Effects of domain wall and pinning center on electron transport in ferromagnetic wire

A. Nakamura a,∗, S. Nonoyama b

a Anan National College of Technology, Anan, Tokushima 774-0017, Japan
b Faculty of Education, Yamagata University, Yamagata 990-8560, Japan

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Abstract

The effects of the domain wall and its pinning center on the electron conduction are studied in a framework of the random phase approximation. We show that the domain wall enhances the resistance due to the spin fluctuation around it. Furthermore, the pinning center plays an important role of suppression of the spin fluctuation, which leads to the reduction of the resistance when the domain wall locates at the pinning center. The results obtained are consistent with the experimental findings.

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Recent advances in the nanofabrication technology enable us to create ferromagnetic metals with various sample structures on nanometer scale. In these nanometer-scale metals, a domain wall (DW) nucleation and dynamics have become the subjects of current interest [1–5]. Specifically, the negative magnetoresistance effect on the electrical resistivity due to the DW in ferromagnetic wires has been reported by many researchers. Also, exotic nonlinear transports were reported in these metallic wires containing ferromagnetic domain walls [2]. In these nonlinear transports, the abrupt change and hysteresis loop with change in external magnetic fields have been observed.

These nonlinear transport phenomena are understood to be closely related to the motion of the ferromagnetic DW. To elucidate these phenomena including the dynamics, many microscopic mechanisms have been proposed [6–12,21,22]. However, in our knowledge, qualitative understanding of the whole phenomena is still in the developing stages, because of the complexity and nonlinearity of the phenomena. Furthermore, the conductance in atomic-scale contacts has also been studied extensively in the experiments [13–15] and simulations [16–18]. When magnetic metals are used as the contact materials [14], the spin fluctuation at the very narrow constriction is expected to affect the quantized conductivity. Thus, it is important to examine the behavior of spins in the vicinity of the DW, and hence, our attention is focused on the effect of the spin excitation near the DW on the electrical resistivity.

∗ Corresponding author.
E-mail address: anakamur@anan-nct.ac.jp (A. Nakamura).
In the previous study [19], to elucidate basic features of a ferromagnetic wire with a DW, we calculated the excitation spectrum for the spin fluctuation. In that study, we treated the Heisenberg model with taking the real sample structures into consideration [19,20].

In this Letter, we have investigated the electron transport through the area of DW for the ferromagnetic wire containing within RPA, to examine the effect of the spin fluctuation in the vicinity of the DW on the transport phenomena. Moreover, we have calculated the conductance taking the pinning effects into consideration. The calculated results are considered to give the qualitative explanation of observed abrupt change of the resistance as the position of the DW changes.

We consider an one-dimensional chain illustrated in Fig. 1, where a finite sample region connects to the left and right leads. The Hamiltonian is given by

\[ H = H_{\text{spin}} + H_{\text{cond}} + H_{\text{int}} + H_{\text{pin}}, \]

\[ H_{\text{spin}} = -2 \sum_{(i,j)} J_{ij} S_i \cdot S_j - \frac{1}{2} \sum_i A_i \langle S_i^z \rangle^2, \]

\[ H_{\text{cond}} = -t \sum_{(i,j)} \sum_{\sigma} (C_{i\sigma}^+ C_{j\sigma} + C_{j\sigma}^+ C_{i\sigma}) + \sum_{i\sigma} \epsilon_i^c C_{i\sigma}^+ C_{i\sigma}, \]

\[ H_{\text{int}} = -2I_{\text{sc}} \sum_{i=1}^{N} \sum_{\sigma\sigma'} (C_{i\sigma}^+ s_{\sigma\sigma'} C_{i\sigma'}) \cdot S_i, \]  \hspace{1cm} (4)

\[ H_{\text{pin}} = -2 \sum_{(i,j)} J_{ij}^\text{pin} S_i \cdot S_j - \sum_i H_i^\text{pin} S_i^z. \]  \hspace{1cm} (5)

Here the Hamiltonian \( H_{\text{spin}} \) is that for the spin system and the sample sites are labeled with the coordinate \( 1 \leq i \leq N \). Two semi-infinite leads are labeled \( i \leq 0 \) (left lead) and \( N + 1 \leq i \) (right lead). \( S_i \) is the spin operator at the \( i \)th site and the quantities \( J_{ij} \) and \( A_i \) are the exchange integral between the nearest neighbor sites and the anisotropy energy of the spin system, respectively. We choose the \( z \)-direction as the uniaxial magnetocrystalline easy axis, which is parallel to the chain. The Hamiltonian \( H_{\text{cond}} \) is for the conduction electrons, and the current flows by those electrons. \( C_{i\sigma} (C_{i\sigma}^+) \) is the annihilation (creation) operator of the conduction electron with spin \( \sigma \) at the site \( i \). The quantity \( t (>0) \) is the hopping integral between the nearest neighbor sites. The scattering of the conduction electrons is carried out by the s–d exchange interaction with the energy \( I_{\text{sc}} \) in the sample region (crossed circle in Fig. 1). Note that we restrict the scattering sites within the sample region including the DW, since we consider the effects of the DW on the conductance. The parameters \( J_{ij}^\text{pin} \) and \( H_i^\text{pin} \) are introduced to discuss the effects on the conductance of the magnetic and structural pinning centers for the DW. For simplicity, the exchange integral and the anisotropy energy do not vary for whole region (\( J_{ij} = J, A_i = A \)). The present method can be extended easily to other parameter regions.

In order to discuss the effects of the spin fluctuation on the conductance, we calculate the retarded Green function [19]

\[ \chi^{(0)}(t) = -i \theta(t) \left[ \langle S^+(t) \rangle \langle S^- \rangle \right], \]  \hspace{1cm} (6)

where \( \langle \cdots \rangle \) is a thermal average at a temperature \( T \) and \( \theta(t) \) is a step function. In the following calculation we consider the boundary condition that spins in the left lead are up and those in the right lead are down, i.e., \( \langle S_j^z \rangle \rightarrow \pm \langle S_j^z \rangle \) for \( j \rightarrow \mp \infty \) (\( \langle S_j^z \rangle \) is the thermal average of the bulk, see Fig. 1). Then a DW exists around the center of the sample region due to the symmetry. In this case the Green function has two poles and two cuts on the real axis [19,20], which can

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**Fig. 1.** Schematic illustration of the system. The sample region \((1 \leq i \leq N)\) connects to left \((i \leq 0)\) and right \((N + 1 \leq i)\) leads. Spins in the left \((i \leq 0)\) and right \((N + 1 \leq i)\) leads are up and down, respectively. Then, a magnetic domain wall exists at the center of the sample region.
spin-wave spectrum

be expressed in a form

\[ \chi_{jj}^{(l)}(z) = \frac{r_{jj}^{(l)-}}{z + E_{DW}} + \frac{r_{jj}^{(l)+}}{z - E_{DW}} + \int_{D} \rho_{jj}^{(l)}(\omega) \, d\omega. \]  

(7)

The domain of integration D is \( E_{1} < |\omega| < E_{2} \) (\( E_{1} = A(S_{R}^{\uparrow}), \ E_{2} = E_{1} + 8J(S_{R}^{\uparrow}) \)). The quantity \( \rho_{jj}^{(l)}(\omega) \) is an excitation spectrum of the spin wave. On the other hand, the poles \( z = \pm E_{DW} \), which lie in the gap of the spin-wave spectrum (\( E_{DW} < E_{1} \)), correspond to the excitation energy based on the local spin fluctuation around the DW, because the poles do not come out in the case where no DW exists in the spin system. In a framework of RPA, the structure of the low energy excitation around the DW for the one-dimensional model was almost same as that for the wire with two-dimensional leads [19]. The purpose of the present Letter is the investigation of the energy dissipation in the vicinity of the DW, and thus, we use the one-dimensional leads as a matter of convenience of the calculation, since the dimensionality of leads is not essential in RPA when the DW locates far from leads.

Here we calculate the conductance \( \Delta G = G - 2G_{0} (G_{0} = e^{2}/h) \) with the use of the linear response theory. Within the order of \( (I_{sc})^{2} \), the conductance for the spin-flip scattering can be calculated from the diagrams in Fig. 2. Then the quantity \( \Delta G \) can be divided into two parts: \( \Delta G = \Delta G_{DW} + \Delta G_{SW} \), where \( \Delta G_{DW} \) is a contribution from the poles due to the DW and \( \Delta G_{SW} \) is that from the spin wave. These quantities can be expressed as \( \Delta G_{DW} = \sum_{jj'}(\Delta G_{DW})_{jj'} \) and \( \Delta G_{SW} = \sum_{jj'}(\Delta G_{SW})_{jj'} \), where

\[ (\Delta G_{DW})_{jj'}/G_{0} = -(I_{sc}/t)^{2}r_{jj'}^{(0)-}F_{j-j'}(-E_{DW}), \]  

(8)

\[ (\Delta G_{SW})_{jj'}/G_{0} = -(I_{sc}/t)^{2} \int_{D} \rho_{jj'}^{(0)+}(\epsilon)F_{j-j'}(\epsilon) \, d\epsilon, \]  

(9)

\[ F_{m}(\epsilon) = (\xi_{m}^{\uparrow}(\epsilon) - \xi_{m}^{\downarrow}(-\epsilon))/2; \]

\[ \eta_{m}^{\uparrow}(\epsilon) = \int d\epsilon' \left( -\frac{df}{d\epsilon'} \right) \left[ P_{B}(\epsilon) + f(\epsilon + \epsilon') \right] \times \frac{\cos[\pi\sigma(\epsilon')\alpha]}{\sin[\pi\alpha(\epsilon')]} \times \frac{\cos[\pi\alpha(\epsilon') - \pi(\epsilon + \epsilon')]\sin[\pi\alpha(\epsilon')]}{2\sin[\pi\alpha(\epsilon')]}, \]  

(10)

\[ \eta_{m}^{\downarrow}(\epsilon) = \int d\epsilon' \left( -\frac{df}{d\epsilon'} \right) \left[ P_{B}(\epsilon) + f(\epsilon + \epsilon') \right] \times \frac{\cos[\pi\sigma(\epsilon') - \pi\alpha(\epsilon + \epsilon')]\sin[\pi\alpha(\epsilon')]}{2\sin[\pi\alpha(\epsilon')]}, \]

(11)

Here \( f(\epsilon) = 1/(e^{\epsilon/T} + 1), \ P_{B}(\epsilon) = 1/(e^{\epsilon/T} - 1), \ P \) means a principal part, and \( \cos[\pi\sigma(\epsilon')] = (\epsilon - \epsilon'_{F})/2t \).

In the following calculation, we consider the case where \( S = 1 \) and \( \epsilon'_{F} = \epsilon_{F} = 0 \) (\( \epsilon_{F} \) is the Fermi energy of the conduction electron). In this case the conduction band is half-filled.

As a mechanism of the pinning for the DW in the Hamiltonian \( H_{pin} \) (Eq. (5)), we consider two cases: (i) a structural pinning such as an artificial neck (1st term of \( H_{pin} \)), and (ii) a pinning caused by a magnetic impurity (2nd term of \( H_{pin} \)). The former case (i) can be expressed as

\[ J_{ij}^{pin} = \begin{cases} J_{cc} & \text{for } (i, j) = (N/2, N/2 + 1), \\ 0 & \text{otherwise,} \end{cases} \]

(13)

and \( H_{ij}^{pin} = 0 \) for all \( i \). Note that the total coupling constant at the pinning center \( J + J_{c} \) varies in the range of \( 0 < J + J_{c} < J \), because of the ferromagnetic wire. Then \(-1 < J_{c}/J < 0\) in this model. In this case the spin distribution at \( T = 0 \) is shown in Fig. 3(a). On

the other hand, the latter case (ii) can be expressed as

$H_{\text{pin}}^i = \begin{cases} H_c, & \text{for } i = N/2, \\ -H_c, & \text{for } i = N/2 + 1, \\ 0, & \text{otherwise}, \end{cases}$

and $J_{ij}^\text{pin} = 0$ for all $(i, j)$. In this case the spin distribution [19] at $T = 0$ is shown in Fig. 3(b). In these figures, it is seen that the slope of the curve increases around the center of the DW as the strength of the pinning increases. This means that the pinning center suppresses the spin fluctuation around the DW when the DW locates at the center. Here we mention about the length scale briefly. It is seen that the width of DW $\lambda_{\text{DW}} (\sim \pi a/\sqrt{2J/A})$, $a$ is lattice constant) is much smaller than the length of the sample region ($1 \leq n \leq 50$) in Fig. 3.

Next, we discuss the effects of the suppression on the conductance $\Delta G$ by calculating Eqs. (8)–(12). Fig. 4 shows the temperature dependences of $\Delta G_{\text{DW}}$ and $\Delta G_{\text{SW}}$ in the case (i). When the pinning center does not exist ($J_c = 0$), the spin fluctuation decreases the conductance due to the scattering of conduction electrons at $T > E_{\text{DW}}$ ($E_{\text{DW}}/J \sim 0.005$ in this case). The strength of the pinning increases ($J_c/J = -0.5$ and $-0.7$), the effect on the conductance ($|\Delta G|$) decreases. This means that the pinning center plays an important role for the suppression of the “reduction of the conductance”. This suppression can be also obtained in the magnetic pinning case. The detailed results will be published elsewhere. As for the resistance $R \sim (1 - \Delta G/2G_0)/2G_0$, the suppression effect decreases $R$ when the DW locates at the pinning center. Here, we consider the abrupt change of the resistance for the ferromagnetic wire, which is illustrated in Fig. 5. When the DW situates far from the pinning sites, the conduction electrons are scattered by the spin fluctuation around the DW. In this case the pinning center hardly suppress the spin fluctuation, so that the resistance nearly corresponds to that for $J_c = 0$ in Fig. 4. If the DW approaches the pinning center and locates at the center, the spin fluctuation is suppressed, which results in the decrease of the resistance. After the DW goes away from the pinning center, the value of the resistance returns to the beginning value. Such a change of the resistance can be expected in a wide temperature range, except for very low temperatures (see Fig. 4). These features are considered to be in agreement qualitatively with the experimental findings [2], although the present calculation is based on RPA and the characteristic energies may be larger than the exact values.
In summary, we have studied the effects of the DW on the transport properties of the conduction electron for the ferromagnetic wire with the use of the RPA. Moreover, we evaluated the effects of the pinning center of the DW and discussed the jump of the resistance using the obtained results.

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