Oscillatory Spin-Filtering due to Gate Control of Spin-Dependent Interface Conductance

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Using the Landauer-Büttiker formalism, we study ballistic transport properties of an interface between a ferromagnetic metal and a mesoscopic two-dimensional electron system in a III-V semiconductor. We show that in a Sharvin point contact spin-filtering occurs due to band structure mismatch. Theory predicts a pronounced effect for Fe on InAs which can be controlled via a gate electrode.

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The discovery of giant magnetoresistance (GMR) in a Fe/Cr layered system [1] has stimulated a large number of theoretical and experimental studies on the spin-dependent transport properties of metallic multilayers consisting of a sequence of magnetic and nonmagnetic thin films [2–7]. Most studies were performed in the so-called CIP (current in plane) geometry, where the current flows in the plane of the layers. As micropatterning of GMR multilayers has evolved, also CPP (current perpendicular plane) experiments were done where a net charge and spin transport is forced through the interfaces between ferromagnetic and nonmagnetic 3D metals [3,4]. Very recently, Rippard and Buhrman have demonstrated that spin-dependent ballistic transport can even be used to monitor ferromagnetic and antiferromagnetic layer alignment on the nm scale and have called this novel technique ballistic electron magnetic microscopy (BEMM) [8]. The CPP experiments were theoretically modeled using the Landauer formalism of quantum transport assuming independent channels for the majority spins ↑ and minority spins ↓ in the ferromagnet [5,7]. Starting from Boltzmann-type equations, Valet and Fert have later shown that the Landauer approach within the two-current scheme is justified in the ballistic transport regime when the layer thicknesses are much smaller than both the mean free path and the spin diffusion length [6]. Based on the idea of a spin field-effect transistor (FET), Datta and Das proposed a hybrid structure consisting of two ferromagnetic electrodes as a source and drain for a ballistic electron channel within a semiconductor heterostructure [9]. A tunable magnetoresistance effect is expected due to spin precession along the channel which is controlled by a gate electrode via the spin-orbit interaction. Such mesoscopic hybrid structures consisting of micron-sized ferromagnetic electrodes, namely NiFe, and a two-dimensional electron system (2DES) have been prepared successfully and magnetotransport experiments have been discussed in terms of spin-polarized transport [10,11].

For the spin FET idea, the injection of spin-polarized electrons entering the semiconductor (sm) from the ferromagnet (fm) is the most crucial challenge and the understanding of the interface property is essential. In the present work, we use the Landauer-Büttiker (LB) approach in order to derive the transmission probabilities across the boundary in the fm/sm point contact. Our calculations differ from previous calculations [5,7,12] in that we consider the spin-orbit coupling in a 2DES and the band structure mismatch at the Fermi energy E_F. For the ferromagnet/2DES interface, we find the fundamental result that adiabatic injection from the 3D magnet into the 2DES is *not* possible for both majority and minority spin currents at the same time. However, a hybrid Fe/2DES system is proposed where the band mismatch can be controlled efficiently via a gate voltage resulting in a spin-filtering which is tunable. Implications for experiments on the spin FET are discussed.

For ferromagnets, photoemission experiments [13] clearly have proven that a distinction between Fermi wave vectors $k_{F,\uparrow}$ and $k_{F,\downarrow}$ for majority and minority spins at E_F is important. The difference stems from the large exchange-induced splitting of the 3D density of states (DOS). In Table I, data on $k_{F,\uparrow}$ and $k_{F,\downarrow}$ are given for some ferromagnetic metals. In III-V semiconductors, the spin dependence of the electronic properties of 2DES at zero applied magnetic field originates from the spin-orbit interaction. The spin degeneracy of the 2D DOS is lifted when the system lacks inversion symmetry. The so-called Rashba spin-orbit term caused by structural inversion asymmetry is linear in momentum k [15] and, in general, is the strongest contribution in the case of narrow gap semiconductors. In the one-band Rashba model, one can assume a simple picture where the motion of electrons with momentum k transforms the asymmetric electric

TABLE I. Fermi wave vectors of majority ($k_{F,\uparrow}$) and minority spins ($k_{F,\downarrow}$) for three ferromagnetic metals in units of 10^8/cm. Data for $Ni_{80}Fe_{20}$ and Ni are in the (011) direction from Ref. [13] and for Fe from Ref. [14] averaged over the three crystal directions. It is interesting to note that as the atomic number increases from Fe to Ni, the d bands become increasingly filled and move down below E_F.

Ferromagnet	$k_{F,\uparrow}$	$k_{F,\downarrow}$
Fe	1.05	0.44
$Ni_{80}Fe_{20}$	1.05	0.88
Ni	1.08	0.96

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field of 2D confinement in growth direction (z direction) into an effective magnetic field B^* which is in the 2D plane and perpendicular to k. This leads to spin splitting, such that two spin eigenstates "+" and "−" have to be considered which are orthogonal and have different energy dispersions. For the purpose of this work, it is important that this results in two Fermi surfaces. A simple estimation assuming parabolic subband dispersions yields for the Fermi wave vectors

$$k_{F,\pm} = \sqrt{2\pi(1 \pm \gamma)n_{2D}}\,, \tag{1}$$

where n_{2D} denotes the total 2D carrier density and γ the asymmetry in the population of the spin-split subbands. To simplify our calculations on transport phenomena which are governed by electronic properties at the Fermi energy E_F, we neglect that the spin "+" subband exhibits a van Hove singularity at the bottom of the band [16].

Theory and experiment on the Rashba spin-orbit term have shown that the asymmetry γ in spin subband population and that $k_{F,\pm}$ [Eq. (1)] are adjustable by the asymmetry of the conduction-band edge in a semiconductor heterostructure [17] as well as by an applied gate voltage [18–21]. In the latter cases, values up to $\gamma \approx 0.1$ have been realized. In particular, using two gate electrodes on the front and on the back of a heterostructure, γ was controlled for a constant carrier density [19,21]. The electron densities n_{2D} investigated so far with respect to the Rashba effect were between about 4 and 30×10^{11} cm^{-2}.

The Landauer-Büttiker formalism, established as a scattering theory approach mainly for the calculation of transport properties of semiconductor nanostructures [22] has been shown to be well suited to explain spin-valve effects if applied to magnetic multilayers [5]. The calculation is thereby reduced to the evaluation of transmission and reflection coefficients. Important for the present work is that the approach can readily account for finite size effects like the Sharvin resistance [23]. For zero temperature, the Landauer conductance formula reads

$$G = \frac{e^2}{h} \sum_a T_a\,, \tag{2}$$

where T_a are the transmission probabilities for all the different spin-nondegenerate modes between two perfect reservoirs at E_F. The motion is assumed to be ballistic; i.e., the mean free path is much longer than the size W of the constriction. Equation (2) applies to a two-probe situation with no mixing between different channels.

Even for an ideal interface (no inelastic scattering), the transmission decreases if there is a band structure mismatch since the longitudinal motion is no longer adiabatic. For nonmagnetic metal(m)/semiconductor(sm) hybrid structures the transmission T of electrons has been calculated according to

$$T = \frac{1}{1 + Z^2} \tag{3}$$

by introducing the parameter [24]

$$Z^2 = \frac{(r_v - 1)^2}{4r_v} \geq 0\,. \tag{4}$$

In this model, the metal and semiconductor are assumed to consist of ballistic one-dimensional modes with normal incidence on the interface. The Z parameter has been derived from the boundary conditions of the wave functions and represents an effective elastic scattering potential. Here it is helpful to define the velocity $v_F = \hbar k_F/m^*$ for the modes in each of the two materials. The ratio $r_v = v_{F,\mathrm{sm}}/v_{F,\mathrm{m}}$ takes into account the discontinuity in the band structure and in the effective mass m^*.

In our case, where we have a ferromagnetic metal and a 2DES exhibiting spin-orbit interaction, we have to distinguish in Eqs. (2)–(4) and in $r_v = v_{F,\mathrm{sm}}/v_{F,\mathrm{fm}}$ between the two orthogonal spin states. For the evaluation, we start within the *two-current model* from the maximum conductance G_0 across the interface which is

$$G_0 = G_{0,+} + G_{0,-} = \frac{e^2}{h}\frac{k_{F,+}W}{\pi} + \frac{e^2}{h}\frac{k_{F,-}W}{\pi}\,. \tag{5}$$

Equation (5) is valid if the transmission T equals one and is known as the Sharvin conductance for a 2D point contact, where the current transport depends only on the absolute number $(k_{F,+} + k_{F,-})W/\pi$ of transverse modes below the Fermi energy. In a spin FET, W should be only a few 100 nm. This cross section thereby determines the conductance of the sample. If the probability T is reduced due to band structure mismatch, the conductance of the point contact has to become smaller than G_0.

In the following, we calculate the transmission coefficients based on Eqs. (3)–(4). For this, the current is assumed to flow along the x axis and k is always perpendicular to the interface at $x = x_0$ (see Fig. 1). Only configurations will be considered where the ferromagnet is single domain and where the magnetization is in the plane of the 2DES and aligned along the y axis, i.e., the spin quantization axis. We note that the effective magnetic field B^* due to spin-orbit interaction is therefore always collinear with the magnetization of the ferromagnetic electrode. We introduce the local velocities $v_{F,s}$ for the spin direction s. For $x < x_0$, these are either $v_{F,\uparrow}$ or $v_{F,\downarrow}$, depending on whether majority or minority spins of the ferromagnet are regarded (Table I). For $x > x_0$, the velocities $v_{F,+}$ and $v_{F,-}$ entering into Eq. (4) have to be calculated from Eq. (1). We note that across a fm/sm interface, the discontinuity in m^* can be rather large, more than an order of magnitude. When we look for the transmission of spin states entering from the ferromagnetic side, we have to distinguish between

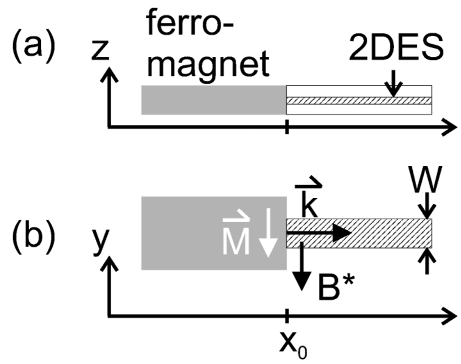

FIG. 1. (a) Schematic cross section and (b) top view of the ferromagnet/semiconductor structure, defining the important parameters used in the calculations. Shown is the configuration P where the magnetization M is parallel to the effective field B^*, k is the wave vector, and W is the width. The mesoscopic 2DES could be realized within an InAs channel embedded in a modulation-doped high-electron mobility transistor.

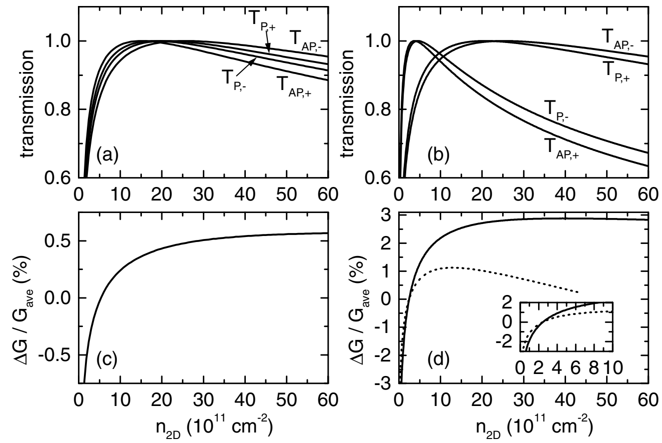

FIG. 2. (a) Transmission probabilities and (c) relative conductance change of the interface in case of a switching NiFe electrode, and (b) and (d) in case of a Fe electrode connected to the 2DES. The asymmetry parameter γ was set to be 0.1 for the full lines. The effective mass was $m^*_{\text{sm}} = 0.036 m_e$ for $x > x_0$, a reasonable value for 2D electrons in an InAs-based heterostructure, and $m^*_{\text{fm}} = m_e$ for $x < x_0$, underestimating somewhat the mass at E_F in case of sp-d hybridization of bands (m_e is the free electron mass). $k_{F,\uparrow}$ and $k_{F,\downarrow}$ for NiFe and Fe were taken from Table I. The broken line is for a smaller γ which is 0.05 at $n_{2D} = 10^{12}$ cm^{-2} and decreases linearly with n_{2D} [18]. The inset in (d) shows the regime of small n_{2D}.

two magnetic configurations. The magnetization can be aligned either parallel (P) or antiparallel (AP) with respect to B^*. This leads to four different Z parameters [Eq. (4)], since in configuration P the majority (minority) spins can transform either into the eigenstate $+$ $(-)$ with a coefficient $T_{\text{P},+}$ $(T_{\text{P},-})$ or in configuration AP into the eigenstate $-$ $(+)$ with $T_{\text{AP},-}$ $(T_{\text{AP},+})$. The contact conductances thus obtained read

$$G_{\text{P}} = T_{\text{P},+} G_{0,+} + T_{\text{P},-} G_{0,-} \tag{6}$$

and

$$G_{\text{AP}} = T_{\text{AP},+} G_{0,+} + T_{\text{AP},-} G_{0,-} \,. \tag{7}$$

In Figs. 2(a) and 2(b) transmission coefficients are calculated from Eq. (3) for two different ferromagnets, namely for NiFe, which has been supposed to be a promising candidate for the realization of the spin FET [10,11] due to micromagnetic reasons [25], and for Fe, which yields, as we will show, the larger effects due to the more favorable band structure parameters. In both cases, the ferromagnetic electrode is assumed to be in Ohmic contact with the 2DES within an InAs channel. The asymmetry in spin subband population due to spin-orbit interaction is set to be $\gamma = 0.1$. Transmissions for configurations P and AP are plotted as a function of 2D carrier density which is easily controlled in an experiment via a gate electrode. Obviously, it is, in principle, not possible to meet $T = 1$ for both ferromagnetic spin states simultaneously. As a general result, the mismatch in band structure parameters at the interface alters the spin polarization of the current entering the 2DES from the ferromagnet.

The calculated transmissions in Figs. 2(a) and 2(b) also suggest that, in principle, $G_{\text{P}} \neq G_{\text{AP}}$ at the boundary. In particular, switching the magnetization direction of the ferromagnetic electrode between the P and AP configuration should cause a change in the "spin-filtering" behavior. The microscopic origin is spin-dependent specular reflection. It is different from the well-known GMR in metallic multilayers where volume and interface spin-dependent inelastic scattering is argued to be its cause [2,5,6]. The relative change $\Delta G/G_{\text{ave}} = 2(G_{\text{P}} - G_{\text{AP}})/(G_{\text{P}} + G_{\text{AP}})$ is a measure of the effectiveness of the spin-filtering process. Calculated traces for NiFe and Fe are shown in Figs. 2(c) and 2(d). For NiFe/InAs(2DES), the ratio is about 0.5% in Fig. 2(c) for a high 2D carrier density starting from $\Delta G/G_{\text{ave}} = 0$ at $n_{2D} \approx 5 \times 10^{11}$ cm^{-2}. Strikingly, the ratio can also be tuned to a negative value at lower n_{2D}, suggesting that spin-filtering now favors the opposite spins. In case of a Fe electrode [Fig. 2(d)], the effects are more pronounced and $\Delta G/G_{\text{ave}}$ is about 3% at high n_{2D} due to the small $v_{F,\downarrow}$ as compared to $v_{F,\uparrow}$. The fm/sm interface is a spin filter which can be tuned between opposite spins. The spin-selective transmission is controlled via a gate electrode on top of the semiconductor. We also modeled the Fe/InAs(2DES) hybrid system in case of a smaller asymmetry parameter γ which has been reported for heterostructures with only a front gate [18]. In this case, γ decreases also with increasing n_{2D}. The expected behavior is shown as the broken line in Fig. 2(d). Strikingly, one now finds an oscillatory ratio $\Delta G/G_{\text{ave}}$ as a function of n_{2D}, i.e., of the gate voltage. This characteristic feature comes close to the idea of Datta and Das of a field-effect controlled oscillation in spin transport.

The LB approach predicts that Fe is a promising metallic ferromagnet for injection of spin-polarized currents into a III-V semiconductor due to its large difference between $v_{F,\uparrow}$ and $v_{F,\downarrow}$. This result is even more interesting since Fe has been shown to be a very good material for epitaxial growth on III-V semiconductors [26]—a stringent prerequisite for a well-defined interface. For experimental investigations, we propose BEMM [8] to be applied at low temperature to a Fe film on the (110) edge of an InAs-based heterostructure [21] where the former is to be grown epitaxially *in situ* by cleaved edged overgrowth [27]. This preparation will lead to an extremely clean interface. BEMM provides a strongly forward-focused momentum distribution of the tunnel-injected electrons which transverse the investigated interface ballistically. By this means, we expect an "imaging" of the results presented in Fig. 2(d) when the contrast between in-plane domains representing the P and AP configuration with respect to B^* is changed via the gate voltage.

Finally we point out that the band structure mismatch will be present in the spin FET [9] if ferromagnetic electrodes are used where the spin polarization is not 100% and where the number of fm modes always exceeds the number of sm modes. The important result of the LB formalism is that for the ballistic device the exact value of spin polarization within the bulk of the ferromagnet does *not* play the important role. Two spin-selective interfaces in series are incorporated in a spin FET. For Fe/InAs/Fe, we expect a magnetoresistance effect large enough to be detected in a magnetotransport experiment. To overcome the fundamental limitation given by the metallic point contact, one really has to think either about alternative concepts of spin injection (e.g., by tunneling) or about optimized material synthesis (e.g., epitaxially grown half-metallic ferromagnets). In the latter case, our study shows that the ferromagnetic electrodes should provide a small $v_{F,\downarrow}$ as compared to $v_{F,\uparrow}$.

In the near future, we expect further improvements with respect to the growth of modulation-doped InAs based heterostructures by molecular-beam epitaxy. This will yield 2DES with smaller carrier densities and higher mobilities than in current devices. Then the full range of n_{2D} depicted in Figs. 2(c) and 2(d) will be accessible in the experiments and spin-filtering; i.e., $\Delta G/G_{\mathrm{ave}}$ will be controlled from negative to positive values via a gate voltage as shown in the inset of Fig. 2(d). This feature will be of great interest for basic research on spin-dependent transport across a boundary as well as for technological applications since one can think of a spintronic sensor which is gate controlled or can be modulated.

In conclusion, spin transmission across a ferromagnet/2DES boundary has been studied based on the Landauer-Büttiker formalism. We have shown that spin filtering occurs. The origin is the velocity mismatch at the interface. This effect can easily be controlled via a gate voltage.

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