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Spin-dependent tunneling through a symmetric semiconductor barrier

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The problem of electron tunneling through a symmetric semiconductor barrier based on zinc-blende-structure material is studied. The k^3 Dresselhaus terms in the effective Hamiltonian of bulk semiconductor of the barrier are shown to result in a dependence of the tunneling transmission on the spin orientation. The difference of the transmission probabilities for opposite spin orientations can achieve several percents for the reasonable width of the barriers.

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Lately spin-polarized electron transport in semiconductors attracts a great attention.[1] One of the major problems of general interest is a possibility and methods of spin injection into semiconductors. A natural way to achieve spin orientation in experiment is the injection of spin-polarized carriers from magnetic materials. Although significant progress has been made recently,[2–5] reliable spin injection into low-dimensional electron systems is still a challenge. Schmidt *et al.* pointed out that a fundamental obstacle for electrical injection from ferromagnetic into semiconductor was the conductivity mismatch of the metal and the semiconductor structure.[6] However, Rashba showed that this problem could be resolved by using tunneling contact at the metal-semiconductor interface.[7] On the other hand, Voskoboynikov, Liu, and Lee[8] proposed that asymmetric nonmagnetic semiconductor barrier itself could serve as a spin filter. It was demonstrated that spin-dependent electron reflection by inequivalent interfaces resulted in the dependence of the tunneling transmission probability on the orientation of electron spin. This effect is caused by interface-induced Rashba spin-orbit coupling[9] and can be substantial for resonant tunneling through asymmetric double-barrier[10–13] or triple-barrier[14] heterostructures. However, in the case of symmetric potential barriers, the interface spin-orbit coupling does not lead to a dependence of tunneling on the spin orientation.

In this communication we will show that the process of tunneling is spin dependent itself. We demonstrate that a considerable spin polarization can be expected at tunneling of electrons even through a single symmetric barrier if only the barrier material lacks a center of inversion such as zinc-blende-structure semiconductors. The microscopic origin of the effect is the Dresselhaus k^3 terms[15] in the effective Hamiltonian of the bulk semiconductor of the barrier.

We consider the transmission of electrons with the initial wave vector $\boldsymbol{k}=(\boldsymbol{k}_\parallel, k_z)$ through a flat potential barrier of height V grown along $z\|[001]$ direction (see Fig. 1); $\boldsymbol{k}_\parallel$ is the wave vector in the plane of the barrier, and k_z is the wave vector component normal to the barrier pointing in the direction of tunneling. The electron Hamiltonian of the barrier in effective mass approximation contains the spin-dependent k^3 term (Dresselhaus term)[15]

$$\hat{H}_D=\gamma[\hat{\sigma}_x k_x(k_y^2-k_z^2)+\hat{\sigma}_y k_y(k_z^2-k_x^2)+\hat{\sigma}_z k_z(k_x^2-k_y^2)], \quad (1)$$

where $\hat{\sigma}_\alpha$ are the Pauli matrices, γ is a material constant (see Table I), and the coordinate axes x,y,z are assumed to be parallel to the cubic crystallographic axes [100], [010], [001], respectively. In the case of tunneling along z one should consider k_z in the Hamiltonian as an operator $-i\partial/\partial z$. We assume the kinetic energy of electrons to be substantially smaller than the barrier height V, then the Hamiltonian (1) is simplified to

$$\hat{H}_D=\gamma(\hat{\sigma}_x k_x-\hat{\sigma}_y k_y)\frac{\partial^2}{\partial z^2}. \quad (2)$$

One can note that essentially $\hat{H}_D$ induces a spin-dependent correction to the effective electron mass along z in the barrier. The Hamiltonian (2) is diagonalized by spinors

$$\chi_\pm=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ \mp e^{-i\varphi}\end{pmatrix}, \quad (3)$$

which correspond to the electron states "+" and "−" of the opposite spin directions. Here φ is the polar angle of the wave vector $\boldsymbol{k}$ in the xy plane, being

$$\boldsymbol{k}=(k_\parallel\cos\varphi,\ k_\parallel\sin\varphi,\ k_z). \quad (4)$$

Transmission probabilities for the electrons of eigen spin states "+" and "−" (3) are different due to spin-orbit term (2). The orientations of spins $\boldsymbol{s}_\pm$ in the states "+" and "−" depend on the in-plane wave vector of electrons and are given by

$$\boldsymbol{s}_\pm=(\mp\cos\varphi,\ \pm\sin\varphi,\ 0). \quad (5)$$

Figure 2 demonstrates the orientations of spins $\boldsymbol{s}_+$ and $\boldsymbol{s}_-$ for various directions of the in-plane electron wave vector $\boldsymbol{k}_\parallel$, i.e. as a function of polar angle φ. If $\boldsymbol{k}_\parallel$ is directed along a cubic crystal axis ([100] or [010]) then the spins are parallel

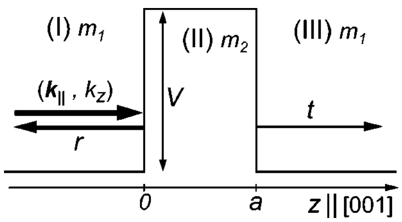

FIG. 1. Sketch of a three-dimensional model of electron tunneling. Transmission of electrons with the wave vector $\boldsymbol{k}=(\boldsymbol{k}_\parallel,k_z)$ through the potential barrier V of width a grown along z.

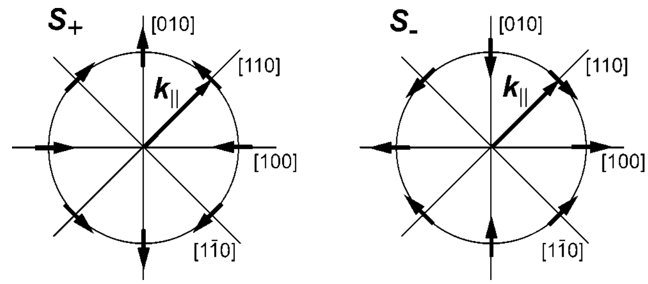

FIG. 2. Spin orientation of eigen states "+" and "−" as a function of the orientation of the in-plane electron wave vector $\boldsymbol{k}_\parallel$.

(or antiparallel) to $\boldsymbol{k}_\parallel$, while $\boldsymbol{s}_\pm$ are perpendicular to $\boldsymbol{k}_\parallel$ if the in-plane wave vector is directed along the axis $[1\bar{1}0]$ or $[110]$.

Electrons of the eigen spin states "+" and "−" propagate through the barrier, conserving the spin orientation. Since the wave vector in the plane of the barrier $\boldsymbol{k}_\parallel$ is fixed, wave functions of the electrons can be written in the form

$$\Psi_\pm(\boldsymbol{r})=\chi_\pm u_\pm(z)\exp(i\boldsymbol{k}_\parallel\cdot\boldsymbol{\rho}), \tag{6}$$

where $\boldsymbol{\rho}=(x,y)$ is a coordinate in the plane of the barrier. The function $u(z)$ in the regions I (incoming and reflected waves, see Fig. 1), II, and III (transmitted wave) has the form

$$u_\pm^{(I)}(\boldsymbol{r})=[\exp(ik_z z)+r_\pm\exp(-ik_z z)], \tag{7}$$

$$u_\pm^{(II)}(\boldsymbol{r})=[A_\pm\exp(q_\pm z)+B_\pm\exp(-q_\pm z)],$$

$$u_\pm^{(III)}(\boldsymbol{r})=t_\pm\exp(ik_z z),$$

respectively. Here $t_\pm$ and $r_\pm$ are the transmission and reflection coefficients for spin states $\chi_\pm$, respectively, and the wave vectors under the barrier $q_\pm$ are given by

$$q_\pm=q_0\left(1\pm\gamma\frac{2m_2k_\parallel}{\hbar^2}\right)^{-1/2}, \tag{8}$$

where q_0 is the reciprocal length of decay of the wave function in the barrier for the case when the spin-orbit interaction (1) is neglected,

$$q_0=\sqrt{\frac{2m_2V}{\hbar^2}-k_z^2\frac{m_2}{m_1}-k_\parallel^2\left(\frac{m_2}{m_1}-1\right)}, \tag{9}$$

and $m_i(i=1,2)$ are the effective masses outside and inside the tunneling barrier, respectively. Taking into account the boundary conditions, which require that

$$u_\pm \quad\text{and}\quad \frac{1}{m}\frac{\partial u_\pm}{\partial z} \tag{10}$$

are continuous at the interfaces, a system of linear equations for $t_\pm$, $r_\pm$, $A_\pm$, and $B_\pm$ can be derived. Note that the small spin-dependent renormalization of the effective mass induced by the Hamiltonian (2) can be neglected in the boundary conditions, since it produces only a small correction to the preexponential factor in final expressions. Solution of the system allows one to calculate the coefficients of the transmission $t_\pm$. For the real case $m_2k_\parallel\gamma/\hbar^2\ll 1$, they are derived to be

$$t_\pm=t_0\exp\left(\pm\gamma\frac{m_2k_\parallel}{\hbar^2}aq_0\right), \tag{11}$$

where t_0 is the transmission coefficient when the spin-orbit interaction (1) is neglected,

$$t_0=-4i\frac{m_2}{m_1}\frac{k_zq_0}{(q_0-ik_zm_2/m_1)^2}\exp(-q_0a-ik_za), \tag{12}$$

a is the width of the barrier. The general problem of tunneling of an electron with arbitrary initial spinor χ can be solved by expanding χ to the eigen spinors $\chi_\pm$.

It is convenient to introduce a polarization efficiency $\mathcal{P}$ that determines the difference of tunneling transmission probabilities for the spin states "+" and "−" through the barrier,

$$\mathcal{P}=\frac{|t_+|^2-|t_-|^2}{|t_+|^2+|t_-|^2}. \tag{13}$$

In our case it has the form

$$\mathcal{P}=\tanh\left(2\gamma\frac{m_2k_\parallel}{\hbar^2}aq_0\right). \tag{14}$$

At a given initial wave vector of electrons, $\boldsymbol{k}$, the polarization efficiency drastically increases with the strength of the Dresselhaus spin-orbit coupling γ [see Eq. (14)], and the barrier width a. However, while increase the barrier width a increases the polarization efficiency, one should keep in mind that the barrier transparency decreases simultaneously

TABLE I. Parameters of band structure of various A_3B_5 semiconductors (Ref. 16), InAs (Ref. 17).

	GaSb	InAs	GaAs	InP	InSb
γ, eV Å^3	187	130	24	8	220
m^*/m_0	0.041	0.023	0.067	0.081	0.013

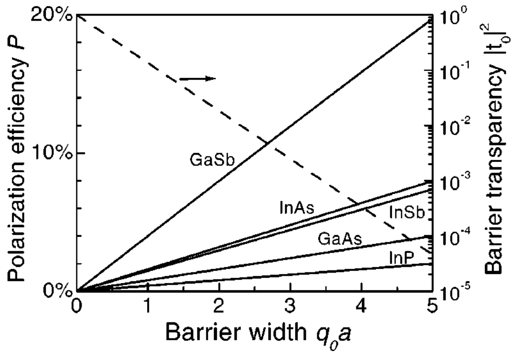

FIG. 3. Coefficient of the polarization efficiency $\mathcal{P}$ as a function of barrier width aq_0 for various barrier materials, and $k_{\parallel}=2\times10^6\ \mathrm{cm}^{-1}$. Dashed line presents the barrier transparency.

[see Eq. (12)]. In Fig. 3 the efficiency $\mathcal{P}$ and the barrier transparency $|t_0|^2$ are plotted as a function of the barrier width q_0a for various barrier materials. The material parameters γ and effective mass $m^*=m_2$ used in the calculations are given in the Table I. One can see that for a reasonable set of parameters given in the figure caption it is possible to achieve spin polarizations of several percents. Tunneling barriers prepared on the basis of GaSb or its solutions seem to be the most efficient barrier materials for spin selective tunneling because of the large value of the product γm^*.

The polarization strongly depends on the electron wave vector $k_{\parallel}$ parallel to the barrier [see Eq. (14)]. This result suggests a device for spin injection into quantum wells. Let us assume two quantum wells separated by a tunneling barrier and a current flowing along one of the quantum wells. The in-plane current results in nonzero average electron wave vector $k_{\parallel}$ and, due to the considered effect, in a spin polarization of carriers.

In conclusion, we have demonstrated that the k^3 Dresselhaus terms in the effective Hamiltonian of semiconductors lacking a center of inversion yield a considerable spin polarization of electrons tunneling through barriers. The effect could be employed for creating spin filters.

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