Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1229-1230

Effects of interface resistance asymmetry on magnetoresistance of spin transistor structures

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1. Introduction

Spintronics has been the one of the emerging fields for the near future electronics and a lot of interesting researches have been carried out[1–10]. 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.*[8] for the local measurement and Jedema *et al.*[9] 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 μ_+ and that of down spin μ_- is described by the diffusion equations[8,9]. The relationship between the spin current density J_s and μ_s ($s = \pm$) is given by $J_s = \frac{\sigma_s}{e}\frac{\partial}{\partial x}\mu_s$ where σ_s is a spin-dependent conductivity. The diffusion equation for the chemical potential is given by $\frac{\partial^2(\mu_+ - \mu_-)}{\partial x^2} = \frac{(\mu_+ - \mu_-)}{\lambda_\eta^2}$ where $\lambda_\eta^{-2} = \lambda_{\eta+}^{-2} + \lambda_{\eta-}^{-2}$ 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 $J_\pm(z_0^+) = J_+(z_0^-)$ and (2) the chemical potential is continuous at the interface z_0 such as $\mu_\pm(z_0^+) - \mu_+(z_0^-) = r_\pm J_\pm(z_0)$. 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 nonmanget N. The important quantities here are $r_F \equiv \rho_F\lambda_F$ and $r_N \equiv \rho_N\lambda_N$. We focus on the spin-dependent interface resistances $r_\pm^L$ and $r_\pm^R$ for a unit surface described by

$$r_\pm^L = 2r_b^L[1 \mp \gamma^L],\ r_\pm^R = 2r_b^R[1 \mp \gamma^R]. \tag{1}$$

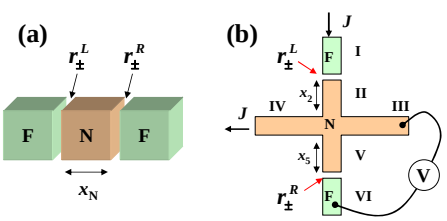

FIG. 1: (a) Local measurement setup[8]. (b) Nonlocal measurement setup[9].

3. Local measurement setup

Fert *et al.*[8] showed that there is an appropriate interface resistance condition in which the MR ratio has a peak when there is an impedance matching $r_N \sim r_b$. Then, the question here is how the peak of the MR ratio shifts when the two interface resistances does not equal.

By the same procedure as that of Ref. [8], we obtain the resistance of anitiparallel (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

$$\Delta R = \frac{2(\gamma_L r_b^L + \beta r_F)(\gamma_R r_b^R + \beta r_F)}{\Theta_1}, \tag{2}$$

where $\Theta_1 = (r_F + (r_b^L + r_b^R)/2)\cosh(x_N/\lambda_N) + (r_N/2)[1 + (r_F + r_b^L)(r_F + r_b^R)/r_N^2]\sinh(x_N/\lambda_N)$. In this equation, we assume that thickness of F is much larger than λ_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 $\gamma_L/\gamma_R = 1$ ((a) and (c)) and that in which γ_L/γ_R increases with r_b^L/r_b^R((b)). For $\gamma^L = \gamma^R$(Fig.2 (a)(c)), the MR ratio has its maximum when interface resistance is symmetric ($r_b^L = r_b^R$). We can also see that the effect of the asymmetry on the MR ratio is not large as long as the difference between r_b^L and r_b^R 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 γ_L changes as $\gamma_L = (r_b^L/r_b^R)\gamma_R$, and it can be found that the MR ratio increases as γ_L/γ_R increases. By comparing Fig.2 (b) with Fig.2 (c), we find that the symmetric structure ($r_b^L = r_b^R$) with higher $\gamma_L(= \gamma_R)$ is better for higher MR ratio.

4. Nonlocal measurement setup

Jedema *et al.*[9] showed the case of no interface resistances in Fig.1(b). Here, we consider the case of asymmetric interface resistances starting form the diffusion equations given by

$$\mu_\pm^{(\mathrm{I})} = A - (Je/\sigma_F)x \pm 2C/[\sigma_F(1 \pm \beta)]e^{-x/\lambda_F}, \tag{3}$$

$$\mu_\pm^{(\mathrm{II})} = -(Je/\sigma_N)x \pm (2/\sigma_N)[Ee^{-x/\lambda_N} + Fe^{x/\lambda_N}], \tag{4}$$

$$\mu_\pm^{(\mathrm{III})} = \pm(2G/\sigma_N)e^{-x/\lambda_N}, \tag{5}$$

$$\mu_\pm^{(\mathrm{IV})} = (Je/\sigma_N)x \pm (2G/\sigma_N)e^{-x/\lambda_N}, \tag{6}$$

$$\mu_{\pm}^{(\mathrm{V})} = \pm(2/\sigma_N)[He^{-x/\lambda_N} + Ke^{x/\lambda_N}], \quad (7)$$

$$\mu_{\pm}^{(\mathrm{VI})} = B \pm 2D/[\sigma_F(1\pm\beta)]e^{-x/\lambda_F}, \quad (8)$$

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

$$\Delta R = \frac{r_N}{S}\frac{4[r_F\beta + (1-\beta^2)r_m^R][r_F\beta + (1-\beta^2)r_m^L]}{B_+^R[2B_+^L b_2^2 - B_-^L]b_5/b_2 - B_+^L B_-^R b_2/b_5}, \quad (9)$$

where $b_2 = e^{x_2/\lambda_N}$, $b_5 = e^{x_5/\lambda_N}$, $r_N = e\lambda_N/\sigma_N$, $r_F = e\lambda_F/\sigma_F$, $r_m^\alpha = r_b^\alpha\gamma_\alpha$, and $B_\pm^\alpha \equiv [r_N \pm r_b^\alpha](1-\beta^2) \pm r_F$ with $\alpha = L, R$.

The current polarization at the interface of the current injecting contact is given by $P = (J_+ - J_-)/(J_+ + J_-)$ and we have

$$P = \frac{[(1+2b_2^2)B_+^R b_5/b_2 - B_-^R b_2/b_5][r_F\beta + (1-\beta^2)r_m^L]}{B_+^R[2B_+^L b_2^2 - B_-^L]b_5/b_2 - B_+^L B_-^R b_2/b_5}. \quad (10)$$

When $r_b = 0$, this result coincides with Eq.(15) in Ref.[9]. Fig.3 shows the calculated P ((a)) and ΔR((b)). It can be seen that the asymmetry of the interface resistance does not significantly affect the P and ΔR. Compared with Ref.[9], we can see that the interface resistance enhances P and ΔR and finally P and ΔR are saturated. When $r_b \gg r_N$, Eq.(9) shows that $\Delta R \sim r_m^R r_m^L/(r_b^R r_b^L)$. As Ref.[10] notes, this saturation comes from the standard theory. Fig.4 shows P for $r_b^L/r_b^R \neq 1$ when x_2 changes. Although the asymmetry of the interface resistance is weak around $r_b^L/r_b^R \approx 1$, when the asymmetry becomes large, the impedance matching point shifts.

5. Conclusions

We studied the effects of asymmetric interface resistances between ferromagnet and nonmanget 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.

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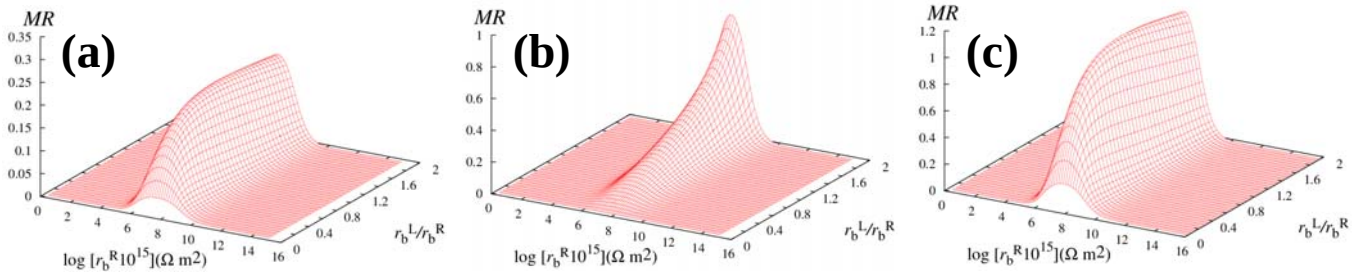

Fig.2: MR ratios of the local measurement setup (Fig.1(a)) as functions of the average interface resistance r_b^R and the asymmetry r_b^L/r_b^R. (a) $\gamma_L=\gamma_R=0.5$. (b) $\gamma_R=0.5$, $\gamma_L=(r_b^L/r_b^R)\gamma_R$, (c) $\gamma_L=\gamma_R=0.8$. x_N=20nm, λ_N=1μm, r_N= 4.0 x10^{-9} Ωm^2, λ_F=5nm, β=0.46, r_F=4.5x10^{-15} Ωm^2. In (a), r_b^L/r_b^R=1 corresponds to Fig.3 of Ref.[8].

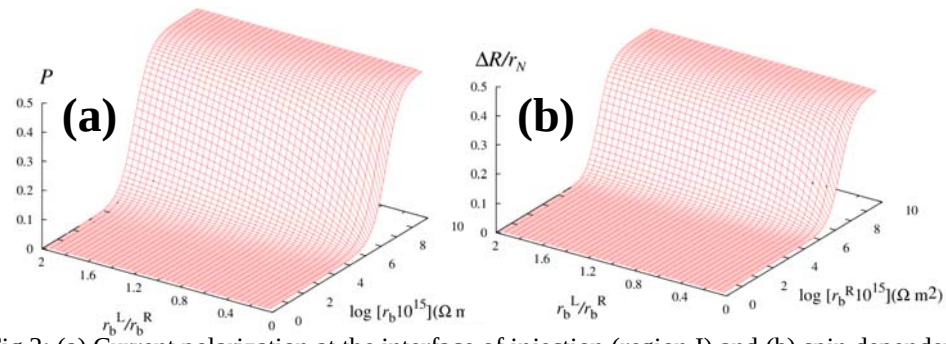

Fig.3: (a) Current polarization at the interface of injection (region I) and (b) spin dependent resistance at the interface of detection (region VI) for the nonlocal measurement setup (Fig.1(b)). x_2=x_5=250nm, λ_N=1μm, r_N= 4.0 x10^{-9} Ωm^2, λ_F=5nm, β=0.46, r_F=4.5x10^{-15} Ωm^2. In (b), cross sectional area S=1 is assumed.

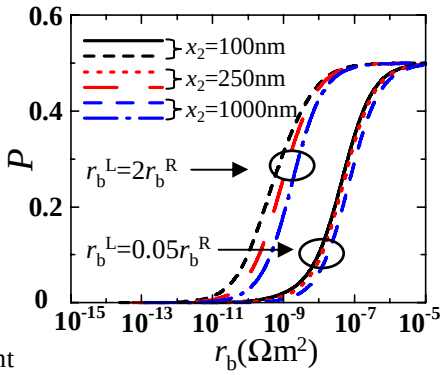

Fig.4: Current polarizations for $r_b^L/r_b^R \neq 1$. x_2=x_5.