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Effects of interface electric field on the magnetoresistance in spin transistors

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Abstract : Effect of interface electric field on magnetoresistance (MR) ratio is investigated by introducing a density-gradient term (quantum effect) to the standard drift-diffusion theory. We also carried out experiments and explain MR ratio that depends on its current direction by the quantum effect.

1. Introduction

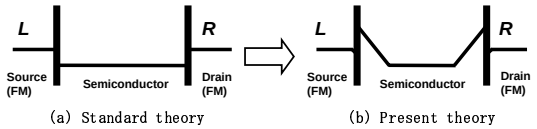
Spin injection and detection between silicon and magnetic material via tunneling barriers are one of the most important issues in spintronics[1-3], and the key factor which determines a performance of spin devices such as spin transistor. The standard drift-diffusion theory [4,5] can successfully describe magnetic transport phenomena of metallic materials. However, there appear experiments which cannot be explained in the standard drift-diffusion theory [3,6,7]. Here we theoretically and experimentally investigate a quantum effect in the context of the drift-diffusion theory of spin transport phenomena. We apply the density-gradient theory studied in the silicon semiconductor devices [8] to two spin current model (Fig.1), and we provide analytical formula of magnetoresistance (MR) ratio beyond the standard theory for a local measurement setup. We also carried out local experiments (Fig.2) which shows that MR ratio differs depending on the current direction (from source to drain or from drain to source). The standard theory cannot explain this directionality of current in MR ratio, because MR ratio of the standard theory has symmetric form regarding source and drain. We show that the introduction of the quantum effect explains this directionality of MR ratio.

2. Formulation

We introduce a quantum effect as the density-gradient term to the spin dependent chemical potentials. The density gradient term is expressed by $b\nabla^2\sqrt{n_s}/\sqrt{n_s}$ with $b=\hbar^2/(2mer_q)$ and the density of carrier n_s ($s=\uparrow,\downarrow$, $\nabla=\partial/\partial z$). The parameter r_q changes depending on physical environment (we take $r_q=2$ here) [8].Assuming that the same macroscopic diffusion equations as those of the standard theories [4,5], we can set $\frac{e}{\sigma_\pm}\frac{\partial J_\pm}{\partial z}=\pm\frac{\mu_+^*-\mu_-^*}{l_\pm^2}$ and $\frac{\partial^2(\mu_+^*-\mu_-^*)}{\partial z^2}=\frac{(\mu_+^*-\mu_-^*)}{l_{sf}^2}$ (l_{sf} is the spin diffusion length l^N or l^F). Combining with the current conservation relation given by $J_+ + J_- = J(\text{const})$, we derive the extended current and chemical potential for the ferromagnetic region:

$$\bar{\mu}_{\alpha\pm}(z) = (1-\beta^2)e\rho_F J_\alpha z + k_1^\alpha \mp (1\mp\beta)\Delta\mu^\alpha(z) - \psi^F_{\alpha b\pm}(z),$$
$$J_{\alpha\pm}(z) = (1\pm\beta)\frac{J_\alpha}{2} \mp \frac{1}{2e\rho_F l^F}\Delta\nu^\alpha(z) - J^F_{\alpha b\pm}(z),$$

with $\Delta\mu^\alpha(z)=K_m^\alpha\sinh([z-z_\alpha^{(0)}]/l^F)$, and $\Delta\nu^\alpha(z)=l^F\partial\Delta\mu^\alpha(z)/\partial z$ ($z_\alpha^{(0)}$ is a center of α-ferromagnet), for both ferromagnetic electrodes $\alpha=L,R$. We write $\rho_\pm=2[1\pm\beta]\rho_F$ and ρ_N for the resistivity of the ferromagnet F and the semiconductor N. Similarly, the chemical potential of the semiconductor part is given by $\bar{\mu}_\pm(z)=e\rho_N Jz+k_1\mp\Delta\mu(z)-\psi_{b\pm}(z)$. with $\Delta\mu(z)=K_p\cosh(z/l^F)+K_m\sinh(z/l^F)$, and $\Delta\nu(z)=l^N\partial\Delta\mu(z)/\partial z$, for the central semiconductor region. K_m, K_m^α, K_p, K_p^α, k_1,k_1^α are unknown coefficients to be determined by boundary conditions. $\psi^F_{b\alpha\pm}$ and $J^F_{b\alpha\pm}$ are the quantum effects given by $\psi^F_{b\alpha\pm}=\left(2b/\sqrt{n^F_{\alpha\pm}}\right)\nabla^2\sqrt{n^F_{\alpha\pm}}$, $\psi^N_{b\pm}=\left(2b/\sqrt{n^N_{\pm}}\right)\nabla^2\sqrt{n^N_{\pm}}$, $J^F_{b\alpha\pm}=2(\sigma_\pm/e)\nabla\psi_{b\alpha\pm}$, and $J^F_{b\pm}=2(\sigma_N/e)\nabla\psi_{b\pm}$. We use the same boundary conditions on chemical potential and current at an interface $z=z_\alpha$ ($\alpha=L,R$) as those of the standard theories [4,5]:$\mu_\pm(z_\alpha^+)-\mu_\pm(z_\alpha^-)=r_\pm J_\pm(z_\alpha)$ and $J_\pm(z_\alpha^+)=J_\pm(z_\alpha^-)$. We also define $r_\pm^\alpha=2r_b^\alpha[1\pm\gamma^\alpha]$, $r_p^\alpha=[r_+^\alpha+r_-^\alpha]/4=r_b$, $r_m^\alpha=[r_-^\alpha-r_+^\alpha]/4=r_b^\alpha\gamma^\alpha$, $r_F=\rho_F l^F$, $r_N=\rho_N l^N$. The important quantities here are $r_F\equiv\rho_F l^F$ and $r_N\equiv\rho_N l^N$.



(a) Standard theory (b) Present theory

FIG. 1: Band for F/N/F structure.

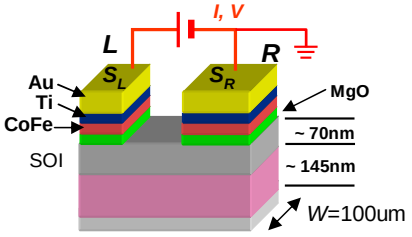


FIG. 2: Schematic diagram of a lateral device. The distance t_N between the two electrodes is $t_N=1\mu$m.Thickness of MgO is 1nm.

3. Electric field at the interface

New additional boundary conditions derived from the current conservation property is given by

$$S_\alpha[J_{\alpha b+}(z_\alpha^-)+J_{\alpha b-}(z_\alpha^-)] = S_N[J_{b+}(z_\alpha^+)+J_{b-}(z_\alpha^+)], \quad (1)$$

where S_α ($\alpha=L,R$) and S_N are the areas of ferromagnets and the semiconductor, respectively. $J_{b\alpha+}$ ($\alpha=L,R$) and J_{b+} are determined by the electron density, estimated from Schrödinger equation $d^2\Psi(z)/dz^2+[V(z)-E_0]\Psi(z)=0$, and the relation $n=|\Psi(z)|^2$, such as $\nabla^2\sqrt{n}/\sqrt{n}\approx\nabla^2\Psi(z)/\Psi(z)=(2m/\hbar^2)[V(z)-E_0]$.

Assuming a triangle potential at the interface between ferromagnet region and the semiconductor region (Fig.1), potentials are expressed by

$$V_L^F(z) = V_L^F - E_L^F z,\ V_L^N(z) = V_L^N - E_L z, \qquad (2)$$
$$V_R^F(z) = V_R^F + E_R^F z,\ V_R^N(z) = V_R^N + E_R z, \qquad (3)$$

where E_α^F and E_α are electric fields at the interface of ferromagnets and semiconductor. Then, we obtain $J_{b\alpha\pm}^F = \sigma_\pm u_\alpha^F$ and $J_{b\alpha\pm}^N = \sigma_N u_\alpha^N/2$, with $u_\alpha^F = -\nabla V_\alpha^F/(er_q)$ and $u_\alpha^N = -\nabla V_\alpha^F/(er_q)$. Using $\sigma_\pm = \rho_\pm^{-1}$ and $\sigma_N = (2\rho_N)^{-1}$. The boundary condition Eq.(1) leads to $\sigma_F u_\alpha^F = \sigma_N u_\alpha^N$.

4. MR ratio

Total resistance through the $F/N/F$ structure is obtained by summation of resistances of F and N elements. The difference between the parallel resistance $r_{\rm AP}$ and the antiparrallel resistance $r_{\rm P}$ is calculated such as

$$r_{\rm AP} - r_{\rm P} = \frac{1}{Jr_F^2\Delta}\{2r_N(c_F^2\gamma_L\gamma_R(J_{L1}+J_{R1})r_p^L r_p^R + \beta c_F r_F(\gamma_L(2J_{L1}+J_{R3})r_p^L + \gamma_R(J_{L3}+2J_{R1})r_p^R)s_F + 2\beta^2(J_{L3}+J_{R3})r_F^2 s_F^2)\}. \qquad (4)$$

where $J_{\alpha 1} = J - \sigma_N u_\alpha^N$, and $J_{\alpha 3} = (S_N/S_\alpha)J_{\alpha 1}$ are the result of the quantum effect. $r_F^2\Delta \equiv ([r_F + r_p^L][r_F + r_p^R]S_N^2 + r_N^2 S_L S_R)s_{2N} + (r_F[S_L + S_R] + r_p^L S_R + r_p^R S_L)r_N S_N c_{2N}$. $c_N \equiv \cosh(t_N/2l^N)$, $s_N \equiv \sinh(t_N/2l^N)$, $c_F \equiv \cosh(t_F/2l^F)$, $s_F \equiv \sinh(t_F/2l^F)$, $c_{2N} \equiv \cosh(t_N/l^N)$, and $s_{2N} \equiv \sinh(t_N/l^N)$. t_F is a thickness of ferromagnet. Compared with MR ratio of the standard theory, Eq.(4) says that $r_{\rm AP} - r_{\rm P}$ has additional terms which increase as $\sigma_N(u_L^N + u_R^N) = \sigma_N(F_L^N - F_R^N)$ increases. When $E_L = E_R$, Eq. (4) corresponds to standard diffusion theory.

5. Comparison with experiments

Let us compare our theoretical results with experiments. We fabricated two-terminal devices for local measurements in which the areas of the two electrodes are different (Fig.2). Detail structures will be discussed elsewhere [2,10]. Because of the different area of the two electrodes, the interface electric fields are different, in which larger electric field is generated with smaller electrode area. We also set that r_b is constant ($S_L R_L = S_R R_R$: R_α is junction resistance). Combining with the current conservation $J_L S_L = J_R S_R$, we have $|E_R| = |E_L|(S_L/S_R)^2$. Thus, $S_L < S_R$ means that $|E_L| > |E_R|$. Fig.3 shows the experimental data of the voltage dependence of the MR ratio. As can be seen, the MR ratio differs depending on the direction of the current. Fig.4(a) shows MR ratio is symmetric to the area difference $S_L - S_R$, in the range of the standard theory. This is because the standard theory has a symmetric structure to the both electrodes. In Fig.4(b), we have added the effect of the interface electric fields to Fig.4(a). We can see that the introduction of the electric field induces different area dependence. Fig.5 shows the MR ratio as a function of the left electric field E_L. For $E_L < 0$ where *electron* current flows from larger interface electric field ($|E_L|$) to smaller interface electric field ($|E_R|$), the MR ratio increases. This result is consistent with Fig.3.

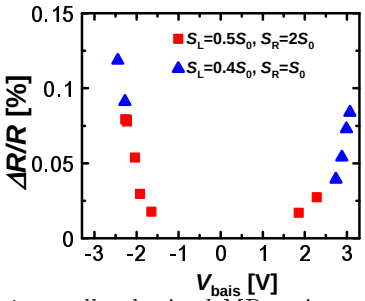


FIG. 3: Experimentally obtained MR ratio as a function of bias voltage between the left and the right electrodes of Fig.2. $S_0 = 100\mu{\rm m}^2$ and T=77K. $V_{\rm bias} > 0$ corresponds to Fig.2 ($E_L > 0$). $V_{\rm bias} < 0$ corresponds to reversed bias direction of Fig.2 ($E_L < 0$).

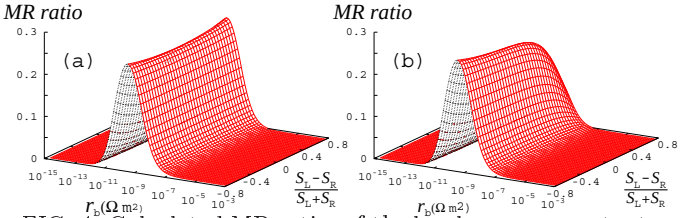


FIG. 4: Calculated MR ratios of the local measurement setup as functions of the interface resistance r_b and area difference. S_L and S_R show areas of the left and right electrodes, respectively. (a) Standard theory (b) Interface electric field is introduced (Eq.(4)). $\gamma_L = \gamma_R = \beta = 0.10$. t_N=1250nm, l^N=5.1μm, r_N= $1.07\times10^{-10}\Omega{\rm m}^2$, l^F=5nm, r_F = $4.5\times10^{-15}\Omega{\rm m}^2$.

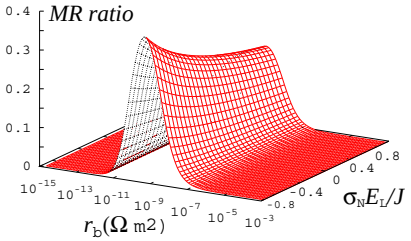


FIG. 5: Calculated MR ratio of the local measurement setup as functions of the left electric field. $S_L = 4S_R$. Parameters are the same as Fig.4.

6. Conclusions

We studied the effect of the interface electric field by extending the standard diffusion theory. We compare our theory with experiments and show that our theory can explain the difference of MR ratio depending on the difference of current direction.

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