Spin pumping and spin-Hall effect observed in metallic films

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Abstract. In spintronics, the spin-Hall effect and its reciprocal, the inverse spin-Hall effect (ISHE), is of crucial importance, since these effects allow the mutual conversion between a charge current and a spin current. We have investigated ISHE in metallic films. The temperature dependence of the ISHE signal critically depends on material species, implying the coexistence of different electronic mechanisms of ISHE in metallic systems.

1. Introduction
In recent years, there has been a rapidly growing interest in the field of spintronics, which involves studies of active control and manipulation of spin degrees of freedom in solid-state systems [1]. In the field of spintronics, generating and detecting spin currents, the flow of electron spins, are the main subject of recent studies. In these studies, intense theoretical and experimental interests have been focused on the spin-Hall effect (SHE) and its reciprocal effect: the inverse spin-Hall effect (ISHE). SHE is the phenomenon where an electric current converts into a spin current in a solid via the spin-orbit interaction. Experimentally, SHE has been observed in an n-doped bulk semiconductor system [2] and in a 2D hole gas system [3]. ISHE, the conversion of spin currents into electric currents, has been observed using a spin-pumping method operated by ferromagnetic resonance (FMR) [4, 5] and by a non-local method.

Theoretically, two different mechanisms have been suggested for SHE and ISHE: One is due to the asymmetric scattering for up and down spins, including the side jump and the skew scattering, which is the extrinsic mechanism [6-8]. The other is due to the band Berry’s phase, which is the intrinsic mechanism [9, 10]. However, these mechanisms have not been fully understood. In this paper, we report the temperature dependence of the ISHE signal induced by the spin pumping in Ni81Fe19/Pt and Ni81Fe19/Au films.

2. Experimental
Figure 1 shows a schematic illustration of the sample used in this study. The samples are Ni81Fe19/Pt and Ni81Fe19/Au bilayer films comprising a 10 nm thick ferromagnetic metallic Ni81Fe19 layer and 10 nm thick nonmagnetic Pt and Au layers. The whole was prepared by sputtering (Pt) and electron beam evaporation (Au and Ni81Fe19) in a high vacuum on a thermally oxidized Si substrate. Two electrodes are attached to both ends of the Pt or Au layer. In our samples, a pure spin current is injected from the Ni81Fe19 layer into the Pt or Au layer via the spin pumping effect operated by FMR.

A schematic illustration of the spin pumping effect and ISHE in our sample system is shown in Fig. 2. In FMR condition, the steady magnetization precession is maintained by balancing the absorption and dissipation of angular momentum of the magnetization. When a nonmagnetic metal is connected to the ferromagnet, this spin propagates into the metal as a spin current. This phenomenon is the spin pumping [11-13]. In our samples, the spin pumping enables us to inject a pure spin current into the Pt or Au layer from the Ni81Fe19 layer. The injected pure spin current into Pt or Au is converted into an...
electric current by ISHE. The relation among the spatial direction of the charge current $J_c$, the spin current $J_s$, and the spin polarization vector of the spin current $\sigma$ is given by $J_c \propto J_s \times \sigma$.

The schematic illustration of this detection method is shown in Fig. 2. The sample systems are placed near the center of a TE$_{011}$ microwave cavity at which the magnetic-field component of the microwave mode is maximized while the electric-field component is minimized. During the measurement, the microwave mode with the frequency $f = 9.39$ GHz is exited in the cavity, and an in-plane external static magnetic field $H$ is applied perpendicular to the direction across the electrodes, as illustrated in Fig. 1. Since the magnetocrystalline anisotropy in Ni$_{81}$Fe$_{19}$ is negligibly small, the magnetization in Ni$_{81}$Fe$_{19}$ layer is uniformly aligned along the magnetic field direction. When $H$ and $f$ fulfill the FMR condition, a pure spin current with a spin polarization $\sigma$ parallel to the external static magnetic field is resonantly injected into the nonmagnetic layer by the spin pumping. Using the lock-in technique, we measured the temperature dependence of the FMR signal and the electric-potential difference $V$ between the electrodes attached to the nonmagnetic Au and Pt layer.

**Figure 1.** A schematic illustration of the sample system used in present study. $H$ denotes an external static magnetic field.

**Figure 2.** A schematic illustration of the spin pumping effect and inverse spin-Hall effect (ISHE) in present system. $J_s$ and $J_c$ denote the spatial directions of a pure spin current generated by the spin pumping and an electric current generated by ISHE, respectively. $\sigma$ is the spin polarization vector of the spin current.

### 3. Results and Discussion

Figures 3(a) and 3(b) show the FMR spectrum and the field dependence of $dV(H)/dH$ spectrum for the Ni$_{81}$Fe$_{19}$/Pt sample under the 200 mW microwave excitation at 270 K, respectively. The FMR spectrum shows that the magnetization in the Ni$_{81}$Fe$_{19}$ layer resonates with the applied microwave at $H_{\text{FMR}} = 115$ mT.

In the $dV(H)/dH$ spectrum, notably, unconventional peak-and-dent signal appears around 115 mT for the Ni$_{81}$Fe$_{19}$/Pt sample. This field coincides with $H_{\text{FMR}}$; evidently, this signal in $dV(H)/dH$ originates from ferromagnetic resonance in the Ni$_{81}$Fe$_{19}$ layer. The resonance spectral shape is well reproduced by a simple Lorentz function. The observed $dV(H)/dH$ signal is attributed to the ISHE signal induced by the spin pumping, as described in the previous literature [5].

Figures 4(a) and 4(b) show the FMR spectrum and the field dependence of $dV(H)/dH$ spectrum for the Ni$_{81}$Fe$_{19}$/Au sample under the 200 mW microwave excitation at 270 K, respectively. The FMR spectrum shows that the magnetization in the Ni$_{81}$Fe$_{19}$ layer in this film resonates with the applied microwave at $H_{\text{FMR}} = 125$ mT. The resonance electromotive force signal in the $dV(H)/dH$ spectrum appears at $H_{\text{FMR}}$, which is attributed to the ISHE in the Au layer.
In Fig. 5, the total amplitude, $I$, of resonance shape in the $dV(H)/dH$ signal (see the inset to Fig. 5), which represents the amplitude of the ISHE signal, is plotted for the Ni$_{81}$Fe$_{19}$/Pt sample as a function of the temperature. The microwave power was 200 mW. With decreasing the temperature, the amplitude $I$ decreases below 150 K and is significantly suppressed at low temperatures. This is consistent with the extrinsic scenario of the inverse spin-Hall effect, in which the inelastic scattering of conduction electron, including the electron scattering due to phonons, is indispensable for generating the Hall voltage [14-16]; at low temperatures, phonons and other fluctuations are suppressed.

In Fig. 6, the total amplitude, $I$, of the resonance shape is plotted for the Ni$_{81}$Fe$_{19}$/Au sample as a function of the temperature. The microwave power was 200 mW. With decreasing the temperature, the electromotive force signal changes its sign across 140 K and then the magnitude of $I$ decreases below 140 K. The magnitude of $I$ is significantly suppressed at low temperatures in the Ni$_{81}$Fe$_{19}$/Au sample too, implying again an importance of the extrinsic mechanism in the inverse spin-Hall effect of the Ni$_{81}$Fe$_{19}$/Au sample. The observed sign change in the electromotive force around 140 K suggests a coexistence of two different contribution with different signs in this extrinsic mechanism of the inverse spin-Hall effect; the skew-scattering mechanism and the side-jump mechanism are the candidates for the two different contribution[17,18].

4. Conclusion
We measured the temperature dependence of the electromotive force induced by ISHE and the spin pumping using Ni$_{81}$Fe$_{19}$/Pt and Ni$_{81}$Fe$_{19}$/Au films. The magnitude of the electromotive force is suppressed at low temperatures significantly in both the films. In the Ni$_{81}$Fe$_{19}$/Au film, the sign reversal of the electromotive force was observed. These results can be argued in terms of the extrinsic mechanism of the inverse spin-Hall effect.

Figure 3. (a) Field ($H$) dependence of the FMR signal for a Ni$_{81}$Fe$_{19}$/Pt film sample at 270 K. (b) Field dependence of $dV(H)/dH$ for the Ni$_{81}$Fe$_{19}$/Pt sample at 270 K. $V$ denotes the electric potential difference between the electrodes on the Pt layer.

Figure 4. (a) Field ($H$) dependence of the FMR signal for a Ni$_{81}$Fe$_{19}$/Au film sample at 270 K. (b) Field dependence of $dV(H)/dH$ for the Ni$_{81}$Fe$_{19}$/Au sample at 270 K. $V$ denotes the electric potential difference between the electrodes on the Pt layer.
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Figure 5. Variation of the total amplitude $I$ of the resonance spectral shape in $dV(H)/dH$ with temperature for the Ni$_{81}$Fe$_{19}$/Pt sample. $V$ denotes the electric potential difference between the electrodes on the Pt layer.

Figure 6. Variation of the total amplitude $I$ of the resonance spectral shape in $dV(H)/dH$ with temperature for the Ni$_{81}$Fe$_{19}$/Au sample. $V$ denotes the electric potential difference between the electrodes on the Au layer.