Spin-Charge Conversion via the Rashba Spin-Orbit Interaction in Spin Pumping Systems

Akihito Takeuchi, Kazuhiro Hosono, and Gen Tatara
Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan
E-mail: atake@phys.metro-u.ac.jp

Abstract. The aim in spintronics is to manipulate the spin degrees of freedom besides the charge ones. Conversion of the spin degrees of freedom into electricity is an important task for development of technology. We derive theoretically the mechanism which spin transport due to the spin pumping effect is converted into the charge current via the Rashba spin-orbit interaction. As a result, it is found that the spin-charge conversion mechanism via the Rashba coupling is the inverse effect of the spin torque rather than the inverse process of the spin Hall effect. We discuss also the charge conservation law, namely the induced charge current is conserved.

1. Introduction
In recent spintronics research, the two main topics have been investigated quite actively; one is the electrical control of the spin degrees of freedom and the other is conversion of spin transport into electric properties. However we don’t yet detect a flow of the spin (spin current) directly in contrast with the charge. The inverse process of the spin Hall effect was proposed as a method of measuring the spin degrees of freedom electrically. Since the spin current is driven in the transverse direction to applied electric voltage via the spin-orbit interaction in the spin Hall effect, we can observe the spin current as the electric voltage through that reciprocal process. The inverse spin Hall effect is composed of two steps; the first process is to create a spin current and the next is a conversion process of generated the spin current into electric voltage by a spin-orbit interaction. There are two different mechanisms in the inverse spin Hall effect corresponding to different techniques of creating the spin current. One is the static inverse spin Hall effect [1–4]. In this effect, injecting a spin-polarized current into normal metal, a diffusive flow of the spin appears. This technique is the nonlocal spin injection. Then the injected spin current is converted into an electric voltage via the inverse spin Hall effect. The other comes from the ferromagnetic resonance effect with magnetization dynamics. Considering a ferromagnetic-normal metal junction, magnetization dynamics in a ferromagnet pumps the spin current into the attached nonmagnetic material. The pumped spin current is detected as electric voltage by the spin-orbit interaction. This is the dynamic inverse spin Hall effect [5–10]. The latter is very useful for application because the dynamic inverse spin Hall effect is interpreted as a novel battery operated by magnetism. We will show microscopic theory of the spin-charge conversion by the spin-orbit interaction in the presence of magnetization dynamics.
Figure 1. Schematic illustration of the spin-charge conversion system on the basis of the dynamic inverse spin Hall effect. The spin degrees of freedom pumped by precession of the local spin \( S \) is converted into the charge current \( j_c \) via the spin-orbit interaction.

2. Model and Method

We assume the uniform Rashba-type coupling as the spin-orbit interaction:

\[
H_{\text{so}} = -\sum_k (c_k^\dagger \hat{\sigma} c_k) \cdot (E_{\text{so}} \times k),
\]

where \( c_k^{(t)} \) represents the annihilation (creation) operator of the conduction electron in momentum space, \( E_{\text{so}} \) is the Rashba coupling field (usually along \( z \) axis), \( \hat{\sigma} \) denotes a vector of the Pauli matrices, and the caret is \( 2 \times 2 \) matrix in spin space. Strength of the Rashba coupling is controlled by applying gate voltage, so it is appropriate for application. The Rashba spin-orbit coupling was a peculiar interaction observed in semiconductors at first, and recently it has been found that similar contribution could be given at the surface of a normal metal with inversion asymmetry. This coupling is much huger than the coupling in semiconductor [11, 12].

We calculate the induced charge current in the disordered Rashba system with precession of magnetization shown in Fig. 1. The exchange interaction between the conduction electron and the local spin (magnetization) \( S \) is given by

\[
H_{\text{ex}}(t) = -J \sum_{k,q} (c_{k-q}^\dagger \hat{\sigma} c_k) \cdot S_q(t).
\]

Here \( J \) is the exchange coupling constant and we assume this local spin varies slowly in space and time. The charge current density is defined as

\[
j_c(x,t) = \frac{ie}{V} \sum_{k,q} e^{-i qx_{tt}} \left[ \left( \frac{\hbar^2}{m} k + E_{\text{so}} \times \hat{\sigma} \right) G_{k-k+q/2}(t,t) \right],
\]

where \( V \) is system volume and \( G \) denotes the lesser component of the path-ordered Green function defined on the Keldysh contour, \( G_{k-k',\sigma}(t,t') = \langle c_{k',\sigma}^\dagger(t') c_k(t) \rangle \langle \cdots \rangle \) denotes the expectation value obtained with the total Hamiltonian and \( \sigma \) is a spin indices of the conduction electron and the second term arises from the anomalous velocity due to the spin-orbit interaction. We here assume a weak coupling regime, \( E_{\text{so}} k_F \ll \hbar/\tau \) and \( J \ll \hbar/\tau \), where \( k_F \) is the Fermi wavelength and \( \tau \) denotes an elastic electron lifetime due to the impurity scattering. This assumption is valid because the spin-orbit coupling is usually not so strong and exchange coupling is weak between magnetization in a ferromagnet and conduction electrons in attached nonmagnetic material. We carry out the perturbation expansion treating the spin-orbit interaction to the first order and the exchange interaction up to the second order. At the first order in the exchange interaction, the charge current vanishes identically [7,8], so we show
Figure 2. Diagrammatic representation of the leading charge current. Three diagrams on the left represent the normal contribution \((j^n_c)\) and the right diagram describes correction by the Rashba coupling \((j^{so}_c)\). The double lines describe the Rashba spin-orbit interaction, the wavy lines are interaction with the localized spin \(S\), and the dotted lines represent the vertex correction by impurity scattering.

A result of the second order in the exchange interaction involving the vertex correction. To take the vertex correction into account is corresponding to impose the charge conservation law and the Ward-Takahashi identity. Nevertheless, the present authors didn’t care about it in the previous papers \([7, 8]\) because the analysis was enough to see that the spin-charge conversion indeed occurs. (In Ref. \([7]\), they included contribution from the diffusion ladder in their calculation, however they neglected to see the charge conservation law.) Thereby, we will present an exact result in the following.

3. Results
We show the Feynman diagrams of the leading charge current in Fig. 2. Calculating those diagrams carefully, we obtain the result:

\[
j_c(x, t) = -\frac{4e\nu J^2 T_2}{\hbar^2 V} E_{so} \times [S(x, t) \times \dot{S}(x, t)] - D \nabla \rho_c(x, t), \tag{4}\]

where \(\nu\) denotes the density of states at the Fermi energy \(\varepsilon_F\), \(D\) characterizes a diffusion coefficient \((\equiv 2\varepsilon_F \tau/3m)\), and \(\rho_c\) represents the charge density given by

\[
\rho_c(x,t) = -\frac{4e\nu J^2 T_3}{\hbar^2 V} \nabla \cdot \langle E_{so} \times [S(x, t) \times \dot{S}(x, t)] \rangle_D. \tag{5}\]

Here \(\langle \cdots \rangle_D\) describes a factor in representing a diffusive motion of conduction electrons by impurity scattering:

\[
\langle A(x,t) \rangle_D = \frac{1}{V} \int d^3x' \int dt' \sum_{q,\Omega} e^{-i\mathbf{q}(\mathbf{x}-\mathbf{x}')} e^{i\Omega(t-t')} A(x', t') \frac{D^q q^2 \tau + i\Omega \tau}{D^q q^2 \tau + i\Omega \tau}. \tag{6}\]

This result satisfies the charge conservation law \(\dot{\rho}_c + \nabla \cdot j_c = 0\) exactly. Since the Rashba coupling mixes the spin degrees of freedom with the direction of the conducting electron, the spin damping \(S \times \dot{S}\) is converted into the charge current.

3.1. Spin-Charge Conversion
The above result can be expressed in terms of the electron spin component:

\[
j_c(x, t) \equiv -\frac{2e\tau}{\hbar^2 V} \left( E_{so} \times \bar{T}_s(x, t) - D \nabla \left\{ \nabla \cdot [E_{so} \times \bar{\rho}_s(x, t)] \right\} \right). \tag{7}\]
The electron spin obeys the spin continuity equation

\[ \dot{\rho}_s^\alpha(x,t) + \nabla \cdot \mathbf{j}_s^\alpha = T_s^\alpha, \]

where \( \rho_s^\alpha(x,t) \) represents the spin density polarized in \( \alpha \) direction, the spin current \( j_s^\alpha \) flows in \( i \) direction and is spin-polarized in \( \alpha \) direction, and \( T_s^\alpha \) denotes the spin source which we call it the spin relaxation torque. The local part (the first term) of Eq. (7) clearly demonstrates that the charge current arises from the spin relaxation torque \( T_s \) and not from the spin current \( j_s \). Thus the spin-charge conversion in the Rashba system is the inverse effect of the spin torque rather than the inverse spin Hall effect. The spin Hall effect depends much on a type of the spin-orbit interaction and the Rashba coupling is well-know as causing an especial effect. In fact, the spin Hall conductivity cancels out with the vertex correction in the Rashba system [13].

4. Conclusions

We have demonstrated that the spin-charge conversion occurred under the Rashba spin-orbit coupling. The analysis satisfies the charge conservation law, unlike the previous studies. The spin damping owing to the spin pumping is converted into the charge current via the Rashba spin-orbit interaction. The current pumping mechanism in the Rashba system is explained as the inverse effect of the spin torque rather than the inverse of the spin Hall effect. It would be natural consequences of vanishing the direct spin Hall effect in the disordered Rashba system [13].

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