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GIANT MAGNETORESISTANCE IN MAGNETIC NANOCONTACTS

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A quasiclassical theory of nanosize point contacts (PC) between two ferromagnets is developed. A maximum available magnetoresistance in PC is calculated for ballistic and diffusive transport at the area of a contact. In the ballistic regime, the magnetoresistance in excess of few hundreds percents is obtained for the iron-group ferromagnets. The regime of quantized conductance through the magnetic nanocontact is considered. It is shown that magnetoresistance is tremendously enhanced at small number of open conductance channels. The quantum spin valve realization is discussed in detail, and recent observations of huge (up to 100’000%) magnetoresistance in the electrodeposited nickel nanocontacts are discussed in the framework of the developed theory.

1. INTRODUCTION

In recent experimental studies of Ni-Ni and Co-Co point contacts (PC) a surprisingly high negative magnetoresistance in excess of 200% has been discovered [1-3]. The set up of the experiments was typical for observation of giant magnetoresistance (GMR), the effect observed earlier in hybrid systems involving ferromagnetic and normal metals [4,5]. However, for the multilayer structures a typical change of the resistance reaches 10-50%, which is considerably lower than the values reported in Refs. [1,2]. Further development of the nanocontacts fabrication techniques raised the above values till 70 000%-100 000% [6-10]. The authors claim that they observed ballistic magnetoresistance (BMR), i.e. the magnetoresistance at ballistic (collisionless) electronic transport at the area and vicinity of the nanocontact.

A negative magnetoresistance can be due to scattering of conduction carriers by a domain wall (DW). According to a general quantum-mechanical prescription any inhomogeneity in the potential landscape results in reflection of quasiparticle wave function, which evokes an additional electric resistance. This effect has been considered for a free-standing domain wall in a number of works [11-14], and low values of MR were obtained assuming that the widths of the DW is large, typically 150-1000 Å. The fact that the enhancement of impurity scattering in a sharp DW may give large MR was utilized in the perturbation theory of Ref. [2] to explain the anomalously large values of MR in the experiments on the point contacts [1,2]. In this paper we review a nonperturbative theory of electron scattering by the constrained domain wall [15-17] aiming to demonstrate that DW scattering enables to provide huge magnitudes of negative magnetoresistance observed in the recent point contact experiments.

2. MODEL OF THE POINT CONTACT AND ITS SOLUTION

2.1Effectively sharp domain wall

The diminishing of the width of DW when decreasing the size of the constriction between two oppositely magnetized domains was proposed by Bruno [18]. In his model the DW width becomes comparable with PC length, and the magnetization rotates almost entirely inside the constriction. This conclusion holds until the diameter of PC is smaller than its actual length. With further increase of the constriction size (diameter) one may expect that the wall will bend outside of PC. This behavior has been clearly demonstrated in recent micromagnetic simulations of domain walls in magnetic nanocontacts [19,20]. In their calculations for two bulk ferromagnetic rods connected by a nanosize thread Savchenko *et al.* [19] demonstrated, that the domain wall is bulged out the constriction on the distance of its size (Figs. 3a-5a of [19]). They also checked that with increasing of material anisotropy the domain wall shrinks towards the connecting thread (Fig. 5 in Ref. [19]). Molyneux *et al.* [20] analyzed in detail nanocontacts between large-area thin films. They concluded, that the width of the constrained DW is about $2a+d$, where d is the length and a is the width of the connecting channel, respectively. In their calculations the magnetization relaxes almost isotropically outside the constriction. Finally, from their numerical calculations the authors of Ref. [20] concluded that 3D domain wall is more localized compared with the 2D (thin-film) one.

The micromagnetic calculation results can be easily understood using simple energy considerations. From the symmetry of the problem it is obvious that in a free-standing, infinite area DW the exchange energy relaxes into the chain of magnetic moments till the total anisotropy energy of the chain equals the loss of the exchange energy (the classic 1D Landau-Lifshitz solution). In the 2D, thin-film case, the portion of the exchange energy, which did not relax inside of constriction, relaxes into the 2D plane outside of the neck. In this 2D-case, two half-circles (we use the conclusion of Ref. [20] about the isotropic relaxation of the magnetization) at mouths of the constriction accommodate the number of magnetic moments in the 1D domain wall chain, minus the number of the moments inside the constriction. In the case of 3D nanocontact, approximately the same amount of magnetic moments has to be accommodated by two semi-spheres at the mouths of the neck. It is clear, that the spatial extent of the domain wall will eventually decrease upon increasing the dimensionality of the magnetization relaxation space (chain -> area -> volume).

Coey *et al.* [21,22] have drawn attention to the fact, that in nanosize constrictions the continuum approximation, used in micromagnetic simulations, is no longer valid. They have analyzed DW in nanocontacts calculating explicitly lattice sums over the magnetic moments in the constriction and the adjacent space. The main conclusions are as follows: discrepancy between results of the continuum and the discrete approaches become marked as the characteristic dimensions fall below 10 inter-atomic spacings; it is possible to have very narrow domain walls with a width determined by the effective length of the constriction, the latter one can be as little as a few inter-atomic spacings.

Another necessary condition for realization of the sharp DW is conservation of the electron spin orientation when crossing the domain wall. The electron spin conserves if the DW width is shorter than the length, at which the electron spin quantization axis adjusts varying direction of the local exchange field. If we assume the DW width 5 nm and the Fermi velocity $v_F \sim 10^5$ m/s, then the time-of-flight is about 5×10^{-14} s - too short compared with Zeeman or spin-relaxation time. At this condition the transmission process looks like transmission through the abrupt DW, and the description of the electron transport through PC with boundary conditions at PC interface is valid.

1.1 *2.2.Formalization of the model and direction of solution*

We believe that extremely large magnetoresistance can be obtained because of the strong spin-dependent reflection of carriers from the effectively sharp DW in the PC area. It is realized in ferromagnetic metals where there is large exchange splitting of conduction band (0.3-1.0 eV). Mapped onto the parabolic conduction band structure the exchange splitting results in non-equivalent values of the spin-subband Fermi momenta, $k_{F\uparrow}$ and $k_{F\downarrow}$ (Ref. [23] gives $k_{F\uparrow} = 1.1$Å^{-1} and $k_{F\downarrow} = 0.42$Å^{-1} for iron).

At the *ferromagnetic* (F) alignment of magnetizations in the contacting ferromagnetic metals there is no domain wall in the constriction, and the current flows through PC independently in each conduction spin-subband. Then, the resistance of PC is actually the Sharvin resistance [24] of spin-channels connected in parallel. At the *antiferromagnetic* (AF) alignment of magnetizations the additional resistance appears, which is associated with reflection of electrons from the potential barrier created by the domain wall. In fact, at AF-alignment the spin-subband assignment in one of the magnetic domains is reversed with respect to the another one, and the current flowing from, say, majority (larger Fermi momentum) subband of one bank of the contact has to be accommodated by the minority (smaller Fermi momentum) subband of the another bank. Then, in terms of quantum mechanics, the incident electron waves will be partially reflected because of the Fermi momenta mismatch of majority and minority subbands ($k_{F\uparrow}>k_{F\downarrow}$). However, the partial reflection of electrons is not the sole reason for the enhanced resistance at the AF-alignment. When the angle of incidence becomes large enough (it depends on the ratio of spin-subband Fermi-momenta, $k_{F\uparrow}$ and $k_{F\downarrow}$) the minority subband can not further accept the momentum transferred from the opposite side of the PC, which is majority subband with the same spin projection. As a result, only a narrow incidence angles cone (for $k_{F\uparrow}>>k_{F\downarrow}$ as in the example given above) around the normal direction to the interface is responsible for the charge transport across the PC. Electrons with more inclined trajectories are completely reflected. Thus, the partial transmission at the steep incidence, and the total reflection at slanted incidence provide high boundary resistance of PC at AF alignment of magnetizations.

The PC model we consider to realize the physics described above is the circular hole of the radius *a* made in a membrane. The membrane divides the space on two half-spaces, occupied by the single-domain ferromagnetic metals. It is impenetrable for the quasiparticles carrying a current, and the connecting channel is assumed to be ballistic (shorter than the mean free path). The *z*-axis of a coordinate system is chosen perpendicular to the membrane plane.

The electron motion on both sides of the contact can be described by the equations for quasiclassical (QC) Green functions derived by Zaitsev [25]. They are, in fact, equivalent to the Boltzmann equations in the τ-approximation. The equations are supplied by boundary conditions [25] which take into account explicitly the quantum mechanical conservation laws for momentum and energy. For the cylindrical geometry of the model the system of kinetic equations can be solved exactly in the mixed, real space in the *z*-direction and the Fourier-transform in the contact plane, representation [15]. The electric current density is expressed via the antisymmetric QC Green function, and the net current ***I*** through the hole in a membrane is calculated integrating the current density over the area of the contact. As far as the currents for the F- and AF alignments are obtained, the magnetoresistance can be found from the definition:

$$MR = \frac{I^F - I^{AF}}{I^{AF}} = \frac{\sigma^F - \sigma^{AF}}{\sigma^{AF}}, \qquad (1)$$

where I^F (σ^F) stands for the current (conductance) at F alignment of magnetizations of contacting ferromagnets, and I^{AF} (σ^{AF}) is for the AF alignment of magnetizations.

3. MAGNETORESISTANCE AT CLASSICAL (NON-QUANTIZED) CONDUCTION

To simplify the general analysis of the solution we use the step-like shape for the potential barrier created by DW. The approximation of DW profile by the abrupt potential gives maximum available magnetoresistance for a particular choice of other physical parameters [15]. For the purely ballistic transport [$a/l_{\uparrow}$->0, where $l_{\uparrow}$ ($l_{\downarrow}$) is the majority (minority) electrons mean free path] the magnetoresistance can be evaluated analytically:

$$MR = \frac{(1-\delta)\left\{5\delta^3 + 15\delta^2 + 9\delta + 3\right\}}{8\delta^3(\delta + 2)} \qquad (2)$$

where

$$\delta = \frac{k_{F\downarrow}}{k_{F\uparrow}} = \frac{v_{F\downarrow}}{v_{F\uparrow}} \le 1. \qquad (3)$$

If δ=1, then MR=0, *i.e.* the magnetoresistance vanishes in the contact of non-magnetic metals. For the set of δ values we obtain from (2): δ=0.5 MR=238%; δ=0.4 MR=455%; δ=0.33 MR=780%; δ=0.3 MR=1012%.

Let us recall here the experimental data on magnetoresistance of magnetic PC by García *et al.* Ni-Ni PC showed maximal MR=280% [1], Co-Co PC showed maximal MR=230% [2]. To obtain the MR values of 280% (Ni) and 230% (Co) we have to use the values δ(Ni)=0.47 and δ(Co)=0.5. These values are in the range of the values, obtained experimentally from the single photon threshold photoemission [26] and from ferromagnet/superconductor point contact spectroscopy [27,28].

For the arbitrary mean free path MR can be calculated numerically. The results for the magnetoresistance (1) as a function of the contact radius are shown in Fig. 1.

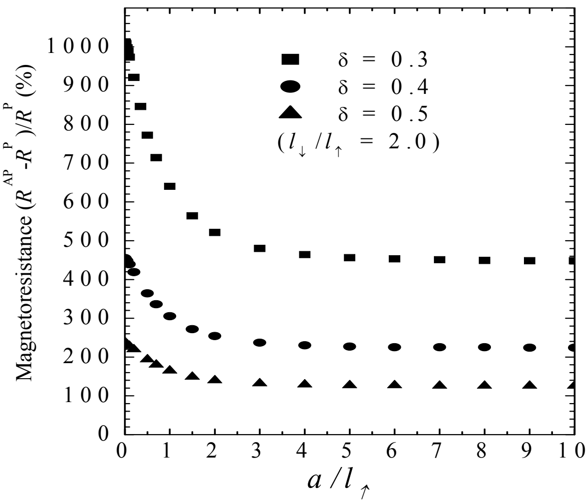

Fig. 1. Dependence of magnetoresistance on the PC radius.

Calculation show that magnetoresistance is enhanced when conductance approaches ballistic regime (small contact radius a).

3. CONDUCTANCE QUANTIZATION AND MAGNETORESISTANCE IN MAGNETIC POINT CONTACTS

Since experiments with two-dimensional electron gas in a semiconductor it is demonstrated that electric conduction is quantized, and elementary conductance quantum is equal to $2e^2/h$. 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 [29-32]. It is possible, because phonon- and magnon-assisted relaxation processes are quenched due to a large, ~1 eV, exchange splitting of the conduction band. In addition, Oshima and Miyano [30] found a clear 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* [32] presented the 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 by exchange field acting from the ferromagnetically ordered spins.

We applied our model described above to the case, when conductance of the constriction is quantized [16,17]. The generalization on the case of conductance quantization means proper re-definition of the transmission coefficient D in the formulas for the conductance. We assume that the connecting channel has the cylindrical shape of arbitrary (but shorter than the mean free path) length d. The channel plays the role of a filter, which selects from the continuous domain of quasiparticle incidence angles only those, which satisfy the energy and momentum conservation laws, and conditions for quantization of the transverse motion of an electron in the channel. As the diameter of the channel is assumed to be very small, we may use the ballistic-limit versions of our formulas to calculate the conductance of the channel. For the numerical calculations we used the step-like potential barrier, as before, and the sloping potential landscape to approximate the constrained domain wall profile [18]. The transmission coefficient D for the sloping potential has been obtained from the exact solution of the Schroedinger equation for the motion of electron in the potential landscape of DW linearly changing inside of the constriction of the length d. The necessary condition for the model is conservation of the electron spin orientation when crossing the domain wall. The electron spin conserves if the DW width is shorter than the length, at which the electron spin quantization axis adjusts varying direction of the local exchange field. If we assume the DW width 5 nm and the Fermi velocity v_F~10^5 m/s, then the time-of-flight is about 5×10^{-14} s – too short compared with the Zeeman or spin-relaxation time. The results of calculations are presented in Fig. 2.

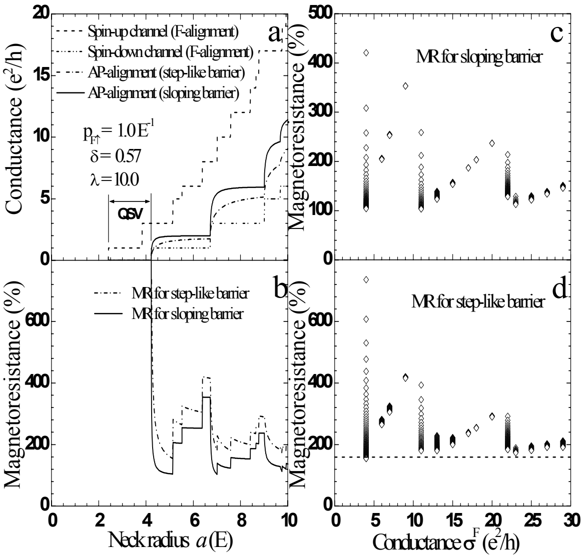

Fig. 2. The dependence of conductance (a), and MR (b) on the cross-sectional size of the neck *a*. Panels (c) and (d) show dependencies of MR on the number of the open conductance channels at the F-alignment of the magnetizations. The maximal MR=3953% and MR=1017% for the step-like potential and MR=1612% for the sloping potential at $\sigma = 4(e^2/h)$ are not shown.

The main conclusion that follows from Fig. 2 is that MR experience huge enhancement at small numbers of open conductance channels. For very moderate polarization of the conduction bans MR may reach few thousand percents. In the range of the PC size labeled by QSV in Fig. 2a the AF-alignment conductance is zero. Then, according to Eq. (1) MR is infinite. In reality there are spin-reversal processes which open small but finite conductance at AF-alignment of magnetization. This introduces natural upper bound preventing infinite growth of magnetoresistance. It is worthy to note, that conductance quantization introduces giant reproducible fluctuations of conductance as it can be seen from Figs. 2b, 2c and 2d. We have put our calculations on the experimental data by N. García *et al.* The results are shown in Fig. 3.

It can be seen that some points do not fit correct abscissa, however, our calculation has been made for the cylindrical cross-section of the connecting channel. This requirement cannot be fulfilled in a contact which is fabricated by a mechanical contact of a tip with a flat surface. If we assume asymmetric cross-section, then the points of magnetoresistance can appear at shifted values of quantized conductance at F-alignments (abscissa). Indeed, our calculations show that for the rectangular cross-section of the bridge the location of the magnetoresistance points depends on the aspect ratio of the cross-section (see Fig. 4 and Fig. 5).

From the model calculation above it can be concluded that deformation of the tip in the contacting process can easily shift the magnetoresistance points along the abscissa of the graph thus giving an additional degree of freedom to improve agreement between the theory and the experiment. However, we do not have data on the shape of the contacts to make particular calculations.

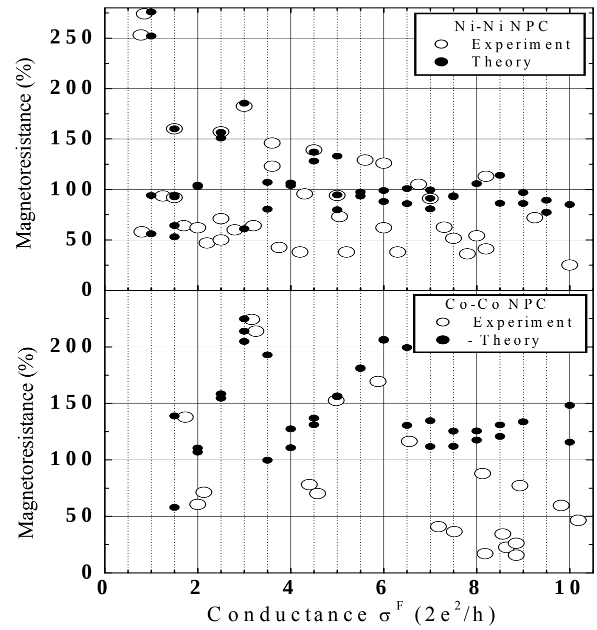

Fig. 3. Experimental data and calculated points (δ(Ni)=0.64 and δ(Co)=0.57) for MR put on the same graph. The experimental data are taken from Ref. [6].

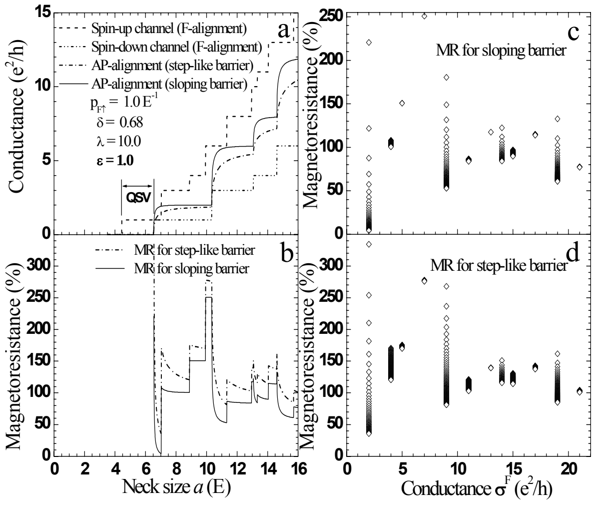

Fig. 4. The dependence of conductance (a), and MR (b) on the cross-sectional size of the neck *a*. Panels (c) and (d) show dependencies of MR on the number of the open conductance channels at the F-alignment of the magnetizations.

5. CONCLUSION

In conclusion, we have investigated theoretically the giant magnetoresistance in nanosize magnetic point contacts made of ferromagnetic metal. Our calculations show that the magnitude of magnetoresistance is dramatically enhanced when the ballistic regime of conductance is realized. The ballistic magnetoresistance (BMR) in the quasiclassical regime of conductance can easily reach few hundred percents at experimentally approved polarizations of the ferromagnet conduction band. Next, the regime of quantized conductance through the point contact is considered, and the conductance is calculated for the ferromagnetic (F) and antiferromagnetic (AF) alignments of magnetizations in contacting ferromagnets. Calculations show that BMR of the quantum point contact experiences huge enhancement at first few open conduction channels for the F-alignment of magnetizations.

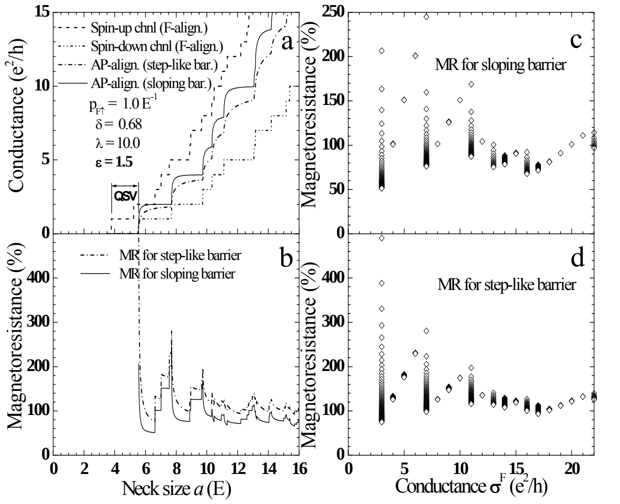

Fig. 5. The same as in Fig. 4, but for ε = 1.5. The maximal MR=758% for the step-like potential and MR=322% for the sloping potential at are not shown.

At certain range of the contact area the BMR is infinitely large as far as the electron-spin is conserved upon transmission through the point contact. We called this regime of the magnetic point contact operation as quantum spin-valve (QSV). In a more realistic model BMR has to be limited from above by the conduction-electron spin-reversal process, and can reach tens of thousand percents. It is very likely, that recent observations of huge, 3 000% to 100 000% BMR in nickel point contacts have origin in conductance quantization and realization of the QSV regime. This huge magnetoresistance 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 (the conduction electron spin-flip rate is slow). Very recent observations [33] of quantized conductance at room temperature and magnetoresistance, which experience giant fluctuations as a function of quantized conductance, give further evidence of the physical picture that we described in this paper.

6. ACKNOWLEDGEMENTS

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