In-Plane Electric Current Is Induced by Tunneling of Spin-Polarized Carriers

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It has been shown that tunneling of spin-polarized electrons through a semiconductor barrier is accompanied by generation of an electric current in the plane of the interfaces. The direction of this interface current is determined by the spin orientation of the electrons and symmetry properties of the barrier; in particular, the current reverses its direction if the spin orientation changes the sign. Microscopic origin of such a "tunneling spin-galvanic" effect is the spin-orbit coupling-induced dependence of the barrier transparency on the spin orientation and the wave vector of electrons.

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Spin-dependent phenomena and particularly transport of spin-polarized carriers in semiconductor heterostructures have attracted a great deal of attention [1]. One of the key problems of spintronics is a development of efficient methods of injection and detection of spin-polarized carriers. Among various techniques ranging from optical orientation [2] to spin injection from magnetic materials (see [3–6] and references therein), special attention has been paid to the development of nonmagnetic semiconductor injectors and detectors. The spin-orbit interaction underlying such devices couples spin states and space motion of conduction electrons and makes possible effects of conversion of electric current into spin orientation and vice versa.

Generation of electric current by spin-polarized electrons was the subject of investigations at first in bulk materials. It was shown that scattering of a spin-polarized electron beam by unpolarized lattice defects is asymmetrical due to spin-orbit interaction and therefore is accompanied by appearance of the transversal current [7,8]. Such anomalous Hall effect driven by the concentration inhomogeneity of the optically oriented electrons was proposed in Ref. [9] and observed on the surface of bulk AlGaAs [10].

Recently, the ability of spin-polarized carriers to drive an electric current was demonstrated in low-dimensional semiconductor systems. It was shown that spin relaxation of the homogeneous spin-polarized two-dimensional electron gas yields the electric current in systems with linear in the wave vector $\mathbf{k}$ spin splitting [11]. This effect referred to as "spin-galvanic" has been recently observed in GaAs and InAs quantum well structures [12,13].

In this Letter we demonstrate the possibility of generation of an electric current by spin-polarized carriers under tunneling through a semiconductor barrier. We show that the spin-polarized electrons transmitted through the barrier create the electric current flow in the plane of the interfaces. The direction of this interface current is determined by the spin orientation of the electrons and intrinsic symmetry properties of the barrier, in particular, the current reverses its direction if the spin orientation changes the sign. In contrast to the spin-dependent currents discussed above, the proposed "tunneling spin-galvanic effect" is not related to scattering. The microscopic origin of the effect under study is the spin-orbit coupling-induced dependence of the barrier transparency on the relative orientation of the electron spin and wave vector [14,15].

The physics of the tunneling spin-galvanic effect is sketched in Fig. 1. We assume two parts of the bulk semiconductor separated by the tunneling barrier grown along z direction, and the spin-polarized electron gas on the left side of the structure. Spin-polarized electrons with various wave vectors tunnel through the barrier. In the absence of spin-orbit interaction the barrier transparency reaches maximum for the carriers propagating along the normal to the barrier. Spin-orbit coupling changes this rule, the optimum tunneling transmission

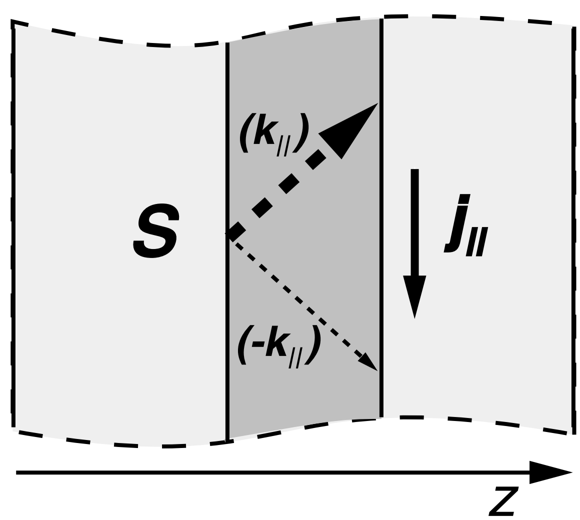

FIG. 1. Origin of the tunneling spin-galvanic effect. Asymmetry of tunneling transmission of spin-polarized carriers caused by spin-orbit interaction results in the in-plane electric current near the barrier.

is reached now for an oblique incidence. The barrier transparency for the spin-polarized carriers with the certain in-plane wave vector $\mathbf{k}_\parallel$ is larger than the transparency for the particles with the opposite in-plane wave vector, $-\mathbf{k}_\parallel$. This asymmetry results in the in-plane flow of the transmitted electrons near the barrier, i.e., in the interface electric current.

Generally, the barrier transparency may depend on the spin orientation of carriers if the system lacks a center of inversion. Two microscopic mechanisms were shown to be responsible for the effect of spin-dependent tunneling. One of them is the Rashba spin-orbit coupling induced by the barrier asymmetry [14,16–20]. The other is the k^3 Dresselhaus spin splitting of the electron states in the barrier grown of a noncentrosymmetrical material such as zinc-blende-lattice semiconductors [15,21,22]. Both these mechanisms lead to the generation of the interface current when the spin-polarized electrons tunnel through the barrier. In the present article we consider the tunneling spin-galvanic effect due to the Dresselhaus splitting as an example.

The theory of the tunneling spin-galvanic effect is developed by using the spin density matrix technique. The interface current of spin-polarized electrons transmitted through the barrier is given by

$$\boldsymbol{j}_\parallel = e\sum_{\boldsymbol{k}} \tau_p \boldsymbol{v}_\parallel(\boldsymbol{k}) \mathrm{Tr}[\hat{g}(\boldsymbol{k})], \tag{1}$$

where e is the electron charge, τ_p is the momentum relaxation time, $\boldsymbol{v}(\boldsymbol{k})$ is the velocity linked to the electron wave vector $\boldsymbol{k}$ by the conventional expression, $\boldsymbol{v}(\boldsymbol{k}) = \hbar\boldsymbol{k}/m_1$, m_1 is the effective electron mass outside the barrier, and $\hat{g}(\boldsymbol{k})$ is the 2×2 spin matrix which describes the flux of the electrons transmitted through the barrier. If the reverse tunneling flux from the right to the left side of the structure is neglected then the matrix $\hat{g}$ is determined by the electron distribution on the left side of the barrier and the spin-dependent coefficient of transmission, and given by

$$\hat{g} = \mathcal{T}\rho_l\mathcal{T}^\dagger v_z \Theta(v_z). \tag{2}$$

Here ρ_l is the electron density matrix on the left side of the structure, $\mathcal{T}$ is the spin matrix of the tunneling transmission linking the incident spinor wave function ψ_l to the transmitted spinor wave function ψ_r, $\psi_r = \mathcal{T}\psi_l$, and Θ-function describes the direction of the tunneling.

We assume the carriers on the left side of the structure to form 3D spin-oriented electron gas, and electron distributions in both spin subband to be thermalized. Thus the density matrix has the form

$$\rho_l = \frac{f_p + f_a}{2}\,\hat{I} + \frac{f_p - f_a}{2}\,(\boldsymbol{n}_s \cdot \hat{\boldsymbol{\sigma}}), \tag{3}$$

where $\boldsymbol{n}_s$ is the unit vector directed along the spin orientation, f_p and f_a are the distribution functions of the electrons with the spins oriented parallel and antiparallel to $\boldsymbol{n}_s$, respectively, and $\hat{\sigma}_\alpha$ are the Pauli matrices. For the case of small degree of spin polarization, the density matrix of 3D electron gas is simplified to

$$\rho_l \approx f_0\hat{I} - \frac{df_0}{d\varepsilon}\,\frac{2p_s}{\langle 1/\varepsilon\rangle}\,(\boldsymbol{n}_s\cdot\hat{\boldsymbol{\sigma}}), \tag{4}$$

where f_0 is the equilibrium distribution function of nonpolarized carriers, p_s is the degree of the spin polarization, and $\langle 1/\varepsilon\rangle$ is the average value of the reciprocal kinetic energy of the carriers. The latter is equal to $3/E_F$ for 3D degenerate electron gas with the Fermi energy E_F, and $2/k_BT$ and 3D nondegenerate gas at the temperature T.

We consider the tunneling spin-galvanic effect for the symmetrical rectangular barrier grown of a zinc-blende-lattice semiconductor along [001] direction (see Fig. 2). In this case the barrier transparency depends on the orientation of electron spin due to the k^3 Dresselhaus spin-orbit interaction. The coefficients of transmission for spin states "+" and "−" corresponding to the most and the less probable tunneling have the form [15]

$$t_\pm = t_0 \exp\left(\pm\gamma\frac{m_2k_\parallel}{\hbar^2}\,aq_0\right), \tag{5}$$

where t_0 is the transmission coefficient when the spin-orbit interaction is neglected, γ is a constant of the Dresselhaus spin-orbit coupling depending on the material, m_2 is the electron effective mass inside the barrier, $q_0 \approx \sqrt{2m_2V/\hbar^2}$ is the reciprocal length of the wave function decay in the barrier, V and a are the height and the width of the barrier, respectively. The orientations of the electron spin of the states "+" and "−" depend on the direction of the electron in-plane wave vector $\boldsymbol{k}_\parallel$ with respect to the crystal cubic axes. The spinors corresponding to the spin eigen-states are given by [15]

$$\chi_\pm = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ \mp e^{-i\varphi} \end{pmatrix}, \tag{6}$$

where φ is the polar angle of the wave vector in the xy plane, being $\boldsymbol{k}_\parallel = (k_\parallel\cos\varphi, k_\parallel\sin\varphi)$, and the coordinate system $x \parallel [100]$, $y \parallel [010]$, and $z \parallel [001]$ is assumed.

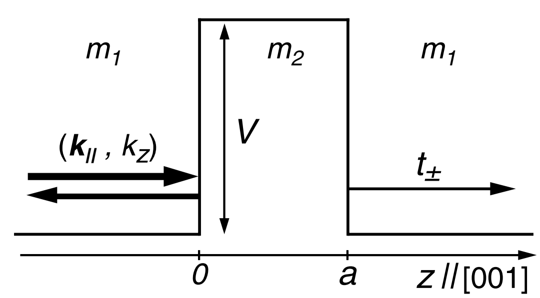

FIG. 2. Tunneling through (001)-grown semiconductor barrier. V and a are the height and the width of the barrier, respectively.

The spin matrix of the electron transmission through the barrier is given by

$$\mathcal{T} = \sum_{s=\pm} t_s \chi_s \chi_s^\dagger. \tag{7}$$

For our case it has the form

$$\mathcal{T} = \frac{1}{2}\begin{bmatrix} t_+ + t_- & (t_- - t_+)\, e^{i\varphi} \\ (t_- - t_+)\, e^{-i\varphi} & t_+ + t_- \end{bmatrix}. \tag{8}$$

We assume spin corrections to be small. The transmission coefficient t_0 is suggested, for simplicity, to depend only on the k_z component of the electron wave vector that is fulfilled if the electron effective masses inside and outside the barrier coincide, $m^* = m_1 = m_2$. Then substituting the density matrix (4) and the transmission matrix (8) into Eqs. (1) and (2), the interface spin-dependent current is derived to be

$$j_{\|,x} = -j_\| \, n_{s,x}, \qquad j_{\|,y} = j_\| \, n_{s,y}, \tag{9}$$

$$j_\| = 4e\gamma \frac{m^* a q_0}{\hbar^2} \frac{\tau_p}{\hbar\langle 1/\varepsilon\rangle} \dot{N} p_s,$$

where $\dot{N}$ is the flux of the electrons through the barrier, $\dot{N} = \sum_{\boldsymbol{k}} \mathrm{Tr}\hat{g}$.

The direction of the spin-dependent interface current (9) induced by the Dresselhaus term is determined by the spin orientation of the electrons with respect to the crystal axes. In particular, the current $\boldsymbol{j}_\|$ is parallel (or antiparallel) to the spin polarization $\boldsymbol{n}_s$, if $\boldsymbol{n}_s$ is directed along the crystal cubic axis [100] or [010]; and $\boldsymbol{j}_\|$ is perpendicular to $\boldsymbol{n}_s$, if the latter is directed along the axis $[1\bar{1}0]$ or [110].

As it was mentioned above, the tunneling spin-galvanic effect can also be induced by Rashba spin-orbit coupling in asymmetrical barriers. In this particular case the spin-dependent interface current flows perpendicular to the spin polarization of the carriers.

The estimations for the tunneling spin-galvanic current (9) give $j_\| \sim 10^{-6}$ A/cm and $j_\| \sim 10^{-7}$ A/cm for barriers based on GaSb and GaAs, respectively, for the structures with the barrier transparency $|t_0|^2 \sim 10^{-5}$ and the momentum scattering time $\tau_p \sim 10^{-12}$ s.

In conclusion, it has been demonstrated that the spin-dependent interface current is generated if spin-polarized carriers tunnel through the semiconductor barrier. The theory of the tunneling spin-galvanic effect has been developed for symmetrical barriers grown of zinc-blende-lattice compounds. The effect could be employed for creating nonmagnetic semiconductor detectors of spin-polarized carriers.

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