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Influence of spin–orbit coupling on spin-polarized electronic transport in magnetic semiconductor nanowires with nanosized sharp domain walls

Lian Liu(刘恋), Wen-Xiang Chen(陈文祥), Rui-Qiang Wang(王瑞强), and Liang-Bin Hu(胡梁宾)†

Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, School of Physics and Telecommunication Engineering, South China Normal University, Guangzhou 510631, *China*

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Influence of spin–orbit coupling on spin-polarized electronic transport in magnetic semiconductor nanowires with nanosized sharp domain walls is investigated theoretically. It is shown that the Rashba spin–orbit coupling can enhance significantly the spin-flip scattering of charge carriers from a nanosized sharp domain wall whose extension is much smaller than the carrier's Fermi wavelength. When there are more than one domain wall presented in a magnetic semiconductor nanowire, not only the spin-flip scattering of charge carriers from the domain walls but the quantum interference of charge carriers in the intermediate domain regions between neighboring domain walls may play important roles on spin-polarized electronic transport, and in such cases the influences of the Rashba spin–orbit coupling will depend sensitively both on the domain walls' width and the domain walls' separation.

Keywords: magnetic semiconductor nanowires, domain wall, spin–orbit coupling, spin-polarized electronic transport

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1. Introduction

In a ferromagnetic material with multiple magnetic domains, domain walls (DWs) will be formed between neighboring domains. Magnetic DWs in low-dimensional ferromagnetic structures have attracted recently a lot of attention since they can serve as important elements of new magnetoelectric devices.[1,2] Many of such applications rely on the interaction between spin polarized electric currents and the magnetic moments forming magnetic DWs. For example, it was recently demonstrated that magnetic DWs in ferromagnetic nanowires can be used in a new type of memory device effectively controlled by a spin polarized electric current.[3,4] From the physical point of views, the interaction between spin polarized electric currents and the magnetic moments forming magnetic DWs are two-fold in general. One one hand, spin polarized electric currents can affect the dynamics of magnetic DWs in low-dimensional ferromagnetic structures. On the other hand, the presence of magnetic DWs can affect significantly the transport of spin polarized charge carriers. Both these aspects of the interaction between spin polarized electric currents and magnetic DWs in low-dimensional ferromagnetic structures have been studied extensively in the recent years and many interesting effects were discovered, e.g., current-induced domain wall motion and huge domain wall resistance in ferromagnetic nanowires.[5–8]

An interesting topic concerning the interaction between spin polarized electric currents and magnetic DWs in low-dimensional ferromagnetic structures is the influence of the spin–orbit coupling of charge carriers.[7–29] For the recent review please refer to Ref. [8]. Compared with bulk ferromagnetic structures, the broken inversion symmetry in low-dimensional ferromagnetic structures can enhance significantly the spin–orbit coupling of charge carriers. It was found that the influences of the spin–orbit coupling of charge carriers in low-dimensional ferromagnetic structures can lead to some new fundamental behaviors that can be exploited in higher performance and low-power spintronic devices.[7–29] For example, the spin–orbit coupling of charge carriers in ferromagnetic ultrathin films or nanowires can generate current-induced spin–orbit torques or spin-Hall torques potentially much stronger than conventional spin-transfer torques.[24–29]

So far most of recent works have concentrated on how the spin–orbit coupling of charge carriers affects the current-induced spin torques and current-induced domain wall dynamics in low-dimensional ferromagnetic structures. In the present paper we study another aspect of the influence of the spin–orbit coupling of charge carriers in low-dimensional ferromagnetic structures with multiple magnetic domains. We investigate theoretically what influences the spin–orbit coupling may have on the transport of spin polarized charge carriers in ferromagnetic nanowires with multiple magnetic domains and pinned DWs, a question that has not yet been addressed sufficiently in the literature. Such a theoretical investigation is desirable in view of some potential applica-

†Corresponding author. E-mail: lbhu26@126.com

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tions of low-dimensional ferromagnetic structures in spintronic devices.[30,31] From the theoretical points of view, the spin–orbit coupling not only mix the spin channels of charge carriers but also mix the spin-dependent scattering of charge carriers from a magnetic DW. Moreover, additional complication may be induced if there are more than one DW presented in a ferromagnetic nanowire. When multiple magnetic DWs are present in a ferromagnetic nanowire, in addition to spin-dependent scattering from a single DW, quantum interference of spin polarized charge carriers will also occur in the intermediate domain regions between neighboring DWs. Such quantum interference effect can also be affected significantly by the presence of the spin–orbit coupling. To analyze such influences, in this paper we take magnetic semiconductor nanowires with nanosized sharp DWs as the examples, in which the extension of a DW is much smaller than the carrier's Fermi wavelength, i.e., the widths of the DWs satisfy the condition $k_{F\uparrow(\downarrow)}\delta \ll 1$, where δ is the width of a DW and $k_{\mathrm{F}\uparrow(\downarrow)}$ the Fermi wavevectors for the majority and minority electrons, respectively. In bulk metallic ferromagnets, the extension of a DW is usually much larger than the carrier's Fermi wavelength ($k_{\mathrm{F}\uparrow(\downarrow)}\delta \gg 1$) and hence the scattering from a DW is usually much weak and the DW resistance is usually rather small. In contrast to bulk metallic ferromagnets, in magnetic semiconductor nanowires, the extension of a DW can be on the atomic scale and considerably smaller than the carrier's Fermi wavelength. In such cases, the spin-dependent scattering of charge carriers from a DW may be considerably stronger than that in the bulk cases, and consequently, the influences of magnetic DWs on the transport of spin polarized charge carriers may also be substantially stronger than that in the bulk cases.[31–38] In this paper we will investigate in some detail what influences the spin–orbit coupling of charge carriers may have on the spin-dependent transmission through nanosized sharp DWs in magnetic semiconductor nanowires with multiple magnetic domains.

The paper is organized as follows. In Section 2 we introduce the theoretical model and the theoretical formulation for the calculation of the conductance of a ballistic magnetic semiconductor nanowire with nanosized sharp DWs. In Section 3 we take magnetic semiconductor nanowires with one, two or three nanosized sharp DWs as the examples to discuss the influences of the spin–orbit coupling on the spin polarized transport of charge carriers. We will calculate numerically the domain wall conductance as functions of some adjustable physical parameters, such as the DW width, the DW separation, the Rashba spin–orbit coupling constant, etc. A summary will be given in the end of the paper.

2. Model and formulation

We consider a ballistic magnetic semiconductor nanowire with Rashba spin–orbit coupling and nanoscale sharp DWs. The wire is along the z axis (the easy axis) and the Rashba field along the x axis. The direction of the magnetization vector field $\boldsymbol{M}(z)$ inside the DWs varies within the xz plane (the easy plane). The magnitude of the magnetization vector field $\boldsymbol{M}(z)$ is assumed to be uniform and will be denoted as M_0 (independent of the coordinate z). For simplicity of calculation, we treat the nanowire as a one-dimensional quantum wire. Actual nanowires are quasi-one-dimensional systems where multi-band effect may play some role on the electronic transport. If only the lowest sub-band is populated by electrons in a nanowire (which can be realized by controlling the density of electrons or the transverse width of a nanowire), the multi-band effect can be neglected and the system can be approximated as a one-dimensional quantum wire. We will assume such approximation in the discussions presented below, i.e., we neglect the multi-band effect on the electronic transport. We also assume that the positions of the DWs are pinned and hence the effect of current-induced domain wall motion are negligible. In such condition the effect of a DW on the electronic transport is equivalent to a spin-dependent static potential.[31–36] Then the Hamiltonian describing independent charge carriers in such a ballistic magnetic semiconductor nanowire reads

$$H = \frac{p_z^2}{2m} - M_x(z)\sigma_x - M_z(z)\sigma_z + \frac{\alpha_{\mathrm{R}}}{\hbar} p_z \sigma_x, \tag{1}$$

where m is the carrier's effective mass, $p_z = -\mathrm{i}\hbar\mathrm{d}/\mathrm{d}z$ is the carrier's momentum operator, $\sigma_{x,y,z}$ is the Pauli matrices, $M_{x(z)}$ is the $x(z)$ component of the magnetization vector field $\boldsymbol{M}(z)$, α_{R} is the Rashba spin–orbit coupling constant.

In the ballistic limit, the only scattering of charge carriers comes from the DWs. The explicit formulation for the calculation of the domain wall conductance depends on the actual structures of the DWs. As an example, below we will discuss in some detail how to calculate the domain wall conductance of a ferromagnetic nanowire with two nanosized sharp DWs, in which the thickness of the two DWs is much smaller than the carrier's Fermi wavelength. In actual ferromagnetic nanowires, the thickness of the DWs may be affected by a number of factors, e.g., by the magnetic anisotropy.[12] We neglect such complexity in the present paper. We assume that the two DWs have the same width δ and the extension of one DW is from $z = -\delta$ to $z = \delta$ and the other from $z = L - \delta$ to $L + \delta$, respectively, where L is the distance between the centers of the two DWs. In the regions outside the DWs, the magnetization field is assumed to be homogeneous in each domain, with $\boldsymbol{M}(z) = [0, 0, M_0]$ for $z < -\delta$, $\boldsymbol{M}(z) = [0, 0, -M_0]$

for $\delta < z < L-\delta$, and $\boldsymbol{M}(z) = [0,0,M_0]$ for $z > L+\delta$. Inside the DWs, the spatial variation of the inhomogeneous magnetization field $\boldsymbol{M}(z)$ is assumed to take the following form: $\boldsymbol{M}(z) = M_0[\sin\theta(z), 0, \cos\theta(z)]$, where $\theta(z)$ is a function of the coordinate z (along the wire) and we approximate $\theta(z)$ as a linear function of z inside the DWs. Inside the DW between $z=-\delta$ and $z=\delta$, $\theta(z)$ varies smoothly from zero to π as z is changed from $z=-\delta$ to $z=+\delta$, and inside the DW between $z=L-\delta$ and $z=L+\delta$, $\theta(z)$ varies smoothly from π to zero as z is changed from $z=L-\delta$ to $z=L+\delta$. Such a spatial variation of the inhomogeneous magnetization field corresponds to the Neel type of domain walls. The approach used below is also applicable if the domain wall profile is the Bloch type.

Now we consider the transmission of a charge carrier incident from the left region of $z<-\delta$ to the right region of $z>L+\delta$. Carrier wave function in each domain can be expressed as the linear combination of the eigenfunctions of the Hamiltonian H. For a given energy E, two degenerated eigenfunctions can be obtained from the Hamiltonian H. Then in the left region of $z<-\delta$, the carrier wave function can be expressed as

$$\Psi^{(1)}(z) = \mathrm{e}^{\mathrm{i}k_+ z}\begin{bmatrix} M_{k_+}/D_{k_+} \\ \alpha_{\mathrm{R}}k_+/D_{k_+}\end{bmatrix} + r^{(1)}\mathrm{e}^{-\mathrm{i}k_+ z}\begin{bmatrix} M_{k_+}/D_{k_+} \\ -\alpha_{\mathrm{R}}k_+/D_{k_+}\end{bmatrix} + r_{\mathrm{f}}^{(1)}\mathrm{e}^{-\mathrm{i}k_- z}\begin{bmatrix} \alpha_{\mathrm{R}}k_-/D_{k_-} \\ M_{k_-}/D_{k_-}\end{bmatrix}, \tag{2}$$

or can be expressed as

$$\Psi^{(2)}(z) = \mathrm{e}^{\mathrm{i}k_- z}\begin{bmatrix} -\alpha_{\mathrm{R}}k_-/D_{k_-} \\ M_{k_-}/D_{k_-}\end{bmatrix} + r^{(2)}\mathrm{e}^{-\mathrm{i}k_- z}\begin{bmatrix} \alpha_{\mathrm{R}}k_-/D_{k_-} \\ M_{k_-}/D_{k_-}\end{bmatrix} + r_{\mathrm{f}}^{(2)}\mathrm{e}^{-\mathrm{i}k_+ z}\begin{bmatrix} M_{k_+}/D_{k_+} \\ -\alpha_{\mathrm{R}}k_+/D_{k_+}\end{bmatrix}. \tag{3}$$

Here $\Psi^{(1,2)}$ denotes two degenerated scattering states with the same incident energy E, $r^{(1,2)}$ and $r_{\mathrm{f}}^{(1,2)}$ are the non-spin-flip and spin-flip reflection coefficients. The wave numbers $k_\pm$ are determined by the following dispersion:

$$\hbar^2 k_\pm^2/2m = E \pm \sqrt{M_0^2 + \alpha_{\mathrm{R}}^2 k_\pm^2}.$$

$M_{k_\pm}$ and $D_{k\pm}$ are functions of the wave numbers $k_\pm$ and are defined by

$$M_{k_\pm} = M_0 + \sqrt{M_0^2 + \alpha_{\mathrm{R}}^2 k_\pm^2}, \tag{4}$$

$$D_{k\pm} = \sqrt{M_{k_\pm}^2 + \alpha_{\mathrm{R}}^2 k_\pm^2}. \tag{5}$$

Correspondingly, in the right region of $z>L+\delta$, the carrier wave function can be expressed as

$$\Psi^{(1)}(z) = t^{(1)}\mathrm{e}^{\mathrm{i}k_+ z}\begin{bmatrix} M_{k_+}/D_{k_+} \\ \alpha_{\mathrm{R}}k_+/D_{k_+}\end{bmatrix} + t_f^{(1)}\mathrm{e}^{\mathrm{i}k_- z}\begin{bmatrix} -\alpha_{\mathrm{R}}k_-/D_{k_-} \\ M_{k_-}/D_{k_-}\end{bmatrix}, \tag{6}$$

$$\Psi^{(2)}(z) = t^{(2)}\mathrm{e}^{\mathrm{i}k_- z}\begin{bmatrix} -\alpha_{\mathrm{R}}k_-/D_{k_-} \\ M_{k_-}/D_{k_-}\end{bmatrix} + t_{\mathrm{f}}^{(2)}\mathrm{e}^{\mathrm{i}k_+ z}\begin{bmatrix} M_{k_+}/D_{k_+} \\ \alpha_{\mathrm{R}}k_+/D_{k_+}\end{bmatrix}, \tag{7}$$

where $t^{(1,2)}$ and $t_{\mathrm{f}}^{(1,2)}$ are the non-spin-flip and spin-flip transmission coefficients, respectively. In the domain region between the two DWs ($\delta < z < L-\delta$), the carrier wave function can be expressed as

$$\begin{aligned}\Psi^{(1,2)}(z) = {} & a^{(1,2)}\mathrm{e}^{\mathrm{i}k_+ z}\begin{bmatrix} \alpha_{\mathrm{R}}k_+/D_{k_+} \\ M_{k_+}/D_{k_+}\end{bmatrix} + b^{(1,2)}\mathrm{e}^{\mathrm{i}k_- z}\begin{bmatrix} M_{k_-}/D_{k_-} \\ -\alpha_{\mathrm{R}}k_-/D_{k_-}\end{bmatrix} \\ & + c^{(1,2)}\mathrm{e}^{-\mathrm{i}k_+ z}\begin{bmatrix} -\alpha_{\mathrm{R}}k_+/D_{k_+} \\ M_{k_+}/D_{k_+}\end{bmatrix} + d^{(1,2)}\mathrm{e}^{-\mathrm{i}k_- z}\begin{bmatrix} M_{k_-}/D_{k_-} \\ \alpha_{\mathrm{R}}k_-/D_{k_-}\end{bmatrix}.\end{aligned} \tag{8}$$

There are eight unknown coefficients in the carrier wave functions $\Psi^{(1,2)}$. They need to be determined self-consistently from the boundary conditions at the two DWs. By integrating the Schrödinger equation $H\Psi = E\Psi$ from $z=-\delta$ to $z=\delta$ and from $z=L-\delta$ to $z=L+\delta$ respectively, one obtains that the carrier wave functions at both sides of the two DWs satisfy the following boundary conditions

$$\frac{\hbar^2}{2m}\left[\left.\frac{\mathrm{d}\Psi^{(1,2)}}{\mathrm{d}z}\right|_{z=-\delta} - \left.\frac{\mathrm{d}\Psi^{(1,2)}}{\mathrm{d}z}\right|_{z=+\delta}\right] - \sigma_x\int_{-\delta}^{\delta} M_x(z)\Psi^{(1,2)}(z)\,\mathrm{d}z = 0, \tag{9}$$

$$\frac{\hbar^2}{2m}\left[\left.\frac{\mathrm{d}\Psi^{(1,2)}}{\mathrm{d}z}\right|_{z=L-\delta} - \left.\frac{\mathrm{d}\Psi^{(1,2)}}{\mathrm{d}z}\right|_{z=L+\delta}\right] - \sigma_x\int_{L-\delta}^{L+\delta} M_x(z)\Psi^{(1,2)}(z)\,\mathrm{d}z = 0. \tag{10}$$

The integrals in the boundary conditions (9) and (10) involve the carrier wave functions inside the DWs, which cannot be obtained analytically. Since in this paper we are interested in the cases in which the width δ of the DWs satisfies the condition $k_{F\uparrow(\downarrow)}\delta \ll 1$, in such condition the integrals in the boundary conditions (9) and (10) can be approximated as

$$\int_{-\delta}^{\delta} M_x(z)\Psi^{(1,2)}(z)\,\mathrm{d}z \simeq \frac{4M_0\delta}{\pi}\Psi^{(1,2)}(0), \tag{11}$$

$$\int_{L-\delta}^{L+\delta} M_x(z)\Psi^{(1,2)}(z)\,\mathrm{d}z \simeq \frac{4M_0\delta}{\pi}\Psi^{(1,2)}(L). \tag{12}$$

By taking such approximation, from the boundary conditions (9) and (10) and supplemented by the wave function continuity at $z = 0$ and $z = L$, we can determine self-consistently the eight unknown coefficients in the carrier wave functions $\Psi^{(1,2)}$, without obtaining the explicit analytical forms of the carrier wave functions inside the DWs. After the transmission coefficients are obtained, the domain wall conductance can be calculated directly by use of the Landauer-Büttiker formula in the linear response regime.[39] Then one obtains

$$G = \frac{\mathrm{e}^2}{h}\left[\left|t^{(1)}\right|^2 + \left|t^{(2)}\right|^2 + \left|t_{\mathrm{f}}^{(1)}\right|^2 \mathrm{Re}\left(\frac{k_-}{k_+}\right) + \left|t_{\mathrm{f}}^{(2)}\right|^2 \mathrm{Re}\left(\frac{k_+}{k_-}\right)\right], \tag{13}$$

where G is the domain wall conductance and $t^{(1,2)}$ and $t_{\mathrm{f}}^{(1,2)}$ are the non-spin-flip and spin-flip transmission coefficients at the Fermi level, respectively. This formulation can be easily extended to the more general cases with more than two nanosized sharp DWs.

3. Results and discussions

Based on the formulation introduced above, in this section we will calculate numerically the variation of the domain wall conductance with the relevant physical parameters involved, such as the DWs' width δ, the DWs' separation L, the Rashba spin–orbit coupling constant α, etc. From the theoretical points of views, the strongest effect of DWs on the electronic transport can be expected in the case of a full spin polarization of the electron gas. In such condition, there are only one type of spin-polarized electrons (spin-up or spin-down) in each domain. Such condition is experimentally realizable in magnetic semiconductor-based structures (e.g., GaMnAs semiconductor). For the theoretical model described by the Hamiltonian (1), this condition is satisfied when the value of the carrier's Fermi energy E_{F} $(= \hbar^2 k_{\mathrm{F}\uparrow(\downarrow)}^2/2m)$ is smaller than the magnitude M_0 of the magnetization field $\boldsymbol{M}(z)$. We will assume such condition in the discussions presented below. We will take magnetic semiconductor nanowires with one, two or three nanosized sharp DWs as the examples in our discussions.

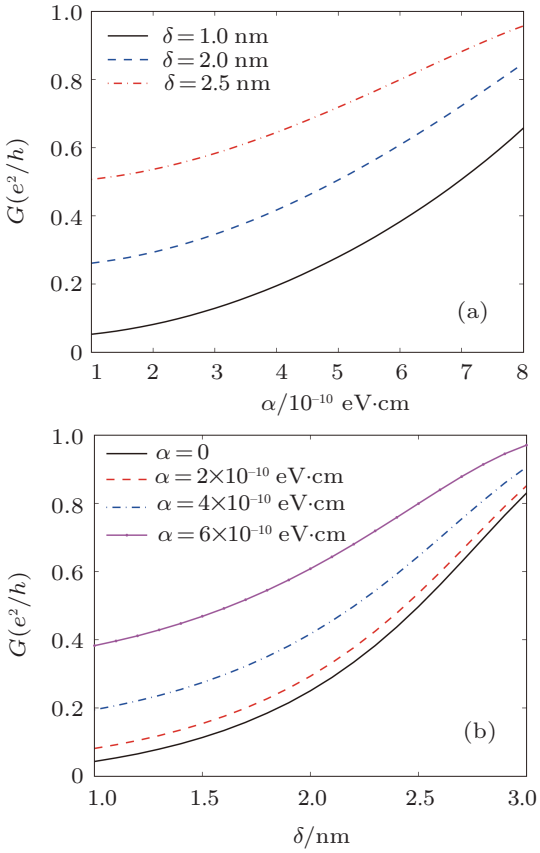


Fig. 1. (color online) (a) The conductance of a single DW versus the Rashba spin–orbit coupling constant α for several different values of the domain width δ. (b) The conductance of a single DW versus the domain width δ for several different values of the Rashba spin–orbit coupling constant α. In both panels, the other parameters are $m = 0.6m_0$, $M_0 = 2.6$ meV, $E_{\mathrm{F}} = 0.6$ meV.

We consider first the simplest case that only one DW presents in a ferromagnetic nanowire. In Fig. 1(a) we show the variation of the conductance of a single DW with the Rashba spin–orbit coupling constant α for several different values of the DW width δ, and in Fig. 1(b) we show the variation of the conductance with the DW width δ for several different values of the Rashba spin–orbit coupling constant α. The other parameters used in the calculations are $m = 0.6m_0$ (m_0 is the free electron mass), $M_0 = 2.6$ meV, $E_{\mathrm{F}} = 0.6$ meV. In GaAs–GaAlAs-based heterostructures, the Rashba spin–orbit coupling constant is estimated to be on the order of 10^{-10} eV·cm and can be modulated by electrically gating the structure. Such values of the relevant parameters are within the experimentally realizable region and also satisfy the sharp DW condition ($k_{\mathrm{F}\uparrow(\downarrow)}\delta \ll 1$) and the full spin polarization condition assumed above. From Fig. 1(a) we can see that the domain wall conductance increases with the increase of the Rashba spin–orbit coupling constant α for different values of the DW width δ. Since for fully spin-polarized electron gas, spin-polarized charge carriers can transmit through a DW only by spin-flip scattering from the DW, the behavior shown in Fig. 1(a) indicates that the Rashba spin–orbit coupling can enhance the spin-flip scattering of spin-polarized charge carriers from nanosized sharp

DWs in magnetic semiconductor nanowires. From Fig. 1(b) we can see that, for a fixed value of the Rashba spin–orbit coupling constant, the domain wall conductance will increase substantially with the increase of the DW width δ. From the theoretical points of view, this behavior indicates that for nanosized sharp DWs in magnetic semiconductor nanowires, a small increase of the DW width can enhance substantially the spin-flip scattering of spin-polarized charge carriers from the DW. This is significantly different from the corresponding cases in bulk metallic ferromagnets.

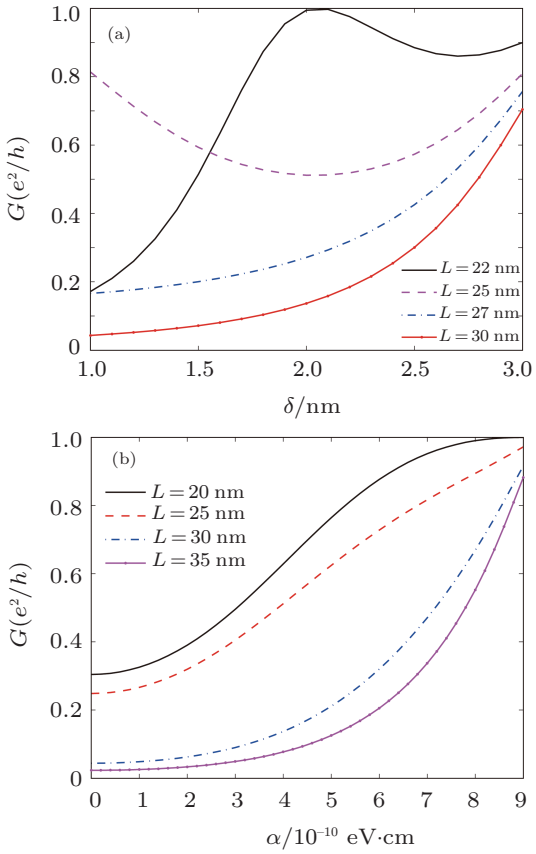


Fig. 2. (color online) (a) The conductance of two DWs separated by a distance L versus the DWs' width δ for several different values of L. The other parameters are $m = 0.6m_0$, $M_0 = 2.6$ meV, $E_F = 0.6$ meV, $\alpha = 4 \times 10^{-10}$ eV·cm. (b) The conductance of two DWs separated by a distance L versus the Rashba spin–orbit coupling constant α for several different values of L. The other parameters are $m = 0.6m_0$, $M_0 = 2.6$ meV, $E_F = 0.6$ meV, $\delta = 2$ nm.

If there are more than one DW presented in a ferromagnetic nanowire, then in addition to the spin-dependent scattering from the DWs, quantum interference of charge carriers will also occur in the intermediate domain region between two neighboring DWs. Such quantum interference effect may also play an important role on the electronic transport in a ferromagnetic nanowire if the separation between two neighboring DWs is much smaller than the decoherence length of charge carriers. Such quantum interference effect can also be affected significantly by the spin–orbit coupling of charge carriers. To illustrate such influences, we take ferromagnetic nanowires with two DWs separated by a distance $L << L_e$ as the examples, where L_e is the decoherence length. In Figs. 2(a) and 2(b) we plot the variation of the domain wall conductance with the DWs' width δ and with the Rashba spin–orbit coupling constant α for several different DWs' separation L, respectively. From Fig.2(a) one can see that, unlike the behavior shown in Fig. 1(b), the variation of the domain wall conductance with the DWs' width δ is not monotonous and the behavior depends sensitively on the distance L between two neighboring DWs. Such sensitive dependence indicates that the quantum interference of charge carriers in the intermediate domain region between two neighboring DWs may play an important role on the electronic transport through the DWs. Similarly, from Fig. 2(b) we can see that the variation of the domain wall conductance with the Rashba spin–orbit coupling constant α also depends sensitively on the separation between two neighboring DWs.

An interesting consequence of the quantum interference of charge carriers between two neighboring DWs is that quasi-stationary states with quasi-discrete levels may be formed in the intermediate domain region between them. To illustrate this fact, in Fig. 3 we show the variation of the conductance of two DWs separated by a distance L with the Fermi energy E_F of charge carriers for several different values of L. From Fig. 3 one can see that the variation of the domain wall conductance with the carriers' Fermi energy show typical resonance characteristics, i.e., when the carriers' Fermi energy E_F equals to a certain value, the effective barrier created by the DWs is basically transparent and hence the domain wall conductance exhibits resonance peaks at such values of E_F. Such resonance effect can also be seen from Fig. 4, where we show the variation of the conductance of two DWs with the DWs' separation L for several different values of the Rashba spin–orbit coupling constant and fixed Fermi energy level. Since the energy of the quasi-stationary state with quasi-discrete level formed in the intermediate domain region between two neighboring DWs depends on the DWs' separation L, as the values of L is varied, the quasi-discrete level of the quasi-stationary state may coincide with the Fermi energy level at some values of L and hence resonant transmission can occur at these values of L. Due to the occurrence of such resonant transmission, the domain wall conductance can exhibit strong oscillations as the DWs' separation L is varied. As can be seen from Fig. 4, such oscillations can be modulated effectively by tuning the Rashba spin–orbit coupling constant, which is experimentally realizable by electrically gating the structure. Such effect may provide some effective means for controlling the spin-polarized electronic transport in DW-based spintronic devices. For example, the sensitive dependence of the domain wall conductance on the DWs' separation can be used to identify the relative position of the DWs. Such effect can also occur when

there are more than two nanosized sharp DWs presented in a magnetic semiconductor nanowire.

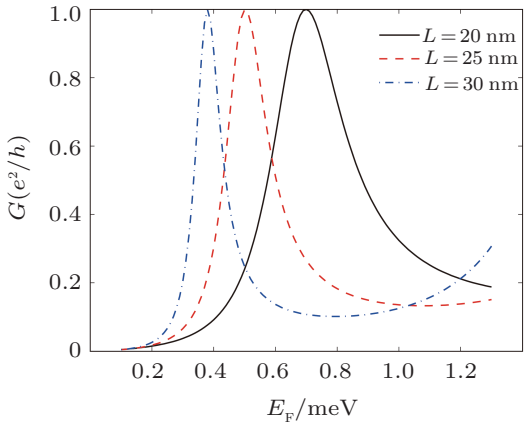


Fig. 3. (color online) The conductance of two DWs separated by a distance L versus the carriers' Fermi energy E_F for several different values of L. Other parameters are $m = 0.6m_0$, $M_0 = 2.6$ meV, $\delta = 2$ nm, $\alpha = 4 \times 10^{-10}$ eV·cm.

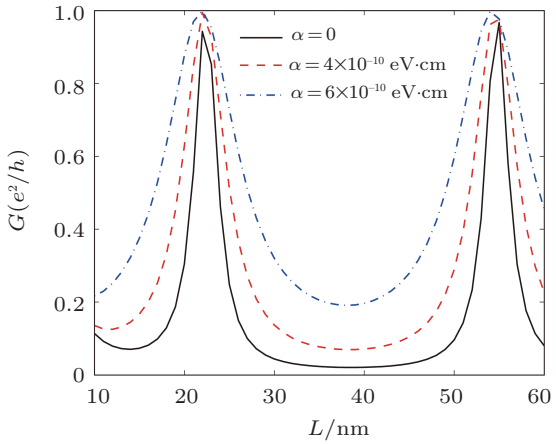


Fig. 4. (color online) The conductance of two DWs versus the DWs' distance L for several different values of the Rashba spin–orbit coupling constant α. Other parameters are $m = 0.6m_0$, $M_0 = 2.6$ meV, $E_F = 0.6$ meV, $\delta = 2$ nm.

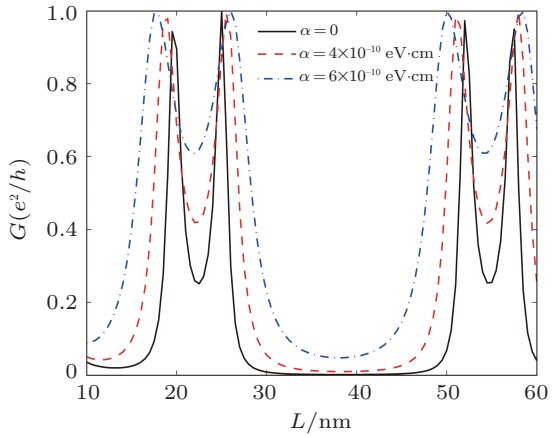


Fig. 5. (color online) The conductance of three equally separated DWs versus the DWs' distance L for several different values of the Rashba spin–orbit coupling constant α. Other parameters are $m = 0.6m_0$, $M_0 = 2.6$ meV, $E_F = 0.6$ meV, and $\delta = 2$ nm.

As an example, in Fig. 5 we show the variation of the conductance of three equally separated DWs with the DWs' separation L for several different values of the Rashba spin–orbit coupling constant and fixed Fermi energy level. From Fig. 5 we can see that, as the number of the DWs is increased, more resonant conductance peaks may be formed as the DWs' separation L is varied. From the physical points of view, this is due to the fact that the coupling between the quasi-stationary states formed in different domain regions may lead to the split of the quasi-discrete levels.

Finally, it should be pointed out that there are some limitations on the validity of the results obtained above. In our calculations we did not include the possible multi-band effect that may exist in actual magnetic semiconductor nanowires. In the presence of multi-band effect, an electron can be scattered from one sub-band to a different sub-band by DWs. If such quantum mixing effect is sufficiently strong, some results obtained above may be modified significantly. In our calculations we have assumed that the positions of the DWs are pinned and hence the effect of current-induced domain wall motion are negligible. From the physical point of view, the effect discussed above should be strongest in such cases. If the positions of the DWs are not pinned, the current-induced domain wall motion may have some effect on the electronic transport. If such effect is sufficiently strong, some results obtained above may also be modified significantly. But the inclusion of such effect is beyond the scope of the approach applied in the present paper. It also should be pointed out that in our calculation we have considered only Rashba spin–orbit coupling. In some ferromagnetic semiconductors (such as GaMnAs) there may exist another type of spin–orbit coupling, namely the Dresselhaus spin–orbit coupling, and its strength may be even stronger than the Rashba spin–orbit coupling.[13] The approach used in the present paper is also applicable in the presence of the Dresselhaus spin–orbit coupling, and from the physical point of view, some effects predicted above should still survive in the presence of both Rashba and Dresselhaus spin–orbit coupling.

4. Summary

In summary, we have analyzed the influences of the Rashba spin–orbit coupling of charge carriers on the electronic transport in magnetic semiconductor nanowires with nanosized sharp DWs. It is shown that for fully spin-polarized electron gas and sharp DWs in which the extension of a DW is much smaller than the carrier's Fermi wavelength, the Rashba spin–orbit coupling can enhance the spin-flip scattering of charge carriers from the DWs in general. When there are more than one DW presented in a magnetic nanowire, not only the spin-flip scattering of charge carriers from the DWs but the quantum interference of charge carriers in the intermediate

domain regions between neighboring DWs may play important roles on the electronic transport through the DWs, and in such cases the influences of the Rashba spin–orbit coupling may depend sensitively both on the DWs' width and the DWs' separation. The characteristics of the variation of the domain wall conductance with the DWs' width and the DWs' separation and the Rashba spin–orbit coupling constant etc. may find some practical applications in DW-based spintronic devices.

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