Effects of interface resistance asymmetry on magnetoresistance of spin transistor structures

Tetsufumi Tanamoto*, Hideyuki Sugiyama, Tomoaki Inokuchi, Mizue Ishikawa, and Yoshiaki Saito
Advanced LSI Technology Laboratory Toshiba R and D Center, Kawasaki 212-8582, Japan.
*Phone: +81-44-549-2192, E-mail:tetsufumi.tanamoto@toshiba.co.jp

1. Introduction
Spintronics has been one of the emerging fields for the near future electronics and a lot of interesting researches have been carried out. Here we theoretically study the effects of the interface resistances asymmetry between ferromagnetic metal (F) and nonmagnetic conductor (N) on the magnetoresistance (MR) in both local measurement setup (Fig.1(a)) and nonlocal measurement setup (Fig.1(b)). In realistic devices such as spin transistors, the device structure is not always symmetric. Thus, magnetic layers of the source electrode are not exactly the same as those of the drain electrode. Because both the spin injection and detection affect the spin-dependent transport properties, the symmetry of the device structure is considered to play an important role for the MR ratio. We extend the standard theories by Fert et al. for the local measurement and Jedema et al. for the nonlocal measurement, and derive the analytical formula for the asymmetric interface resistances.

2. Formulation
The spin accumulation effect, the difference between the chemical potential of the up spin $\mu_+$ and that of down spin $\mu_-$ is described by the diffusion equations. The relationship between the spin current density $J_s$ and $\mu_s$ ($s = \pm$) is given by $J_s = \frac{\sigma_s}{\tau} \frac{\partial}{\partial z} \mu_s$ where $\sigma_s$ is a spin-dependent conductivity. The diffusion equation for the chemical potential is given by

$$\frac{\partial^2 \mu_s}{\partial z^2} = -\frac{\mu_+ - \mu_-}{\sigma_s^2} \frac{\partial \lambda_\eta}{\partial z},$$

where $\lambda_\eta = \lambda_{\eta+}^2 + \lambda_{\eta-}^2$ is an average spin diffusion length for $F$ region ($\eta = F$) and $N$ region ($\eta = N$). The boundary conditions at the interface ($z = z_0$) are (1) spin current is continuous $J_{\pm}(z_0^+)$ = $J_{\pm}(z_0^-)$ and (2) the chemical potential is continuous at the interface $z_0$ such as $\mu_+(z_0^+) - \mu_-(z_0^-) = r_{\pm} J_{\pm}(z_0)$. We also write $\rho_\pm = 2[1 \pm \beta] \rho_F$ and $\rho_\pm = 2\rho_N$ for the resistivity of the ferromagnet F and the nonmagnet N. The important quantities here are $r_F = \rho_F / \rho_F$ and $r_N = \rho_N / \rho_N$. We focus on the spin-dependent interface resistances $r_{\pm}$ and $r_{\mp}$ for a unit surface described by

$$r_{\pm} = 2r_{\pm}[1 \pm \gamma_{L}], \quad r_{\mp} = 2r_{\mp}[1 \pm \gamma_{R}].$$

3. Local measurement setup
Fert et al. showed that there is an appropriate interface resistance condition in which the MR ratio has a peak when there is an impedance matching $r_N \sim r_F$. Then, the question here is how the peak of the MR ratio shifts when the two interface resistances do not equal. By the same procedure as that of Ref. [8], we obtain the resistance of antiparallel (AP) configuration, $r_{AP}$, and that of parallel (P) configuration, $r_{P}$. The resistance change $\Delta R = r_{AP} - r_{P}$ for Fig.1(a) is given by

$$\Delta R = \frac{2(\gamma_{F} r_{P} + \beta r_{AP})(\gamma_{N} r_{P} + \beta r_{AP})}{\Theta_1},$$

where $\Theta_1 = (r_F + (r_F^L + r_F^R)/2) \cosh(\pi \rho_N / \lambda_N) + (r_N/2)[1 + (r_F + r_F^L)(r_F + r_F^R)/r_F^2] \sinh(\pi \rho_N / \lambda_N)$. In this equation, we assume that thickness of F is much larger than $\lambda_F$. The MR ratio is defined by $(r_{AP} - r_{P})/r_{P}$. Fig.2 shows the result of Eq.(2) for the case of $\gamma_{L}/\gamma_{R} = 1$ and (c) and that in which $\gamma_{L}/\gamma_{R}$ increases with $r_F^L / r_F^R$ (b). For $\gamma_{L} = \gamma_{R}$ (Fig.2 (a) (c)), the MR ratio has its maximum when interface resistance is symmetric ($r_F = r_F^L$). We can also see that the effect of the asymmetry on the MR ratio is not large as the difference between $r_F$ and $r_F^L$ is not large. This is a good news for fabrication, because we cannot avoid size fluctuations in conventional device process. Fig.2 (b) shows the case that $\gamma_{L}$ changes as $\gamma_{L} = (r_F / r_F^L) \gamma_{R}$, and it can be found that the MR ratio increases as $\gamma_{L} / \gamma_{R}$ increases. By comparing Fig.2 (b) with Fig.2 (c), we find that the symmetric structure ($r_F = r_F^L$) with higher $\gamma_{L}(= \gamma_{R})$ is better for higher MR ratio.

4. Nonlocal measurement setup
Jedema et al. showed the case of no interface resistances in Fig.1(b). Here, we consider the case of asymmetric interface resistances starting from the diffusion equations given by

$$\mu_{z_0}^{(1)} = A - (J_0 / \sigma_F) x \pm 2 \sigma_F (1 \pm \beta) |e^{\pm \beta |x|} r_{\pm},$$

$$\mu_{z_0}^{(II)} = - (J_0 / \sigma_N) x + (2 \sigma_N |e^{\pm \beta |x|} r_{\pm} + Fe^{\pm \beta |x|}),$$

$$\mu_{z_0}^{(III)} = \pm (2G / \sigma_N |e^{\pm \beta |x|} r_{\pm} + Fe^{\pm \beta |x|}),$$

$$\mu_{z_0}^{(IV)} = (J_0 / \sigma_N) x \pm (2G / \sigma_N |e^{\pm \beta |x|} r_{\pm} + Fe^{\pm \beta |x|}),$$

where $A$ is a constant, $J_0$ is the applied current density, $\sigma_F$ is the spin-dependent conductivity, $\sigma_N$ is the spin-independent conductivity, $G$ is the nonmagnetic conductivity, $F$ is the external field, $x$ is the distance from the interface, $r_{\pm}$ is the interface resistance, $\beta$ is the spin splitting, $\gamma_{L}$ is the high-field asymmetry parameter, $\gamma_{R}$ is the low-field asymmetry parameter, $\lambda_F$ is the spin diffusion length, $\rho_F$ is the spin-dependent resistivity, $\rho_N$ is the spin-independent resistivity, $\rho_N$ is the nonmagnetic resistivity, $\rho_N$ is the nonmagnetic resistivity, $\lambda_N$ is the spin diffusion length, $\rho_N$ is the nonmagnetic resistivity, $\lambda_N$ is the spin diffusion length.
\[ \mu_{\pm} = \pm (2/\sigma N) [He^{-\nu /\lambda N} + Ke^{\nu /\lambda N}], \]
\[ \mu_{\pm}^V = B = 2D \sigma \Gamma (1 + \beta) e^{-\nu /\lambda N}, \]
where \( A, B, C, D, E, F, H, K \) and \( G \) are unknown constants that are determined by boundary conditions. The resistance change, \( \Delta R = r_{AP} - r_P = -2B/eJS \), where \( S \) is the cross-sectional area of the nonmagnetic strip, is obtained by
\[ \Delta R = r_N 4\beta [\beta^2 - (1 - \beta^2)] [r^N \beta + (1 - \beta^2) r^N_\beta] \]
\[ B^N = B/N [B^N b_1 - B^N b_2/b_3 = B^N b_3/b_2 - B^N b_2/b_3] \]
where \( b_2 = e^{\nu/\lambda N}, b_3 = e^{\nu/\lambda N}, r_N = e\lambda N /\sigma N, r_F = e\lambda F /\sigma F, r_N^\gamma = r_N^\gamma a, \) and \( B^N \equiv [r_N \pm r_N^\gamma (1 - \beta^2) \pm r_F] \) with \( a = L, R \).

The current polarization at the interface of the current injecting contact is given by
\[ P = (J_+ - J_-) / (J_+ + J_-) \]
and we have
\[ P = \frac{1 + 2B^N b_2/b_3}{B^N [B^N b_1 - B^N b_2/b_3] - B^N b_2/b_3} \]
\[ B^N = B/N [B^N b_1 - B^N b_2/b_3 = B^N b_3/b_2 - B^N b_2/b_3] \]
When \( r_F = 0 \), this result coincides with Eq.(15) in Ref.[9]. Fig.3 shows the calculated \( P \) (a) and \( \Delta R \) (b). It can be seen that the asymmetry of the interface resistance does not significantly affect the \( P \) and \( \Delta R \). Compared with Ref.[9], we can see that the interface resistance enhances \( P \) and \( \Delta R \) and finally \( P \) and \( \Delta R \) are saturated. When \( r_F \gg r_N \), Eq.(9) shows that \( \Delta R \sim r_m r_m / (r_F^2 r_F) \).

As Ref.[10] notes, this saturation comes from the standard theory. Fig.4 shows \( P \) for \( r_F^L / r_F^R \neq 1 \) when \( x_2 \) changes. Although the asymmetry of the interface resistance is weak around \( r_F^L / r_F^R \approx 1 \), when the asymmetry becomes large, the impedance matching point shifts.

5. Conclusions
We studied the effects of asymmetric interface resistances between ferromagnet and nonmagnet on the spin-dependent transport properties for both the local and nonlocal measurement setups based on diffusion equations. We showed that the MR ratio and current polarization have their maximum at the symmetric structure. We also found that, as long as the asymmetry is not large, spin-dependent transport properties are robust against the asymmetry of the interface resistance for both the local and nonlocal measurements.