Spin Injection and Detection in Magnetic Nanostructures

S. Takahashi and S. Maekawa

Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

(August 21, 2002)

We study theoretically the spin transport in a nonmagnetic metal connected to ferromagnetic injector and detector electrodes. We derive a general expression for the spin accumulation signal which covers from the metallic to the tunneling regime. This enables us to discuss recent controversy on spin injection and detection experiments. Extending the result to a superconducting device, we find that the spin accumulation signal is strongly enhanced by opening of the superconducting gap since a gapped superconductor is a low carrier system for spin transport but not for charge. The enhancement is also expected in semiconductor devices.

PACS numbers: 72.25Ba, 72.25.Hg, 72.25.Mk, 73.40.Gk

There has been considerable interest recently in spin transport in magnetic nanostructures. The spin polarized electrons injected from ferromagnets (F) into nonmagnetic materials (N) such as a normal metal, semiconductor, and superconductor create nonequilibrium spin accumulation in N. The efficient spin injection, accumulation, and transport are central issues to be explored in manipulating the spin degree of freedom of the electron. Johnson and Silsbee have demonstrated that the injected spins penetrate into N over the spin-diffusion length of $\mu$m scale using the spin injection and detection techniques in F1/N/F2 trilayer structures. Very recently, Jedema et al. have made a permalloy/copper/permalloy (Py/Cu/Py) structure and observed spin accumulation at room temperature. Subsequently, they have shown that the efficiency of spin injection and accumulation is greatly improved in a cobalt/aluminum/cobalt (Co/I/Al/I/Co) structure with tunnel barriers (I).

In this paper, we study the spin injection and detection in a device of F1/N/F2 structure by taking into account the geometry of nonlinear measurement. By proper modeling of the system in the diffusive transport regime, we derive an analytical expression for the spin accumulation signal which covers from the metallic to the tunnel regime. A controversial issue on the analysis of spin accumulation has been raised in the structures which covers from the metallic to the tunneling regime. A controversial issue on the analysis of spin accumulation is greatly improved in a device containing a superconductor, we find that the spin accumulation signal is strongly enhanced by opening of the superconducting gap.

The electrical current $j_\sigma$ for spin channel $\sigma$ is driven by the electric field $E$ and the gradient of the carrier density deviation $\delta n_\sigma$ from equilibrium:

$$ j_\sigma = eD_\sigma \nabla \delta n_\sigma, $$

where $\sigma$ and $D_\sigma$ are the electrical conductivity and the diffusion constant. Making use of $\delta n_\sigma = N_\sigma \delta \sigma$ and $\delta \sigma = e^2 N_\sigma D_\sigma$ ($N_\sigma$ is the density of states in the spin subband and $\delta \sigma$ is the shift in the chemical potential of carriers from its equilibrium value) gives:

$$ j_\sigma = -(\sigma/e) \nabla \phi, $$

where $\mu_\sigma = e \sigma + e \phi$ is the electrochemical potential (ECP) and $\phi$ the electric potential. The continuity equations for charge and spin in the steady state are:

$$ \nabla \cdot (j_\uparrow + j_\downarrow) = 0, $$

$$ \nabla \cdot (j_\downarrow - j_\uparrow) = -e \delta n_\uparrow/\tau_{\uparrow\uparrow} + e \delta n_\downarrow/\tau_{\downarrow\downarrow}, $$

where $\tau_{\sigma\sigma'}$ is the scattering time of an electron from spin state $\sigma$ to $\sigma'$. Using these equations and detailed balancing $N_{\uparrow}/\tau_{\uparrow\uparrow} = N_{\downarrow}/\tau_{\downarrow\downarrow}$, one obtains

$$ \nabla^2 (\sigma_\uparrow \mu_\uparrow + \sigma_\downarrow \mu_\downarrow) = 0, $$

$$ \nabla^2 (\mu_\uparrow - \mu_\downarrow) = \lambda^2 (\mu_\uparrow - \mu_\downarrow), $$

with the spin-diffusion length $\lambda = \sqrt{D_\sigma \tau_{sf}}$, where $\tau_{sf}^{-1} = \frac{1}{2}(\tau_{\uparrow\uparrow}^{-1} + \tau_{\downarrow\downarrow}^{-1})$ and $D^{-1} = (N_{\downarrow}D_{\downarrow}^{-1} + N_{\uparrow}D_{\uparrow}^{-1})/(N_{\uparrow} + N_{\downarrow})$.

The material parameters in N are spin-independent:

![Basic structure of a spin injection and detection device](image)
We employ a simple model for the interfacial currents of the junctions. The distribution of the interfacial spin currents is uniform over the contact area $A_j = w_F w_N$ since the $\lambda_N$ is much longer than $w_F$ and $w_N$, and ECP has a discontinuous drop at the interface of junction $i$ (Fig. 1). We neglect the interfacial spin-flip scattering for simplicity. The interfacial current $I^\sigma_{l/F}$ across the interface ($z = 0$) is given by $I^\sigma_{l/F} = (G^\sigma_i / e)(\mu^\sigma_{l/F}|_{z=0} - \mu^\sigma_{R}|_{z=0})$, where $G^\sigma_i$ is the interface conductance ($G^\sigma_i = G^\uparrow_i + G^\downarrow_i = R_i^{-1}$). In the transparent contact ($G_i \to \infty$) the ECPs are continuous at the interfaces, while in the tunneling junction the discontinuity in ECP is much larger than the spin splitting in ECP. The interfacial charge and spin currents are $I^c_i = I^\uparrow_i + I^\downarrow_i$ and $I^\sigma_i = I^\uparrow_i - I^\downarrow_i$.

When the bias current $I$ flows from F1 to the left side of N ($I_1 = I$) and no charge current through the F2/N junction ($I_2 = 0$), the solutions for ECPs that satisfy Eqs. (1) and (2) are constructed as follows. In the N electrode whose thickness and contact dimensions are much smaller than $\lambda_N$, $\mu^\sigma_N$ varies only in the $z$ direction: $\mu^\sigma_N(x) = \tilde{\mu}_N + \sigma a^\sigma_N x$, where $\tilde{\mu}_N = -(\mu/e)\delta\mu_N$, $\delta\mu_N = a_1 e^{-|x|/\lambda_N} + a_2 e^{-|x-L|/\lambda_N}$ with the $a_1$-term being the ECP shift due to spin injection from F1 at $x = 0$, and the $a_2$-term being the feedback shift due to the presence of F2 at $x = L$. The spin current $j_s = j_1 - j_2$ flows in the $x$ direction according to $j_s = -(\sigma a_1 e^{-|x|/\lambda_N} + a_2 e^{-|x-L|/\lambda_N})x$. The continuity of the spin current at junction $i$ yields $I^\sigma_i = 2(\sigma a_1 A_N/e \lambda_N) a_i$, where $A_N = w_N d_N$ is the cross-sectional area of N. Note that only the spin current flows in the region of $x > 0$ and no charge current there.

In the F1 and F2 electrodes whose thickness and contact dimensions are much larger than $\lambda_F$, the spin splitting of $\mu^\sigma_F$ decays quickly along the $z$ direction, so the solution has the form near the interface ($0 < z < \lambda_F$): $\mu^\sigma_F(z) = \tilde{\mu}_F + \sigma b^\sigma_F e^{-z}/\lambda_F$, where $\tilde{\mu}_F = -(\mu/e)\delta\mu_F$, $\delta\mu_F = a^\sigma_F e^{-|z|/\lambda_F}$, and $b^\sigma_F = (\sigma \mu_F/A_F e \lambda_F) a_i$, $a_i$ is the in-plane area of N. Note that $\sigma \mu_F$ and $\lambda_F$ are decays quickly along the $F$ direction.

The spin-dependent voltage $V_2$ detected at F2, i.e., the potential difference between the right side of N electrode and the F2 electrode, is given by

$$V_2/I = \pm 2 \rho_{NE} e^{-\lambda_N} \prod_{i=1}^{2} \left( \frac{P_i R_i}{\rho_{NI} R_N} + \frac{\rho_{FE} R_F}{\rho_{FE} R_{NF}} \right),$$

where $\rho_{NI} = \rho_{NE} = \rho_{NF}$, $\rho_{FE} = \rho_{FD}$, and $\rho_{FP} = \rho_{FD}/A_F$.

The spin accumulation signal $R_s$ depends on whether each junction is a metallic contact or a tunnel junction. Since $R_F/R_N \sim 0.01$ for the typical values ($\rho_F/\rho_N \sim 10$, $\lambda_F/\lambda_N \sim 0.01$, and $A_F/A_N \sim 0.1$), we have the following limiting cases: When both junctions are transparent contact ($R_1, R_2 \ll R_F$), we have

$$R_s = \frac{4 \rho_{F} P_1}{(1 - p_F^2) R_N} \frac{R_F}{R_N} \frac{2 e^{-L/\lambda_N}}{1 - e^{-2L/\lambda_N}}.$$  

When one of the junctions is a transparent contact and the other is a tunnel junction, i.e., ($R_1 \ll R_F \ll R_N \ll R_2$) or ($R_2 \ll R_F \ll R_N \ll R_1$), we have

$$R_s = \frac{2 \rho_F P_1}{(1 - p_F^2) R_N} \frac{R_F}{R_N} e^{-L/\lambda_N}.$$  

When both junctions are tunneling junctions ($R_1, R_2 \gg R_N$), we have

$$R_s = P^2 e^{-L/\lambda_N}.$$  

Note that $R_s$ in the above limiting cases is independent of $R_i$. Equations (4)–(8) indicate that the resistance mismatch factor ($R_F/R_N$) is removed systematically when a transparent contact is replaced with a tunnel junction ($R_1, R_2 \gg R_N$). Thus, the maximum spin signal is achieved when all the junctions are tunnel junctions.

Figure 2 shows the spin accumulation signal $R_s$ in Eqs. (4)–(8) as $P = 0.4$, $P_1 = 0.4$, and $R_F/R_N = 10^{-2}$. We see that $R_s$ increases by one order of magnitude by replacing a transparent contact with a tunnel barrier. The value $R_N = 3$ $\Omega$ used in the experimental value 0.1 $\Omega$. The Co/I/Al/I/Co structure yields $R_s = 10 \Omega$ at $L = \lambda_N$. If one takes into account the cross-shaped Cu I, one expects one-third of the above value, which is in reasonable agreement with the experimental value 0.1 $\Omega$. This discrepancy may be attributed to the reduction in $P_3$ due to the spin-flip scattering at the barriers.

A question arises on whether the contacts of metallic F1/N/F2 structures is transparent ($R_i \ll R_F$) or tunneling-like ($R_i \gg R_N$). The experimental values
of Py/Cu ($R_1 \sim 5 \times 10^{-12} \Omega \text{cm}^2$) and $\lambda_F \sim 5 \text{nm}$ yields $R_1 \sim R_F$, which is strictly speaking neither transparent nor tunneling-like. However, the values of $R_s$ for $R_i = R_F$ calculated from Eq. (1) are about 2 times higher than those for the transparent case in Fig. 2, indicating that the Py/Cu/Py structure lies on the verge of transparent regime. However, depending on sample fabrication processes, there will be cases that belong to the intermediate regime ($R_F \ll R_i \ll R_N$), for which one should use

$$R_s = \frac{4P_2^2}{(1 - P_2^2)^2} R_N \left( \frac{R_1 R_2}{R_F^2} \right) \frac{e^{-L/\lambda_N}}{1 - e^{-2L/\lambda_N}}. \quad (7)$$

If $R_i \sim R_N$, then $R_s$ is close to the values of tunneling case, so that the contacts of $R_i \gtrsim R_N$ belong to the tunneling regime.

The spin injection into a superconductor (S) is of great interest from both basic and practical points of views. We show that $S$ becomes a low-carrier system for spin transport by opening of the superconducting gap $\Delta$ and the resistivity of the spin current increases below the superconducting critical temperature $T_c$. In the tunneling device of $F_1/I/S/I/F_2$, the signal would increase due to the increase of $R_N$ below $T_c$ (see Eq. (1)). Therefore, we investigate in detail how the spin signal is enhanced by opening of $\Delta$. In the following, we consider the situation where the spin splitting of ECP, the maximum of which is $\delta \mu_S (0) \sim 1/2eP_2R_N I$, is smaller than $\Delta$, i.e., $I < 2\Delta/(eP_2R_N)$, for which the suppression of $\Delta$ due to spin accumulation can be neglected. We also neglect charge imbalance created by injection of QP charge into $S$, which originates from the conversion of injected QPs into condensate, and produce the excess voltage due to charge accumulation at $F_2$. However, the effect is spin-independent and does not contribute to $R_s$.

In the superconducting state, the equation for the spin splitting ($\mu_S - \mu_F$) is the same as Eq. (2) with $\lambda_S$ in the normal-state which is intuitively understood as follows. Since the dispersion curve of the QP excitation energy is given by $E_k = \sqrt{\epsilon_k^2 + \Delta^2}$ with one-electron energy $\epsilon_k$, the QP’s velocity $v_k = (1/h)(\partial E_k/\partial k) = (\epsilon_k/E_k)v_k$ is slower by the factor $|\epsilon_k/E_k|$ compared with the normal-state velocity $v_k (\approx v_F)$. By contrast, the impurity scattering time $\tau_{\sigma\sigma'} = (E_k/|\epsilon_k|)\tau_{\sigma\sigma'}$ is longer by the inverse of the factor. Then, the spin-diffusion length $\lambda_S = (D\tau_\text{imp})^{1/2}$ in $S$ with $D = 1/2e^2\tau_\text{imp}$ and $\tau_\text{imp}^{-1} = \sum_{\sigma\sigma'} \tau_{\sigma\sigma'}^{-1}$ results in $\lambda_S = \sqrt{D\tau_\text{imp}} = \lambda_N$ owing to the cancellation of the factor $|\epsilon_k/E_k$. Consequently, the spin splitting in $S$ has the same form of solution as in $N$.

Utilizing the so-called semiconducting property for electron tunneling between $F$ and $S$, the charge and spin currents across junction 1 are calculated as $J^i_F = G_T V$ and $J^i_S = P_i G_T V$ at low bias $V = (V_i < \Delta/2)$ and $G_T$ those across junction 2 are $I^i_F = G_T V_2 - P_2 \delta \mu_N (L)/e$ and $I^i_S = P_2 G_T V_2$. Here, $P_2$ takes $P_1$ ($-P_1$) for the P (AP) alignment, $G_T = \chi_s (T)G_T$ is the tunnel conductance in the superconducting state, and $\chi_s (T)$ is the Yosida function, which represents the reduction of the tunnel conductance by opening of $\Delta$ below $T_c$.

The spin accumulation in $S$ is determined by balancing the spin injection rate with the spin-relaxation rate:

$$\frac{dS_f}{dt} = \sigma \left[\frac{2}{\tau_\text{sf}} I^i_F - \frac{1}{\tau_\text{df}} \frac{\partial S_f}{\partial t}\right]. \quad (8)$$

Using the golden rule formula we can calculate $(\partial S_f/\partial t)_{\text{df}}$ and obtain $\rho^s = (2f_0(\Delta)/\tau_\text{df})\alpha_i$, where $2f_0(\Delta)$ represents the QP populations and $f_0(\Delta) = 1/[\exp(\Delta/k_B T) + 1]$.

From the matching condition of the spin currents across the barriers, we obtain the spin signal $R_s$ in the superconducting state

$$R_s = \frac{V_s}{I} = \frac{1}{2f_0(\Delta)} P_2^2 R_N e^{-L/\lambda_N}. \quad (9)$$

If the $I - V$ characteristics, $I = \chi_s (T)V/R_T$, is used, then

$$V_s = \frac{\chi_s (T)}{2f_0(\Delta)} P_2^2 R_N e^{-L/\lambda_N}. \quad (10)$$

The above results are obtained from those of the normal state by the scalings $\rho_N \rightarrow \rho_N/\rho^s_f$ and $R_T \rightarrow R_T/\chi_s (T)$. Equation (8) is interpreted as follows: The spin-current density in SC is given by $j_s = -\langle \sigma_{\sigma\sigma'} e \rangle 2f_0(\Delta)\nabla \delta \mu_N |\partial_\text{df}|$ where the effective conductivity $2f_0(\Delta)\sigma_{\sigma\sigma'}$ decreases due to the decrease of QP populations by opening the gap $\Delta$ below $T_c$. The boundary condition that the injected spin current $P_2 I$ is equal to $2f_0(0^+)A_N \delta \mu_N$ yields $\delta \mu_N \approx \langle e P_2 I R_N/2f_0(\Delta) \rangle e^{-|\zeta|/\lambda_N}$. The decrease of the effective conductivity is compensated by the increase of $\delta \mu_N$ to maintain the same spin injection in the constant $I$, and therefore $R_s$ increases as $e^{-1}(\Delta)$ below $T_c$. Note that the $T$-dependent factor in Eq. (9) is
the same as that in the spin-relaxation time \( \tau_s = [\chi(T)/2f_0(\Delta)] \tau_{sf} \), which is derived from \((\partial S/\partial t)_{sf} = -\mathbf{S}/\tau_s\).

Figure 3 shows the temperature dependence of \( R_s = V_s/I \) and \( V_s/V \). The values are normalized to those at \( T_c \). The strong increase of \( V_s/I \) reflects the \( T \)-dependence of the resistivity of the spin current below \( T_c \). The signal \( V_s/V \) increases with the same \( T \)-dependence as \( \tau_s(T) \), indicating that the spin-relaxation time \( T \) is directly obtained by measuring \( V_s \) vs \( T \) at constant \( V \). To test these predictions, it is highly desirable to measure \( V_s \) of Co/I/Al/I/Co structures by lowering \( T \) below \( T_c \).

A large enhancement of spin signals is also expected in degenerate semiconductors, because the resistivity is much larger compared with normal metals and the spin-diffusion length is relatively long. In degenerate semiconductors, the spin current is given by

\[
\mathbf{j}_s = -\mu_m n \nabla_x (\mu_\uparrow - \mu_\downarrow),
\]

where \( \mu_m \) is the mobility and \( n \) the carrier concentration. For Si-doped GaAs with \( n = 10^{18} \text{cm}^{-3} \) and \( \mu_m = 2 \times 10^6 \text{cm}^2/\text{Vs} \) at room temperature, \( \rho_n = 1/\epsilon \mu_m n \) and \( 0.1 \Omega \text{cm} \). For (Mn,Ga)As, \( \rho_n = 0.01 \sim 0.1 \Omega \text{cm} \). It follows from Eqs. (5) and (6) that \( R_s \propto \rho_F \) for a (Ga,Mn)As/I/(Ga,Mn)As device and \( R_s \propto \rho_n \) for a F1/I/GaAs(n-type)/I/F device. Therefore, we expect that \( R_s \) is larger by several orders of magnitude than that of metal case. This result is promising for applications for spintronic devices.

In summary, we have studied the spin injection and detection in the F1/N/F2 structure, and derived an expression for the spin accumulation signal which covers from the metallic to the tunneling regime. This enables us to resolve the recent controversy of spin injection and detection experiments. Extending the result to a superconducting device, we have found that the signal is strongly enhanced below \( T_c \), because superconductors become a low carrier system for spin transport by opening of the gap and a larger spin splitting is required for carrying the same spin current. Our finding can be tested in superconducting devices such as Co/I/Al/I/Co by lowering temperature below \( T_c \). A large spin accumulation signal is also expected in semiconductor devices.

This work is supported by a Grant-in-Aid for Scientific Research from MEXT and CREST.

1 Spin Dependent Transport in Magnetic Nanostructures, edited by S. Maekawa and T. Shinjo (Taylor and Francis, London and New York, 2002).
2 A. G. Aronov, JETP Lett. 24, 32 (1976); JETP 44, 193 (1976); Sov. Phys. Semicond. 10, 698 (1976).
3 M. Johnson and R. H. Silsbee, Phys. Rev. Lett. 55, 1790 (1985); ibid. 60, 377 (1988); ibid. 70, 2142 (1993).
4 F.J. Jedema et al., Nature (London) 410, 345 (2001).
5 S. Takahashi and S. Maekawa, Phys. Rev. Lett. 88, 047004 (2002).
6 G. Schmidt et al., J. Magn. Magn. Mater. 170, L1 (1997); S. Dubois et al., Phys. Rev. B 60, 477 (1999).
7 P. C. van Son et al., Phys. Rev. Lett. 58, 2271 (1987).
8 T. Valet and A. Fert, Phys. Rev. B 48, 7090 (1993).
9 A. Fert and S.F. Lee, Phys. Rev. B 53, 6554 (1996).
10 S. Hershfield and H.L. Zhao, Phys. Rev. B 56, 3296 (1997).
11 E.I. Rashba, Phys. Rev. B 62, R16267 (2000).
12 A. Fert and H. Jaffrès, Phys. Rev. B 64, 184420 (2001).
13 G. Schmidt et al., Phys. Rev. B 62, 4790 (2000).
14 The mismatch arises from those in length and area (\( \lambda N \gg A_F, A_I \gg A_N \)), not in the resistivity as in Refs. [19-21].
15 M. Johnson and J. Bayers (unpublished).
16 S. Takahashi et al., Phys. Rev. Lett. 82, 3911 (1999).
17 C. D. Chen et al., Phys. Rev. Lett. 88, 047004 (2002).
18 J. Clarke, Phys. Rev. Lett. 28, 1363 (1972); M. Tinkham and J. Clarke, Phys. Rev. Lett. 28, 1366 (1972).
19 T. Yamashita et al., Phys. Rev. B 65, 172509 (2002).
20 T. Yamashita et al., Phys. Rev. B 65, 172509 (2002).
21 M. Johnson, Phys. Rev. B 113, 982 (1959).
22 M. Johnson and J. Clarke, Phys. Rev. Lett. 28, 1366 (1972).
23 M. Johnson and J. Clarke, Phys. Rev. Lett. 28, 1366 (1972).
24 S. Takahashi et al., Phys. Rev. Lett. 88, 116601 (2002).
25 \( \chi(T) = 2 \int_0^\infty \frac{E}{\sqrt{E^2 - \Delta^2}} [-f(E)/(\partial \rho(E)/\partial E)]dE \), whose asymptotic values are \( 1 - [7(3/4\pi^2)] (\Delta/k_B T)^4 \) near \( T_c \) and \( (\pi/2k_B T)^{1/2} \exp[-(\Delta/k_B T)] \) well below \( T_c \).
26 Y. Yafet, Phys. Lett. A 98, 287 (1983).
27 J.M. Kikkawa and D.D. Awschalom, Phys. Rev. Lett. 80, 4313 (1998).
28 F. Matsukura et al., Phys. Rev. B 57, 2037 (1998).