangements of the impurities. Unlike Ref. 10 and according to Eq. (13), we conclude that the correlator B has to be neglected in the calculation of the current within the order of T^2. In the method used here, this result appears quite naturally; however, it can be similarly traced in the diagrammatic technique used in Ref. 10. For the same reason, the tunneling term is to be dropped from Eq. (10). By means of Fourier transformation on energy variable, the system of Eqs. (9) and (10) can be reduced to the system of linear algebraic equations. Finally, $\hat{S}_k^{ll'}$ can be expressed as a function of $\hat{S}_k^{(0)l}$. Finally, the current [Eq. (5)] is expressed through $\langle\hat{\rho}_{k\sigma}^{(0)R}\rangle$ and $\langle\hat{\rho}_{k\sigma}^{(0)L}\rangle$. For the considered case of zero temperature,

$$\langle\rho_{k\sigma}^{(0)l}\rangle = \frac{1}{2W}\theta(\varepsilon_F^l + \Delta^l - \varepsilon - \varepsilon_\sigma),$$

where W is the lateral area of the layers,

$$\varepsilon_\sigma = \pm|\alpha^l(k_x - ik_y) - \beta^l(ik_x - k_y)|.$$

Without loss of generality, we consider the case of identical layers and external voltage applied, as shown in Fig. 1,

$$\varepsilon_0^R = \varepsilon_0^L,$$

$$\Delta^L = -\frac{eU}{2}, \quad \Delta^R = +\frac{eU}{2},$$

$$\Delta^{RL} = -\Delta^{LR} = eU.$$

We obtain the following expression for the current:

$$I = \frac{ie}{2\pi\hbar}T^2\nu\int_0^{2\pi}\int_0^{\infty}(\zeta^L + \zeta^R)\mathrm{Tr}(\rho_\sigma^{(0)R} - \rho_\sigma^{(0)L})d\varepsilon d\varphi, \tag{14}$$

where

$$\zeta^l = \frac{C^l[(C^l)^2 - 2bk^2\sin 2\varphi - gk^2]}{(f + 2d\sin 2\varphi)^2k^4 - 2(C^l)^2(c + 2a\sin 2\varphi)k^2 + (C^l)^4},$$

$$C^l(U) = \Delta^l + i\frac{\hbar}{\tau},$$

$$a = \alpha^L\beta^L + \alpha^R\beta^R,$$

$$b = (\beta^L + \beta^R)(\alpha^L + \alpha^R),$$

$$c = (\beta^L)^2 + (\beta^R)^2 + (\alpha^L)^2 + (\alpha^R)^2,$$

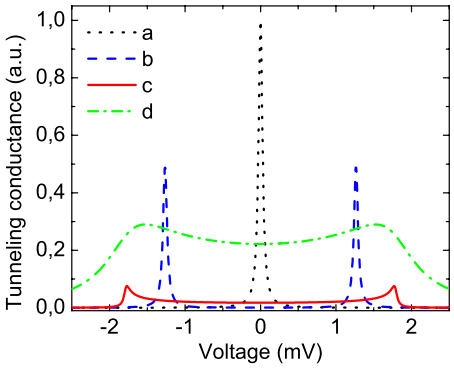

FIG. 2. (Color online) Tunneling conductance. (a) $\varepsilon_F = 10$ meV, $\alpha = \beta = 0$, $\tau = 2\times10^{-11}$ s; (b) same as (a), but $\alpha k_F = 0.6$ meV; (c) same as (b), but $\beta = \alpha$; (d) same as (c), but $\tau = 2\times10^{-12}$ s.

$$d = \alpha^L\beta^L - \alpha^R\beta^R,$$

$$f = (\beta^L)^2 - (\beta^R)^2 + (\alpha^L)^2 - (\alpha^R)^2,$$

$$g = (\beta^L + \beta^R)^2 + (\alpha^L + \alpha^R)^2. \tag{15}$$

Parameters $a-g$ are various combinations of the Rashba and Dresselhaus parameters. Both types of SOI are known to be small in real structures so that $\alpha k_F \ll \varepsilon_F$ and $\beta k_F \ll \varepsilon_F$. We also use the assumptions: $\frac{\varepsilon_F\tau}{\hbar} \gg 1$ and $eU \ll \varepsilon_F$. This allows us to reduce Eq. (14) to

$$I = \frac{ie^2}{2\pi\hbar}T^2\nu WU\int_0^{2\pi}[\zeta^L(\varepsilon_F) + \zeta^R(\varepsilon_F)]d\varphi. \tag{16}$$

The integral over φ in Eq. (16) can be calculated analytically by means of a complex variable integration. The result for arbitrary α^l and β^l is not given here for it is rather cumbersome. Instead, we will discuss most important limit cases and plot a few examples for the arbitrary case.

III. RESULTS AND DISCUSSION

The general expression of Eq. (16) can be simplified in a few particular cases. It appears that the tunneling conductance can exhibit qualitatively different behaviors depending on the relation between Rashba and Dresselhaus contributions. We shall start from the case when SOI is completely absent, then consider situations when one type of SOI, say, Rashba mechanism, dominates, and, finally, turn to the case when both Rashba and Dresselhaus contributions are present and have comparable strengths. The analytical results for each of these cases are illustrated with conductance vs voltage characteristics for the following parameters taken to resemble typical GaAs structures: $\varepsilon_F = 10$ meV and $\alpha^l k_F = 0.6$ meV. The plots shown in Figs. 2(a)–2(c) and 5 were calculated for negligibly small scattering (still not strictly zero to avoid delta peaks in the plots). The plots presented in Figs. 2(d) and 6 were calculated with electron's scattering time being of the order of picosecond. This was proven to be quite achievable in real structures prepared for tunneling experiments.[7]

In the absence of SOI, the tunneling conductance has a Lorentz-type dependence centered at zero voltage.[4,6] The width of the peak corresponds to the electron's scattering time τ. As will be shown below, the same behavior is expected when the parameters of SOI are equal for both layers. In this case, the tunneling current does not possess any footprints of SOI. However, if any of the SOI parameters in the one 2D layer differs from that in the other layer, they immediately affect the dependence of the tunneling conductance on voltage. Moreover, it appears that the particular shape of this dependence is determined not merely by the difference in one SOI parameter (say, Rashba term $\alpha^L \neq \alpha^R$) but also by the absolute values of both Rashba and Dresselhaus parameters even if one of them remains equal for both layers (in our example, $\beta^L = \beta^R$). Therefore, theoretically, it becomes possible to determine the magnitude and, particulary, the relation between both types of SOI from a plain tunneling experiment whenever one manages to obtain electron layers with different values of either type of SOI. The difference in Dresselhaus contributions can be achieved by using different materials for the layers. While this at first seems to be questionable from the technological point of view, the idea of using a solid solution with varied composition does not seem that exotic. Obviously, the difference in Rashba terms seems to be much easier to achieve. The Rashba mechanism originates from the structure inversion asymmetry caused by the builtin electrical field. Thus, if the electric fields are not equal in the two layers, the Rashba parameters α^L and α^R will be different also. A most vivid manifestation of SOI in the tunneling conductance is expected if these parameters are made of the same magnitude but opposite signs. This case corresponds to the electric field directed normally to the layer planes and in opposite directions in the left and right layers. Hypothetically, this will be the case if a charged plane is placed in the middle of the barrier. Such a plane can be created by a delta layer of ionized impurities.[9,10] The experimental realization of this has some uncertainty as such a layer might significantly affect the tunneling barrier. Nevertheless, the doping regions positioned at both outer sides of the system rather than in the barrier can also produce the electrical field having opposite directions for both layers.

Now, we shall turn to the consideration of each of the different possible cases and obtain the analytical expressions for the tunneling current. In each case, the behavior of the conductivity is explained, considering the structure of the electron eigenstates in the layers and with account of the conservation of energy, in-plane momentum, and spin polarization (if accounted for). In fact, with no accounting of the scattering, the results can be obtained in a simpler way, by means of Fermi's golden rule (FGR). This gives an opportunity to verify our general result in the limit of infinite scattering time by comparison with those obtained via FGR calculation. Such a comparison is shown below for the case of equal magnitudes of Rashba and Dresselhaus terms.

A. No spin-orbit interaction

In the absence of SOI ($\alpha^R = \alpha^L = 0$, $\beta^R = \beta^L = 0$) the energy spectrum for each of the layers forms a paraboloid,

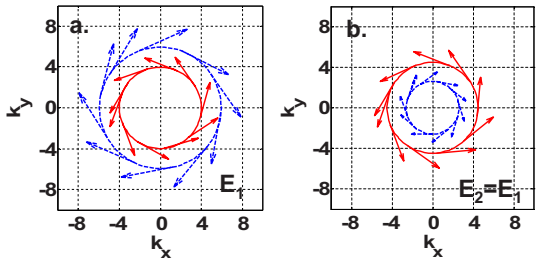

FIG. 3. (Color online) Cross section of electron energy spectra in the left (a) and right (b) layers for the cases $\alpha^L = -\alpha^R$ and $\beta^L = \beta^R = 0$.

$$E^l(k^l) = \varepsilon_0 + \frac{\hbar^2 (k^l)^2}{2m} \pm \frac{eU}{2}. \tag{17}$$

The tunneling requires energy and momentum conservation simultaneously,

$$E^R = E^L,$$

$$k^R = k^L. \tag{18}$$

Both conditions are satisfied only at $U=0$ so that a nonzero external voltage does not produce any current despite the fact that it produces empty states in one layer aligned to the filled states in the other layer (Fig. 1). The momentum conservation restriction in Eq. (18) is weakened if the electrons scatter at the impurities. Accordingly, one should expect a nonzero tunneling current within a finite voltage range in the vicinity of zero. For the considered case, the general formula [Eq. (16)] is simplified radically as all the parameters [Eq. (15)] reduce to zero. Finally, we get the well-known result,[4]

$$I = 2e^2 T^2 \nu W U \frac{\frac{1}{\tau}}{(eU)^2 + \left(\frac{\hbar}{\tau}\right)^2}. \tag{19}$$

The conductance defined as $G(U) = I/U$ has a Lorentz-shaped peak at $U=0$ turning into a delta function at $\tau \to \infty$. This case is shown in Fig. 2(a).

B. Spin-orbit interaction of Rashba type

The spin-orbit interaction gives qualitatively new option for the dc conductance to be finite at nonzero voltage. SOI splits the spectra into two subbands. Now, an electron from the first subband of the left layer can tunnel to a state in a second subband of the right layer. Let us consider a particular case when only Rashba type of SOI interaction exists in the system, its magnitude being the same in both layers, i.e., $|\alpha^R| = |\alpha^L| \equiv \alpha$ and $\beta^R = \beta^L \equiv \beta = 0$. In this case, the spectra splits into two paraboloidlike subbands "inserted" into each other. Figure 3 shows their cross sections for both layers; arrows show spin orientation. By applying a certain external voltage $U_0 = \frac{2\alpha k_F}{e}$, the layers can be shifted on the energy scale in such a way that the cross section of the "outer" subband of the right layer coincides with the "inner" subband

of the left layer (see solid circles in Fig. 3). At that, both conditions [Eq. (18)] are satisfied. However, if the spin is taken into account, the interlayer transition can still remain forbidden. It happens if the appropriate spinor eigenstates involved in the transition are orthogonal. This very case occurs if $\alpha^R=\alpha^L$. Consequently, the conductance behavior remains the same as that without SOI. In contrast, if the Rashba terms are of opposite signs, i.e., $\alpha^R=-\alpha^L$ the spin orientations in the outer subband of the right layer and the inner subband of the left layer are the same, and tunneling is allowed at a finite voltage but forbidden at $U=0$. This situation, pointed out in Refs. 9 and 10, should reveal itself in sharp maxima of the conductance at $U=\pm U_0$, as shown in Fig. 2(b). From this dependence, the value of α can be immediately extracted from the position of the peak. Evaluating Eq. (15) for this case and, further, expression (16), we obtain the following result for the current:

$$I=\frac{2e^2T^2W\nu U\frac{\hbar}{\tau}\left[\delta^2+e^2U^2+\left(\frac{\hbar}{\tau}\right)^2\right]}{\left[(eU-\delta)^2+\left(\frac{\hbar}{\tau}\right)^2\right]\left[(eU+\delta)^2+\left(\frac{\hbar}{\tau}\right)^2\right]}, \quad (20)$$

where $\delta=2\alpha k_F$. The result is in agreement with that derived in Ref. 10, taken for an uncorrelated spatial arrangement of the impurities. As we have already noted, the interlayer correlator B should be neglected because parametrically it has higher order of tunneling overlap integral t than the intralayer correlator A [Eq. (13)]. Therefore, we conclude that the result [Eq. (20)] is valid for an arbitrary degree of correlation in the spatial distribution of the impurities in the system. It is worth noting that the opposite case when only the Dresselhaus type of SOI exists in the system leads to the same results. However, it is less practical to study the case of the different Dresselhaus parameters in the layers because this type of SOI originates from the crystallographic asymmetry and, therefore, cannot be varied if the structure composition is fixed. For this case to be realized, one needs to make the two layers of different materials.

C. Both Rashba and Dresselhaus contributions

The presence of the Dresselhaus term in addition to the Rashba interaction can further modify the tunneling conductance in a nontrivial way. A special case occurs if the magnitude of the Dresselhaus term is comparable to that of the Rashba term. We shall always assume the Dresselhaus contribution to be the same in both layers: $\beta^L=\beta^R\equiv\beta$. Let us add the Dresselhaus contribution to the previously discussed case so that $\alpha^L=-\alpha^R\equiv\alpha$ and $\alpha=\beta$. The corresponding energy spectra and spin orientations are shown in Fig. 4. Note that while the spin orientations in the initial and final states are orthogonal for any transition between the layers, the spinor eigenstates are not, so that the transitions are allowed whenever the momentum and energy conservation requirement [Eq. (18)] is fulfilled. It can also be clearly seen from Fig. 4 that the condition [Eq. (18)], meaning overlap of the cross sections (a) and (b), occurs only at a few points. This is unlike the previously discussed case where the overlapping

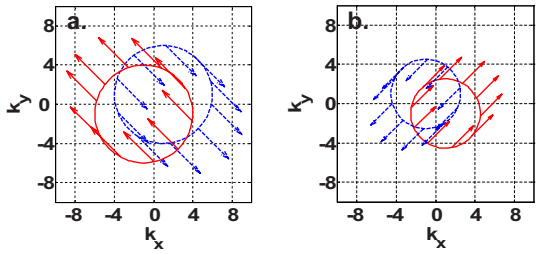

FIG. 4. (Color online) Cross section of electron energy spectra in the left (a) and right (b) layers for the case $\alpha^R=-\alpha^L=\beta$.

occurred within the whole circular cross section shown by solid lines in Fig. 3. One should naturally expect the conductance for the case presently discussed to be substantially lower. Using Eq. (16), we arrive at a rather cumbersome expression for the current,

$$I=eT^2W\nu U\left[\frac{G_-(G_-^2-\delta^2)}{\sqrt{F_-(\delta^4+F_-)}}-\frac{G_+(G_+^2-\delta^2)}{\sqrt{F_+(\delta^4+F_+)}}\right], \quad (21)$$

where

$$G_\pm=eU\pm i\frac{\hbar}{\tau},$$

$$F_\pm=G_\pm^2(G_\pm^2-2\delta^2).$$

Alternatively, for the case of no interaction with impurities, a precise formula for the transition rate between the layers can be obtained by means of Fermi's golden rule. We obtained the following expression for the current:

$$I=\frac{2\pi eT^2W}{\hbar\alpha^2}\left(\sqrt{K+\frac{8m\alpha^2eU}{\hbar^2}}-\sqrt{K-\frac{8m\alpha^2eU}{\hbar^2}}\right), \quad (22)$$

where

$$K=2\delta^2-e^2U^2+\frac{16m^2\alpha^4}{\hbar^4}.$$

Comparing the results obtained from Eqs. (21) and (22) is an additional test for the correctness of Eq. (21). Both dependencies are presented in Fig. 5 and show a good match. The same dependence of conductance on voltage is shown in Fig. 2(c). As can be clearly seen in the figure, the conductance is indeed substantially suppressed in the whole voltage range. This is qualitatively different from all previously mentioned cases. Furthermore, the role of the scattering at impurities appears to be different as well. The previously considered cases were characterized by the resonance behavior of the conductance. The scattering broadened the resonances into Lorentz-shaped peaks with the characteristic width $\delta=\hbar/(e\tau)$. On the contrary, for the last case, the weakening of momentum conservation due to the scattering increases the tunneling conductance and restores the manifestation of SOI in its dependence on voltage.

To understand such an unusual role of the scattering, let us again consider the overlap of the spectra cross sections in

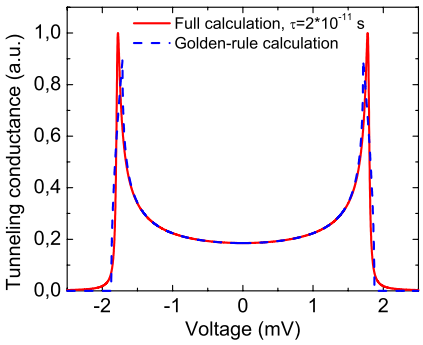

FIG. 5. (Color online) Tunneling conductance calculated for the case $\alpha^R=-\alpha^L=\beta$ and very weak scattering compared to the precise result obtained through Fermi's golden rule calculation.

Figs. 4(a) and 4(b). Note that the scattering weakens the requirement of momentum conservation. To account for that, one should add a certain thickness to the circles shown in the figure. This thickness is proportional to τ^{-1}. Consequently, the overlap of the cross sections now having "thick" lines occurs at a larger number of points, providing increased tunneling current. Figure 2(d) shows this dependence for a realistic scattering time $\tau=2\times10^{-12}$ s.

In general, for arbitrary α and β, the dependence of conductance on voltage can exhibit various complicated shapes, with a number of maxima being very sensitive to the relation between Rashba and Dresselhaus contributions. The origin of such sensitivity is the interference of the angular dependencies of the spinor eigenstates in the layers. A few examples of such interference are shown in Figs. 6(a)–6(c). All the dependencies shown were calculated for the scattering time $\tau=2\times10^{-12}$ s. Figure 6(a) summarizes the results for all previously discussed cases of SOI parameters, i.e., no SOI (curve 1), the case $\alpha_R=-\alpha_L$, $\beta=0$ (curve 2), and $\alpha_R=-\alpha_L=\beta$ (curve 3). Following the magnitude of τ, all the reasonances are broadenered compared to that shown in Fig. 2. Figure 6(b) (curve 2) demonstrates the conductance calculated for the case $\alpha_L=-\frac{1}{2}\alpha_R=\beta$, and Fig. 6(c) (curve 2) for the case $\alpha_L=\frac{1}{2}\alpha_R=\beta$. Curve 1 corresponding to the case of no SOI is also shown in all the figures for reference. Despite the scattering, all the patterns shown in Fig. 6 remain very distinctive. That means that, in principle, the relation between the Rashba and Dresselhaus contributions to SOI can be extracted merely from the *I-V* curve measured in a proper tunneling experiment.

IV. SUMMARY

As we have shown, in the system of two 2D electron layers separated by a potential barrier, SOI can reveal itself in the tunneling current. The difference in spin structure of eigenstates in the layers results in a sort of interference and affects the tunneling rate. Consequently, the dependence of tunneling conductance on voltage appears to be very sensitive to the parameters of SOI. Thus, we propose a way to extract the parameters of SOI and, in particular, the relation between Rashba and Dresselhaus contributions in the tunneling experiment. We emphasize that unlike many other spin-related experiments, the manifestation of SOI studied in this paper should be observed without external magnetic field. Our calculations show that the interference picture may be well resolved for GaAs samples with the scattering times down to $\sim10^{-12}$ s; in some special cases the scattering even restores the traces of SOI otherwise not seen due to destructive interference.

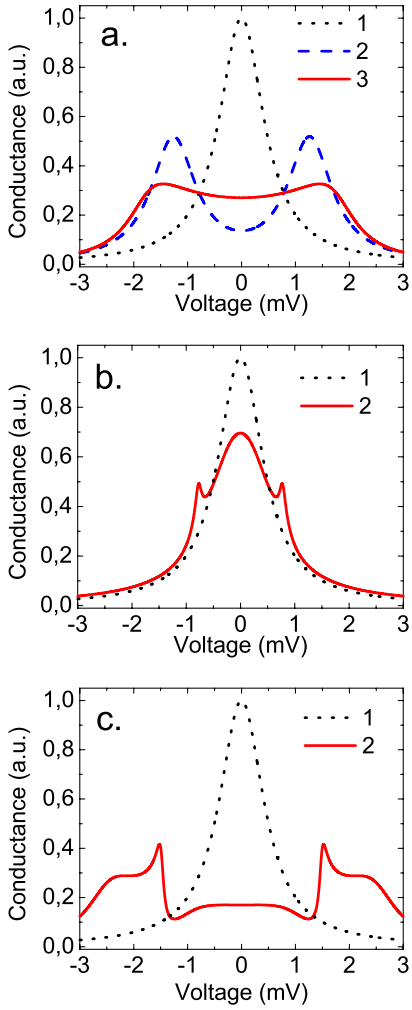

FIG. 6. (Color online) Tunneling conductance calculated for various parameters of SOI.

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*igor@quantum.ioffe.ru

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