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Magnetoresistance of non-180° domain wall in the presence of electron-photon interaction

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Abstract

In the present paper, influence of photon on resistance of non-180° domain wall in metallic magnetic nanowires has been studied using the semiclassical approach. The analysis has been based on the Boltzmann transport equation, within the relaxation time approximation. The one-dimensional Néel-type domain wall between two ferromagnetic domains with relative magnetization angle less than 180° is considered. By increasing this angle, the contribution of the domain wall in the resistivity of the nanowire becomes considerable. It is also found that the fundamental contribution of the domain wall in resistivity can be controlled by propagating photon. These results are valuable in designing spintronic devices based on magnetic nanowires.

Keywords: Magnetoresistance, Non-180° Néel-type domain wall, Metallic nanowire, Magnetization rotation angle, Electron-photon interaction

Background

Spintronics is an emerging technology with a great promise to provide a new generation of electronic devices where spin of carriers would play a crucial role in addition to or in place of their charge [1,2]. The design and manufacture of such new spintronic devices require a proper understanding of spin-dependent transport especially in magnetic systems [1,2]. In recent years, investigating the unique spin transport property and determining the magnetoresistance (MR) of magnetic nanostructures such as nanowires have attracted much attention. Results indicate that MR as a characteristic property of the magnetic nanostructures can be modified significantly by the presence of non-collinear magnetization regions named domain walls (DWs) [3]. From both scientific and technological points of view, understanding the resistance caused by DWs and determining the effect of different scattering sources on the DW resistance (DWR) are essential. For that reason, many research efforts have been made to understand the role of DW in resistivity [4-15]. Experiments on iron whiskers demonstrate that DWs are a source of electrical resistance [4]. Contrary to bulk samples, it has been found that the MR associated with nanosize DWs can be significantly large [4,5]. Theoretically, Levy and Zhang, by studying MR effect due to the magnetic DW scattering, found that the DWs are a source of spin channel mixing and MR enhancement [6]. In addition, investigation of the effect of Rashba spin orbit interaction on the resistance of DW indicates that this interaction causes an increase in the DWR [7,8]. The temperature dependence of the resistivity of DWs has been also studied. The results clarify that the positive contribution of DWs in increasing the resistivity is enhanced by increasing temperature [10-12]. In recent years, applying an external magnetic field or propagating a photon to control the DWR has been investigated [13-15]. It should be mentioned that most of the present studies [4-15] have focused on the ideal 180° DWs despite the fact that DWs with a magnetization rotation of less than 180° appear in artificial materials [16,17]. Meanwhile, realization of spintronic devices with improved functionality and performance requires controlling DW configurations and understanding their role in electronic transport. In recent years, contributions of 90°, 180°, and 360° DWs in the resistivity of samples in the presence of external magnetic field are compared [18]. It is found that that resistance of 360° DW is more considerable than that of 90° and 180° DWs. In the present paper, we have studied the influence of photon on the resistivity of the non-180° DW in metallic magnetic nanowires.

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Methods

Theoretical considerations

We have studied a metallic magnetic nanowire containing a Néel-type DW. For this DW, the angle between the local direction of the magnetization and the z-axis can be expressed as $\theta(z) = \phi\, z/d$, where φ is the magnetization rotation angle of the DW and considered less than 180°. It means that the DW is confined between two magnetic domains with relative magnetization angle of φ, and in such DW, θ changes smoothly from zero to φ over the DW width, d. In Figure 1, the 180° DW with φ = 180° and non-180° DW with φ < 180° are shown.

The following Hamiltonian has been used to describe the DW in the presence of photon:

$$H = H_0 + H_{\text{ex}} + H_{\text{el-ph}}. \tag{1}$$

The first term, H_0, contains kinetic energy and non-magnetic periodic potential. The second term, H_{ex}, represents the exchange interaction between the spin of conduction electrons and the localized magnetic moments. These terms are given by

$$H_0 = -\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + V(z), \tag{2}$$

$$H_{\text{ex}} = -\Delta_{\text{ex}}\hat{\sigma}.\hat{M}(z), \tag{3}$$

in which $V(z)$ is the lattice periodic potential, Δ_{ex} represents the exchange interaction strength, $\hat{\sigma}$ denotes the Pauli spin matrices, and $\hat{M}(z)$ is the unit vector along the direction of local magnetization.

The third term, $H_{\text{el-ph}}$, which represents the electron-photon interaction is determined by

$$H_{\text{el-ph}} = -\mu_B\hat{\sigma}\cdot\left(\vec{\nabla}\times\vec{A}\right) - \frac{e}{mc}\vec{A}\cdot\vec{P} + \frac{e^2}{2mc^2}A^2, \tag{4}$$

where μ_{B} is the Bohr magneton, and $\vec{A}$ is the vector potential of the electromagnetic field. In the present study, we have focused on photons propagating in the z-direction. For these photons, the second term which includes $\vec{A}\cdot\vec{P}$, is zero. Moreover, our results indicate that the contribution of term $A^2$is negligible. Hence, the electron-photon interaction can simply determined by the Zeeman interaction of conduction electron spin in the magnetic field induced by the photon, namely,

$$H_{\text{el-ph}} = -\mu_B\hat{\sigma}\cdot\left(\vec{\nabla}\times\vec{A}\right), \tag{5}$$

in which the vector potential of the electromagnetic field is given by

$$\vec{A} = \sum_s A_q\left(a_{qs}\hat{e}_{qs}e^{iqz} + a^\dagger_{qs}\hat{e}^*_{qs}e^{-iqz}\right), \tag{6}$$

where $A_q = \sqrt{(2\pi\hbar c^2)/(V\omega)}$, $\omega = qc$ is the photon frequency, and V is the volume where photon is propagating. $a^\dagger_{qs}$ and a_{qs} are the photon creation and annihilation operators which create and annihilate a photon with wave vector $\vec{q}$ and polarization s, respectively. The unit vector of polarization $\hat{e}_{qs}$ represents the direction of the electric field vector, and so, the unit vector $\hat{b}_{qs}$ is parallel to the induced photon magnetic field which can be written as $\hat{b}_{qs} = \hat{q}\times\hat{e}_{qs}$. For photon along the z-direction, the unit vector of polarization can be specified by two vectors along the x-axis and y-axis ($\hat{e}_x$ and $\hat{e}_y$) as $\hat{e}_{qs} = e_x\hat{e}_x + e_y\hat{e}_y$, where $e_x = 1, 0, 1/\sqrt{2}$ and $e_y = 0, 1, i/\sqrt{2}$ for x-linear, y-linear, and circular polarizations, respectively.

The eigenstates of $H_0 + H_{\text{ex}}$ for a one-dimensional system can be determined as follows:

$$\left|\psi^\uparrow(k)\right\rangle = \frac{\widetilde{\alpha}(k)}{\sqrt{d}}e^{ikz}R_{\theta(z)}\begin{pmatrix}1\\ ik\zeta\end{pmatrix}, \tag{7a}$$

$$\left|\psi^\downarrow(k)\right\rangle = \frac{\widetilde{\alpha}(k)}{\sqrt{d}}e^{ikz}R_{\theta(z)}\begin{pmatrix}ik\zeta\\ 1\end{pmatrix}, \tag{7b}$$

where $\widetilde{\alpha}(k) = \left(1 + k^2\zeta^2\right)^{-1/2}$ and $\zeta = \left(\varphi^2\,\hbar^2\right)/(8m\Delta_{\text{ex}}d^2)$ are the normalization and perturbation parameters, respectively, in which k is the electron wave vector. Finally, $R_{\theta(z)} = \exp(-i\theta(z)\hat{\sigma}.\hat{n}/2)$ is the spin rotation operator, and $\hat{n}$ denotes the direction of the DW rotation axis which in this case, is assumed to be along the y-axis (Figure 1).

As mentioned in our previous works [10,15], the Boltzmann equation with relaxation time approximation can be employed to calculate the spin-dependent relaxation times and, consequently, the other spin transport

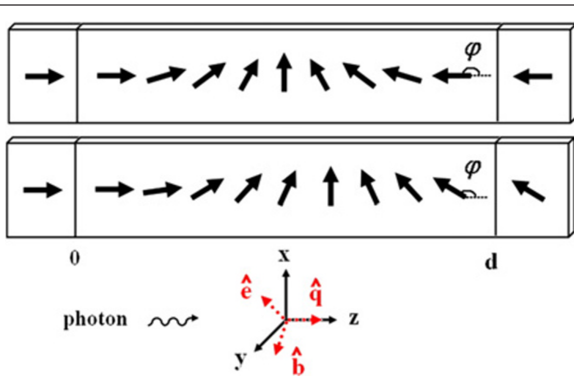

Figure 1 The (top) 180°DW (bottom) non-180° DW.

quantities. The spin-dependent relaxation times, $\tau^{\sigma}(k)$, are as follows [10,15]:

$$[\tau^{\sigma}(k)]^{-1} = \frac{d}{\hbar}\sum_{\sigma'}\int dk' \left|V^{\sigma',\sigma}(k',k)\right|^2 \left[1 - \frac{\tau^{\sigma'}(k')v_{k',\sigma'}}{\tau^{\sigma}(k)v_{k,\sigma}}\right] \delta(\varepsilon_{k\sigma} - \varepsilon_{k'\sigma'}) \tag{8}$$

where the elements of the scattering matrix related to the electron-photon interaction are given by

$$V^{\sigma',\sigma}(k',k) = \left\langle \psi^{\sigma'}(k')\middle|H_{\text{el-ph}}\middle|\psi^{\sigma}(k)\right\rangle. \tag{9}$$

According to Equations 5, 6, 7a, and 7b, $V^{\sigma',\sigma}(k',k)$ terms are found to be

$$\begin{aligned} V^{\uparrow\uparrow}(k',k) = -\mu_B\widetilde{\alpha}(k')\frac{q}{d}A_q & \Bigg[\widetilde{\alpha}(k+q)\left((k-k'+q)\zeta(k-k'+2q)+\left(\frac{\varphi}{d}\right)\right) \frac{\exp(i(k-k'+2q)d)+1}{(k-k'+2q)^2+\left(\frac{\varphi}{d}\right)^2}e_y \\ & -\widetilde{\alpha}(k-q)\left((k-k'-q)\zeta(k-k'-2q)+\left(\frac{\varphi}{d}\right)\right) \frac{\exp(i(k-k'-2q)d)+1}{(k-k'-2q)^2+\left(\frac{\varphi}{d}\right)^2}e_y^* \\ & +\widetilde{\alpha}(k+q)(k+k'+q)\zeta\frac{\exp(i(k-k'+2q)d)-1}{i(k-k'+2q)}e_x \\ & -\widetilde{\alpha}(k-q)(k+k'-q)\zeta\frac{\exp(i(k-k'-2q)d)+1}{i(k-k'-2q)}e_x^*\Bigg], \end{aligned} \tag{10a}$$

$$\begin{aligned} V_{\uparrow\downarrow}(k',k) = -\mu_B\widetilde{\alpha}(k')\frac{q}{d}A_q & \Bigg[\widetilde{\alpha}(k+q)\left((k-k'+2q)-(k+k'+q)\zeta\left(\frac{\varphi}{d}\right)\right) \frac{\exp(i(k-k'+2q)d)}{(k-k'+2q)^2-\left(\frac{\varphi}{d}\right)^2}e_y \\ & +\widetilde{\alpha}(k-q)\left((k-k'-2q)-(k+k'-q)\zeta\left(\frac{\varphi}{d}\right)\right) \frac{\exp(i(k-k'-2q)d)}{(k-k'-2q)^2-\left(\frac{\varphi}{d}\right)^2}e_y^* \\ & +\widetilde{\alpha}(k+q)\left(1-k'(k+q)\zeta^2\right)\frac{\exp(i(k-k'+2q)d)}{i(k-k'+2q)}e_x \\ & -\widetilde{\alpha}(k-q)\left(1-k'(k-q)\zeta^2\right)\frac{\exp(i(k-k'-2q)d)}{i(k-k'-2q)}e_x^*\Bigg], \end{aligned} \tag{10b}$$

the terms $V^{\downarrow\downarrow}(k',k)$ and $V^{\downarrow\uparrow}(k',k)$ are obtained with inversion of spin in Equations 10a and 10b, respectively.

The resistivity of the DW per unit length can be expressed as

$$\Re = \left[\frac{1}{2\pi}\left(\frac{e\hbar}{m}\right)^2 \sum_{\sigma}\int dk\, k^2\tau^{\sigma}(k)\delta(\varepsilon_{k\sigma}-\varepsilon_F)\right]^{-1}, \tag{11}$$

where ε_F is the Fermi energy.

Results and discussion

We have calculated the resistance corresponding to the non-180° DW in metallic magnetic nanowires. The parameters have been chosen in such a way that the condition for validity of the semiclassical approximation, $k_F d >> 1$, will be applicable.

In our study, the ζ-dependent parts of Equations 7a and 7b describe the deviation from the adiabatic regime and the non-adiabaticity in the up- and down-spin electron transfer through the DW. The non-adiabaticity causes the mixing of the spin channels within the DW and consequently increases the resistance of the DW. Therefore, without considering the spin dependence of the resistivity, the extra resistivity of the DWs is not understandable. The DW width and the exchange energy are two main parameters that determine the adiabaticity of the transport. For very wide DW and strong exchange interaction, the spin adiabatically follows the local magnetization direction. In contrast, for narrow DW and weak exchange interaction, the spin of electrons is not directed along the local magnetization direction, and the transport is non-adiabatic. In Figure 2, the resistance per unit length of the 120° DW versus the DW width

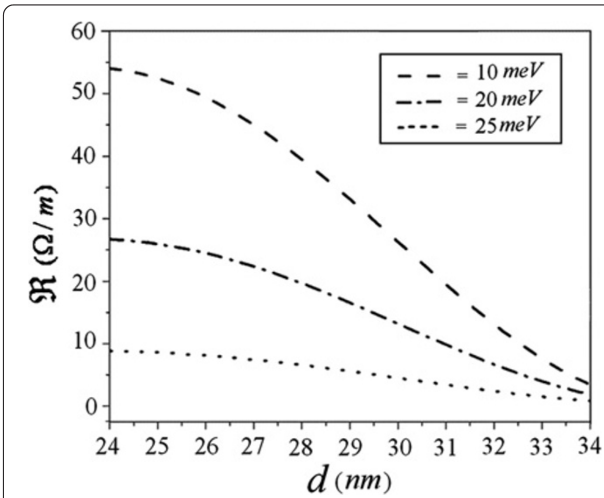

Figure 2 The DWR per unit length versus DW width for different values of exchange interaction strength. It was calculated for 120° DW in the presence of *x*-linearly polarized photon with λ = 100 nm.

in the presence of x-linearly polarized photon for different strength of the exchange interaction is shown. We have found that increasing the DW width and the exchange interaction strength leads to reduction of the non-180° DWR.

Besides the role of the DW width and the exchange interaction strength, the non-adiabatic transport inside the DW can be attributed to the relative magnetization angle between two ferromagnetic domains, φ. In Figure 3, the resistance per unit length of the DW as a function of φ in the presence of x-linearly polarized photon with different wavelengths is presented. As φ increases, the resistivity of the DW becomes more considerable. This can be explained by the fact that the spin can follow adiabatically the local magnetization direction which changes smoothly over the DW with small relative magnetization rotation angle. By φ enhancement, the non-adiabaticity and consequently the contribution of the DW in the resistivity of the magnetic nanowires are increased.

To clarify the role of the photon, the dependence of the DWR on the photon wavelength and polarization is demonstrated. The DWR versus the wavelength of the x-linearly polarized photon is shown in Figure 4. As shown, increasing the wavelength of the photon with x-linear polarization leads to the reduction of the DWR. This can be explained by the fact that the x-linearly polarized photon causes an effective magnetic field perpendicular to the DW and changes the DWR same as a transverse external magnetic field. Therefore, increasing the photon wavelength which decreases the effect of the Zeeman interaction leads to DWR reduction. The similar DWR reduction by decreasing the external magnetic field [8] and increasing photon wavelength is reported in our previous studies [15] for 180° DWs. To compare non-180° DWs with 180° DW, the resistance of 30°, 60°, and 180° DWs in the presence of x-linearly polarized photons is also shown in Figure 4. It is clear that the resistance of non-180° DW is smaller than that of 180° DW.

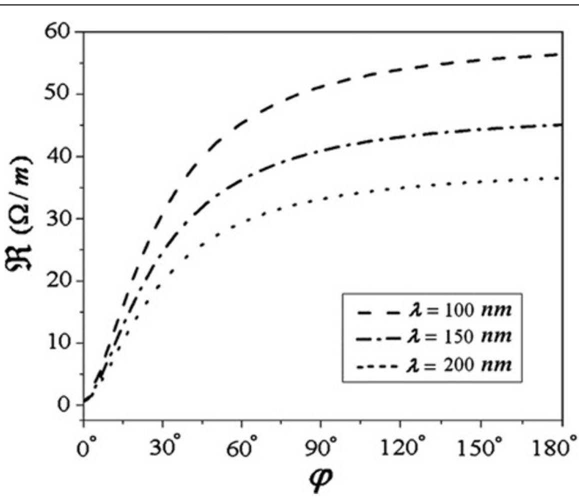

Figure 3 The DWR per unit length versus magnetization rotation angle of the DW. It was calculated for d = 25 nm and Δ_{ex} = 1 meV in the presence of x-linearly polarized photon with different wavelengths.

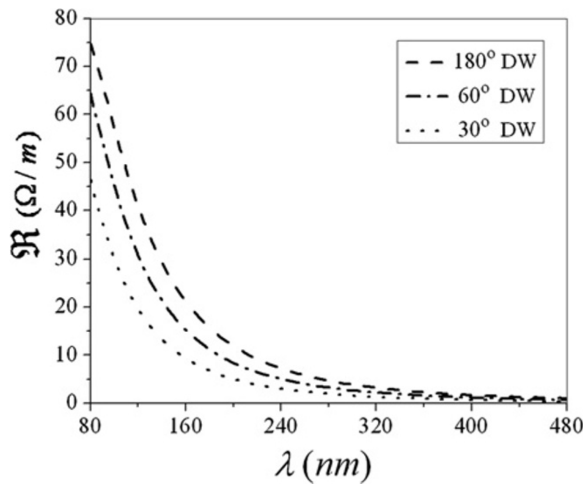

Figure 4 The resistance of 30°, 60°, and 180° DWs versus wavelength of x-linearly polarized photon. It was calculated for d = 25 nm, Δ_{ex} = 1 meV.

We have also shown that the polarization of the photons has significant effect on the DWR [15]. Repeating the calculations for non-180° DW indicates that the electron-photon interaction have no contribution to resistance, and resistance of the nanowire remains invariant in the presence of y-linearly polarized photon. For the circularly polarized photon, the effect of the Zeeman interaction and DWR is smaller than that in the x-linearly polarized photon due to the reduction of the effective magnetic field [15]. The resulting resistance originating from a photon with circular polarization is smaller than that of the x-linear polarization at a special photon wavelength.

Conclusions

We have used the semiclassical approach to study how the photon affects the MR of the non-180° DW in metallic nanowires. The results indicate that the non-adiabaticity and consequently the DWR becomes significant by increasing φ. It is also found that the effectiveness of the photon on the resistivity of the DW with φ about 180° is not negligible. In addition, polarization and wavelength of the photon play a significant role in the contribution of DW in the resistivity of magnetic nanowires. Therefore, understanding the effect of both photons and magnetization rotation angle is essential for providing spintronic devices based on metallic magnetic nanowires.

Competing interests

The author declares that she has no competing interests.

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References

1. Liu, JP, Fullerton, E, Gutfleisch, O, Sellmyer, DJ: Nanoscale magnetic materials and applications. Springer, New York (2009)
2. Xu, Y, Thompson, S: Spintronic materials and technology (series in material science and technology). Taylor and Francis, Florence (2006)
3. Das Sarma, S, Fabian, J, Xuedong, HZ: Theoretical perspectives on spintronics and spin-polarized transport. I: IEEE Trans. Magn. **36**, 2821–2526 (2000)
4. Taylor, GR, Acar, I, Coleman, RV: Resistivity of iron as a function of temperature and magnetization. Phys. Rev. **165**, 621–631 (1968)
5. Gregg, GF, Allen, A, Ounadjela, K, Viret, M, Hehn, M, Thompson, SM, Coey, JMD: Giant magnetoresistive effects in a single element magnetic thin film. Phys. Rev. Lett. **77**, 1580–1583 (1996)
6. Levy, PM, Zhang, S: Resistivity due to domain wall scattering. Phys. Rev. Lett. **79**, 5110–5113 (1997)
7. Phirouznia, A, Tehranchi, MM, Ghanaatshoar, M: Influence of Rashba coupling on the magnetoresistance of a smooth domain wall. Phys. Rev. B **75**(224403), 1–11 (2007)
8. Ghanaatshoar, M, Fallahi, V, Tehranchi, MM, Phirouznia, A: Dependence of a one-dimensional Neel-type magnetic domain wall resistance on transverse external magnetic field in presence of Rashba spin-orbit coupling. IEEE Tran. on Magn. **44**, 3127–3130 (2008)
9. Kent, A, Rudiger, U, Yu, J, Thomas, L, Parkin, SSP: Magnetoresistance, micromagnetism, and domain wall effects in epitaxial Fe and Co structures with stripe domains. J. Appl. Phys. **85**, 5243–5248 (1999)
10. Majidi, R, Tehranchi, MM, Phirouznia, A, Ghafoori Tabrizi, K: Influence of longitudinal acoustic phonons on domain wall magnetoresistance in magnetic nanowires. Phys. Rev. B **83**(035413), 1–5 (2011)
11. Majidi, R, Tehranchi, MM, Phirouznia, A, Ghafoori Tabrizi, K: Influence of longitudinal optical phonons on domain wall resistance in nanowires based on diluted magnetic semiconductors. Eur. Phys. J. B **81**, 209–213 (2011)
12. Majidi, R, Tehranchi, MM, Phirouznia, A: Effect of non-polar longitudinal optical phonons on domain wall resistance in diluted magnetic semiconductor nanowires. J. Supercond. Novl. Magn. **25**, 1597–1601 (2012)
13. Phirouznia, A, Tehranchi, MM, Ghanaatshoar, M: Magnetic field dependence of the domain wall resistance in a quantum wire. Eur. Phys. J. B **54**, 103–107 (2006)
14. Majidi, R, Tehranchi, MM, Phirouznia, A, Ghafoori Tabrizi, K: The effect of a pulsed magnetic field on domain wall resistance in magnetic nanowires. J. Phys.: Conf. Ser **292**(1–5), 012009 (2011)
15. Majidi, R, Tehranchi, MM, Phirouznia, A, Ghafoori Tabrizi, K: Optical-controlled domain wall resistance in magnetic nanojunctions. Eur. Phys. J. B **76**, 475–480 (2010)
16. Hubert, A, Schäfer, R: Magnetic domains: the analysis of magnetic microstructures. Springer, New York (2008)
17. Rudiger, U, Yu, J, Kent, AD, Parkin, SSP: Magnetoresistance due to domain walls in an epitaxial microfabricated Fe wire. Appl. Phys. Lett. **73**, 1298–1301 (1998)
18. Majidi, R: Magnetic field control of 901, 1801, and 3601 domain wall resistance. Physica B **407**, 4005–4007 (2012)

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