Spin accumulation and mistracking effects on the magnetoresistance of a ferromagnetic nano-contact

Hiroshi Imamura$^{1,†}$ and Jun Sato$^{2}$

$^{1}$ Nanosystem Research Institute, AIST, Tsukuba 305-8568, Japan
$^{2}$ Department of Physics, Graduate School of Humanities and Sciences, Ochanomizu University, 2-1-1 Ohtsuka, Bunkyo-ku, Tokyo 112-8610, Japan

E-mail: $^{†}$ h-imamura@aist.go.jp

Abstract. We theoretically studied spin accumulation and mistracking effects on the current-perpendicular-to-plane magnetoresistance of a domain wall confined in a nano-contact which is experimentally fabricated as current-confined-path structure made in a nano-oxide layer between ferromagnetic metal layers. We calculated the magnetoresistance (MR) ratio by evaluating the voltage drop due to the spin accumulation and additional resistivity due to mistracking. We showed that both the spin accumulation and mistracking give the same order of magnitude to the MR ratio for the nano-contact with 2 nm diameter.

1. Introduction

Current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) has attracted much attention for its potential application as a read sensor for high-density magnetic recording. In order to realize high-density magnetic recording, we need MR devices with high MR ratio and low resistance area product (RA). Although the RA value of a CPP-GMR system is much smaller than that of a tunneling magnetoresistance (TMR) system, the MR ratio of a conventional CPP-GMR system still remains as a small value of a few %. Much effort has been devoted to increase the MR ratio of the CPP-GMR system. One of the candidates for such a device is a spin-valve with nano-oxide-layer (NOL) [1]. The NOL is an insulator layer sandwiched between two ferromagnetic metal layers, and has a lot of metallic nano-contacts.

Recently, Fuke et al. obtained the MR ratio about 10% for the CoFe ferromagnetic nano-contacts in the NOL[2]. For CoFe nano-contacts with anti-parallel magnetic alignment the domain wall of nano-meter size is created in the nano-contact, and both the spin accumulation [3, 4, 5] and the mistracking can be the origin of the MR. Therefore, it is important to analyze both the effects of spin accumulation and mistracking on MR of a ferromagnetic nano-contact. The enhancement of the MR ratio due to nano contact was discussed in Refs. [6, 7, 8] from the view point of parasitic resistance of electrode and spin accumulation around contacts.

2. Model and Method

The system we consider is schematically shown in Fig. 1 (a). We assume that when the magnetization vectors of top and bottom ferromagnetic layers are aligned to be anti-parallel to each other the Bloch-type domain wall is created in the contact. The unit vector of the local magnetization of the Bloch-type domain wall is given by $\mathbf{M} = (\cos(\pi z/h), \sin(\pi z/h), 0)$,
Figure 1. (a) A current-confined-path (CCP) spin-valve with a domain wall. The current is flowing perpendicular to the plane. (b) The spin configuration in the contact region. (c) The cross-sectional view of the CCP spin-valve. The curve of the contact region is modeled by the half ellipse, which is tangent to the ferromagnetic layers.

where $h$ is the thickness of the nano-contact ($=2\text{nm}$) and $z$ is the height from the bottom of the nano-contact as shown in Fig. 1 (b). The cross-sectional view of the system is shown in Fig. 1 (c). The boundary of the contact region is modeled by the half ellipse, which is tangent to the ferromagnetic layers.

The MR of a domain wall due to mistracking was calculated by P. M. Levy and S. Zhang in Ref. [9]. Within the perturbation formalism, they obtained the wave function of conduction electron whose spin can not follow the direction of local magnetization in a domain wall. Then they calculate the scattering rate within the Fermi Golden rule with the Born approximation. The spin-up(+) and spin-down(-) components of conductivity is obtained as

$$
\sigma^\pm = \sigma^\pm(0) \left[ 1 \mp 2\xi^2 \left( \frac{3\beta}{5(1 \mp \beta)} - \frac{2\beta}{3\sqrt{1 - \beta^2}} \right) \right],
$$

(1)

Where the quantization axis is taken to be along the direction of the rotating local magnetization, $\xi = \pi \hbar^2 k_F / 4 m h J$ is the perturbation parameter which is implicitly assumed to be less than 1, $k_F$ is the Fermi wave number, $m$ is electron mass, $J$ represents the exchange coupling constant between conduction electron and local magnetization. $\sigma^\pm(0)$ represents the spin-up(+) and spin-down(-) conductivity of bulk material and the spin polarization $\beta$ is defined as

$$
\beta = \frac{\rho^+(0) - \rho^-(0)}{\rho^+(0) + \rho^-(0)},
$$

(2)

where $\rho^\pm(0) = 1/\sigma^\pm(0)$. From Eq. (1) one can easily see that conductivity is suppressed by mistracking, i.e., the resistance increases due to mistracking.

The spin accumulation is another origin of the MR of a ferromagnetic nano-contact. The spin accumulation is obtained by solving the spin diffusion equation. According to Ref. [4], the
electric current \( \vec{j}_e \) and the spin current \( \vec{j}_m \) are given by
\[
\vec{j}_e = 2C_0\vec{E} - 2\vec{D} \cdot \vec{\nabla}m, \\
\vec{j}_m = 2C\vec{E} - 2D_0\vec{\nabla}m,
\]
where we choose the unit such as the charge of an electron and the Bohr magneton are set to be 1, i.e., \( e = \mu_B = 1 \). The vectors denoted by the arrow \( \vec{v} \) and the bold font \( \vec{v} \) represent those in the real space and in the spin space, respectively. \( \vec{E} \) is the electric field and \( m \) is the spin accumulation. The conductivity \( \hat{C} \) and the diffusion constant \( \hat{D} \) are written in the spinor form as \( \hat{C} = C_0 + \hat{\sigma} \cdot \vec{C}, \hat{D} = D_0 + \hat{\sigma} \cdot \vec{D} \), where the \( \hat{\sigma} \) is the vector of the Pauli matrices. \( \vec{C} \) and \( \vec{D} \) are proportional to \( M \) with the spin polarization parameters \( \beta \) and \( \beta' \). Hereafter we assume \( \beta' = \beta \).

Eliminating the electric field \( \vec{E} \) from the Eqs. (3) and (4), and introducing the matrix
\[
\hat{A} = -2D_0 \begin{pmatrix}
1 & \beta^2 & M_xM_y & M_xM_z \\
\beta & M_yM_x & M_y^2 & M_yM_z \\
M_xM_y & M_yM_z & M_y^2 & M_z^2 \\
\end{pmatrix}
\]
(5)
where \( M = (M_x, M_y, M_z) \), the spin current is expressed as
\[
\vec{j}_m = \beta M \vec{j}_e + \hat{A}\vec{\nabla}m.
\]
In the stationary state, the continuity equation for the spin accumulation takes the form
\[
\vec{\nabla} \cdot \vec{j}_m + (J/h)m \times M + \frac{m}{\tau_{sf}} = 0,
\]
where \( \tau_{sf} \) is the spin-flip relaxation time. Introducing the matrix,
\[
\hat{B} = \frac{1}{\tau_{sf}} \begin{pmatrix}
1 & 1 \\
1 & 1 \\
\end{pmatrix} + \frac{(J/h)}{M_xM_yM_z} \begin{pmatrix}
0 & M_x & -M_y \\
-M_z & 0 & M_x \\
M_z & -M_x & 0 \\
\end{pmatrix}
\]
we obtain the following diffusion equation for the spin accumulation \( m \) to be solved
\[
\vec{\nabla} \cdot \left( \beta M \vec{j}_e + \hat{A}\vec{\nabla}m \right) + \hat{B} m = 0.
\]

The determination of the MR ratio was made as follows. First we determine the charge current density \( \vec{j}_e \) from the continuity equation \( \vec{\nabla} \cdot \vec{j}_e = 0 \). Next we solve the Eq. (9) for a given local magnetization \( M \) in the domain wall and determine the spin accumulation \( m \). Finally we determine the voltage drop of the system by integrating the electric field \( E = (\vec{j}_e + 2\vec{D} \cdot \vec{\nabla}m)/(2C_0) \). Since we apply the constant electric current density, the voltage drop is proportional to the total resistance, from which we obtain the MR ratio of the system.

We use material parameters for the conventional CPP-GMR spin-valve system: \( \rho_F = 150 \Omega \text{nm}, \lambda_F = 12 \text{ nm}, \lambda_N = 14 \text{ nm}, J = 0.5 \text{ eV}, \) where subscripts \( F(N) \) indicates the ferromagnetic (non-magnetic) material and \( \lambda_{F(N)} \) denotes the spin diffusion length. We set the resistivity of non-magnetic capping layers to be \( \rho_N = 1 \Omega \mu m \) so that the total RA without CCP structure becomes about 0.1 \( \Omega \mu m^2 \), which is the value reported in the experiments [1, 2]. The diffusion constant \( D_0 \) and the relaxation time \( \tau_{sf} \) are determined by the relation \( C_0 = N_F D_0 \) and \( \lambda = \sqrt{2\tau_{sf}D_0(1-\beta^2)} \), where we set the density of states at the Fermi level as \( N_F = 7.5 \text{ nm}^{-3} \text{ eV}^{-1} \).
3. Results

We numerically solve the spin diffusion equation of Eq.(9) by use of the finite element method. We take into account the effect of mistracking by substituting Eq.(1) into $\hat{C}$ of Eq.(4) as

$$\hat{C} = \left( \frac{\sigma^+ + \sigma^-}{2} \right) \hat{I} + \left( \frac{\sigma^+ - \sigma^-}{2} \right) \hat{\sigma} \cdot M.$$  

(10)

In Fig. 2 we plot the MR ratio obtained by considering both the spin accumulation and mistracking effects by the solid line. The dotted line indicates the MR ratio obtained by neglecting the contribution from mistracking. For $\beta = 0.65$ which is value of the spin polarization of CoFe, the calculated MR ratio (solid line) is 41 %, and can see that both spin accumulation and mistracking give the same order of magnitude to the MR for the nano-contact made of conventional ferromagnetic metal with $\beta$ around 0.5. The MR ratio rapidly increases with increasing the spin polarization $\beta$ and it reaches 100% for $\beta = 0.79$.

The MR ratio increases with decreasing the diameter of the contact. If we reduce the diameter of the contact from 2 nm to 1 nm, the MR ratio exceeds 100 % for $\beta > 0.71$.

4. Conclusion

In conclusion, we theoretically studied spin accumulation and mistracking effects on MR of a ferromagnetic nano-contact. We showed that both the spin accumulation and mistracking give the same order of magnitude to the MR ratio for the nano-contact made of conventional ferromagnetic metals. We also showed that the MR ratio of 100% is available for materials with $\beta = 0.79$. 

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Figure 2. MR ratio of the ferromagnetic nano-contact is plotted against the spin polarization $\beta$. Solid line indicates the MR ratio obtained by considering both spin accumulation and mistracking. Dashed lines indicate that obtained by neglecting the contribution from mistracking. Thin dotted lines are guide to eyes for MR=100%.
Acknowledgements
The authors would like to thank K. Matsushita, M. Sahashi, M. Doi, K. Miyake, H. Iwasaki, H. Fuke, and M. Takagishi for valuable discussions they had with. The work has been supported by The New Energy and Industrial Technology Development Organization (NEDO).

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