Eur. Phys. J. B **54**, 103–107 (2006)
DOI: 10.1140/epjb/e2006-00415-3

THE EUROPEAN PHYSICAL JOURNAL B

Magnetic field dependence of the domain wall resistance in a quantum wire

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Received 9 January 2006 / Received in final form 18 October 2006
Published online 22 November 2006 –

Abstract. For an ideal one-dimensional ferromagnetic wire with a magnetic domain wall (DW), contribution of the DW to the resistivity of the system has been investigated. We have studied the resistance due to the magnetic impurities in the domain wall which was suspended in a weak magnetic field for two types of chiralities. The analysis has been based on Boltzmann transport equation, within the relaxation time approximation. Through this formalism, both increasing and decreasing of the resistance due to the DW have been predicted in presence of Zeeman interaction as an extrinsic mechanism.

PACS. 73.63.-b Electronic transport in nanoscale materials and structures – 72.25.Rb Spin relaxation and scattering

1 Introduction

The advances in nano-technology have enabled researchers to fabricate low dimensional devices. Because of some especial quantum mechanical effects many different transport properties are expected in these systems. This has made an enormous interest for observing novel transport phenomena especially in the magnetic systems which have a spin degree of freedom more than their corresponding nonmagnetic samples [1–3]. In these systems spin-dependent scattering makes accountable role in the electrical resistance. In addition, the long dephasing time of electron's spin and easy manipulation of the spin polarization by an external magnetic field, have made these kinds of materials to be one of the suitable candidates for information transmission devices.

Transport in magnetic systems can be influenced by various magnetic parameters. Experiments on iron whiskers [4] demonstrate that domain walls (DWs) are a source of electrical resistance. The domain wall magnetoresistance (DW-MR) can be either positive or negative, i.e. the DW can either increase or decrease the resistivity of the sample. Positive magnetoresistance (MR) due to the DW has been reported by Gregg et al. in striped domain structures [5]. Positive MR also have been observed in the Ni wires [6], in single layer ferromagnetic wires of $Ni_{80}Fe_{20}$ [7] and in a junction of mesoscopic ferromagnetic NiFe wires [8]. In contrast, a number of experiments on very narrow wires and thin films have been conducted which show negative MR [9–13].

Accordingly, there are various theoretical studies about the MR of a DW. Quantum decoherence caused by the DW has been mentioned as a source for reduction of the resistance in which the wall leads to negative MR in the weakly localized regime (for example see [14]). On the other hand, spin-dependent impurity scattering which was proposed by Levy and Zhang was supposed to be responsible for mixing the spin channels and positive MR [15]. In the frame work of two-band ferromagnet Stoner model, with noncollinear magnetization, van Gorkom et al found that the semiclassical DW-MR is either negative or positive depending on the difference between the spin-dependent scattering lifetimes [16]. In this model, only the intrinsic mechanisms are assumed to be responsible for the sign of the MR of diffusive ferromagnets.

In some experiments of the DW-MR, a variative magnetic field was applied to erase the DW and then the change in the MR was measured [5,9]. Indeed, magnetic field as an extrinsic parameter can change the magnitude and sign of the MR [13]. It should be noted that the Zeeman interaction can not be responsible for scatterings in a ferromagnet region with well defined k-states. One might naively expect the same for the DW, but structural nature of the eigenstates in the presence of a DW makes the situation different even if the DW configuration does not change under the influence of applied magnetic field. Furthermore, the finite size effect of the DW should not

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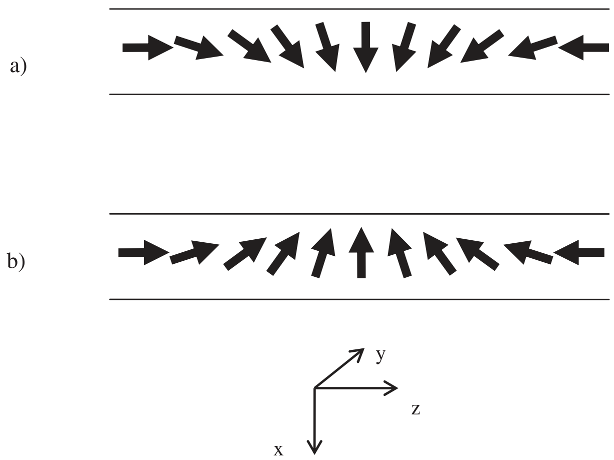

Fig. 1. (a) Positive and (b) negative DW chirality.

be ignored. The finite size effect is introduced by the difference between effective potentials which are experienced by an electron outside and inside the DW. It has been shown that the difference in the density of states for spin's majority and minority bands in a ferromagnet results in discontinuity of the electrostatic potential at the domain boundaries [17]. This potential variation can also be described by the magnetic energy shift due to the DW and charge accumulation inside the DW [18]. Finite size effect can also result in some other interesting effects such as band mixing [19].

In this paper, we have suggested a mechanism which predicts the role of a DW in both increasing and decreasing of a wire resistivity in presence of impurities and weak magnetic fields which do not affect the DW configuration. In this order, we have found spin-dependent relaxation times and the other spin-transport quantities within the Boltzmann theory. The studies have been carried out on the ideal one-dimensional linear Néel type DWs with two types of positive and negative chiralities which are shown in Figure 1. For a linear DW the local direction of magnetization can be described by $\phi(z) = \pm\frac{\pi}{d}z$ in which plus and minus signs are corresponding to the positive and negative chiralities, respectively, d is the DW width and ϕ is the angle between the local direction of magnetization and z axis. Although the following method is independent of the direction of the magnetizations in the ferromagnetic regions and depends only on functional form of the DW, regarding the shape anisotropy the magnetization of the system is considered to be along the wire axis (Fig. 1).

2 Approach

2.1 Description of interaction

We have taken the following Hamiltonian for a Néel type DW which is located between two ferromagnetic regions with opposite directions of magnetization:

$$H = H_0 + H_{sf} + H_H + H_{im}, \tag{1}$$

where H_0 contains periodic potential and kinetic energy, H_{sf} is the s-f exchange between the conduction electrons and the localized magnetic moments, H_H is the Zeeman interaction and H_{im} represents the interaction of localized magnetic impurities with the electrons. Other relaxation mechanism, the Elliott-Yafet spin-orbit interaction, is zero for an ideal one dimensional system. We can express each term of the Hamiltonian as follows:

$$\begin{aligned} H_0 &= -\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r}), \\ H_{sf} &= \Delta\hat{\sigma}\cdot\hat{M}(\vec{r}), \\ H_H &= -\Delta_H\hat{\sigma}\cdot\hat{n}_H, \end{aligned} \tag{2}$$

in which $V(\vec{r})$ is the lattice periodic potential, Δ is the s-f exchange interaction strength, $\hat{\sigma}$ is the Pauli matrix, $\hat{M}$ is the unit vector along the direction of local magnetization, $\hat{n}_H$ is the unit vector along the external magnetic field, $\Delta_H = \mu_B H/2$ in which μ_B is the Bohr magneton and H is the external magnetic field. The last term in (1) for the magnetic impurities is:

$$H_{im} = \sum_i [v_{im} + \Delta_{im}\hat{\sigma}\cdot\hat{M}(\vec{r})]\delta(\vec{r}-\vec{r}_i), \tag{3}$$

where the summation is over all impurities. Δ_{im} and v_{im} are the exchange interaction strength and on-site electrical potential of the localized impurities, respectively. The direction of impurity magnetic moments is assumed to be as the same as that of the local magnetization of host atoms.

To determine the eigenstates of $H_0 + H_{sf}$ we applied an approach based on the perturbation method [15]. In this approach, for a linear DW and up to any order of approximation, the s-f interaction can not produce any mixing between different k-states. This is because of position-independent perturbation potential which is introduced by the s-f interaction for linear DW. It means that we can expect the contribution of s-f exchange interaction to the resistivity for nonlinear DWs.

In terms of the dimensionless distance, wave vector and eigenenergy which are defined as $z \to z/d$, $k \to k/(\pi/d)$ and $\varepsilon \to \varepsilon/\Delta$, respectively, one can express the eigenstates for a one dimensional linear DW as follows [15]:

$$\begin{aligned} \Psi_\uparrow^k &= \frac{\alpha(k_\uparrow)}{\sqrt{d}}\exp(i\pi k_\uparrow z)R_\phi\begin{pmatrix}1\\ i\xi k_\uparrow\end{pmatrix}, \\ \Psi_\downarrow^k &= \frac{\alpha(k_\downarrow)}{\sqrt{d}}\exp(i\pi k_\downarrow z)R_\phi\begin{pmatrix}i\xi k_\downarrow\\ 1\end{pmatrix}, \end{aligned} \tag{4}$$

where α is the normalization parameter, R_ϕ is the spin rotation operator about $\hat{y}$ axis corresponding to Figure 1, $\xi = \pm\hbar^2\pi^2/(8m\Delta d^2)$ in which the positive and negative signs are corresponding to the positive and negative chiralities, respectively, and the DW width, d, can be as small as a few nanometers. These eigenstates have been used in [20] within a static method for determination of the spin dependent transmission and reflection coefficients and the nonlinear $I-V$ curve characteristics of two oppositely magnetized regions.

2.2 Spin dependent transport characteristics

Boltzmann equation prepares a framework for finding deviation of equilibrium distribution function and understanding the physics of non-equilibrium systems. Confinement of the electrons in one dimension eliminates the magnetic part of the Lorentz force which is exerted on electrons, but the magnetic field still contributes in collision term through the Zeeman interaction. So the Boltzmann equation in the relaxation time approximation reduces to:

$$e\vec{E}\cdot\frac{1}{\hbar}\nabla_k f_\sigma+\frac{1}{\hbar}\nabla_k\varepsilon\cdot\nabla_r f_\sigma=-\frac{f_\sigma-f_0}{\tau^\sigma}, \qquad (5)$$

in which f_σ is the distribution function in the presence of external electric field, f_0 is the equilibrium Fermi-Dirac distribution function, $\vec{E}$ is the electric field, τ^σ is the relaxation time for up and down spinors and σ is the index of spinors inside the DW. It should be emphasized that σ corresponds to one of the states in equation (4) and does not represent the spin components along the $\hat{z}$ as an axis of quantization. In the relaxation time approximation this equation for a homogeneous system has a solution of the form:

$$f_\sigma(\vec{k})=f_0(\varepsilon)-\tau^\sigma(\vec{k})e\vec{E}\cdot\vec{v}\frac{\partial f_0}{\partial\varepsilon}, \qquad (6)$$

where $\vec{v}$ is the electron velocity. In the elastic regime and assuming that $\vec{E}$ is along the z axis, τ^σcan be determined as follows:

$$\frac{1}{\tau^\sigma(k)}=\int\sum_{\sigma'}W_{kk'}^{\sigma\sigma'}\left[1-\frac{\tau^{\sigma'}(k')v_z(k')}{\tau^\sigma(k)v_z(k)}\right]dk', \qquad (7)$$

where the scattering rates of relaxation interaction between specified states, $W_{kk'}^{\sigma\sigma'}$, are given by

$$W_{kk'}^{\sigma\sigma'}=\frac{2\pi}{\hbar}V_{kk'}^{\sigma\sigma'}\delta(\varepsilon_{k\sigma}-\varepsilon_{k'\sigma'}), \qquad (8)$$

in which the matrix elements of scattering potentials, $V_{kk'}^{\sigma\sigma'}$, are:

$$V_{kk'}^{\sigma\sigma'}=\left|\left\langle\Psi_\sigma^k\right|H_H+H_{im}\left|\Psi_{\sigma'}^{k'}\right\rangle\right|^2. \qquad (9)$$

Writing equation (7) for up and down components, gives coupled equations for $\tau^\uparrow$ and $\tau^\downarrow$. These equations are solved using the relations

$$\delta(\varepsilon_\sigma(k')-\varepsilon_\sigma(k))=\frac{1}{8|\xi k|}[\delta(k-k')+\delta(k+k')], \qquad (10)$$

$$\delta(\varepsilon_{-\sigma}(k')-\varepsilon_\sigma(k))=\frac{\theta(k^2+\sigma/2|\xi|)}{8|\xi k_\sigma|}\left[\delta(k_\sigma-k')+\delta(k_\sigma+k')\right], \qquad (11)$$

where k_σ is defined as $k_\sigma=\sqrt{k^2+\sigma/2|\xi|}$ and the step function, θ, guarantees that there is not any transition between two spin bands in the elastic regime, when the Fermi level locates in the gap of these two bands.

If the equilibrium Fermi wave vector, k_f, satisfies the condition $k_f\gg\sqrt{\pi/2|\xi|}$ which is appropriate for smooth DWs and semiclassical approach, it will be convenient to approximate the scattering amplitude between these states as $\left|V_{kk'_\sigma}^{\uparrow\downarrow}\right|\cong\left|V_{kk}^{\uparrow\downarrow}\right|$. Then by considering that amplitudes of non-spin-flip back scatterings are relatively small in comparison with that of spin-flip scatterings, the relaxation times will be given by:

$$\tau^\uparrow(k)\approx\frac{\hbar}{\Delta}\frac{8\xi k}{\pi\left|V_{kk}^{\uparrow\downarrow}\right|}\frac{k_-(k+sgn(k)k_+)}{k^2-k_+k_-}$$

$$\tau^\downarrow(k)\approx\frac{\hbar}{\Delta}\frac{8\xi k}{\pi\left|V_{kk}^{\uparrow\downarrow}\right|}\frac{k_+(k+sgn(k)k_-)}{k^2-k_+k_-}. \qquad (12)$$

Using $\tau^\uparrow$ and $\tau^\downarrow$ we can immediately determine the conductivity, σ_z, and therefore the resistivity, $\rho(H)$, of the DW which are given by:

$$\sigma_z=\sum_\sigma\int\frac{1}{E_z}ev_zf_\sigma(\vec{k})dk$$
$$\rho(H)=\sigma_z^{-1}. \qquad (13)$$

Using the resistivity at a given magnetic field we can calculate the ratio of the resistivity change as follows:

$$\frac{\delta\rho}{\rho_0}=\frac{\rho(H)-\rho(0)}{\rho(0)}. \qquad (14)$$

3 Results and discussion

Calculations of matrix elements, $W_{kk'}^{\sigma\sigma'}$, should perform with some care, especially for the Zeeman interaction. If the Fermi energy level locates in the gap of the two spin bands, i.e. $\varepsilon_f<1$, then $W_{kk'}^{\uparrow\downarrow}=W_{kk'}^{\downarrow\uparrow}=0$. This means that, there is not any spin-flip scattering due to the relaxations, across these bands in the elastic regime. But when the Fermi energy level is above the gap, i.e. $\varepsilon_f>1$, for the magnetic field along the rotation axis of the DW, the Zeeman interaction can produce elastic scatterings only while $k_f\gg\sqrt{\pi/2|\xi|}$. Furthermore, when the magnetic field is parallel to the rotation axis of the DW, the finite size effect of the DW is essential for the contribution of the Zeeman interaction to the scatterings. (It is easy to show that when the magnetic field is perpendicular to the rotation axis there is also a range of the Fermi energies, in which the Zeeman interaction contributes to the elastic regime regardless of the finite size effect of the DW.)

The system which was considered in this work has been confined in x and y directions. This confinement results in discrete transverse modes. Because the momentum transfer that can be obtained by an electron due to the mentioned relaxations is much smaller than the required one for a transition between the nearest transverse modes, one can use the single transverse mode approximation. It means that the transport is significantly in one dimension along the z axis. Within this approximation the integration of equation (7) was performed over the one dimensional k-space. For the elastic regime and high Fermi energies, spin-flip scattering process is more effective than non-flip process in the resistivity of the one-dimensional sample. In this case, contribution of non-flip scattering to the resistivity through the back scattering process, requires nonnegligible overlap between the states with wave vector difference of the order of $2k_f$, which can not be satisfied.

Assuming the configuration of Figure 1 and using the matrix elements $W_{kk'}^{\sigma\sigma'}$ and the relaxation times, the resistivity and the ratio of its change have been determined. Figure 2 shows the results of $\frac{\delta\rho}{\rho_0}$ for two different chiralities versus applied magnetic field which is parallel to the rotation axis of the DW. As can be seen, at a given magnetic field and effective impurity interaction strength, $n_i\Delta_{im}/\Delta$, values of $\frac{\delta\rho}{\rho_0}$ for two chiralities are significantly different but one may find an obvious symmetry for these situations. In fact, $\frac{\delta\rho}{\rho_0}$ remains invariant under simultaneous change of the sign of the chirality and applied magnetic field. Figure 2 also demonstrates both negative and positive $\frac{\delta\rho}{\rho_0}$ ratios which indicate that in the presence of the external magnetic field, the DW can either decrease or increase the resistivity. In the ideal case where other relaxation mechanisms such as electron-electron and electron-phonon interactions are absent and when the DW is stable under influence of magnetic field, reduction of the resistivity by the magnetic field can be continued to zero resistivity, i.e. $\frac{\delta\rho}{\rho_0} = -1$. Generally, reaching this point requires a large magnetic field especially for strong exchange interaction of electrons with local moments.

Furthermore, for the mentioned ideal case, the resistivity change due to the DW at higher magnetic fields is large. The most important reason for such a high value of resistivity change is the finite size effect of the DW which determines the effectiveness of the external magnetic field. It is easy to show that as the DW width increases, at a given magnetic field, $\frac{\delta\rho}{\rho_0}$ decreases. Especially, for very wide DWs, i.e. when the finite size effects of the DW are negligible, the Zeeman interaction can not produce any change in the resistivity. Considering the large DW widths, the spins can adapt in an adiabatic way to the changing magnetization orientation [21], but for the thin DWs, resistivity enhancement occurs due to the non-adiabaticity and mistracking effect where the transport electron spins lag behind in orientation with respect to the local magnetic field orientation inside the DW. Specially, it has been realized that for a DW width smaller than the spin diffusion length, the mistracking effect will be large [22].

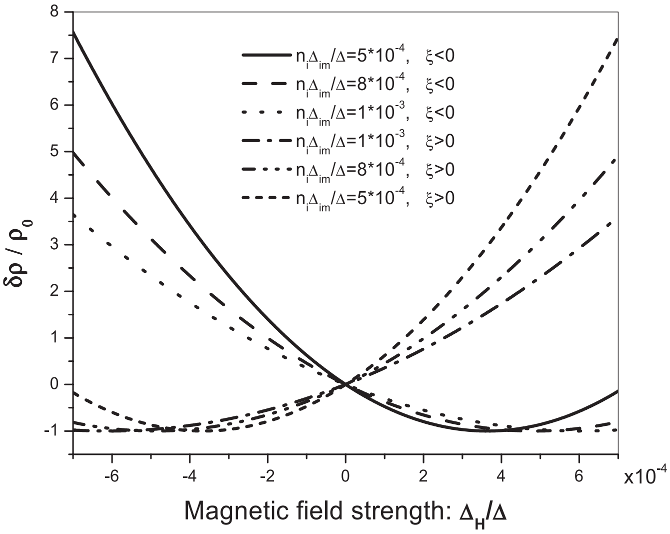

Fig. 2. The ratio of the resistivity change for various effective impurity interaction strengths versus magnetic field for two kinds of chiralities recognized by the sign of parameter $\xi = \pm 0.008$.

Existence of both negative and positive $\frac{\delta\rho}{\rho_0}$ is a direct consequence of competition between the magnetic Zeeman interaction and the exchange interaction of electrons with the local impurities. In other words, one can manipulate the scattering probability by changing the magnitude of the magnetic field. It can be shown that, in the mentioned geometry, the phases associated with the scattering amplitudes related to the both of the relaxations i.e. magnetic field and impurities, are the same. This is due to the fact that at high Fermi energies where the interband transitions are dominant, the inequality $|k_f^{\uparrow} - k_f^{\downarrow}| \ll 1$ is satisfied and one can easily show that the imaginary part of the impurity scattering matrices can be ignored and both types of the relaxations are real, approximately. Therefore the effect of magnetic field can be either subtractive or additive.

The dependence of $\frac{\delta\rho}{\rho_0}$ on the effective impurity interaction strength for positive chirality is depicted in Figure 3 It is appeared by this figure that in the case of positive chirality and positive magnetic fields, only positive $\frac{\delta\rho}{\rho_0}$ appears but the reversed magnetic field results in both positive and negative $\frac{\delta\rho}{\rho_0}$ ratios. Effectiveness of the Zeeman interaction is truly considerable at low effective impurity interaction strengths, while at high values, the effect of the Zeeman interaction becomes very small and there is no considerable distinction between the behavior of $\frac{\delta\rho}{\rho_0}$ for positive and negative magnetic fields. In addition, from Figure 3 or using equations (12–14), one can deduce that for a DW with no impurities, $\frac{\delta\rho}{\rho_0}$ is always positive. Furthermore, it can be shown that in contrast to the DW

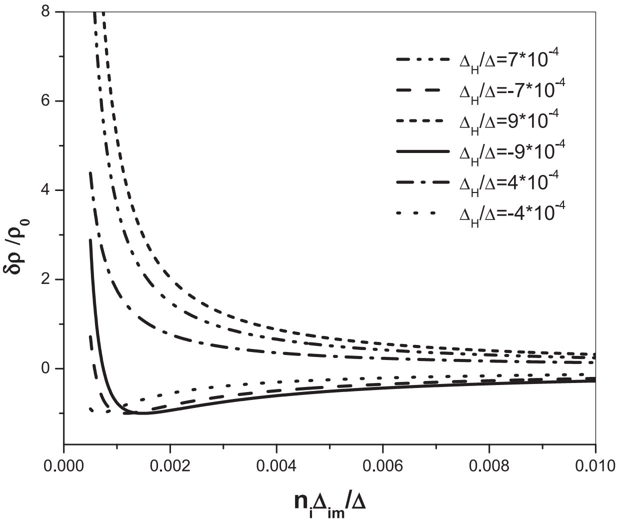

Fig. 3. The ratio of the resistivity change for positive chirality at different magnetic fields versus effective impurity interaction strength ($\xi = +0.008$).

with impurities, for the DWs with no impurities, $\frac{\delta\rho}{\rho_0}$ is the same for magnetic fields which are parallel or anti-parallel to the DW rotation axis.

4 Conclusion

The ratio of the resistivity change due to a DW in a ferromagnetic wire investigated using the Boltzmann equation and within the relaxation time approximation. This analysis has resulted in two distinct regimes which are specified by impurity density and impurity exchange interaction, Fermi wave vector and external magnetic filed. These two regimes correspond to positive and negative $\frac{\delta\rho}{\rho_0}$ ratios. The magnetic Zeeman interaction has not any contribution to the resistivity for a magnetized ferromagnetic region, but the finite size effect of the DW and spatial dependence of DW eigenstates make a characteristic roll in the contribution of an external magnetic field in elastic or nearly elastic scatterings. When the scattering amplitude associated with the Zeeman interaction is comparable to that of the impurity scattering at the Fermi level, the contribution of the DW to the $\frac{\delta\rho}{\rho_0}$ ratio can be negative. Calculations have also shown that for a DW with impurities the final resistance of the DW is sensitive to the chirality.

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