Spin-current-induced magnetoresistance in trilayer structure with nonmagnetic metallic interlayer

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Magnetoresistance effects are important for applications in sensor and memory devices and for investigation of spin-dependent transport.1–3 Recently, a new type of magnetoresistance has been demonstrated, in which a spin current generated via spin–orbit coupling from an applied charge current plays a central role.4–12 The generated spin current interacts with a magnetic material and changes its magnitude.5,8,11,13) When the spin current is converted back to a charge current by spin–orbit coupling,14,15) the spin-current transport modulates the conductivity of the system, and then gives rise to magnetoresistance. This spin-current-induced magnetoresistance is now recognized as an indispensable tool for investigating the spin transport in ferromagnetic material/metal heterostructures.16–19)

The spin Hall magnetoresistance (SMR) refers to the resistance change due to the spin current generated by the spin Hall effect (SHE), which interacts with a ferromagnetic material.4,6) Typically in materials consisting of heavy metals such as Pt and W,4,9) a spin current is induced by an applied charge current, jch, due to the SHE. This spin current propagates in the material and forms spin accumulation, jμs, around the system edges.20) When jμs acts on a ferromagnetic material, it exerts spin transfer torque on the magnetization m, which is given by

\[ j_{\text{STT}} = \frac{G_t}{c} \mathbf{m} \times (\mathbf{m} \times \mathbf{\mu}_s |_{\text{interface}}). \]  

(1)

Here, the spin current is defined as positive when it flows out of the F layer, and ε > 0, Gt, m, and μs |_{interface} respectively denote the elementary charge, the real part of the mixing conductance per unit area, and the magnetization unit vector, the spin accumulation at the interface. Since j_{\text{STT}} is absorbed by the magnetization, the resultant spin accumulation jμs decreases, which results in the reduction in backflow spin current and thus the additional charge current due to the SHE (Fig. 1). As j_{\text{STT}} depends on the magnetization direction, the spin-current absorption finally appears as a magnetoresistance effect, under which the total conductivity σ shows a different dependence on m from the conventional anisotropic magnetoresistance6), i.e.,

\[ \sigma = \sigma_0 + \Delta \sigma_{\text{SMR}} \left( \mathbf{m} \cdot (\mathbf{n} \times \frac{j_{\text{add}}}{|j_{\text{add}}|}) \right)^2, \]  

where n, \sigma_0, and \Delta \sigma_{\text{SMR}} respectively denote the unit vector normal to the junction interface and the conductivities insensitive and sensitive to the magnetization.

In the context of SMR research, an interlayer with a large spin-diffusion-length is often inserted between the ferromagnetic material and heavy metal layers to distinguish the SMR from the static magnetic proximity effect.4,5,21) For example, the effects of Cu and Au insertion were examined in ferromagnetic insulator yttrium iron garnet (Y3Fe5O12; YIG)/heavy metal Pt bilayer systems, and the existence of the SMR has been confirmed. However, the SMR magnitude decreases...
more rapidly than expected even when a current shunting effect is considered. Although such trilayer SMR provides a versatile method to extract spin diffusion length, an analytic expression for quantitative interpretation has not yet been obtained.

In this letter, we derive the interlayer thickness dependence of the SMR in the diffusive regime based on the spin diffusion equation and magneto-circuit theory and show that the intrinsic magnitude of the SMR decreases as a result of spin-current transport over the trilayer structure. We consider a system composed of a ferrimagnetic insulator (F), a nonmagnetic metal (N), and a heavy metal (H) used for converting a charge current to a spin current. We find that the intrinsic magnitude of the SMR decreases even when the spin relaxation in the N layer is negligibly small. This is due to the reduction in the spin accumulation for driving spin relaxation in the N layer. 

The system coordinate is shown in Fig. 1. The layers are stacked in the z-direction, and we assume translational symmetry in the xy plane. The thicknesses of the F, N, and H layers are $d_F$, $d_N$, and $d_H$, respectively. The N/H interface is at $z = 0$ and the F/N interface $z = -d_N$. Hereafter, we will use the superscript and subscript $a = (F, N, H)$ to represent the corresponding quantity in the $a$ layer. In this F/N/H system, we calculated the distribution of spin accumulation $\sigma_s(z)$ and spin current flowing in the $z$-direction $j_s^{\text{diff}}(z)$ with its vector direction representing its spin polarization using the diffusion equation $\partial_z^2 \sigma_s(z) = \mu_s(z)/\lambda_s^2$, where $\lambda_s$ is the spin diffusion length.\textsuperscript{11} We imposed the boundary conditions with Eq. (1) and $j_s^{\text{STT}} = \Gamma_s^{(H)}(-d_N)$ at the F/N interface ($z = -d_N$), zero spin current at the N surface ($z = d_N$), and $\mu_s^{N/H} \equiv \mu_s^{N}(0) = \mu_s^{H}(0)$ at the H/N interface. For the SMR, the continuity of $j_s^{N}(0)$ is assumed at the N/H interface and, for the REMR, the derived condition in Eq. (9) is assumed. The spin current in the $a$ layer is given by\textsuperscript{6}

$$j_s^{a}(z) = -\frac{\sigma_{s}^{a}}{2e} \partial_z \mu_{s}^{a}(z) + j_s^{\text{SHE},a},$$

where the vector represents the spin polarization, and $\sigma_{s}^{a}$ denotes the conductivity. $j_s^{\text{SHE},a} = \theta_{s}^{\text{SHE}}\sigma_{s} z \times E$ represents the SHE-induced spin current, where $\theta_{s}^{\text{SHE}}$ denotes the spin Hall angle, $z$ the unit vector of the $z$-axis, and $E$ the applied electric field. We assumed $j_s^{\text{SHE},N} = 0$ because $\theta_{s}^{\text{SHE}}$, which is proportional to $\Delta \sigma_{\text{SHE}}$,\textsuperscript{6} is smaller in the N layer in experiments than in the H layer.\textsuperscript{4,21}

The SMR magnitude is determined from the difference in the magnitude of the spin current flowing through the N/H interface with $j_s^{\text{STT}}$ on $(\mathbf{m} \perp \mu_s^{N/H})$ and off $(\mathbf{m} || \mu_s^{N/H})$ \textit{[cf. Eq. (1)]}. In the trilayer structure, this spin current in the N layer is given by

$$j_s^{N}(0) = \Gamma_s^{N} \mu_{s}^{N/H} e + G_r^{N} \mathbf{m} \times \left( \mathbf{m} \times \mu_{s}^{N/H} e \right),$$

where $\Gamma_s^{N} = (\sigma_{s}^{N}/2\lambda_s^{N})\tan(h_{N}/\lambda_s^{N})$ and $G_r^{N} = \Gamma_s^{N} \cos^{-2}(h_{N}/\lambda_s^{N}) + \Gamma_s^{N} \sinh^2(h_{N}/\lambda_s^{N})$.\textsuperscript{22,23}

In Fig. 2, we show a typical profile of $\mu_s^{N}$ along the $z$-axis and $j_s^{N}$ generated by the SHE in the F/N/H system with and without $j_s^{\text{STT}}$ $(\mathbf{m} \perp \mu_s^{N/H})$ and $(\mathbf{m} || \mu_s^{N/H})$. As one can see, when the absorption is introduced, $\mu_s$ for driving $j_s$ decreases with $j_s$ propagation, and the dependence of $j_s^{N}$ on $\mathbf{m}$ becomes weaker than that in the bilayer system \textit{[see Fig. 2(a)]}. In the above calculation, $\mu_s^{N/H}$ is self-consistently determined by the condition in the H layer:

$$\Gamma_s^{H} = \mu_s^{N/H} = \Gamma_s^{H} - \frac{h_{H}}{\lambda_s^{H}} \left[ 1 - \cosh \left( \frac{h_{H}}{\lambda_s^{H}} \right) \right]^{-1},$$

and $j_s^{N}(0) = j_s^{N}(0)$. $(\mathbf{m} \perp \mu_s^{N/H})$ $(\mathbf{m} || \mu_s^{N/H})$ is realized by setting $\mathbf{m} \perp \theta_{s}^{\text{SHE}} z \times \mathbf{E}$(m || $j_s^{\text{SHE}}$).

The magnitude of the SMR can be calculated by integrating the additional charge current induced by the inverse SHE, $j_s^{\text{add},a} = \theta_{s}^{\text{SHE}} z \times j_s^{a}$, and taking the difference between the $j_s^{N,\perp}$ on and off states, i.e.,
The magnetoresistance ratio $MR \equiv \Delta \sigma_{\text{SMR}}/\sigma_0$ is given by

$$MR = R_{\text{shunt}} \frac{\Gamma_H}{\Gamma_N + \Gamma_H} \left( \frac{d_H}{\Omega_H} \right)^2 G_s \tanh \left( \frac{d_H}{\lambda_0} \right) \tanh \left( \frac{d_H}{2 \lambda_0} \right),$$

where $R_{\text{shunt}} = \sigma_H d_H / \sum \sigma_i d_i$ is the current shunting factor for the SMR. For local magnetoresistance effects, such as the anisotropic magnetoresistance (AMR), its intrinsic magnetoresistance ratio $MR_{\text{int}}$ is related to $MR$ in the multilayers via $MR = R_{\text{shunt}} MR_{\text{int}}$ by considering parallel circuiting.9,12) Obviously, Eq. (8) shows the dependence of $MR_{\text{int}}$ on $G_s$ and $\Gamma_N$, which is a distinct contribution from the shunting effect. Since $\Gamma_H \approx \Gamma_N \geq G_s$, holds in typical experiments (see the inset in Fig. 3), $MR$ is approximately proportional to $G_s$ and thus is reduced by the spin transport in the $N$ layer. Figure 3 shows that $MR_{\text{int}}$ for the SMR depends on the thickness $d_N$. As expected from the discussion in the last paragraph, $MR_{\text{int}}$ decreases even when $\lambda_N \gg d_N$. In this regime, $\Gamma_N$ becomes zero and only the effective mixing conductance $G'_{\text{s}} = (G_s^{-1} + 2d_N/\sigma_2)^{-1}$ contributes to the SMR, which again shows the importance of the reduction in the spin accumulation across the $N$ layer.

The experimentally reported $MR_{\text{int}}$ values of YIG/Cu/Pt trilayers in Ref. 4 are smaller than that expected from Eq. (8). This difference can be attributed to the thickness dependence of the spin diffusion length due to that of the conductance and the spin memory loss effect at the interfaces.25-27) The spin diffusion length decreases at a smaller thickness because of the interfacial scattering,5,12,28) such that the decreased spin-current transmission reduces the SMR magnitude. Similarly, the spin memory loss effect reduces the spin current transmission through the interface. Besides these factors, the spin accumulation reduction considered in this report is important, especially for the larger thickness limit, where most of the spin transport is determined by the bulk properties.

Finally, we apply our calculations to the REMR. Since the REMR appears in F/N/H trilayer structures, it is relevant to the trilayer SMR, which has not been clarified yet. Under the Rashba–Edelstein effect (REE), an applied electric field induces spin accumulation at the N/H interface, which is given by

$$\frac{\mu_s}{e} = \lambda_{\text{REE}} e \mathbf{E} \times \mathbf{z} + \frac{\tau_s}{e^2 N} \left[ H^0(0) - J^0(0) \right] \delta(z),$$

where $\lambda_{\text{REE}}$ is the REE coefficient, and $N$ and $\tau_s$ denote the density of states and spin relaxation time for the N/H interface, respectively.21) Note that the second term on the right-hand side of Eq. (9), given by Eqs. (5) and (6) with $J^{\text{SHE}} = 0$, is the contribution of outflow spin currents driven by the REE and is crucial to describing the effect of $J^{\text{SHE}}$ on $\sigma_2$, i.e., the resultant magnetoresistance. We use Eq. (9) for the boundary condition instead of the continuity of $J$. Considering the spin-to-charge conversion relation, $J^{\text{add}} = -\lambda_{\text{REE}} (e^2 N/\tau_s) \mathbf{E} \times \mathbf{z} \delta(z)$,5,12,23) and Eqs. (4), (5), and (9), the magnetoresistance ratio of the REMR is given by

$$MR_{\text{REMR}} = \frac{R_{\text{shunt}}}{\Gamma_N + \Gamma_H + e^2 N/\tau_s} \sigma_2 \sinh \left( \frac{d_H}{\lambda_0} \right) \tanh \left( \frac{d_H}{2 \lambda_0} \right)$$

$$\times \left( \frac{\mu_s}{e} \right)^2 \sigma_2 G_{\text{eff}} \left( \frac{e^2 N/\tau_s}{e^2 N/\tau_s} \right),$$

where $R_{\text{shunt}} = \sigma_{\text{int}} / (\sigma_{\text{int}} + \sum \sigma_i d_i)$ denotes the shunting factor for the REMR and $\sigma_{\text{int}}$ expresses the sheet conductivity of the N/H interface. As in Eq. (8), $MR_{\text{REMR}}$ in Eq. (10) also decreases with increasing $d_N$. Figure 4 shows the calculated thickness dependence of $MR_{\text{REMR}} = MR_{\text{REMR}} / R_{\text{shunt}}$. In Ref. 12, the $d_N$ dependence of $MR_{\text{REMR}}$ is analyzed by assuming constant $MR_{\text{REMR}}$, and the experimental data shows a sharper peak at a smaller $d_N$ than the calculated data. This difference can be explained by the $MR_{\text{REMR}}$ reduction revealed here. Note that our calculations are for systems with magnetic insulators, but the experiment was performed with a metallic ferromagnet.12) This may affect the $MR$ value,
but only a small difference may be expected for the thickness dependence, as in the SMR case.  

In summary, we formulated the magnitude of the spin-current-induced magnetoresistance effects in a ferrimagnetic insulator/nonmagnetic metal/heavy metal trilayer structure with the spin Hall and Rashba–Edelstein effects. We showed that the spin-current-induced magnetoresistances are sensitive to the spin-current transport in the interlayer, which gives rise to the reduction in the magnetoresistance ratio in addition to the shunting of the applied charge current. Our derived thickness dependence will be useful for quantitatively understanding the spin transport of the inserted layer using the spin-current-induced magnetoresistances.

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