

Nonlocal spin Hall effect and spin–orbit interaction in nonmagnetic metals

S. Takahashi^{a,*}, S. Maekawa^b

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

^b*CREST, Japan Science and Technology Agency, Kawaguchi, 332-0012, Japan*

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Abstract

Spin Hall effect in a nonlocal spin-injection device is theoretically studied. Using a nonlocal spin-injection technique, a pure spin current is created in a nonmagnetic metal (N). The spin current flowing in N is deflected by spin–orbit scattering to induce the Hall current in the transverse direction and accumulate charge at the edges of N, yielding the spin current induced Hall effect. We propose a method for extracting the spin–orbit coupling parameter in nonmagnetic metals via the nonlocal spin-injection technique.

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There has been growing interest in spin transport in magnetic nanostructures, because of potential applications to spin electronic devices [1]. Recent experimental studies have demonstrated that the spin polarized carriers injected from a ferromagnet (F) into a nonmagnetic material (N) such as a normal metal [2–5] and superconductor [6,7] create a spin accumulation in N. In this paper, we consider a nonlocal spin-injection Hall device, and discuss the spin Hall effect (SHE) in the presence of spin current (or charge current) flowing in N, taking into account *side jump* and *skew scattering*.

The basic mechanism for SHE is the spin–orbit interaction in N, which causes a spin-asymmetry in the scattering of conduction electrons by impurities; up-spin electrons are preferentially scattered in one direction and down-spin electrons in the opposite direction. Spin-injection techniques makes it possible to induce SHE in *nonmagnetic* conductors. When spin-polarized electrons are injected from F to N, these electrons moving in N are deflected by the spin–orbit scattering to induce the Hall current in the transverse direction and accumulate charge at the edges of

N, yielding the spin current induced spin Hall effect (SHE) [8–10].

Using the Boltzmann transport equations which incorporates the spin-asymmetric scattering of conduction electrons by nonmagnetic impurities in N within the Born approximation, we can derive the “total” spin and charge currents flowing in N [10,11]

$$\mathbf{J}_s = \mathbf{j}_s + \mathbf{j}_s^H, \quad \mathbf{J}_q = \mathbf{j}_q + \mathbf{j}_q^H. \quad (1)$$

where $\mathbf{j}_s = -(\sigma_N/e)\nabla\delta\mu_N$ and $\mathbf{j}_q = \sigma_N\mathbf{E}$ are the *longitudinal* spin and Ohmic currents, $\sigma_N = 2e^2N(0)D$ is the electrical conductivity, $\delta\mu_N = \frac{1}{2}(\mu_N^\uparrow - \mu_N^\downarrow)$ is the chemical potential shift, μ_N^σ is the chemical potential of electrons with spin σ , and D is the diffusion constant. The second terms in Eq. (1) are the transverse spin and charge Hall currents caused by spin–orbit scattering:

$$\mathbf{j}_s^H = \alpha_H[\hat{\mathbf{z}} \times \mathbf{j}_q] = \alpha_H\sigma_N(\hat{\mathbf{z}} \times \mathbf{E}), \quad (2)$$

$$\mathbf{j}_q^H = \alpha_H[\hat{\mathbf{z}} \times \mathbf{j}_s] = -\frac{\alpha_H\sigma_N}{e}(\hat{\mathbf{z}} \times \nabla\delta\mu_N), \quad (3)$$

with $\alpha_H = \alpha_H^{\text{SJ}} + \alpha_H^{\text{SS}}$, where $\alpha_H^{\text{SJ}} = \hbar\eta_{\text{so}}/(3mD)$ is the side jump (SJ) contribution, and $\alpha_H^{\text{SS}} = (2\pi/3)\eta_{\text{so}}N(0)V_{\text{imp}}$ is the skew scattering (SS) contribution, $\eta_{\text{so}} = k_F^2\eta_{\text{so}}$ is the

*Corresponding author. Tel.: +81 22 215 2008; fax: +81 22 215 2006.
E-mail address: takahasi@imr.tohoku.ac.jp (S. Takahashi).

dimensionless spin–orbit coupling parameter, k_F is the Fermi momentum, and V_{imp} is the impurity potential.

Eqs. (2) and (3) indicate that the spin current \mathbf{j}_s induces the transverse *charge* current (charge Hall current) \mathbf{j}_q^H , whereas the charge current \mathbf{j}_q induces the transverse *spin* current (spin Hall current) \mathbf{j}_s^H . Eq. (1) is expressed in the matrix forms

$$\begin{bmatrix} J_{q,x} \\ J_{s,y} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & -\sigma_{xy} \\ \sigma_{xy} & \sigma_{xx} \end{bmatrix} \begin{bmatrix} E_x \\ -\nabla_y \delta\mu_N/e \end{bmatrix}, \quad (4)$$

$$\begin{bmatrix} J_{s,x} \\ J_{q,y} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & -\sigma_{xy} \\ \sigma_{xy} & \sigma_{xx} \end{bmatrix} \begin{bmatrix} -\nabla_x \delta\mu_N/e \\ E_y \end{bmatrix}, \quad (5)$$

where $\sigma_{xx} = \sigma_N$ is the longitudinal conductivity and σ_{xy} is the Hall conductivity contributed from SJ and SS: $\sigma_{xy} = (\alpha_H^{\text{SJ}} + \alpha_H^{\text{SS}})\sigma_N = \sigma_{xy}^{\text{SJ}} + \sigma_{xy}^{\text{SS}}$ with

$$\sigma_{xy}^{\text{SJ}} = \frac{e^2}{\hbar} \eta_{\text{so}} n_e, \quad \sigma_{xy}^{\text{SS}} = \alpha_{xy}^{\text{SJ}} \frac{2\pi}{3} k_F l_{\text{imp}} N(0) V_{\text{imp}}, \quad (6)$$

where n_e is the carrier (electron) density and l_{imp} is the mean free path. Note that σ_{xy}^{SJ} is *independent* of impurity concentration n_{imp} .

The ratio of the SJ and SS Hall contributions is

$$\frac{\sigma_{xy}^{\text{SJ}}}{\sigma_{xy}^{\text{SS}}} = \frac{3}{2\pi} \frac{1}{k_F l_{\text{imp}}} \frac{1}{N(0) V_{\text{imp}}}. \quad (7)$$

When $k_F l_{\text{imp}} \gg 1$ and $N(0) V_{\text{imp}} \sim 1$, SS gives the dominant contribution to SHE. On the other hand, when the impurity potentials are distributed with positive and negative sign and their average is nearly zero but the average 1 of the absolute values is of the order of unity, i.e., $N(0) \langle V_{\text{imp}} \rangle \ll 1$ and $N(0) |\langle V_{\text{imp}} \rangle| \sim 1$, then the SJ conductivity is larger than the SS conductivity in SHE.

In the following, we consider a spin-injection Hall device shown in Fig. 1, and concentrate on the spin current induced SHE. The magnetization of F electrode points to the z direction. When the current I is sent from F to the left side of N, the spin-polarized electrons are injected to create a pure spin current \mathbf{j}_s in N on the right side, where the total

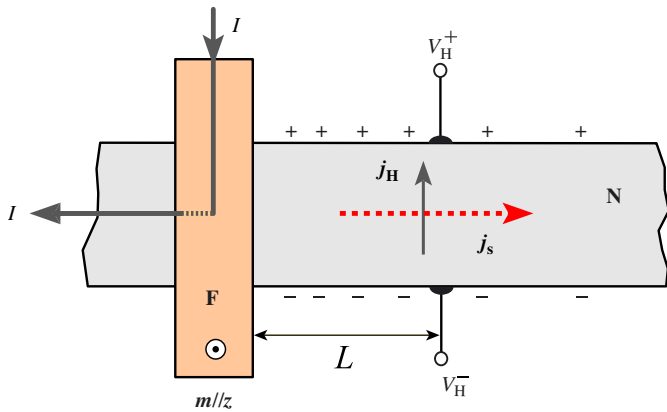


Fig. 1. Spin injection Hall device (top view). The magnetic moment of F is aligned perpendicular to the plane. The spin current induced Hall voltage $V_H = V_H^+ - V_H^-$ is induced in the transverse direction by injection of pure spin current \mathbf{j}_s .

charge current is expressed as

$$\mathbf{j}_q = -(\alpha_H \sigma_N / e) (\hat{z} \times \nabla \delta\mu_N) + \sigma_N \mathbf{E}, \quad (8)$$

where the first term is the Hall current induced by \mathbf{j}_s , and the second term is the Ohmic current induced by surface charge. In the open circuit condition in the transverse direction, where J_q^y vanishes, the nonlocal Hall resistance $R_H = V_H / I$ becomes

$$R_H = \frac{1}{2} \alpha_H P_T (\rho_N / d_N) e^{-L/\lambda_N}, \quad (9)$$

in the case of tunnel junction, where P_T is the tunneling spin polarization, ρ_N is the resistivity, λ_N is the spin-diffusion length, and d_N is the thickness of N. In the case of metallic-contact junction

$$R_H = \frac{1}{2} \alpha_H \frac{p_F}{1 - p_F^2} (\rho_N / d_N) \frac{R_F}{R_N} \sinh^{-1}(L/\lambda_N), \quad (10)$$

where p_F is the spin polarization of F, R_N and R_F are the spin resistances of the N and F electrodes: $R_N = (\rho_N \lambda_N) / A_N$ and $R_F = (\rho_F \lambda_F) / A_J$ with A_N the cross-sectional area of N and A_J the contact area between N and F. Usually, R_N is one or two orders of magnitude larger than R_F [12]. Recently, the spin current induced SHE have been measured using spin-injection techniques [13,14].

It is worthwhile to make the product $\rho_N \lambda_N$, which is related to the spin–orbit coupling parameter $\bar{\eta}_{\text{so}}$ as

$$\rho_N \lambda_N = \frac{\sqrt{3}\pi R_K}{2} \frac{1}{k_F^2} \sqrt{\frac{\tau_{\text{sf}}}{\tau_{\text{imp}}}} = \frac{3\sqrt{3}\pi R_K}{4} \frac{1}{k_F^2 \bar{\eta}_{\text{so}}}, \quad (11)$$

where $R_K = h/e^2 \sim 25.8 \text{ k}\Omega$ and τ_{sf} is the spin-flip scattering time. Formula (11) provides a method for extracting the physical parameters of spin–orbit scattering in nonmagnetic metals. Using experimental data of ρ_N and λ_N in Eq. (11), we obtain the value of the spin–orbit coupling parameter $\bar{\eta}_{\text{so}} = 0.01 - 0.04$ in Cu, Al, and Ag as listed in Table 1. Therefore, Eqs. (9) and (10) yields R_H of the order of $0.1 - 1 \text{ m}\Omega$, indicating that the spin current induced SHE is observable by using nonlocal spin-injection Hall devices. The prediction is confirmed by recent experiments [15,16].

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Table 1
Spin–orbit coupling parameter $\bar{\eta}_{\text{so}}$ of Cu, Al, and Ag

	λ_N (nm)	ρ_N ($\mu\Omega\text{cm}$)	$\tau_{\text{imp}}/\tau_{\text{sf}}$	$\bar{\eta}_{\text{so}}$
Cu ^a	1000	1.43	0.70×10^{-3}	0.040
Cu ^b	1500	1.00	0.64×10^{-3}	0.037
Cu ^c	546	3.44	0.41×10^{-3}	0.030
Al ^d	650	5.90	0.36×10^{-4}	0.009
Ag ^e	195	3.50	0.50×10^{-2}	0.110

^aRef. [2].

^bRef. [3].

^cRef. [4].

^dRef. [2].

^eRef. [5].

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