Giant magnetoresistance in quantum magnetic contacts

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Abstract

We present calculations of quantized conductance and magnetoresistance in nanosize point contacts between two ferromagnetic metals. When conductance is open for only one conduction electrons spin-projection, the magnitude of magnetoresistance is limited by the rate of conduction electron spin-reversal processes. For the case when both spin-channels contribute to the conductance we analyze the influence of the point contact cross-section asymmetry on the giant magnetoresistance. Recent experiments on magnetoresistance of magnetic point contacts are discussed in the framework of the developed theory.

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1 Introduction

Since experiments with two-dimensional electron gas in a semiconductor [1,2] it is demonstrated that electric conduction is quantized, and elementary conductance quantum is equal to $2e^2/h$. When measured on tiny contacts of non-magnetic semiconductors and metals the conductance quantization is limited to low temperatures by thermal fluctuations, and the factor 2 is attributed to the two-fold spin degeneracy of conduction electron states. Recently, sharp conductance quantization steps have been observed in nanosize point contacts of ferromagnetic metals at room temperature [3–6]. It was possible, because phonon and magnon assisted relaxation processes are quenched due to a large, $\sim 1eV$, exchange splitting of the conduction band. In addition, Oshima and Miyano [4] found an indication of the odd-valued number $N$ of open conductance channels ($\sigma = N(e^2/h)$) in nickel point contacts from room temperature up to 770K. Ono et al. [6] presented an evidence of switching from $2e^2/h$ conductance quantum to $e^2/h$ quantum at room temperature in the nickel nanocontacts of another morphology. Obviously, the change of conductance quantum from $2e^2/h$ to $e^2/h$ is a result of lifting-off the spin degeneracy of the conduction band. Recent calculations [7,8] confirmed the $e^2/h$ conductance quantization in ferromagnetic metals, which is due to non-synchronous opening of ”up” and ”down” spin-channels in the point contact conduction.

New pulse to studies of electric transport in ferromagnets has been given by observation of giant magnetoresistance (GMR) in nanosize magnetic contacts by García et al. [9–11]. Magnetoresistance magnitudes of 280% for Ni-Ni [9] and 200% for Co-Co [10] nanosize contacts were obtained at room temperature. Somewhat smaller ($\sim 30\%$), but also very large for a single interface, magnetoresistance was observed in Fe-Fe point contacts [11]. In these experiments there is a huge spread in the measured values of magnetoresistance, drawn as a function of conductance at ferromagnetic alignment of magnetizations in contacting ferromagnetic domains (F-conductance). The spread of MR points for Ni-Ni and Co-Co contacts is extremely large at F-conductance lying in the range of 2-8 elementary conductances $e^2/h$. The above mentioned observations of conductance quantization steps in point junctions of ferromagnetic metals at room temperature give anticipation that conduction quantization is responsible for the giant magnitude and the giant fluctuations of magnetoresistance in tiny magnetic contacts.

In this article we develop a simple model of conductance and magnetoresistance for nanosize magnetic contacts in the regime of conductance quantization (quantum magnetic contacts), proposed in the previous work [12]. In [12] we argued, that if only one conduction electron spin-channel is open at F-conductance, then the magnitude of GMR is limited only by spin-flip processes of conduction electrons when passing through the point contact [13].
Then the magnetic nanocontact serves as quantum spin-valve. When both spin-channels of F-conduction are open we established, that GMR is a multi-valued function of conductance at ferromagnetic alignment of magnetizations (at least at low temperatures and absence of disorder). This means that if the conductance is quantized, different samples, having the same F-conductance, reveal different magnetoresistance. Distribution of magnetoresistance values is not normal or flat in the statistical sense. Rather, at fixed F-conductance values, smaller magnitudes are much more probable than the maximal ones. The width of distribution is extremely large for the first few open F-conductance channels. Thus, we concluded that the giant raw-data fluctuations observed in the experiments by García et al. [9–11] might be the consequence of conduction quantization. In the present study we focus out attention on the influence of the point contact cross-section asymmetry on GMR. We find that number of open conduction channels, at which conductance shows up for the antiferromagnetically aligned magnetizations, depends not only on the conduction band spin-polarization [12], but also on the aspect ratio of the contact cross-section. We discuss the above mentioned as well as very recent experiments on GMR in magnetic nanocontacts.

2 Calculation of conductance and magnetoresistance

We consider a model of two ferromagnetic, single-domain half-spaces contacting via a narrow and short neck with typical length from one to several nanometers. For the F-alignment of domains the magnetization is homogeneous along the constriction, therefore current carriers move in a constant potential created by the magnetization. At antiferromagnetically (AF) aligned domains a domain wall (DW) is created inside the neck. Then, the carriers move in a potential landscape created by the domain wall. According to the general quantum-mechanical prescription, any inhomogeneity in the potential energy landscape results in a reflection of quasiparticle wave function, which evokes an additional electric resistance [14]. For the free DW between unconstrained domains this domain-wall resistance is very small because the profile of DW is smooth, and free domain wall width $\delta_0$ is large, typically in the range 15-150 nm for the strong elemental ferromagnets like Co, Fe and Ni [15]. However, if DW is created in the constriction, then the wall width $\delta$ is approximately equal to the length of the neck $l$, which is at least an order of magnitude shorter than $\delta_0$ [16]. The sharpening of DW leads to huge enhancement of quasiparticle reflection from DW [17], as well as some increase of impurity scattering [18]. When the external DC magnetic field aligns the domains magnetizations parallel (F-alignment), it eliminates DW and domain-wall reflection, which results in essential decrease of resistance, i.e. leads to GMR [17].
Now we consider the regime of quantized conductance through the nanosize neck. The cross-section size of the neck is assumed very small, typically about 1 nm, so that the transverse motion of electron in the neck is quantized. In our previous work \[12\] we considered the neck of cylindrical cross-section, in this paper we give solution for the neck of rectangular shape. The length of the neck, \(l\), is considered shorter than the electron mean free path, that is why the electron transport through the neck is ballistic. Actually, the neck is a conducting bridge which plays the role of a quantum filter. It selects from the continuous domain of quasiparticle incidence angles only those, which meet the allowed (and quantized) transverse momentum in the channel, and satisfy the energy and momentum conservation laws. For the particular calculations of conductance we may use the ballistic-limit versions of the formulas \(14\), \(18\) and \(19\) of our work \[17\]:

\[
\sigma^F = \sigma_{\uparrow \uparrow} + \sigma_{\downarrow \downarrow} = \frac{e^2}{h} \sum_{m,n} \left\{ D_{\uparrow \uparrow}(x_{mn}) + D_{\downarrow \downarrow}(x_{mn}) \right\}, \tag{1}
\]

\[
\sigma^{AF} = \frac{2e^2}{h} \sum_{m,n} D_{\uparrow \downarrow}(x_{mn}). \tag{2}
\]

The same formulas may be also obtained within the Landauer-Büttiker scattering formalism \[19,20\]. In the above expressions \(\sigma^F(\sigma^{AF})\) is the conductance at ferromagnetic (antiferromagnetic) alignment of domains, \(\sigma_{\alpha\alpha}\) is the conductance for the \(\alpha\)-th spin-channel, and \(x_{mn} = \cos \theta\) is the cosine of the quasiparticle incidence angle \(\theta\), measured from the longitudinal symmetry axis of the neck, indices \(m\) and \(n\) refer to quantum numbers of transverse motion in the neck. \(D_{\alpha\beta}(x)\) is the quantum-mechanical transmission coefficient for the connecting channel (see below). The magnetoresistance is defined as follows:

\[
MR = \frac{R^{AF} - R^F}{R^F} = \frac{\sigma^F - \sigma^{AF}}{\sigma^{AF}}. \tag{3}
\]

Quantization of transverse motion in the channel obliges the parallel to the interface projection of the incident quasiparticle momentum to satisfy the requirement:

\[
p_{||} = p_{F\alpha} \sin \theta = p_{mn} \equiv \hbar \lambda_{mn}, \tag{4}
\]

where \(p_{F\alpha}\) is the Fermi momentum for the \(\alpha\)-th spin-channel, \(\lambda_{mn}\) is the quantized wave number (see definition below). This is the first basic selection rule, which comes from quantization. Tilde in (1) and (2) means that the summations should be done over the open conduction channels satisfying the condi-
When the magnetizations alignment is ferromagnetic, the Fermi momenta on both sides of the contact are equal in each, spin-up and spin-down, channel, respectively. The energy and momentum conservations are satisfied, and the transmission coefficients are equal to unity. At the antiferromagnetic alignment the conservation of the parallel to the interface momentum ($p_\parallel$ = $p_{F1a} \sin \theta_1 = p_{F2a} \sin \theta_2$, where the subscript 1 or 2 labels left- or right-hand side of the contact, respectively) introduces the additional selection rule into Eq. (4):

$$p_{Fa} = \min(p_{Fj\uparrow}, p_{Fj\downarrow}).$$

This selection rule is strictly valid, if the electron spin conserves upon transmission through the DW. We believe, that conservation is realized in the atomic-size point contacts, when the length of the connecting channel is comparable with the Fermi wave-length of the current carriers. It was argued that the above scenario is realized, if the DW width $\delta < \delta_s$, where $\delta_s = \min(v_F/\omega_Z, v_F T_1)$, $T_1$ is the longitudinal relaxation rate time of the carriers magnetization [17], and $\omega_z$ is the Larmore precession frequency [21]. Imamura et al. [7] justified the above hypothesis for a quantum DW by numerical calculations for the linear chain of spins.

We perform concrete calculations for the neck of rectangular cross-section, which models a contact with asymmetric cross-section. The solution to the Schrödinger equation for the electron moving in the neck is sought in the form

$$\Psi(x, y, z) = \Phi(z) \sin \frac{\pi n x}{a} \sin \frac{\pi m y}{b}. \quad (7)$$

The function $\Phi(z)$ describes motion along the channel, it obeys the equation

$$\hbar^2 \frac{\partial^2 \Phi}{\partial z^2} + \left( p_{F0}^2 - \lambda_{mn}^2 \hbar^2 + 2MU(z) \right) \Phi = 0, \quad (8)$$

where $U(z) = z E_{ex}/l$ is the potential landscape created in the neck by the constrained domain wall, $E_{ex}$ is the conduction band exchange energy splitting, $M$ is the conduction electron mass, $a$ and $b$ are the width and height of the neck and $p_{F0}$ is the Fermi momentum in absence of conduction band splitting. In Eqs. (7) and (8) $m$ and $n$ are positive integer quantum numbers.

The discrete function $\lambda_{mn}$ is given by

$$\lambda_{mn} = \pi \sqrt{\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2}. \quad (9)$$
The choice of potential energy $U(z)$ in the form of linear function of $z$ is based on the calculations by Bruno (Ref. [16], Fig. 2). Eq. (8) has an exact solution in terms of Airy functions, the explicit expression for the transmission coefficient $D_{\alpha\beta}$ is given in Ref. [12].

A numerical routine consists of the summation over the consecutive values of the roots $\lambda_{mn}$ satisfying the constraints, Eqs. (4) and (5). At the antiferromagnetic alignment the minority Fermi momentum of the either spin projection should be used instead of $p_{F\alpha}$ in Eqs. (4) and (5) to calculate the conductance $\sigma^{AF}$, Eq. (2). The results are displayed on Figures 1 and 2, important for the discussion conduction band spin-polarization parameter $\gamma$ is defined as: $\gamma = p_{F\downarrow}/p_{F\uparrow} \leq 1$. Calculations revealed that the results depend on the absolute value of $p_{F\uparrow}$, we have chosen $\hbar^{-1}p_{F\uparrow} = 1\text{Å}^{-1}$ for the presentation.

3 Results of calculations

Fig.1 displays the results of calculations for the neck of the square cross-section ($b = a$) and $\gamma = 0.68$. Panel (a) shows the dependence of F- and AF-conductances on the channel radius. $l$ and $\lambda = lp_{F\uparrow}\hbar^{-1}$ are the length in Å and dimensionless length of the connecting channel, respectively. The chosen value, $\lambda = 10.0$, corresponds to the connecting channel length 10Å (1 nm). Panel (b) shows the dependence of magnetoresistance on the channel size $a$. The panels (c) and (d) display the magnetoresistance against F-conductance for the sloping (c) and the step-like (d) potential landscapes in the channel, the latter one is the limiting case of very sharp DW. Physically, Fig.1 demonstrates the case, when the AF-alignment conduction opens in the interior part of the first F-conductance plateau. It allows us to make the following conclusions: 1) the F-alignment conductance is spin-dependent, the conduction of spin-channels open asynchronously (panel (a)), thus resulting in $e^2/h$ quantization of conductance [7,8]; 2) if some number of conduction channels are open for the F-alignment ($\sigma^F$ is finite), but there is no conduction for the AF-alignment ($\sigma^{AF} = 0$), then, according to definition Eq. (3), MR diverges. Magnetoresistance is infinite in the idealized model with no reversal of the carriers spin upon transmitting the neck. In a more realistic treatment the magnitude of MR of this quantum spin-valve is restricted by the spin-flip process, which gives rise to a finite AF-conductance at any number of open F-conductance channels. It is the quantum spin-valve regime; 3) the magnitude of MR beyond the quantum spin-valve regime is well above 200% for very moderate polarization of the conduction band ($\gamma = 0.68$, see discussion below); 4) the magnetoresistance has very sharp and high peak, when the first channel for AF conductance step appears (panel (b) in correlation with panel(a)); 5) sudden jumps in magnetoresistance, followed by practically flat plateaus, appear at the moments when new F-alignment spin-up conductance channel
opens. They persist until the spin-down projection opens new channel (panel (b) in correlation with panel (a)); 6) panels (c) and (d) show that the magnetoresistance drawn as a function of quantized F-alignment conductance is a multivalued function of F-conductance, $\sigma^F$ [12]. The issue 4) leads to weakly disperse, or even non-disperse behavior of magnetoresistance at certain numbers of open F-alignment channels: $N^F = 4, 5, 7, 11, 13, 17...$ (see panels (c) and (d)). Non-disperse behavior of MR comes if the AF-conductance is practically independent on the contact size when a new F-conductance channel opens (see panel (a)). The issue 6) means, that if the temperature and disorder effects can be neglected, several values of magnetoresistance correspond to the same number of open conductance channels for the F-alignment of magnetizations (abscissa in the panels (e) and (d)). The overall width of distributions of MR points, which belong to the same value of the quantized F-conductance, may be comparable with maximal value of MR, i.e. magnetoresistance acquires giant fluctuations because of conductance quantization.

Next, we change the aspect ratio $\varepsilon$ of the sides of the rectangular cross-section, $\varepsilon = b/a$. Fig. 2 is drawn with $\varepsilon = 1.5$. Main changes compared to Fig. 1 can be summarized as follows: 1) the AF-conductance opens now at three open channels of F-conductance ($\sigma^F = 3e^2/h$, panels (c) and (d)); 2) the range of the neck sizes with zero AF-conductance (quantum spin-valve) becomes broader; 3) the overall magnitudes of MR increase (panels (b)-(d)); 4) magnetoresistance points appear at almost every number of open F-conductance channels (compare panels (c) and (d) of Figs. 1 and 2). We emphasize the issue which has important implication to point contact GMR experiments: number of open F-conductance channels, at which the AF conductance opens ($\sigma^F = 2e^2/h$ in Fig.1 and $\sigma^F = 3e^2/h$ in Fig.2) depends not only on the polarization of the conduction band [12], but also on the asymmetry of the point contact cross-section.

4 Discussion of the results

There are techniques, which provide the information about the spin-polarization of the ferromagnet’s conduction band at the Fermi energy. These are the ferromagnet-insulator-superconductor tunneling spectroscopy (see Ref. [22] and references therein) and the Andreev-reflection spectroscopy [23–28]. The tunneling spectroscopy suggests the following estimates for the mean values of conduction band polarization parameter $\gamma$: 0.6 for permalloy ($\text{Ni}_{80}\text{Fe}_{20}$); 0.63 for pure Ni; 0.48 for Co and 0.43 for Fe. From the Andreev-reflection spectroscopy we obtain the ranges for the values of $\gamma$: $\sim 0.68$ for permalloy; $\sim 0.62 - 0.72$ for Ni; $\sim 0.6 - 0.68$ for Co; $\sim 0.62 - 0.64$ for Fe. Observing the tunneling and Andreev-reflection data on $\gamma$ and our figures we may confirm our conclusion made from calculations for the cylindrical neck in Ref.
[12]: using realistic values of $\gamma$ we may reproduce maximal values as well as giant fluctuations of MR data obtained by García et al. [9–11]. However, the agreement between the theory and the experiment on Fig. 3 in [12] could be even better, if some MR points would appear at neighboring number of open F-conductance channels. Comparison of Figs. 1 and 2 of the present work with Fig. 3 from Ref. [12] shows, that varying the aspect ratio in the range $\sim 1.0 - 2.0$ one may get a desired re-assignment of some MR points to number of conduction channels, and to improve agreement between the theory and the experiment.

Independent on the actual shape of the neck, when its length is comparable or longer than the cross-section size, the dipole-dipole anisotropy energy may cause fluctuations between Bloch, Néel or more complicated types of domain walls. Coey et al. concluded [29,30] that giant MR of a nanocontact may be reduced somewhat by these fluctuations, but not eliminated. In recent calculations Zhuravlev et al. [31] also predicted giant values and fluctuations of MR in segmented nanowires, when conductance of the wire is quantizes.

When the cross-section of the point contact is very small, so that F-conduction is open for only one spin-channel, the magnitude of GMR is limited from above by the spin-reversal rate of conduction electrons upon passing through the neck [12]. Our calculations show (see panels (a) of Figs. 1 and 2), that higher the polarization of the conduction band and larger the asymmetry of the cross-section, then wider the range of neck sizes, at which the regime of quantum spin-valve can be realized. Magnetic half-metal contacts with $\sim 100\%$ polarization of conduction band would be almost always quantum spin-valves at nanometer range of size. In very recent experiments [32,33] the ballistic magnetoresistance (BMR) in the range 3000-4000% has been observed in Ni point contact. These really giant MR values can be easily reproduced in the ballistic regime of quasiclassical conductance, Eq. (23) of Ref. [17], for a moderate polarization of the conduction band: with $\gamma = 0.2$ ($P(\text{DOS}) = 100 \cdot (1 - \gamma)/(1 + \gamma) = 67\%$) we get $MR = 3090\%$, and with $\gamma = 0.18$ ($P = 70\%$) we get $MR = 4140\%$. However, García et al. [33] reported also in the footnote, Ref. 9, that few times GMR up to 100000% was observed in magnetic nanocontacts. Concerning this information, we may guess that this huge magnetoresistance could be actually the result of the quantum spin-valve realization. In contrast to the explanation proposed in [33], the quantum spin-valve hypothesis does not need in almost completely ($100\%$) polarized conduction band to predict $100000\%$ effect. Theoretically, these numbers may appear even at experimentally approved polarizations of Ni conduction band in the range 35-45% [22–27]. It seems, that quantum spin-valve concept brings us to the upper physical limit of magnetoresistance for a non-superconducting spin-valve-type device. The true infinite (but positive) magnetoresistance can be reached in the proximity-effect superconducting spin-valve (PRESUS-valve) proposed in [34,35].
In conclusion, we have investigated theoretically the giant magnetoresistance of a nanosize magnetic point contact in the regime of conductance quantization. Concrete calculations have been made for the neck of rectangular cross-section, and dependence of GMR on the asymmetry of cross-section has been studied. Results of calculations show that taking into consideration possible asymmetry of the point contact cross-section one may improve agreement between the theory and the experiment. We argued, that if conductance is open for only one spin-channel, the MR magnitude of this quantum spin-valve is limited by the spin-reversal rate of conduction electrons. For larger areas of the nanocontact the magnetoresistance becomes a multivalued function of the conductance $\sigma^F$ at ferromagnetic alignment of contacting magnetic domains. This multivalued behavior of MR (which may be treated as giant reproducible fluctuations of MR) is the intrinsic property of quantum magnetic nanocontacts. This property survives for every shape of the nanocontact and disorder, provided that: 1) conductance at the ferromagnetic alignment is quantized (steps are not destroyed); 2) the domain wall in the constriction is effectively sharp. When observed experimentally, such MR distributions should not be interpreted as being due to poor reliability or reproducibility of experimental data.

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Figure captions

Fig. 1. The dependence of conductance (a), and MR (b) on the cross-sectional size of the neck $a, \varepsilon = 1.0$. Panels (c) and (d) show dependencies of MR on the number of the open conductance channels at the F-alignment of the magnetizations. The maximal MR=563% for the step-like potential at $\sigma^F = 2e^2/h$ is not shown.

Fig. 2. The same as in Fig.1, but for $\varepsilon = 1.5$. The maximal MR=758% for the step-like potential and MR=322% for the sloping potential at $\sigma^F = 3e^2/h$ are not shown.
Fig. 1 by
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- Spin-up channel (F-alignment)
- Spin-down channel (F-alignment)
- AP-alignment (step-like barrier)
- AP-alignment (sloping barrier)

Conductance ($e^2/h$)

Magnetoresistance (%)

Neck size $a$ (Å)

Conductance $\sigma^F (e^2/h)$

Magnetoresistance (%)

MR for step-like barrier

MR for sloping barrier

 Parameters:
- $p_{\text{up}} = 1.0 \text{ Å}^{-1}$
- $\gamma = 0.68$
- $\lambda = 10.0$
- $\varepsilon = 1.0$
Fig. 2 by Tagirov, Vodopyanov, Garipov

\[ \rho_{\text{Fup}} = 1.0 \, \text{Å}^{-1} \]
\[ \gamma = 0.68 \]
\[ \lambda = 10.0 \]
\[ \varepsilon = 1.5 \]