Interface Conductance of Ballistic Ferromagnetic-Metal-2DEG Hybrid Systems with Rashba Spin-Orbit Coupling

Spin splitting due to spin-orbit (SO) coupling is very different, both in its physical origin and dynamical consequences, from the energy splitting of orthogonal spin states in a ferromagnet or due to the Zeeman effect. Ramifications of this difference are not always fully appreciated in the literature. A recent example is Ref. [1] where transport through the interface between a ferromagnetic metal (F) and a two-dimensional electron gas (2DEG) was considered. The tunable oscillatory spin-filtering effect found there is absent in the correct treatment of this problem which we provide here.

A proposal [2] to realize a field-effect transistor by using an external gate voltage to control spin precession of electrons in a 2DEG has attracted a lot of interest recently. The physical origin of spin precession is the intrinsic SO coupling of electrons in 2DEG due to structural inversion asymmetry [3]. It can be described, to a good approximation, by the Rashba Hamiltonian [4]

$$H = \frac{\vec{p}^2}{2m_S} + \frac{\alpha_0}{\hbar}\,\hat{z}\cdot(\vec{\sigma}\times\vec{p})\,. \tag{1}$$

Even with $\alpha_0 \neq 0$, eigenstates of H are still labeled by 2D wave vector $\vec{k}$. However, the energy spectrum is split into two branches: $E^{(\pm)}_{\vec{k}} = \frac{\hbar^2 k^2}{2m_S} \pm \alpha_0 k$, where $k = |\vec{k}|$. Furthermore, the projection of electron spin on any fixed axis cannot, in general, be chosen as a good quantum number simultaneously for all eigenspinors. Finally, *canonical* and *kinetic* momentum are not identical anymore. From the continuity equation for the quantum-mechanical probability density, we find the current

$$\vec{j} = \frac{1}{m_S}\,\mathrm{Re}\{\Psi^\dagger(\vec{p} + \hbar k_{so}[\hat{z}\times\vec{\sigma}])\Psi\}\,. \tag{2}$$

Here, $\Psi = (\psi_1, \psi_2)^T$ denotes a normalized spinor, and $k_{so} = m_S\alpha_0/\hbar^2$. Straightforward calculation shows that the velocity of an eigenstate of H with energy E is given by $v(E) = \frac{1}{m_S}(2m_S E + \hbar^2 k_{so}^2)^{1/2}$. In contrast to assumptions in Ref. [1], it is *independent* of branch index.

Practical realization of the spin transistor [2] depends crucially on the possibility to control the Rashba coefficient α_0 via an external gate voltage, which was demonstrated experimentally [5], and the ability to inject spin-polarized electrons into the 2DEG from a ferromagnetic contact. It was the latter problem that motivated the study of Ref. [1]. A clean interface between F and 2DEG was assumed, the only nonideality being their differing band bottoms and effective masses. With interface $\perp\hat{x}$ and magnetization direction in F $\parallel \hat{y}$, the simplest model Hamiltonian of the F-2DEG system is given by [6] $H_{hyb} = \vec{p}\frac{1}{2m(x)}\vec{p} + \frac{\hat{z}}{2\hbar}\cdot[\alpha(x)(\vec{\sigma}\times\vec{p}) + (\vec{\sigma}\times\vec{p})\alpha(x)] + \Delta(x)\sigma_y$. The usual simplifying assumption is that x-dependent parameters in H_{hyb} are piecewise constant, i.e., $m(x) = m_F\Theta(-x) + m_S\Theta(x)$, $\alpha(x) = \alpha_0\Theta(x)$, and $\Delta(x) = \Delta\Theta(-x)$. The scattering problem through the interface is solved by matching appropriate *Ansätze* for eigenstates of H_{hyb} in the F and 2DEG regions. With SO coupling present, the condition for continuity of wave-function derivatives reads

$$\partial_x\Psi(0^+) - \frac{m_S}{m_F}\,\partial_x\Psi(0^-) = ik_{so}\sigma_y\Psi(0)\,. \tag{3}$$

We focus on the case of normal incidence, as was done in Ref. [1], and assume n_{2D} (the sheet density of the 2DEG) to be larger than k_{so}^2/π. This is the relevant situation for operating the spin transistor. While transmission amplitudes for majority (↑) and minority (↓) spins in F turn out to be different, they are *independent* of the magnetization direction in F. Intuitively, this is not surprising because, even though spin degeneracy is lifted, there is no preferred spin quantization axis in the 2DEG. Analytical expressions for transmission probabilities are analogous to those obtained previously [7] for the spin-degenerate case: $T_{\uparrow(\downarrow)} = 1/(1 + Z^2_{\uparrow(\downarrow)})$ with an effective spin-dependent scattering strength $Z_{\uparrow(\downarrow)} = |r_{\uparrow(\downarrow)} - 1|/\sqrt{4r_{\uparrow(\downarrow)}}$. Denoting the Fermi wave vector for majority (minority) spins in F by $k_{F\uparrow(\downarrow)}$ we find

$$r_{\uparrow(\downarrow)} = \frac{m_F}{m_S}\,\frac{\sqrt{2\pi n_{2D} - k_{so}^2}}{k_{F\uparrow(\downarrow)}}\,. \tag{4}$$

In Ref. [1], the existence of two separate Fermi surfaces in the 2DEG was used to argue *ad hoc* that $r_{\uparrow(\downarrow)}$ has to depend also on the branch index of states in the 2DEG. Our calculation shows that this is not the case. Hence, the quantity ΔG (as defined in Ref. [1]) vanishes identically—and with it the possibility to tune spin-filtering between opposite spin states. Also, the variation of $T_{\uparrow(\downarrow)}$ as a function of gate voltages that change n_{2D} and k_{so} has to be obtained using Eq. (4).

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