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Materials Science and Engineering C 25 (2005) 705 – 709

MATERIALS SCIENCE & ENGINEERING C

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Magnetoresistance due to domain walls in semiconducting magnetic nanostructures

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Available online 20 July 2005

Abstract

Magnetoresistance of a semiconducting ferromagnetic nanostructure with a laterally constrained domain wall is analyzed theoretically in the limit of sharp domain walls and fully polarized electron gas is considered. The spin–orbit interaction of Rashba type is included into considerations. It is shown that the magnetoresistance in such a case can be relatively large, which is in a qualitative agreement with recent experimental observations. It is also shown that spin–orbit interaction can enhance the magnetoresistance. The role of localization corrections is also briefly discussed.

Keywords: Domain walls; Spin–orbit interaction; Magnetic semiconductors

1. Introduction

There is a growing interest in the magnetoresistance associated with domain walls (DWs) in metallic ferromagnets [1]. Owing to recent progress in nanotechnology, it became possible now to extract a single DW contribution to electrical resistance [1–4]. In a series of experiments, the magnetoresistance associated with DWs was found to be very large [5–10]. In particular, the experiments on Ni microjunctions showed that a constrained DW at the contact between ferromagnetic wires produces an unexpectedly large contribution to electrical resistance, and consequently leads to a huge negative magnetoresistance [9]. Very recently, the magnetoresistance of up to 2000% has been measured in semiconducting magnetic nanoconstrictions [10].

It has been shown theoretically [11] that DWs in magnetic nanoconstrictions can be very sharp, with the characteristic width L being of atomic scale. This is much less than typical DW width in bulk materials or thin films. Theoretical descriptions of transport properties of DWs are mainly restricted to smooth DWs [12–16], typical for bulk ferromagnets. Electron scattering from DWs is then rather weak and the spin of an electron propagating across the wall follows the magnetization direction almost adiabatically. The additional resistance calculated in the semiclassical approximation can be either positive or negative and is rather small. The condition for validity of the semiclassical approximation is $k_{F\uparrow(\downarrow)}L \gg 1$, where $k_{F\uparrow}$ and $k_{F\downarrow}$ are the Fermi wavevectors for the majority and minority electrons, respectively.

Scattering of electrons from sharp DWs can be, however, quite strong and the semiclassical approximation is then no

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doi:10.1016/j.msec.2005.06.021

longer applicable. Large magnetoresistance in magnetic junctions was found by Tagirov et al. [17], who considered DW as a potential barrier independent of the electron spin orientation. Ballistic electron transport through DWs has also been analyzed by numerical simulation methods [18–20]. Recently, the ballistic motion through a nanocontact has been studied by Zhuravlev et al. [21], who found a large magnetoresistance effect due to the presence of a non-magnetic region within the constriction considered as a one-channel wire.

The one-dimensional model of a sharp DW has been considered in Ref. [22] in the limit of $k_{F\uparrow(\downarrow)}L \ll 1$. It has been shown there that the problem can be viewed as transmission through a spin-dependent barrier. It has been also shown, that the magnetoresistance can be then quite large and increases with increasing spin polarization of electrons. Thus, the largest magnetoresistance effect can be expected in fully spin polarized electron gas [23]. Here we study such a case in the limit of a sharp DW [22]. Additionally, we take into consideration also spin–orbit interaction.

2. Model and scattering states

We consider a ferromagnetic narrow channel with a magnetic DW. The magnetization is a function of the coordinate z (along the channel), $\mathbf{M}(z)=[M_0 \sin\varphi(z), 0, M_0 \cos\varphi(z)]$, where $\varphi(z)$] varies from zero to π for z changing from $z=-\infty$ to $z=+\infty$. Let the characteristic length scale of this change be L. Thus, the magnetization is oriented along the axis z for $z<-L$, and points in the opposite direction for $z>L$. The DW width L in constrained magnetic contacts can be of an atomic order.

Magnetization leads to a splitting of the spin-up and spin-down electron bands (we take the quantization axis along z). We assume the parabolic band model, that is suitable for description of conduction electrons in semiconductors. Due to the spatial variation of magnetization $\mathbf{M}(\mathbf{r})$, spin-flip scattering of electrons can take place within the domain wall. In addition, the spin-up electrons propagating along the axis z are reflected from the effective potential barrier at $z=0$, which occurs when DW is sharp. Correspondingly, the spin-down electrons moving in the same direction do not feel any barrier and are not reflected back. Hence, the strongest effect of DWS on electronic transport can be expected in the case of full spin polarization of electron gas, when there are no spin-down electrons at $z<0$, and no spin-up electrons at $z>0$. This takes place when $JM_0>E_F$, where J is the exchange integral, and E_F is the Fermi energy in the absence of magnetization (it characterizes the total electron density n of the semiconducting material, $n=(2mE_F)^{3/2}/3\pi^2\hbar^3$, where m is the electron effective mass). We assume that the requirement of full spin polarization is fulfilled. In the case of magnetic semiconductors, this means the depletion of a region near DW.

The condition of sharp DW means that the wall width is smaller than the electron Fermi wavelength, $L\kappa_F<1$, where κ_F is the electron Fermi wavevector. This condition can be easily fulfilled in semiconductors, especially in the case of low electron concentration. When DW is laterally constrained, the number of quantum transport channels can be reduced to a small number. In the extreme case only a single conduction channel is active. The corresponding condition is $L_c\kappa_F<1$, where L_c is the wire width. This condition can be easily obeyed in semiconductors with low density of carriers.

We adopt the model of a 1D electron gas in spatially varying magnetization field due to DW. An important element we add to the model is the presence of spin–orbit interaction. Under the condition of full spin polarization, the spin-flip scattering provides mixing of different spin channels that is responsible for the transfer of electrons through the domain wall. Thus, we can expect a strong influence of the spin–orbit interaction on the total resistance. We assume the spin–orbit interaction in the form of Rashba term. Such interaction is usually associated with the asymmetric form of the confining potential leading to size quantization in quantum wells and wires, and also with the effect of substrate. In p-type semiconductors, the spin–orbit interaction can also be related to the complex form of the Hamiltonian describing holes, but the corresponding model becomes much more complicated.

Thus, we assume the model Hamiltonian in the form

$$H = -\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}z^2} - JM_z(z)\sigma_z - JM_x(z)\sigma_x + i\alpha\sigma_x\frac{\mathrm{d}}{\mathrm{d}z}, \quad (1)$$

where α is the parameter of spin–orbit interaction, whereas σ_x and σ_z are the Pauli matrices. We choose the axis x normal to the wire and assume the magnetization in the wall rotates in the x–z plane. The Rashba spin–orbit interaction in Eq. (1) corresponds to the axis y perpendicular to the substrate plane. The magnetization vector rotates then in the substrate plane. Although the one-dimensional model describes only a single-channel quantum wire, it is sufficient to account qualitatively for some of the recent observations. It can be generalized to the case of a wire with more conduction channels (the conductance can be then presented as a sum over conductive channels).

In the following description we use the basis of scattering states. The asymptotic form of such states (taken sufficiently far from DW, $|z| \gg L$) can be written as

$$\psi_{kR}(z) = \frac{e^{ikz}}{D_k}\begin{pmatrix} M_k \\ \alpha k \end{pmatrix} + \frac{re^{-ikz}}{D_k}\begin{pmatrix} M_k \\ -\alpha k \end{pmatrix} + \frac{r_f e^{\kappa z}}{D_\kappa}\begin{pmatrix} i\alpha\kappa \\ M_\kappa \end{pmatrix}, \quad z<-L, \quad (2)$$

$$\psi_{kR}(z) = \frac{t_f e^{ikz}}{D_k}\begin{pmatrix} \alpha k \\ M_k \end{pmatrix} + \frac{te^{-\kappa z}}{D_\kappa}\begin{pmatrix} M_\kappa \\ -i\alpha\kappa \end{pmatrix}, \quad z>L, \quad (3)$$

where $k=[2m(E+M)]^{1/2}/\hbar$ and $\kappa=[2m(M-E)]^{1/2}/\hbar$, whereas the other parameters are defined as $M_k=M+(M^2+\alpha^2k^2)^{1/2}$, $M_\kappa=M+(M^2-\alpha^2\kappa^2)^{1/2}$, $D_k=(M_k^2+\alpha^2k^2)^{1/2}$, $D_\kappa=(M_\kappa^2+\alpha^2\kappa^2)^{1/2}$, with $M=JM_0$ and E denoting the electron energy.

Due to spin–orbit interaction, electron states are superpositions of spin-up and spin-down components. For simplicity, we call them in the following as spin-up and spin-down waves, because they reduces to such waves in the limit of vanishing spin–orbit interaction. Thus, the scattering state (2), (3) describes the spin-up wave incident from $z=-\infty$ to the right, which is partially reflected and also partially transmitted into the spin-up and spin-down channels. The coefficients t and t_f are the transmission amplitudes without and with spin reversal, respectively, whereas r and r_f are the corresponding reflection amplitudes. Even though there are no minority carriers far from the domain wall, the corresponding waves exist in the vicinity of the domain wall, and decay exponentially to the bulk. Similar forms also have the scattering states $\psi_{k\mathrm{L}}$ describing electrons incident from the right to left.

When $kL \ll 1$, the reflection and transmission coefficients can be calculated analytically. Upon integrating the Schrödinger equation $H\psi=E\psi$ (with the Hamiltonian given by Eq. (2)) from $z=-\delta$ to $z=+\delta$, and assuming $L \ll \delta \ll k^{-1}$, one obtains

$$\frac{\hbar}{2m}\left(\left.\frac{\mathrm{d}\psi_{Ki}}{\mathrm{d}z}\right|_{z=+\delta}-\left.\frac{\mathrm{d}\psi_{ki}}{\mathrm{d}z}\right|_{z=-\delta}\right)+\lambda\sigma_x\psi_{k;i}(z=0)=0 \tag{4}$$

for each of the scattering states $(i=(R,L))$, where

$$\lambda\simeq\frac{J}{\hbar}\int_{-\infty}^{\infty}\mathrm{d}z\,M_x(z). \tag{5}$$

Eq. (4) has the form of a spin-dependent condition for electron transmission through a δ-like potential barrier located at $z=0$. To obtain this equation we made use of the condition $kL \ll 1$. The magnitude of the parameter λ in Eq. (5) can be estimated as $\lambda \simeq JM_0L/\hbar=ML/\hbar$.

Using the full set of scattering states, together with the wave function continuity condition, one can find a set of equations for transmission amplitudes t and t_f. Since the wave conserving spin decays exponentially away from the wall, only spin-flip amplitude t_f determines electric current in the wire. Let us denote by $v=k/m$ the velocity of incident electrons, and by $\nu=\kappa/m$ the corresponding quantity for the exponentially decaying wave. In the absence of spin–orbit interaction, $\alpha=0$, one finds

$$t_f=\frac{4i\lambda v}{(v+i\nu)^2+4\lambda^2}. \tag{6}$$

In the limit of $\nu \gg v$ and $\lambda \ll \nu$ (low density of carriers and small spin–orbit interaction) one can find another limiting formula,

$$t_f=-\frac{4iv\lambda^2}{\nu^2(\lambda-i\alpha v\kappa/M)}. \tag{7}$$

In the general case, the coefficient t_f can be found analytically but the corresponding formula is rather cumbersome.

In the limit of $\lambda \to 0$ (very thin DW), the transmission through the wall vanishes, which corresponds to the complete reflection from the barrier. In the case of nonzero spin–orbit interaction, we could naively expect nonvanishing penetration through the wall even in the limit of thin domain wall. However, the condition of matching wave functions at $z<L$ and $z>L$ do not allow penetration of one spin component because both incident and transmitted waves are certain superpositions of spin-up and spin-down electrons. Eq. (7) shows that the transmission through the wall decreases with increasing spin–orbit interaction.

3. Resistance of the domain wall

To calculate the conductance of the system, we use the Büttiker–Landauer formula, which can be essentially simplified due to suppression of all channels but spin-flip through the wall. (The derivation of such a formula for transmission through the wall in the case of all nonvanishing channels has been done in Ref. [22].) Thus, one obtains

$$G=\frac{e^2}{2\pi\hbar}|t_f|^2. \tag{8}$$

Due to the current conservation, the conductivity is determined by the propagating (non-decaying) component of the transmitted wave. Using Eq. (6) one finds

$$G=\frac{8e^2}{\pi\hbar}\frac{\lambda^2v^2}{\left(v^2-\nu^2+4\lambda^2\right)^2+4v^2\nu^2} \tag{9}$$

for vanishing spin–orbit interaction. All the velocities are taken here at the Fermi level.

In the general case, the calculated dependence of electrical conductance on the Fermi-energy E_F is presented in Fig. 1. The curves shown there were calculated for the parameters: $m=0.6\ m_0$, $M_0=0.2$ eV, and $L=2\times10^{-8}$ cm. These parameters correspond to GaMnAs semiconductor and critical temperature $T_c \simeq 200$ K. The conductance monotonically increases with increasing E_F, since the barrier is smaller for electrons of higher energy. The spin–orbit interaction, however, diminishes the conductance of a magnetic wire with DW.

The dependence of magnetoresistance on the Fermi energy E_F is presented in Fig. 2 for different values of the parameter α. The magnetoresistance was calculated with respect to the state without DW, $MR=R_{DW}/R_0-1$, where R_{DW} is the resistance of the wire with DW and $R_0=2\pi\hbar/e^2$ is its resistance in the absence of the wall (only spin-up channel is active). For our choice of parameters, the magnetoresistance is rather high and increases substantially with spin–orbit interaction.

The magnetoresistance measurements on magnetic semiconductors are usually performed at low temperatures because the corresponding Curie temperature is rather low. At such conditions, one can expect significant contribution of the localization corrections to conductivity. The role of localization in the case of smooth DWs (for $kL \gg 1$) has been studied before [24,25], and it was shown that the localization corrections are suppressed by an effective gauge field of the wall. This means that the contribution of the wall to resistance is negative, and the corresponding magnetoresistance is positive. We have analyzed the role of localization corrections in the case of sharp DW. Qualitatively, it can be described as the DW induced suppression of the quantum interference in triplet Cooperon channel [26]. The singlet channel in ferromagnets is strongly suppressed by the internal magnetization [27]. The suppression of the interference by DWs is related to dephasing of the wave function of electron transmitted through the barrier. If the transmission through the wall is small, the corresponding dephasing length roughly equals to the distance of electron moving from a point z (within the constriction) to the domain wall position ($z=0$), and the dephasing time is $\tau_{\rm dw}(z) \sim z^2/D$, where D is the diffusion coefficient. After averaging over z of the local localization correction $\delta G(z)$, we find that the characteristic dephasing length L_0 is the constriction length itself, $\delta G_{\rm dw} \simeq -e^2 L_0/\pi\hbar$. In the case of sharp DWs, the localization correction diminishes the magnetoresistance due to the reflection from the wall, since it has a different sign.

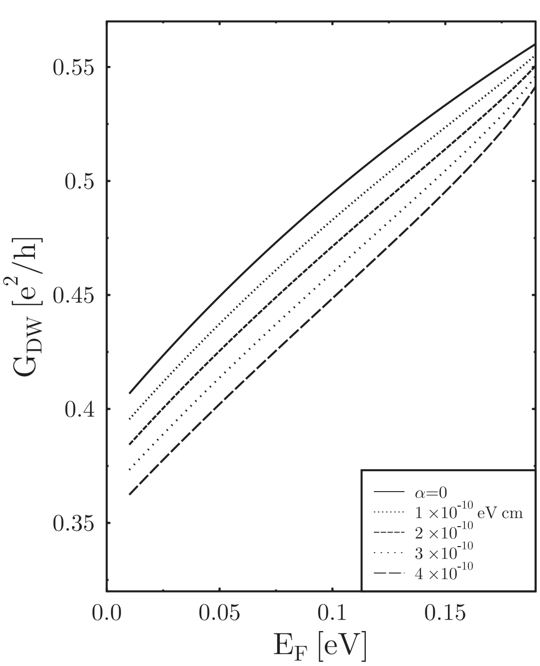

Fig. 1. Conductance of magnetic wire with a domain wall vs. Fermi energy of electrons. Different curves correspond to different values of the spin–orbit coupling parameter α.

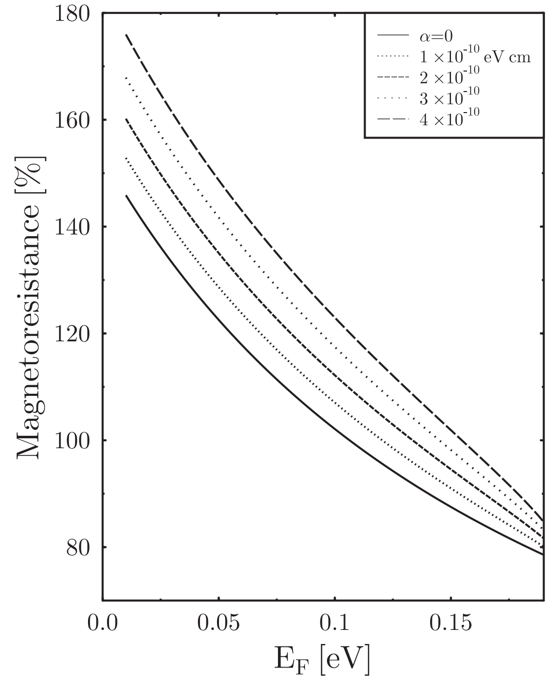

Fig. 2. Magnetoresistance of the wire with a domain wall vs. Fermi energy for different values of α.

4. Conclusions

We have presented a theoretical description of the resistance of a semiconducting magnetic nanojunction with a constrained DW in the case of full spin polarization of electron gas. In the limit of $\kappa L \ll 1$, the electron transport across the wall was treated effectively as electron tunneling through a spin-dependent potential barrier. For such a narrow and constrained DW, the electron spin does not follow adiabatically the magnetization direction, but its orientation is rather fixed. However, DW produces some mixing of the spin channels. The spin–orbit interaction essentially enhances the magnetoresistance of such a structure, whereas the localization corrections play an opposite role. However, the localization corrections can be totally suppressed by the spin–orbit interaction [27]. This indicates that the spin–orbit interaction can play an important role and can lead to large enhancement of the magnetoresistance effect.

The magnetoresistance effect of a similar origin can occur in nonmagnetic semiconductors in external magnetic field. Splitting of spin-up and spin-down electron states is then created by the magnetic field. In strongly disordered semiconductors the magnitude of effective field acting on electrons is not uniform, which makes the problem similar to the case of nonuniform magnetic semiconductors.

Acknowledgements

This work is supported by Polish State Committee for Scientific Research, Grants No. PBZ/KBN/044/P03/2001 and No. 2 P03B 053 25, and also by INTAS Grant No. 00-0476.

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