The Effect of a Pulsed Magnetic Field on Domain Wall Resistance in Magnetic Nanowires

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Abstract. The effect of a pulsed magnetic field on domain wall magnetoresistance for an ideal one-dimensional magnetic nanowire with a domain wall has been investigated. The analysis has been based on the Boltzmann transport equation, within the relaxation time approximation. The results indicate that the domain wall resistance increase when enhancing the magnetic field. The evaluation of local magnetization has been considered in the presence of a pulsed magnetic field. The time evaluation of the magnetization also has an effect on the domain wall resistance. The resistance depends on the contribution of the Zeeman and exchange interactions.

1. Introduction

Currently there is a great interest in spin dependent transport phenomena in magnetic systems due to the potential application of these phenomena in spin electronic devices [1]. Among magnetic systems, nanowires with their unique transport properties have a special position in spintronics [2]. In these systems, spin dependent scattering plays a significant role in electrical resistance; named magnetoresistance (MR). The MR associated with nanowires containing regions of non-collinearity such as domain walls (DWs) is an outstanding problem [3]. The study of the effects of different scattering mechanisms on resistance and controlling the DWR has gained crucial importance [4-8]. For instance, the DWR of a ferromagnetic nanowire has been investigated in the presence of an external magnetic field [5, 7].

For practical applications, DWR when affected by magnetic fields should lead to new insights into its control. However, DWR has only been investigated in constant external magnetic fields and the effects of pulsed magnetic fields on DWR are still unclear. In this paper, we have studied the contribution of DW to the resistance of magnetic nanowires in the presence of a pulsed magnetic field. The analysis has been based on the Boltzmann transport equation, within the relaxation time approximation.
2. Theoretical Considerations

2.1. Description of Model and Interactions
We have studied a 180° Néel-type DW between two ferromagnetic regions with opposite directions of magnetization (Figure 1). For this ideal one-dimensional DW, the rotation angle can be written as

$$\theta(z) = \frac{\pi}{d} z,$$

which describes the angle between the local direction of the magnetization, $\hat{M}_0(\vec{r})$, and the wire direction, $z$-axis.

![Figure 1. A 180º Néel-type DW between two ferromagnetic regions.](image)

The Hamiltonian of the system in the presence of an external magnetic field can be written as:

$$H = H_0 + H_{ex} + H_H.$$

The first term $H_0$ contains kinetic energy and nonmagnetic periodic potential, $V(z)$, as follows:

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

The second term $H_{ex}$ represents the exchange interaction between the conduction electrons and the localized magnetic moments, and can be expressed as:

$$H_{ex} = -\Delta_{ex} \hat{\sigma} \hat{M}(\vec{r}, t),$$

in which $\Delta_{ex}$ is the exchange interaction strength and $\hat{\sigma}$ denotes the spin operators in terms of the Pauli spin matrices. We considered a system which has the equilibrium value $\hat{M}_0(\vec{r})$, and asked what the response would be to a time varying transverse magnetic field $H(t)$. We write magnetization as $\hat{M}(\vec{r}, t) = \hat{M}_0(\vec{r}) - \hat{m}(\vec{r}, t)$ in the presence of a pulsed magnetic field. The unit vector along the direction of the local magnetization is introduced by $\hat{M}(\vec{r}, t)$ in the presence of a pulsed magnetic field. Therefore, the term of the exchange interaction is:

$$H_{ex} = H_{ex}(0) + H_{ex}(\hat{m})$$

$$= -\Delta_{ex} [\hat{M}_0(\vec{r}) - \hat{m}(\vec{r}, t)].$$

In the presence of a pulsed magnetic field the time evaluation of the local magnetization is:

$$\frac{d\hat{M}(\vec{r}, t)}{dt} = -\gamma \hat{M}(\vec{r}, t) \times H(t) + \alpha \hat{M}(\vec{r}, t) \times \frac{d\hat{M}(\vec{r}, t)}{dt}. $$

When the field is turned off the local magnetization is considered as:

$$\hat{M}(\vec{r}, t) = \hat{M}_0(\vec{r}) - \hat{m}(\vec{r}, \Gamma) e^{-(t-\Gamma)/\tau},$$

where $\gamma = g\mu_B/h$ is the gyromagnetic ratio and $\alpha$ is a phenomenological damping constant. For simplicity, the equation (5) is linearized by neglecting terms which are quadratic in $H(t)$ or the components of $\hat{M}(\vec{r}, t)$. 
The last term in the Hamiltonian is the Zeeman interaction,
\[ H_\text{H} = -\Delta_\text{H} \hat{\sigma} \cdot \hat{n}_\text{H}, \]  
(7)
where \( \Delta_\text{H} = g \mu_B H(t)/2 \), \( \mu_B \) is the Bohr magneton and \( \hat{n}_\text{H} \) is the unit vector along the external magnetic field. The rectangular pulsed magnetic field with an amplitude of \( H_0 \) and duration of \( \Gamma \) is considered as:
\[ H(t) = \begin{cases} H_0 & 0 \leq t \leq \Gamma \\ 0 & t < 0, \Gamma > t \end{cases} \]  
(8)

Using an approach based on the perturbation method of Ref. [4], the eigenstates of \( H_0 + H_\text{ex}(0) \) for a one-dimensional system may be formulated as:
\[ |\psi^\uparrow_k\rangle = \frac{\tilde{\alpha}(k)}{\sqrt{d}} e^{ik\zeta} R_{\theta(k)} \left( \frac{1}{ik\zeta} \right), \]  
(9a)
\[ |\psi^\downarrow_k\rangle = \frac{\tilde{\alpha}(k)}{\sqrt{d}} e^{ik\zeta} R_{\theta(k)} \left( \frac{1}{ik\zeta} \right), \]  
(9b)
where \( \tilde{\alpha}(k) = (1 + k^2 \zeta^2)^{-1/2} \) and \( \zeta = \pi^2 \hbar^2 / (8m\Delta d^2) \) are the normalization coefficient and the perturbation parameter, respectively. Here, \( R_{\theta(k)} = \exp(-i\theta(z)\hat{\sigma}) \hat{n}_\text{H} / 2 \) is the spin rotation operator about \( y \)-axis corresponding to Figure 1.

2.2. Spin dependent transport characteristics

To calculate the DWR, we consider the Boltzmann equation in the relaxation time approximation for finding the deviation from equilibrium distribution function.

Using the approach based on the method used in Ref. [8], the spin dependent relaxation time will be simplified by:
\[ \tau^\uparrow(k) = \frac{\hbar}{md} \left( k^2 \left| V^\uparrow_{k,k} \right|^2 + k_x \left| V^\downarrow_{k,k} \right|^2 \right), \]  
(10a)
\[ \tau^\downarrow(k) = \frac{\hbar}{md} \left( k^2 \left| V^\downarrow_{k,k} \right|^2 + k_x \left| V^\uparrow_{k,k} \right|^2 \right), \]  
(10b)
in which \( k_x = \sqrt{k^2 + 4m\Delta/\hbar^2} \). The value of \( \sqrt{4m\Delta/\hbar^2} \) is small enough in relation to the Fermi wave vector, \( k_F \).

The matrix elements of scattering potentials, \( V^\sigma_{k,k} \), can be determined by considering the Zeeman term as scattering potential,
\[ V^\sigma_{k,k} = \left\langle \psi^\sigma_k | H_\text{H} + H_\text{ex}(\vec{m}) \right| \psi^\sigma_k \rangle \]  
(11a)
\[ V^\sigma_{k,k} = \tilde{\alpha}(k) \frac{\exp[(k-k')d]}{i(k-k')d} \left( -\Delta_\text{H} + \Delta_\text{ex} \alpha \gamma H_0 t \right) \left( \begin{array}{cc} (k' + k)\zeta & -i(1-k'k\zeta^2) \\ i(1-k'k\zeta^2) & -(k' + k)\zeta \end{array} \right), \]  
(11b)
and,
\[ V^\sigma_{k,k} = \left\langle \psi^\sigma_k | H_\text{ex}(\vec{m}) \right| \psi^\sigma_k \rangle \]  
(12a)
\[ V_{k',k}^{\sigma,\sigma} = \frac{\Delta_k \exp[i(k-k')d]}{i(k-k')d} \Delta_{\sigma} \alpha \gamma H_0 \Gamma \left( \begin{array}{c} (k' + k)\zeta \\ i(1 - k'k\zeta^2) \\ -(k' + k)\zeta \end{array} \right) e^{-i(k-k')/\tau}, \]  

(12b)

Here, \( T \) is the spin lattice relaxation time.

Using \( \tau^\sigma(k) \), the resistivity per unit length can be determined as follows:

\[ \Re = \frac{e^2 h^2}{2\pi m^2} \int \sigma \int d\epsilon \epsilon^\sigma \delta(\epsilon_{k\sigma} - \epsilon_F) \],

(13)

where \( \epsilon_F \) is the Fermi energy.

3. Results and Discussion

In our calculations, the parameters had been chosen in such a way that the condition for validity of the semiclassical approximation \( (k_Fd >> 1) \) would be applicable. We have used the typical acceptable parameters: \( d = 20 \text{ nm}, \epsilon_F = 10 eV, \Delta_{\sigma} = 0.1 eV, \) and \( m = m_e \).

The resistance per unit length of DW versus time in the presence of the pulsed magnetic field is shown in Figure 2. Both increasing and decreasing of the DWR have been observed depending on the contribution of the Zeeman and exchange interactions. When the magnetic field is applied, the change in the transverse component of the magnetization, \( M_y \), is small, so the effect of the Zeeman interaction is more significant than that of the exchange interaction. It should be note that increasing \( M_y \) enhances the width of DW, and this enhancement results in the reduction of DWR. A similar trend is observed in previous studies \([6, 7]\) which indicates DWR reduction when increasing the width of DW. After some time, \( M_y \) becomes significant and the exchange interaction plays an important role in DWR. In this case, DWR is increased by enhancing \( M_y \).

The resistance per unit length of DW versus time in the absence of a magnetic field is presented in Figure 3. When the pulse is turned off, the magnetization returns to its equilibrium value of \( M_0 \). Therefore, the effect of exchange interaction is decreased and reduction of DWR is observed for \( \Gamma < t \).

![Figure 2](image2.png)

**Figure 2.** The resistance per unit length of DW versus time for different values of the magnetic field. It was calculated for \( d = 20 \text{ nm} \) and \( 0 \leq t \leq \Gamma \).

![Figure 3](image3.png)

**Figure 3.** The resistance per unit length of DW versus time for different values of the magnetic field. It was calculated for \( d = 20 \text{ nm} \) and \( \Gamma < t \).
As can be seen in Figures 2 and 3, the external magnetic field parallel to the \( y \)-axis significantly affects DWR. The increase of the resistance resulting from DW has been observed with the enhancement of the magnetic field.

4. Conclusions

We have studied DWR in a ferromagnetic nanowire using the Boltzmann equation, within the relaxation time approximation. The one-dimensional Néel-type DW between two ferromagnetic regions with antiparallel magnetization has been considered. We have investigated how the Zeeman and exchange interactions affect the resistance associated to DW. Calculations show that the resistance of DW increases as the magnetic field becomes stronger. In the presence of the pulsed magnetic field, both increasing and decreasing of DWR are observed depending on the contribution of the Zeeman and exchange interactions. When the magnetic field is turned off, DWR shows a fast decrement.

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