Journal of
NANOSTRUCTURES
JNS NANOSTRUCTURES
JNS.kashanu.ac.ir

Quantum Interference Control of Ballistic Magneto-resistance in a Magnetic Nanowire Containing Two Atomic-Size Domain Walls

V. Fallahi[a,*], M. Ghanaatshoar[b]

[a] *Department of Optics and Laser Engineering, University of Bonab, 5551761167 Bonab, Iran,*

[b] *Laser and Plasma Research Institute, Shahid Beheshti University, G.C., Evin,1983963113, Tehran, Iran.*

Article history:
Received 23/5/2012
Accepted 24/7/2012
Published online 1/9/2012

Keywords:
Domain walls
Magnetic nanowire
Ballistic transport
Spin-orbit interaction

**Corresponding author:*
E-mail address*:*
fallahi@kth.se
Phone: 98 912 4786025
Fax: +98 412 7240194

Abstract

The magnetoresistance of a one-dimensional electron gas in a metallic ferromagnetic nanowire containing two atomic-size domain walls has been investigated in the presence of spin-orbit interaction. The magnetoresistance is calculated in the ballistic regime, within the Landauer-Büttiker formalism. It has been demonstrated that the conductance of a magnetic nanowire with double domain walls can be controlled through the domain walls separation. Also, we have represented another alternative way that enables us to handle easily the magnetoresistance of such a system as well as its conductance by utilizing the Rashba-type spin-orbit interaction induced by the external gates.

1. Introduction

The study of spin-dependent transport in ferromagnetic systems containing a domain wall has recently attracted much attention from both fundamental and technological viewpoints. Controllably generation, manipulation and detection of the spin polarization are important issues for the potential applications of domain walls in magnetic devices [1]. Recently, much attention has been focused on the sharp domain walls $(k_F d \ll 1)$ which demonstrate huge magnetoresistance [2–5]. The value of magneto-resistance can be controlled by the domain wall width [6]. In the experiment done by Hamida *et al.* [7], they found a negative domain wall resistance for nanometer-sized constrictions, becoming positive in the atomic-contact regime. Also, one can manipulate the domain wall magnetoresistance by changing the distance between two domain walls. In the first paper has been emerged in recent years looking at double domain walls [8], Dugaev *et al.* have shown that the quantum interference results in spin-split quasi-stationary states localized mainly between the domain walls in a semiconducting magnetic nanowire with double magnetic domain walls. They demonstrated that the strength of spin mixing and hence the width of the resonance peaks in the transmission coefficient can be controlled by varying the domain walls separation as well as the width of the domain walls.

In addition to manipulating the domain walls parameters, one can apply an external electric field to mix the spin channels via the Rashba spin-orbit coupling and control the conductance of the system. Recently, the effect of the Rashba spin-orbit interaction on the domain wall magneto-resistance has been calculated by Dugaev *et al.* [9], indicating that the Rashba interaction may result in an increase in the magnetoresistance of a semiconducting magnetic wire with a domain wall of width d. Such calculations were carried out for the case of a sharp domain wall corresponding to the limit of $k_{F\uparrow(\downarrow)}d \ll 1$, where $k_{F\uparrow(\downarrow)}$ is the magnitude of Fermi vector for the majority (minority) spins. Nevertheless, as in the recent similar work [10], we showed that the Rashba coupling may lead to a negative or positive change in the domain wall magnetoresistance, depending on the Fermi energy and the lateral confinement potentials which can be induced by both parabolic lateral confinement and lateral gate potentials. The effect of the Rashba interaction on the magnetoresistance of a smooth domain wall in ferromagnetic metals has been studied, too. It has been shown that the spin-flip scattering and consequently the resistivity due to the domain wall increase monotonically with the Rashba interaction strength [11, 12].

In this paper, we study the conductance and subsequently the magnetoresistance of a double sharp domain wall in a metallic magnetic nanowire. The investigation is carried out in the presence of the Rashba spin-orbit interaction. In this order, we conduct ballistic transport calculations using the Landauer-Büttiker formula. Then, we find the scattering spin states at both sides of the domain wall modeled by a δ-like potential. Finally, the reflection and the transmission coefficients are determined by applying the boundary conditions for the spin states at the nanocontacts positions.

2. Model and formalism

The full quantum scattering theory is utilized to investigate the conductance of a metallic ferromagnetic nanowire containing two atomic-size domain walls pinned in the nanocontacts. The general configuration of two 180° head-to-head domain walls with lateral gate potential applied between them is illustrated in Fig. 1. It is assumed that the magnetization depends just on the local coordinate along the nanowire, *i.e.*, $\widehat{\boldsymbol{M}}(z) = (\sin\varphi(z), 0, \cos\varphi(z))$, where $\varphi(z)$ abruptly changes from 0 to π at $z = -L$, and then abruptly

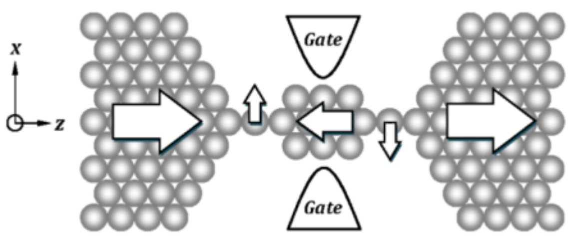

Fig. 1. The considered structure of two atomic-size domain walls between two semi-infinite nanowires with

a lateral confinement potential, arising from the side gates in the system.

changes from π to 2π at $z = L$, counterclockwise. The one-dimensional Hamiltonian of the system in the presence of the Rashba spin-orbit coupling brought by transverse electric field in the ferromagnetic nanowires can be written as

$$H = \frac{p_z^2}{2m} - J_{ex}\sigma \cdot \widehat{M}(z) + \frac{\hbar k_{SO}(z)}{m}\sigma_y p_z + \frac{1}{2m}\sigma_y \frac{\hbar}{i}\frac{\partial}{\partial z}\hbar k_{SO}(z)\,, \quad (1)$$

where J_{ex} is the exchange integral, σ denotes the spin operators in terms of the Pauli spin matrices, and $k_{SO}(z) = \frac{m\alpha}{\hbar^2}\Theta(L+z)\Theta(L-z)$ is Heaviside step function with wave-vector scale that measures the spin-orbit coupling strength α. This can be tuned by means of the lateral external gates positioned between two nanocontacts at the local coordinates $z = -L$ and $z = L$. The last term in Eq. (1) ensures that the current density is continuous across the interfaces. In other words, it is needed to get a Hermitian Hamiltonian. The full wave functions of an incident carrier with the Fermi energy E_F in the left (L), middle (M), and right (R) regions are:

$$\Psi_{k,L}(z) = I^{\uparrow}\binom{1}{0}e^{ik^{\uparrow}z} + r^{\uparrow}\binom{1}{0}e^{-ik^{\uparrow}z} + I^{\downarrow}\binom{0}{1}e^{ik^{\downarrow}z} + r^{\downarrow}\binom{0}{1}e^{-ik^{\downarrow}z}, \quad (2)$$

$$\Psi_{k,M}(z) = A\binom{1}{i\zeta_-}e^{ik_-z} + B\binom{1}{-i\zeta_-}e^{-ik_-z} + C\binom{i\zeta_+}{1}e^{ik_+z} + D\binom{-i\zeta_+}{1}e^{-ik_+z}, \quad (3)$$

$$\Psi_{k,R}(z) = t^{\uparrow}\binom{1}{0}e^{ik^{\uparrow}z} + t^{\downarrow}\binom{0}{1}e^{ik^{\downarrow}z}, \quad (4)$$

in which $k^{\uparrow\downarrow} = \sqrt{k_F^2 \pm k_{ex}^2}$, $k_F = \sqrt{2mE_F/\hbar^2}$, $k_{ex} = \sqrt{2mJ_{ex}/\hbar^2}$, $k_R = m\alpha/\hbar^2$, $k_\pm = \sqrt{k_F^2 + 2k_{SO}^2 \pm \sqrt{k_{ex}^4 + 4k_F^2k_{SO}^2 + 4k_{SO}^4}}$, and $\zeta_\pm = \frac{2k_\pm k_{SO}}{\sqrt{k_{ex}^4 + 4k_\pm^2k_{SO}^2 + k_{ex}^2}}$. The scattering states $\Psi_{k,L}(z)$ and $\Psi_{k,R}(z)$ describe the incoming unpolarized spin wave from $z = -\infty$ to the right, which is partially reflected and partially transmitted into the two spin channels. The wave function $\Psi_{k,M}(z)$ demonstrates multiple reflections and transmissions between two nanocontacts. The coefficients $t_\uparrow \equiv t_{\uparrow\uparrow} + t_{\uparrow\downarrow}$ and $t_\downarrow \equiv t_{\downarrow\uparrow} + t_{\downarrow\downarrow}$ are the transmission amplitudes, and $r_\uparrow \equiv r_{\uparrow\uparrow} + r_{\uparrow\downarrow}$ and $r_\downarrow \equiv r_{\downarrow\uparrow} + r_{\downarrow\downarrow}$ are the corresponding reflection amplitudes. In order to calculate the transmission amplitudes, we first assume that the incoming wave to be entirely "up" and then consider purely "down" spin states.

In the case of a sharp domain wall, *i.e.*, $k_F d \ll 1$, one can consider the domain wall as a δ-like potential at the $z = \pm L$ to calculate the transmission amplitudes. Regarding this δ-like potential, the first derivative of scattering states shows a discontinuity at $z = \pm L$. By integrating the Schrödinger equation between $z = \pm L - \epsilon$ and $z = \pm L + \epsilon$, where $d \ll \epsilon \ll k_F^{-1}$, one can find

$$\left.\frac{\partial \Psi_{k,M}(z)}{\partial z}\right|_{z=-L} - \left.\frac{\partial \Psi_{k,L}(z)}{\partial z}\right|_{z=-L} + \left(\lambda_{-L}^{-1}\sigma_x + ik_{SO}\sigma_y\right)\Psi_{k,M\{L\}}(z=-L) = 0, \quad (5)$$

$$\left.\frac{\partial \Psi_{k,R}(z)}{\partial z}\right|_{z=+L} - \left.\frac{\partial \Psi_{k,M}(z)}{\partial z}\right|_{z=+L} + \left(\lambda_{+L}^{-1}\sigma_x - ik_{SO}\sigma_y\right)\Psi_{k,M\{R\}}(z=+L) = 0, \quad (6)$$

where $\lambda_{\pm L}^{-1} = \left(\frac{2mJ_{ex}}{\hbar^2}\right)\int_{\pm L-\epsilon}^{\pm L+\epsilon}\sin\varphi(z)\,dz$. Then, using this equation and the continuity of the wave function at the interfaces, transmission amplitudes can be obtained.

We use the two-probe Landauer formula to obtain the conductance from transmission coefficients. The transmission coefficients are evaluated as the ratio of the transmitted to the incident probability current density. Due to the presence of spin-orbit coupling, the probability current density has the following form:

$$j = \frac{1}{m} Re\{\Psi^{\dagger}[p_z + \hbar k_{SO}(z)\sigma_y]\Psi\}, \tag{7}$$

and subsequently, the transmission coefficients will be obtained as follows

$$T^{pq} = \frac{j_t^q}{j_i^p} \Xi(k^p)\Xi(k^q), \quad p, q = \uparrow and \downarrow, \tag{8}$$

in which $j_t^{\uparrow(\downarrow)}$ and $j_i^{\uparrow(\downarrow)}$ are incident and transmitted probability current densities for up-spin and down-spin states, respectively. Then, the total transmission coefficients for incoming up-spin and down-spin states will be equal to $T^{\uparrow} = T^{\uparrow\uparrow} + T^{\uparrow\downarrow}$ and $T^{\downarrow} = T^{\downarrow\uparrow} + T^{\downarrow\downarrow}$, respectively. The function $\Xi(k^{\uparrow(\downarrow)})$ is considered in order to eliminate evanescent spin wave functions. In this way, $\Xi(k^{\uparrow(\downarrow)})$ will be equal to zero in the case of $Im(k^{\uparrow(\downarrow)}) \neq 0$; otherwise it will be equal to one. By assuming that the incoming electronic spin is an unpolarized statistical mixture, *i.e.*, $\rho_{in} = \frac{1}{2}(|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow|)$, the output will be obtained by $\rho_{out} = \frac{1}{2}(T^{\uparrow}|\uparrow\rangle\langle\uparrow| + T^{\downarrow}|\downarrow\rangle\langle\downarrow|)$ [13]. Therefore, the overall transmission coefficient of the unpolarized carriers will be given by $T = \frac{1}{2}(T^{\uparrow} + T^{\downarrow})$. In the case reported here, it is not taken into account the possibility that carriers could be partially polarized before ballistic transport through the ferromagnetic material. The conductance of the nanowire is calculated according to Landauer-Büttiker formalism [14]. This approach, which is widely used in mesoscopic physics, expresses the conductance in terms of the transmission properties of coherent electron states as follows:

$$G = \frac{e^2}{h} T. \tag{9}$$

So, the magnetoresistance can be calculated using the following relation:

$$\frac{\delta\rho}{\rho_0} = -\frac{\delta G}{G} = \frac{G_0}{G} - 1, \tag{10}$$

in which $\rho_0 = G_0^{-1}$ and $G_0 = \frac{e^2}{h}\left(\frac{\Xi(k^{\uparrow})+\Xi(k^{\downarrow})}{2}\right)$ is the conductance of a nanowire without a domain wall.

3. Results and discussion

In the limit of weak spin-flip scattering approximation, *i.e.*, $\lambda_{\pm L}^{-1} \approx 0$, and in the absence of the Rashba spin-orbit interaction, one can obtain the overall transmission coefficient as

$$T = \frac{0.5}{1 + \left(\frac{{k^{\uparrow}}^2 - {k^{\downarrow}}^2}{2k^{\uparrow}k^{\downarrow}}\right)^2 \sin^2(2k^{\uparrow}L)} + \frac{0.5}{1 + \left(\frac{{k^{\uparrow}}^2 - {k^{\downarrow}}^2}{2k^{\uparrow}k^{\downarrow}}\right)^2 \sin^2(2k^{\downarrow}L)}. \tag{11}$$

Regarding above equation, the full transmission of the electrons will occur in certain domain walls distances, if the two conditions $2k^{\uparrow}L = m\pi$ and $2k^{\downarrow}L = n\pi$ (m and n are integer) are fulfilled, simultaneously. In other words, the maximum transmission coefficient will occur, if the domain walls distance is nearly equal to $l\pi/(k^{\uparrow} - k^{\downarrow})$ in which l is an integer number. Furthermore, the conductance has an oscillatory behavior with the periodicity of $2L = \pi/(k^{\uparrow} - k^{\downarrow})$ over domain walls distance. Such a behavior is a consequence of quantum interference between two domain walls. The oscillation period in the metallic magnetic

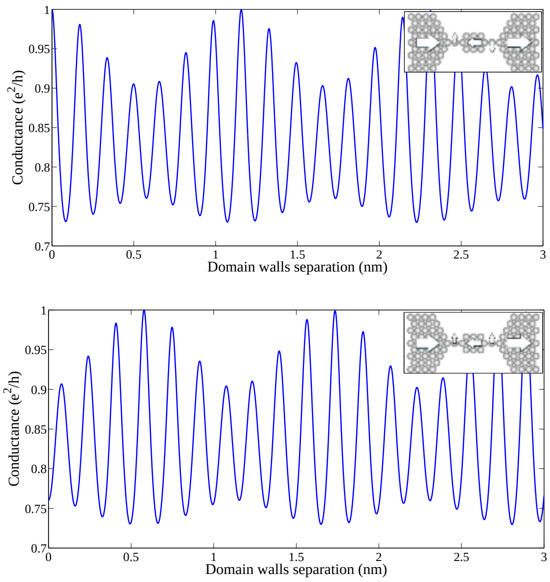

Fig. 2. Plot of conductance as a function of domain walls separation without considering the spin-orbit coupling effects in two parallel (lower) and anti-parallel (upper) configurations of magnetization at the noncontacts.

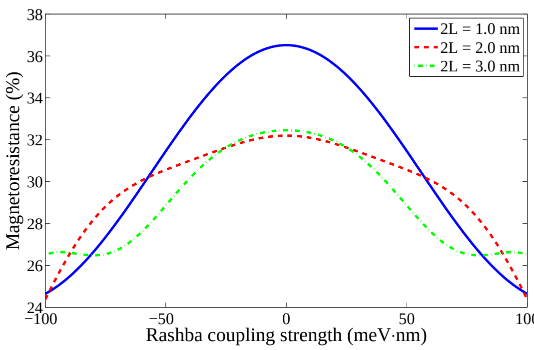

Fig. 3. Plot of the magnetoresistance as a function of Rashba spin-orbit coupling strength for different values of domain walls distances in the anti-parallel configuration of magnetization at the noncontacts.

nanowires is less than one in the semiconducting magnetic system because of its lower Fermi energy as well as demonstrated in Ref. [8].

We present results for a Ni and Co ferromagnetic nanowire fabricated by electrodeposition technique with the commonly accepted material properties $E_F = 3.5$ eV and $J_{ex} = 1$ eV [15]. The dependence of conductance on the domain walls separation has been shown in Fig. 2 for two possible configurations of magnetization at the noncontacts, namely the parallel and the anti-parallel configurations. In the limit of zero domain walls separation, the incoming electrons from the left lead can pass through the structure without any scattering in the anti-parallel case, while they experience deflection by the effectively nonzero spin-dependent barrier at the nanocontact in the parallel case of domain wall magnetization. Increasing the distance between the two sharp domain walls alters the conductance due to multiple quantum interference effect.

In order to control the conductance and consequently the magnetoresistance by the external electric field, we introduced the Rashba spin-orbit interaction into the Hamiltonian. The effect of Rashba spin-orbit interaction on the magnetoresistance has been shown in Fig. 3. It is easily seen that the highest value of magnetoresistance can be achieved in the absence of spin-orbit interaction for different values of domain walls separations. Increasing the strength of spin-orbit coupling, regardless of its sign (positive or negative), results in magnetoresistance reduction. The results show that the magnetoresistance can be changed up to %10 by applying external electric fields or gate voltages related Rashba effects which would be suitable for data handling.

4. Conclusion

We have studied the influence of the Rashba spin-orbit interaction on the magnetoresistance in the metallic magnetic nanowires containing two atomic-size domain walls. It has been revealed that the conductance has an oscillatory behavior over domain walls distance. Furthermore, it has been shown that the magnetoresistance can be controlled with the Rashba spin-orbit coupling strength induced by the external gates.

References

[1] S. S. P. Parkin, M. Hayashi, L. Thomas, Science 320 (2008) 190–194.
[2] H. D. Chopra, S. Z. Hua, Phys. Rev. B 66 (2002) 020403.
[3] J. W. F. Egelhoff, L. Gan, H. Ettedgui, Y. Kadmon, C. J. Powell, P. J. Chen, A. J. Shapiro, R. D. McMichael, J. J. Mallett, T. P. Moffat, M. D. Stiles, E. B. Svedberg, J. Appl. Phys. 95 (2004) 7554–7559.
[4] M. R. Sullivan, D. A. Boehm, D. A. Ateya, S. Z. Hua, H. D. Chopra, Phys. Rev. B 71 (2005) 024412.
[5] N. Useinov, L. Tagirov, J. Magn. Magn. Mater. 321 (2009) 3246–3249.
[6] S. Mangin, C. Bellouard, P. Turban, S. Andrieu, F. Canet, A. Schuhl, B. Barbara, J. Appl. Phys. 89 (2001) 7203–7205.
[7] A. B. Hamida, O. Rousseau, S. Petit-Watelot, M. Viret, Europhys. Lett. 94 (2011) 27002.
[8] V. K. Dugaev, J. Berakdar, J. Barnaś, Phys. Rev. Lett. 96 (2006) 047208.
[9] V. K. Dugaev, J. Barnaś, J. Berakdar, V. I. Ivanov, W. Dobrowolski, V. F. Mitin, Phys. Rev. B 71 (2005) 024430.
[10] V. Fallahi, M. Ghanaatshoar, Phys. Stat. Sol. (b) 249 (2012) 1077–1082.
[11] A. Phirouznia, M. M. Tehranchi, M. Ghanaatshoar, Phys. Rev. B 75 (2007) 224403.
[12] V. Fallahi, M. Ghanaatshoar, Phys. Rev. B 82 (2010) 035210.
[13] V. M. Ramaglia, D. Bercioux, V. Cataudella, G. D. Filippis, C. A. Perroni, J. Phys.: Condens. Matter 16 (2004) 9143–9154.
[14] M. Lundstrom, Fundamentals of Carrier Transport, Cambridge University Press, (2000).
[15] H. Imamura, N. Kobayashi, S. Takahashi, S. Maekawa, Phys. Rev. Lett. 84 (2000) 1003–1006.