Spin pumping due to spin waves in magnetic vortex structure

Norinobu Hasegawa¹, Kouta Kondou², Motoi Kimata¹, and YoshiChika Otani¹,²*

¹Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan
²CEMS, RIKEN, Wako, Saitama 351-0198, Japan
*E-mail: yotani@issp.u-tokyo.ac.jp
Received March 27, 2017; accepted April 10, 2017; published online April 27, 2017

We performed spin pumping into a Pt wire by using various spin-wave modes excited in a magnetic vortex structure. Radial and azimuthal modes were excited by applying an in-plane radiofrequency magnetic field with a variable frequency. We observed a mode-dependent sign change in the inverse spin Hall voltage induced along the Pt wire. Micromagnetic simulation revealed that the observed behavior reflected the spatial distribution of the spin wave. These findings suggest that spin pumping can be used for the electrical detection of the spatial distribution of confined spin-wave modes in small magnetic structures. © 2017 The Japan Society of Applied Physics

Spin pumping is a common method for generating a spin current in a multilayer structure consisting of ferromagnetic (FM) and nonmagnetic (NM) materials, in which the spin current is pumped by the FM resonance in the FM layer and detected as a direct-current (dc) voltage via the inverse spin Hall effect (ISHE) in the NM layer with a strong spin–orbit interaction. This method allows the spin current to be injected into various materials, such as normal metals, semiconductors, and topological insulators. In these measurements, a uniform precessional mode is normally used to generate the spin current. Inversely, the spin pumping combined with the ISHE can be utilized to detect the local dynamics of the spin waves and the skyrmion. To establish this detection method, it is essential to understand the relationship between the excited spin-wave modes and the voltage signals induced by the ISHE.

In the present study, we focused on a simple fundamental magnetic structure—the magnetic vortex (MV)—which is characterized by two degrees of freedom, the polarity of the out-of-plane core, and the chirality of the in-plane whirling magnetization. The MV can accommodate various excited modes, including a low-frequency gyration mode and radial and azimuthal spin-wave modes. These excited modes have been studied in association with the core switching assisted by spin waves, mostly via magnetic Kerr microscopy, but not by the aforementioned combined spin-pumping method. We demonstrated the electrical detection of the spin-wave modes in an MV using the spin-pumping method.

Figures 1(a) and 1(b) show schematics of the structure of our device, which consisted of a chain of permalloy 250 (Ni₈₀Fe₂₀; hereinafter, Py) disks formed on a Ti field with a variable frequency. We observed a mode-dependent sign change in the inverse spin Hall voltage induced along the Pt wire. Micromagnetic simulation revealed that the observed behavior reflected the spatial distribution of the spin wave. These findings suggest that spin pumping can be used for the electrical detection of the spatial distribution of confined spin-wave modes in small magnetic structures. © 2017 The Japan Society of Applied Physics

A Ti layer was used as a buffer layer for the deposition of Pt and Au.

First, to confirm the existence of the MV and its excitation states in the magnetic disk, we measured the S parameter using a vector network analyzer, by applying an external magnetic field H in the x-axis direction (field angle θ = 0°). Figure 1(c) shows the measured transmission (S₂₁) spectrum with respect to the rf frequency and the external field for θ = 0°. The black arrow shows the field sweep direction.

Fig. 1. Schematic of the measurement circuit (a) and the wire structure (b). Approximately 250 disks were prepared in a line on a Ti/Pt wire. (c) Transmission (S₂₁) spectrum with respect to the frequency and the external field for θ = 0°. The black arrow shows the field sweep direction.
azimuthal modes \((n = 0, m = \pm 1)\) at 5 and 6 GHz and one radial mode \((n = 1, m = 0)\) at 8 GHz, where \(n\) (m) is the number of nodes in the radial (azimuthal) direction. Between 200 and 500 Oe, there were several modes, most of which located outside the vortex core.\(^{15}\) These excitation modes agree well with a previous report.\(^{15}\)

Next, we measured the spin-pumping-induced dc voltages with an rf current and \(H\) applied in the \(y\)-axis direction \((\theta = 90°)\). The rf power was set to 0 dBm. Excited spin dynamics were detected as a dc voltage of \(V_{dc}\) because of the spin-pumping effect, where the spin current was pumped into the Pt layer and converted into the charge current via the ISHE. Figure 2 shows the \(V_{dc}\) spectrum with respect to \(f\) and \(H\). At \(H = 0\) Oe, no voltage peak was observed, because of the rotational symmetry of the in-plane circular magnetization. When \(H\) was applied, voltage peaks were observed. The sign of the ISHE voltage changed with respect to the direction of \(H\), which agrees with previous reports on the spin pumping.\(^{2-4,17-19}\) However, interestingly, the sign of the detected voltage also depended on the frequency, i.e., the excited spin-wave mode.

To investigate this frequency-dependent sign change, we performed a micromagnetic simulation\(^{20}\) by numerically solving the Landau–Lifshitz–Girbert equation. Here, we performed calculations for a single vortex confined in an FM disk divided into cells having dimensions of \(5 \times 5 \times 30\) nm\(^3\) with typical physical parameters for Py; a saturation magnetization of \(M_s = 1\) T, an exchange stiffness constant of \(A = 1.05 \times 10^{11}\) J/m, and a damping coefficient of \(\alpha = 0.01\).\(^{21}\) To determine the frequency dependence, we used a pulse field and the Fourier transform. At a specific external field, we applied a rectangular pulse field 10 ps in width and 5 Oe in amplitude, and then calculated the time evolution for 10 ns with time steps of 0.25 ps. According to the obtained time evolution, we calculated the Fourier transform and obtained the power spectrum of the magnetization oscillation amplitude for every direction in each cell. Using the power spectrum, we calculated the spin current as follows.

The Lamor precession of magnetization generates a spin current, and the spin current density is phenomenologically expressed as\(^{22}\)

\[
j_{x',y',z'} = \frac{h}{4\pi} g_{eff}^{(1)} |m_c| |m_y|, \tag{1}\]

where the subscripts \(x', y',\) and \(z'\) represent Cartesian coordinates; \(\omega\) is the angular frequency; \(h\) is the reduced Planck constant; \(g_{eff}^{(1)}\) is the real component of the effective mixing conductance, and \(|m_c| (|m_y|)\) is the absolute value of the \(x' (y')\) component of the normalized precession amplitude. The \(z'\)-axis is set along the precession axis.

\[g_{eff}^{(1)} = \frac{4\pi M_s d_{Py}}{g \cdot \mu_B} (\alpha_{Py} - \alpha_{Py}), \tag{2}\]

where \(g\), \(\mu_B\), \(M_s\), \(d_{Py}\), \(\alpha_{Py}\), and \(\alpha_{Py}\) are the g-factor, susceptibility, saturation magnetization, thickness of Py, damping constant of Py in the Py/Pt structure, and damping constant of Py alone, respectively. As shown in Eq. (2), \(g_{eff}^{(1)}\) is determined by only physical and dimensional parameters, which do not depend on the measurement scheme. Thus, we can treat \(g_{eff}^{(1)}\) as a constant and obtain the spin current density as

\[j_{x',y',z'} \propto \omega |m_c| |m_y|. \tag{3}\]

By substituting the spectrum of precession amplitude determined by the micromagnetic simulation for \(|m_c|\) and \(|m_y|\) in Eq. (3), we obtained the spectrum of the spin current density generated from each cell. Finally, by integrating the \(y\)-polarized component of the spin current density over the disk, we obtained the \(y\)-polarized component of the spin current \(I_{s,y}\), which is proportional to the dc voltage. To determine the external field dependence, this process was repeated with different external fields.

Figure 3(a) shows the \(I_{s,y}\) spectrum calculated using the aforementioned method. This spectrum well reproduces the experimentally observed \(V_{dc}\) spectrum shown in Fig. 2. However, there are discrepancies in the resonance frequency and line width between the simulation and the experiment. The difference of the resonance frequency is attributed to the reduced magnetization, as reported in Ref. 21. The experimentally obtained broad line width was caused by the damping enhancement due to the spin-pumping effect.\(^{1}\) If we treat the magnetic disk as a single macro spin, i.e., if we average the magnetization over the disk before applying the
Fourier transform, we obtain a completely different calculated spectrum that does not reproduce the experimental results. Thus, we must consider the spatial distribution of the spin dynamics in the disk.

The calculated $j_s$ distribution inside the disk is shown in Figs. 3(b) and 3(c), corresponding to the white circles at $(f, H) = (6.6 \text{ GHz}, 50 \text{ Oe})$ and $(5.6 \text{ GHz}, 50 \text{ Oe})$ in Fig. 3(a). In Fig. 3(b), we observe that spin dynamics are distributed throughout the disk, but the spin polarization of the spin current alternates between the left and right sides of the disk. The spin polarization of the integrated spin current is along the $+y$-direction, producing a positive dc voltage. However, in Fig. 3(c), the spin dynamics are induced mostly on the right side of the disk, generating a spin current with spin polarization along the $-y$-direction, resulting in a negative dc voltage. In this way, we determined the spin wave distribution by utilizing the amplitude of the output voltage due to spin pumping.

Importantly, these spin-pumping results were independent of the polarity and chirality. In our experiments, neither the polarity nor the chirality was controlled; they were random in each disk. However, neither the polarity nor the chirality contributed to the $V_{dc}$ arising from the spin pumping. The chirality represents the circumference-in-plane magnetization where most of the spin waves are distributed; thus, the chirality only contributed to the spatial inversion of the spin dynamics with respect to the disk center. The polarity contributed only to the mode splitting of the azimuthal modes $(n = 0, m = \pm 1)$.

Finally, we discuss the influence of the rectification voltage due to the anisotropic magnetoresistance (AMR) in the Py layer. To estimate the contribution of the AMR to the dc voltage, we prepared a control sample. Figure 4(a) shows the structure of the sample, where Pt was replaced with Cu$_{97}$Mn$_3$, which has a comparable resistivity to Pt and a negligible spin Hall angle compared with Pt. Figure 4(b) shows the $V_{dc}$ spectrum with respect to $f$ and $H$. The peak shape and sign completely differ from those in the case of Pt, which is shown in Fig. 2. Additionally, the peak amplitude is approximately five times smaller than that in the case of Pt. Therefore, we conclude that the dc voltage spectrum shown in Fig. 2 mainly arose from the spin pumping induced by the ISHE.

In summary, we demonstrated the electrical detection of the spin dynamics in an MV using the spin-pumping method. By measuring the transmission parameter ($\Sigma_2$), we confirmed that the MV structure appeared in a low-external field region in the Py disk structured on the Pt wire. In the low-field region, dc voltage signals were observed, and the sign of the dc voltage depended on the excited mode. Our analysis based on the micromagnetic simulation well reproduced the experimental results and indicated that the frequency-dependent sign change originates from the spin wave distribution. The spin pumping allows us to obtain information regarding the distribution of the spin dynamics in confined magnetic structures such as an FM disk.

Acknowledgments The authors thank S. Takizawa for the kind help with the Cu$_{97}$Mn$_3$ deposition. This work was partly supported by a Grant-in-Aid for Scientific Research on Innovative Areas “Nano Spin Conversion Science” (Grant No. 26103002), a Grant-in-Aid for JSPS Fellows, the RIKEN Junior Research Associate Program, and the CREST program of the Japan Science and Technology Agency (Grant No. JPMICR15Q5).