Detection of inverse spin-Hall effect in Nb and Nb$_{40}$Ti$_{60}$ thin films

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Abstract. The inverse spin-Hall effect (ISHE) has been investigated using the spin pumping, spin current generation from magnetization dynamics, in Ni$_{81}$Fe$_{19}$/N (N = Nb and Nb$_{40}$Ti$_{60}$) bilayer films. We found an electromotive force due to ISHE in Ni$_{81}$Fe$_{19}$/Nb film and the ISHE signal in the Ni$_{81}$Fe$_{19}$/Nb$_{40}$Ti$_{60}$ bilayer film is greater than that in the Ni$_{81}$Fe$_{19}$/Nb bilayer film, suggesting an important role of the impurity doping for ISHE and the spin pumping in Nb.

1. Introduction

Spintronics, which is new device technology manipulating electron spins, has recently attracted great interest [1]. In this field, methods for generating and detecting spin currents [2, 3], a flow of electron spins in a solid, play an important role. In this stream, the research interest in the field of spintronics has been focused on the inverse spin-Hall effect (ISHE) [4-8] during recent years.

ISHE converts a spin current into a charge current in a solid via the spin-orbit interaction. There are two different theoretical models suggested for ISHE; one is due to the spin-dependent impurity scattering, which is the extrinsic ISHE [9, 10], and the other is due to the band Berry’s phase, which is the intrinsic ISHE [11, 12]. The electromotive force induced by ISHE was recently observed using the spin pumping, generation of spin currents from magnetization precession [13]. ISHE enables the electric detection of a spin current even in the absence of spin accumulation and thus it is essential in combining spintronics with conventional electronics based on a charge current. Especially, the spin pumping method requires only a simple bilayer system and it can be applicable to various systems, a situation which favors exploring ISHE in a solid.

ISHE can be argued using a simple model as follows. In a solid, considering two electrons traveling in opposite directions along $\mathbf{J}_s$, where $\mathbf{J}_s$ represents the spatial directions of the spin current (see figure 1), these two electrons tend to have opposite spins: parallel and antiparallel to the spin current polarization $\sigma$. The spin-orbit interaction bends these two electrons to the same direction and induces a charge current or an electromotive force transverse to $\mathbf{J}_s$, which is ISHE. The relation between $\sigma$, $\mathbf{J}_s$, and $\mathbf{J}_c$ are given by

$$\mathbf{J}_c \propto \mathbf{J}_s \times \sigma.$$  (1)
The electromotive force induced by ISHE due to the spin pumping has been measured so far in Pt, Pd, and Au thin films [14, 15]. To achieve the higher sensitive spin-current detection, we have to find the material which generates the greater electromotive force induced by ISHE. In this paper, we investigate ISHE in Ni$_{81}$Fe$_{19}$/N ($N$=Nb and Nb$_{40}$Ti$_{60}$) bilayer films by using the spin pumping method.

**Figure 1.** A schematic illustration of the inverse spin-Hall effect (ISHE). $J_c$, $J_s$, and $\sigma$ denote the charge current induced by ISHE, the spatial direction of a spin current, and the spin polarization vector of the spin current, respectively.

**2. Experimental Procedure**

Figure 2(a) shows a schematic illustration of the sample used in the present study. The sample is a bilayer film comprising a 10-nm-thick ferromagnetic Ni$_{81}$Fe$_{19}$ layer and a 50-nm-thick paramagnetic Nb or Nb$_{40}$Ti$_{60}$ layer. The paramagnetic layer was sputtered on a thermally oxidized Si substrate and then the Ni$_{81}$Fe$_{19}$ layer was evaporated in a high vacuum. Since the magnetocrystalline anisotropy in Ni$_{81}$Fe$_{19}$ is negligibly small, the magnetization in the Ni$_{81}$Fe$_{19}$ layer is uniformly aligned along the magnetic field direction. Two electrodes are attached to both edges of the paramagnetic layer (see figure 2(a)). ISHE can be observed using the spin-pumping operated by ferromagnetic resonance (FMR) [16]. During the measurement, the sample is placed at the center of a TE$_{011}$ cavity. A microwave mode with frequency $f$=9.43 GHz exists in the cavity, and the external magnetic field $H$ along the film plane is applied perpendicular to the direction across the electrodes (see figure 2(a)). When $H$ and $f$ fulfill the FMR condition, a pure spin current with $\sigma$ parallel to $H$ is resonantly injected into the paramagnetic layer by the spin pumping (see figure 2(b)). The microwave power ($\leq 200$ mW) is much lower than the saturation of the FMR absorption for the present sample. Using the field lock-in technique, we measured the FMR signal and the electric potential difference $V$ between the electrodes. All the experiments were performed at room temperature.

**Figure 2.** (a) A schematic illustration of the sample used in the present study. $H$ is the external magnetic field. (b) A schematic illustration of the spin pumping and the inverse spin-Hall effect in the Ni$_{81}$Fe$_{19}$/Nb and Ni$_{81}$Fe$_{19}$/Nb$_{40}$Ti$_{60}$ systems. $J_c$, $J_s$, and $\sigma$ denote the spatial direction of a charge current, the spatial direction of a spin current, and the spin polarization direction of the spin current, respectively.
3. Results and Discussion

Figures 3(a) and 3(b) show the FMR spectrum \(dI(H)/dH\) and the field dependence of \(dV(H)/dH\) for the Ni\(_{81}\)Fe\(_{19}\)/Nb system under the 200 mW microwave excitation, respectively. The FMR spectrum shows that the magnetization in the Ni\(_{81}\)Fe\(_{19}\) layer resonates with the microwave at \(H_{\text{FMR}}=109.5\) mT. In the electromotive force spectrum, an unconventional signal appears around the resonance field \(H_{\text{FMR}}\). Notable is that, the shape of the electromotive force is well reproduced using a Lorentz function. Lorentzian resonance shape indicates that the electromotive force is dominated by ISHE induced by the spin pumping [17].

Figures 3(c) and 3(d) show the FMR spectrum \(dI(H)/dH\) and the field dependence of \(dV(H)/dH\) for the Ni\(_{81}\)Fe\(_{19}\)/Nb\(_{40}\)Ti\(_{60}\) under the 200 mW microwave excitation, respectively. The \(dV(H)/dH\) spectrum shown in figure 3(d) shows that the observed electromotive force is also attributed to ISHE induced by the spin pumping.

In figure 4, the amplitude of the ISHE signal in Ni\(_{81}\)Fe\(_{19}\)/Nb\(_{40}\)Ti\(_{60}\) and Ni\(_{81}\)Fe\(_{19}\)/Nb are plotted as a function of \(P_{MW}\). This indicates that the electromotive force observed in the Ni\(_{81}\)Fe\(_{19}\)/Nb\(_{40}\)Ti\(_{60}\) and the Ni\(_{81}\)Fe\(_{19}\)/Nb systems are consistent with the dc spin pumping senario [17]. In the DC spin pumping scenario, generated spin current \(J_s\) is described as [18]

\[
J_s \propto \frac{4\pi M_s h^2 \gamma (4\pi M_s \gamma)^2 + \sqrt{\gamma^2 ((4\pi M_s)^2 \gamma^2 + 4\omega^2)}}{8\pi \alpha ((4\pi M_s)^2 \gamma^2 + 4\omega^2)},
\]

where \(h, M_s, \gamma, \alpha\) and \(\omega\) are the amplitude of the microwave magnetic field, the saturation magnetization, the gyromagnetic ratio, the damping constant, and the microwave frequency, respectively. Equation 2 shows that \(J_s\) is proportional to the microwave power \(P_{MW}\), or \(h^2\).
In the dV(H)/dH data, the ISHE signal for the Ni$_{81}$Fe$_{19}$/Nb$_{40}$Ti$_{60}$ is strong, comparable to that for a typical ISHE system Ni$_{81}$Fe$_{19}$/Pt, and is about two times greater than that for the Ni$_{81}$Fe$_{19}$/Nb. This result suggests an important role of the impurity doping for ISHE in Nb.

**Figure 4.** The amplitude of the ISHE signals in the Ni$_{81}$Fe$_{19}$/Nb$_{40}$Ti$_{60}$ and the Ni$_{81}$Fe$_{19}$/Nb bilayer films as a function of the microwave power $P_{MW}$.

4. Conclusion
Inverse spin-Hall effect have been investigated in Ni$_{81}$Fe$_{19}$/Nb and Ni$_{81}$Fe$_{19}$/Nb$_{40}$Ti$_{60}$ films. A spin current generated by the spin pumping was electrically detected using ISHE. We observed strong ISHE signals in the Nb$_{40}$Ti$_{60}$ film.

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