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. 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, 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. However, Rashba showed that this problem could be resolved by using tunneling contact at the metal-semiconductor interface. On the other hand, Voskoboynikov, Liu, and Lee proposed that asymmetric nonmagnetic semiconductor interface. 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.

\[
\hat{H}_D = \gamma \left[ \sigma_z k_z (k_z^2 - k_x^2) + \sigma_y k_y (k_y^2 - k_x^2) + \sigma_x (k_x^2 - k_y^2) \right],
\]

(1)

where \( \sigma_x, \sigma_y, \sigma_z \) are the Pauli matrices, \( \gamma \) 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], and [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

\[
\hat{H}_D = \gamma (\sigma_z k_z - \sigma_y k_y) \frac{\partial^2}{\partial z^2}.
\]

(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

\[
\chi_\pm = \frac{1}{\sqrt{2}} \left( \begin{array}{c} 1 \\ \mp e^{-i\varphi} \end{array} \right),
\]

(3)

which correspond to the electron states ‘‘+’’ and ‘‘−’’ of the opposite spin directions. Here \( \varphi \) is the polar angle of the wave vector \( k \) in the \( xy \) plane, being

\[
k = (k_x \cos \varphi, k_y \sin \varphi, k_z).
\]

(4)

Transmission probabilities for the electrons of eigen spin states ‘‘+’’ and ‘‘−’’ (3) are different due to spin-orbit term (2). The orientations of spins \( s_\pm \) in the states ‘‘+’’ and ‘‘−’’ depend on the in-plane wave vector of electrons and are given by

\[
s_\pm = (\mp \cos \varphi, \pm \sin \varphi, 0).
\]

(5)

Figure 2 demonstrates the orientations of spins \( s_+ \) and \( s_- \) for various directions of the in-plane electron wave vector \( k_\parallel \), i.e. as a function of polar angle \( \varphi \). If \( k_\parallel \) 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 \( k = (k_x, k_y) \) through the potential barrier \( V \) of width \( a \) grown along \( z \).

(or antiparallel) to \( k_z \), while \( s_z \) are perpendicular to \( k_z \) if the in-plane wave vector is directed along the axis \([1 
 1 0] \) or \([11 0] \).

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 \( k_z \) is fixed, wave functions of the electrons can be written in the form

\[
\Psi_\pm(r) = \chi_\pm u_\pm(z) \exp(ik_z \cdot \rho),
\]

where \( \rho = (x, y) \) 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

\[
\begin{align*}
  u_\pm^{(I)}(r) &= [\exp(ik_z z) + r_\pm \exp(-ik_z z)], \\
  u_\pm^{(II)}(r) &= [A_\pm \exp(q_\pm z) + B_\pm \exp(-q_\pm z)], \\
  u_\pm^{(III)}(r) &= t_\pm \exp(ik_z z),
\end{align*}
\]

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

\[
q_\pm = q_0 \left( 1 \pm \gamma \frac{2m_z k_z}{h^2} \right)^{-1/2},
\]

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,

\[
q_0 = \sqrt{\frac{2m_z V}{h^2} - k_z^2 \frac{m_2}{m_1} - k_0^2 \left( \frac{m_2}{m_1} - 1 \right)}.
\]

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

\[
\begin{array}{|c|}
\hline
\text{TABLE I. Parameters of band structure of various A}_x\text{B}_y \text{ semiconductors (Ref. 16), InAs (Ref. 17).} \\
\hline
\hline
\text{GaSb} & \text{InAs} & \text{GaAs} & \text{InP} & \text{InSb} \\
\hline
\gamma, \text{ eV A}^3 & 187 & 130 & 24 & 8 & 220 \\
\frac{m^*}{m_0} & 0.041 & 0.023 & 0.067 & 0.081 & 0.013 \\
\hline
\end{array}
\]

FIG. 2. Spin orientation of eigen states “+” and “−” as a function of the orientation of the in-plane electron wave vector \( k_z \).

\[
u_\pm \quad \text{and} \quad \frac{1}{m} \frac{\partial u_\pm}{\partial z} \]

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 \( m_2 k_z \gamma h^2 \ll 1 \), they are derived to be

\[
t_\pm = t_0 \exp \left( \pm \gamma \frac{m_z k_z}{h^2} a q_0 \right),
\]

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

\[
t_0 = -4i \frac{m_z}{m_1} \frac{k_z q_0}{(q_0 - i k_z m_2/m_1)} \exp(-q_0 a - i k_z a),
\]

\( \alpha \) is the width of the barrier. The general problem of tunneling of an electron with arbitrary initial spinor \( \chi \) can be solved by expanding \( \chi \) to the eigen spinors \( \chi_\pm \).

It is convenient to introduce a polarization efficiency \( P \) that determines the difference of tunneling transmission probabilities for the spin states “+” and “−” through the barrier,

\[
P = \frac{|t_+|^2 - |t_-|^2}{|t_+|^2 + |t_-|^2}.
\]

In our case it has the form

\[
P = \tanh \left( 2 \gamma \frac{m_z k_z}{h^2} a q_0 \right).
\]

At a given initial wave vector of electrons, \( k \), the polarization efficiency drastically increases with the strength of the Dresselhaus spin-orbit coupling \( \gamma \) [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.
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 $g m^*$. 

The polarization strongly depends on the electron wave vector $k_i$ 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 $k_i$ 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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