The origin of dispersion of magnetoresistance of a domain wall spin valve

Jun Sato, Katsuyoshi Matsushita and Hiroshi Imamura
Nanotechnology Research Institute (NRI), Advanced Industrial Science and Technology (AIST), AIST Tsukuba Central 2, Tsukuba, Ibaraki 305-8568, Japan.
E-mail: jun-sato@aist.go.jp

Abstract. We theoretically study the current-perpendicular-to-plane magnetoresistance of a domain wall confined in a nanocontact which is experimentally fabricated as current-confined-path (CCP) structure in a nano-oxide-layer (NOL). We solve the non-collinear spin diffusion equation by using the finite element method and calculate the MR ratio by evaluating the additional voltage drop due to the spin accumulation. We investigate the origin of dispersion of magnetoresistance by considering the effect of randomness of the size and distribution of the nanocontacts in the NOL. It is observed that the effect of randomness of the contact size is much larger than that of the contact distribution. Our results suggest that the origin of dispersion of magnetoresistance observed in the experiments is the randomness of the size of the nanocontacts in the NOL.

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. One of the candidates for such a device is a CPP-GMR spin-valve with a current-confined-path (CCP) structure [1, 2]. The insulator layer called nano-oxide-layer (NOL) is sandwiched between two ferromagnetic metal layers. The NOL has a lot of fine metallic holes, and the electric current flows through these confined channels (See Fig. 1 (a).) This device has an advantage to realize a low resistance area product (RA) since the electron conduction path is metallic. The MR ratio over 10% is obtained by the CPP spin-valve with non-magnetic Cu nanocontacts. This MR enhancement by the CCP structure was theoretically studied in detail in Refs. [3, 4]. Recently, Fuke et al. showed that such an MR enhancement appears also in the system with ferromagnetic nanocontacts. They obtained the MR ratio of 7%-10% for the CoFe nanocontacts in the NOL with the CCP structure [6]. Similar to the CPP-spin valve the MR of this system seems to originate from the spin accumulation around the domain wall confined in the nanocontact.

In order to analyze this experimental result, we calculate the MR ratio of the CCP system with a domain wall. We solved the non-collinear spin diffusion equation [7, 8] by the finite element method (FEM) [9, 10] and calculated the MR ratio by evaluating the additional voltage drop due to the spin accumulation. It was confirmed from our previous work that the MR ratio is enhanced by the confinement of the nanocontact [5]. In Ref. [5], we considered the system with a single contact with periodic boundary condition, i.e., a perfectly uniform system with infinite number of contacts of the same size and interval. In the experiment, however, the size and distribution of the nanocontacts in the NOL are observed to be rather random [6]. Therefore, the effect of randomness should be taken into account in the theoretical analysis.
In this paper we investigate the origin of dispersion of magnetoresistance by considering the effect of randomness of the size and distribution of the nanocontacts in the NOL. We consider the system with two contacts of different size and interval. (See Fig. 3 (a), (b).) The periodic boundary condition yields the infinite system with two different contacts alternating in size and interval. It is observed that the effect of randomness of the contact size is much larger than that of contact distribution. Our results suggest that the origin of dispersion of magnetoresistance observed in the experiments is the randomness of the size of the nanocontacts in the NOL.

According to Ref. [8], the electric current $\mathbf{j}_e$ and the spin current $\mathbf{j}_m$ can be written as

$$\mathbf{j}_e = 2C_0 \mathbf{E} - 2D_0 \mathbf{\nabla} \mathbf{m}, \quad \mathbf{j}_m = 2C \mathbf{E} - 2D_0 \mathbf{\nabla} \mathbf{m},$$

where $\mathbf{E}$ is the electric field and $\mathbf{m}$ is the spin accumulation. The conductivity $\hat{C}$ and the diffusion constant $\hat{D}$ are written in the spinor form as

$$\hat{C} = C_0 + \sigma \cdot C, \quad \hat{D} = D_0 + \sigma \cdot D,$$

where the $\sigma$ are the Pauli matrices. $C$ and $D$ are proportional to the spin polarization parameters $\beta$ and $\beta'$ as $C = \beta C_0 \mathbf{M}$ and $D = \beta' D_0 \mathbf{M}$, where $\mathbf{M}$ is the unit vector in the direction of the local magnetization. The continuity equation for the spin current takes the form [8] $\partial \mathbf{m} / \partial t = -\mathbf{\nabla} \cdot \mathbf{j}_m - (J/\hbar) \mathbf{m} \times \mathbf{M} - \mathbf{m} / \tau_{sf}$, where $J$ is the coupling constant of the interaction between the spin accumulation and the local moment, and $\tau_{sf}$ is the spin-flip relaxation time of the conduction electron. In order to obtain the solution for the stationary state, we set $\partial \mathbf{m} / \partial t = 0$ and obtain

$$\mathbf{\nabla} \cdot \left( \beta \mathbf{M} \mathbf{j}_e + \hat{A} \mathbf{\nabla} \mathbf{m} \right) + (J/\hbar) \mathbf{m} \times \mathbf{M} + \mathbf{m} / \tau_{sf} = 0, \quad (1)$$

Here we introduce an operator $\hat{A}$ acting on the spin space as $\hat{A} = -2D_0 \left[ \mathbf{1} - \beta' \mathbf{M} \otimes \mathbf{M} \right]$. The determination of the MR ratio of the system consists of the following three steps. First we determine the charge current density $\mathbf{j}_e$ from the continuity equation $\mathbf{\nabla} \cdot \mathbf{j}_e = 0$. Next we solve the Eq. (1) for a given local magnetization $\mathbf{M}$ in the domain wall and determine the spin accumulation $\mathbf{m}$. Finally we determine the voltage drop of the system by integrating the electric field $\mathbf{E} = (\mathbf{j}_e + 2D \mathbf{\nabla} \mathbf{m}) / (2C_0)$. 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.

Figure 1. (a) The multilayer structure of a CCP spin-valve with a domain wall is schematically shown. There are a lot of fine nanocontacts in the NOL through which the electric current flows. Domain walls are confined in nanocontacts. (b) The model of a domain wall spin valve with a single nanocontact is schematically shown.

Now we move onto the analysis of the MR ratio of the CCP spin-valve with domain walls. As is shown in Fig. 1 (a), NOL contains a lot of nanocontacts in which domain walls are confined. Let us start with a system with a single nanocontact, which is schematically shown in Fig. 1 (b). We impose periodic boundary condition, which makes this system equivalent to the perfectly uniform system with infinite number of nanocontacts of the same size and interval.

In our simulation we assume that the free and pinned layers and the nanocontact are all made of CoFe. We use material parameters for the conventional CPP-GMR spin-valve system;
$\beta = 0.65$, $\rho_{\text{CoFe}} = 150 \Omega \text{ nm}$, $\lambda_{\text{CoFe}} = 12 \text{ nm}$, $J = 1.0 \text{ eV}$, where $\lambda$ denotes the spin diffusion length. The diffusion constant $D_0$ and the relaxation time $\tau_{sf}$ are determined by the relation $C_0 = N_F D_0$ and $\lambda = \sqrt{\frac{2\tau_{sf}D_0}{1 - \beta\beta'}}$, where we set the density of states at the Fermi level as $N_F = 7.5 \text{ nm}^{-3}\text{ eV}^{-1}$. The cross-sectional view of the system is shown in Fig. 2 (a). We take in the Pt capping layer with thickness 50 nm in our simulation in order to take the effect of parasitic resistance into account. We set the value of the resistivity of Pt layer as $\rho_{\text{Pt}} = 200 \Omega \text{ nm}$ so that the total RA without CCP structure is 0.1 $\Omega \mu\text{m}^2$ which is the value reported in the experiments [1, 2]. We also let this layer serve as a spin-absorber since we impose a Dirichlet boundary condition for spin accumulation such that it vanishes at the both ends of the electrode. In order to do so we set the spin diffusion length as short as $\lambda_{\text{Pt}} = 5 \text{ nm}$.

In order to examine the MR enhancement effect by the CCP structure, we vary the contact diameter $r$ with the fixed size of the electrode. The dependence of MR on $r$ is shown in Fig. 2 (b). The MR enhancement effect by the CCP structure is confirmed by the simulation as is shown in the figure, where the MR ratio increases with decreasing the contact diameter $r$ from $r = 10 \text{ nm}$ to $r = 1 \text{ nm}$. In Fig. 2 (c) we replot the MR ratio against the resistance area product RA. The value of RA without CCP structure is set at 0.1 $\Omega \mu\text{m}^2$. It is observed that if we decrease the contact diameter, the MR increases with increasing RA and saturate around $\text{RA} \sim 3 \Omega \mu\text{m}^2$.

![Figure 2](image)

Figure 2. (a) The cross-sectional view of the model of our simulation is schematically shown. (b) MR is plotted against contact diameter $r$. (c) MR is plotted against resistance area product RA. The value of RA without CCP structure is set at 0.1 $\Omega \mu\text{m}^2$.

Now we investigate the effect of randomness of the size and distribution of the nanocontacts by considering the system with two contacts of different sizes. (See Fig. 3 (a), (b).) The periodic boundary condition yields the infinite system with two different contacts alternating in size and interval.

First we investigate the effect of randomness of the contact size with the fixed interval of two contacts. (See Fig. 3 (a).) We vary the ratio of the size of two contacts while fixing the sum of cross sectional area of two contacts in order to keep the RA value of the system constant. The result is shown in Fig. 3 (c). It is clear that the MR ratio is suppressed by the mismatch of the contact sizes. The value of MR ratio decays by about fifteen percent for $r_1/r_2 = 10$.

Next we investigate the effect of randomness of the distribution of the nanocontacts in the NOL. We vary the interval of two contacts while fixing the size of two contacts to be the same. (See Fig. 3 (b).) Imposing the periodic boundary condition on this system yields the infinite system with two different intervals $d_1 = d$ and $d_2 = D - d$, where $d$ is the interval of the two contacts of our simulation and $D$ is the width of the electrode, see Fig. 3 (b). We vary $d$ with fixed $D = 80 \text{ nm}$. We plot the MR ratio against the ratio of two intervals $d_1/d_2$, which is shown in Fig. 3 (d). Although it is also observed that the MR ratio is suppressed by the disarray of the distribution of nanocontacts, its suppression is much smaller than that by the mismatch of
size of two contacts. Actually the value of MR ratio decays by less than one percent even for 
\( d_1/d_2 \sim 10 \).

In summary, we studied the current-perpendicular-to-plane magnetoresistance of a domain 
wall confined in a CCP structure made of an NOL. We solved the non-collinear spin diffusion 
equation with the three-dimensional CCP geometry by use of finite element method. We 
investigated the effect of randomness of the size and distribution of the nanocontacts in the 
NOL by considering the system with two contacts of different size and interval. We found that 
MR ratio is suppressed by the mismatch of the contact size. It is observed that the MR ratio is 
also suppressed by the disarray of the distribution of nanocontacts, and this suppression is much 
smaller than that by the mismatch of size of two contacts. In the experiment, the dispersion of 
the size of the nanocontact is observed to be less than 10% and that of MR with fixed value of RA 
is observed to be around 10%. This indicates that the origin of dispersion of magnetoresistance 
with fixed value of RA is considered to be the effect of randomness of size of nanocontact.

Acknowledgement
The authors thank M. Sahashi, M. Doi, H. Iwasaki, M. Takagishi, Y. Rikitake and K. Seki 
for valuable discussions. The work has been supported by The New Energy and Industrial 
Technology Development Organization (NEDO).

[1] H. Fukuzawa, et al., H. Yuasa, S. Hashimoto, K. Koi, H. Iwasaki, M. Takagishi, Y. Tanaka, and M. Sahashi, 
IEEE Trans. Magn. Mater. 40, 2236 (2004).
[2] H. Fukuzawa, H. Yuasa, S. Hashimoto, H. Iwasaki, Y. Tanaka, Appl. Phys. Lett. 87, 082507 (2005).
[3] H. Imamura, PHYSICA STATUS SOLIDI B-BASIC SOLID STATE PHYSICS 244, 4394 (2007).
[4] J. Sato, K. Matsushita and H. Imamura, IEEE Trans. Magn. 44, 2608 (2008).
[5] J. Sato, K. Matsushita and H. Imamura, J. Appl. Phys. 105, 07D101 (2009).
[6] H. N. Fuke, S. Hashimoto, M. Takagishi, H. Iwasaki, S. Kawasaki, K. Miyake, and M. Sahashi, IEEE Trans. 
Magn. 43, 2848 (2007).
[7] T. Valet and A. Fert, Phys. Rev. B 48, 7099 (1993).
[8] S. Zhang, P.M.Levy and A. Fert, Phys. Rev. Lett. 88, 236601 (2002).
[9] L. Ramdas Ram-Mohan, “Finite element and Boundary Element Applications in Quantum Mechanics”, Oxford 
University Press(2002)
[10] M. Ichimura, J. Ieda, H. Imamura, S. Takahashi and S. Maekawa, "Numerical analysis of spin accumulation 
due to a domain wall," J. Magn. Magn. Mater. 310, 2055 (2007)