Spin Wave Propagation in a Permalloy Film under Tangentially Fields with an Arbitrary Direction

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Abstract

Spin wave propagation in a permalloy film under tangentially magnetic fields with an arbitrary direction was investigated. As the field changes from the magnetostatic surface spin wave configuration to the magnetostatic backward volume configuration, the spin wave resonant frequency decreases and the signal intensity also decreased. The angle dependence of the spin wave resonant frequency is in good agreement with the theoretical calculation using the dispersion relation from the expression of Damon and Eshbach.

1. Introduction

Spin wave propagation in ferromagnetic metals has attracted attention for novel spintronic devices such as signal transfer and signal processing. In particular, interference properties of the spin wave are hot topics for logic circuit applications in this research field [1-3]. Compared to the conventional radio frequency (rf) devices using yttrium iron garnet films, rf-devices using metal films are suitable for integration with a Si process, which is expected to be information transfer and logic operations using interference of spin waves. These challenges on the spin dynamics research grow a new research field of 'magnonics' [4, 5]. Spin wave propagation in ferromagnetic films has been investigated mainly on magnetostatic surface spin wave (MSSW). Recently, magnetostatic backward volume spin wave (MSBVW) was successfully observed using a thick permalloy (Py) film, which is the first MSBVW observation in a metal system [6]. These excited spin waves depend on the relationship between the tangentially magnetic field direction and propagation direction of the spin waves. For MSSW, the magnetization direction is perpendicular to the wave vector, while for MSBVW, the magnetization direction is parallel to the wave vector. There are, however, only a few reports between MSSW and MSBVW configurations. Lassale-Balier and Fermon reported the spin wave propagation using 45°-tilted antennas from the propagation direction to use spin wave interferometer [7]. In order to design various spin wave devices, the degree of freedom of the field direction is indispensable. In spin waves in Py films, the spin wave resonant frequency is easily determined by the antenna excitation/detection method, which is an advantage to investigate the magnetic field dependence of the resonant frequency. In this paper, we investigated spin wave propagation in Py films under tangentially fields with an arbitrary direction. The variations from MSSW to MSBVW are discussed.

2. Experimental procedures

Figure 1(a) shows the photograph of a sample. A Py film with a thickness of 300 nm and a width of 120 μm was prepared on a Si/SiO_2 substrate. After isolating with a SiO_2 film, a pair of coplanar waveguides (CPWs) for excitation and detection antennas was formed by depositing Ta/Au. The line width of the antenna was 3 μm for a signal line and 9 μm for a ground line, and their gap is 2 μm. Therefore, the main wave number of the excited spin wave is estimated to be 0.34 μm^{-1} [9]. The CPWs were of the signal-ground (SG) type and the distance between antennas were 10 μm. Spin wave transmission measurements were performed by a vector network analyzer (VNA) and a microprobe station with an electromagnet for applying

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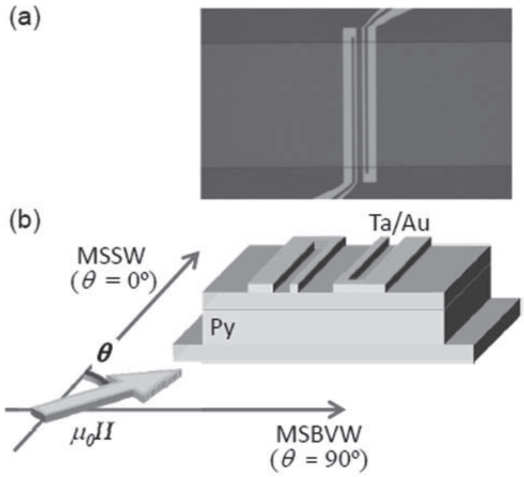

Figure 1 (a) Photograph of a typical sample. (b) Schematic illustration of a sample and definition of the external magnetic field angle to the antenna direction θ.

in-plane magnetic field at room temperature. The field direction is defined as shown in Fig. 1(b): the field angles to the antenna direction $\theta = 0°$ for the MSSW configuration, and $\theta = 90°$ for the MSBVW configuration. The spin wave spectra were measured every 15° between 0° from 90°. Two-port transmission measurement was used, and obtained S_{21} signals (transmission signal from port 1 to port 2) under a static magnetic field μ_0H were analyzed by subtracting the background signal obtained under high magnetic field of $\mu_0H = 300$ mT. Hereafter we called them ΔS_{21} as subtracted signals. All measurements were performed at room temperature.

3. Results and discussion

The variation of the spin wave spectra on θ under $\mu_0H =$ 80 mT is shown in Fig. 2. When $\theta = 0°$, the spectrum is for the MSSW configuration. Some resonant peaks correspond to the each spin wave mode reflected by the antenna shape. As increasing field angle θ, the spin wave resonant frequency decreases, and the spectra shape do not change very much up to $\theta = 45°$. The signal intensity also decreased with increasing θ. The intensity at $\theta = 45°$ become about 0.4 times of that at $\theta = 0°$, which is in good agreement with the previous report [7]. Generally, the amplitude of the MSBVW ($\theta = 90°$) is very low because excitation efficiency is low because the necessary field for excitation of MSBVW is generated at only a small area of the side of the antenna. Additionally since the group velocity is low, the spin wave is easy to decay before reaching the detection antenna. The θ dependence of amplitude is summarized in Fig. 3(a). We found that the amplitude drastically decreases

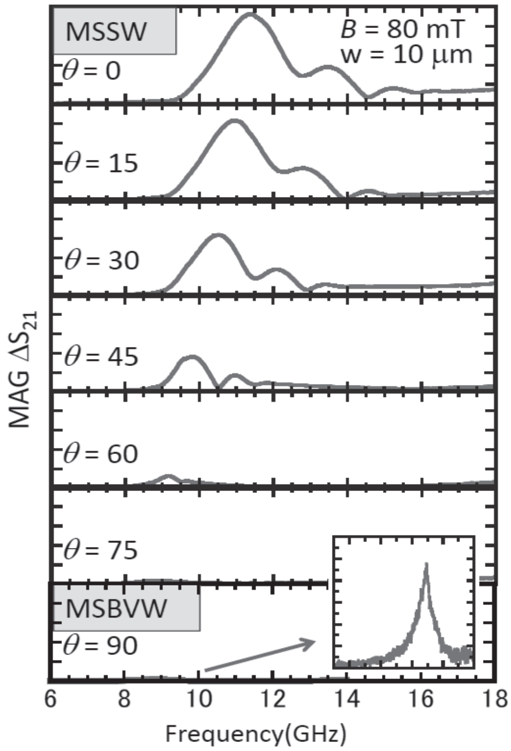

Figure 2 Variation of the spin wave spectra on the angle θ under $\mu_0H = 80$ mT. The distance between antennas is 10 μm. The spectra are shifted to lower frequency with increasing θ.

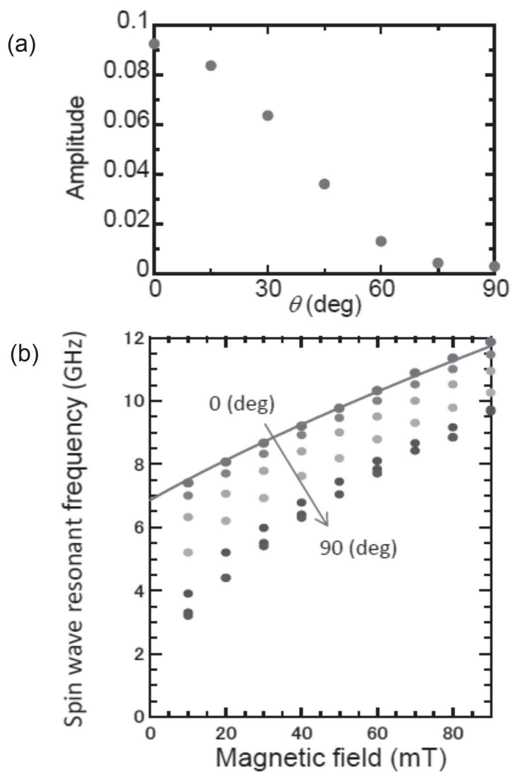

Figure 3 (a) The θ dependence of spin wave amplitude under $\mu_0H = 80$ mT. (b) Magnetic field dependence of the spin wave resonant frequency of the main peak at various θ. The solid line for $\theta = 0°$ is a fitting curve of the dispersion relation of MSSW.

more than θ = 30º, and it becomes about 1/30 at θ = 90º. Figure 3(b) is the magnetic field dependence of the spin wave resonant frequency of the main peak at various θ. The resonant frequency increases with increasing magnetic field regardless of the θ. The solid lines for θ = 0º are the fitting curves with the dispersion relation of the MSSW, using the parameters of saturation magnetization $M_S = 1.05$ T and $\gamma/2\pi = 29.7$ GHz/T, and the estimated wave vector k is 0.36 μm^{-1}. This is in good agreement with the wave number expected by the antenna shape (k = 0.34 μm^{-1}). The θ variation of the spin wave resonant frequency at μ_0H = 80 mT is shown in Fig. 4(a). The frequency changes like a cosine curve for θ. We defined the relationship between the magnetic field direction and wave vector as shown in Fig. 4(b), and the angle dependence of the resonant frequency was calculated. Following Ref. 8, the dispersion relation using wave vectors of k_x and k_z can be written as,

$$(k_x^2+k_z^2)+2\mu\sqrt{(k_x^2+k_z^2)}\cdot\sqrt{\left[-\left(k_x^2+\frac{k_z^2}{\mu}\right)\right]}\cdot\cot\sqrt{d\left[-\left(k_x^2+\frac{k_z^2}{\mu}\right)\right]}+\mu^2\left(k_x^2+\frac{k_z^2}{\mu}\right)-\mu_a^2k_x^2=0, \quad (1)$$

$$\mu=\frac{\omega_H\cdot(\omega_H+\omega_M)-\omega^2}{\omega_H^2-\omega^2},\ \mu_a=\frac{\omega_M\cdot\omega}{\omega_H^2-\omega^2} \quad (2)$$

where d is the film thickness, and μ and μ_a of Eq. (2) are the diagonal and off-diagonal components of the microwave permeability tensor with being, $\omega_M=\gamma\mu_0M_S$, $\omega_H=\gamma\mu_0H$, respectively. In order to see the angle dependence, equation (1) is rewritten to the function of θ using the definition of $k_x=k\cos\theta$, $k_z=k\sin\theta$, and the imaginary argument of the cot term is converted to the real quantities,

$$1+2\mu\cos\theta\sqrt{(1+\tan^2\theta/\mu)}\cdot\coth\left[kd\cos\theta\sqrt{(1+\tan^2\theta/\mu)}\right]+\mu^2\cos^2\theta(1+\tan^2\theta/\mu)-\mu_a^2\cos^2\theta=0 \quad (3)$$

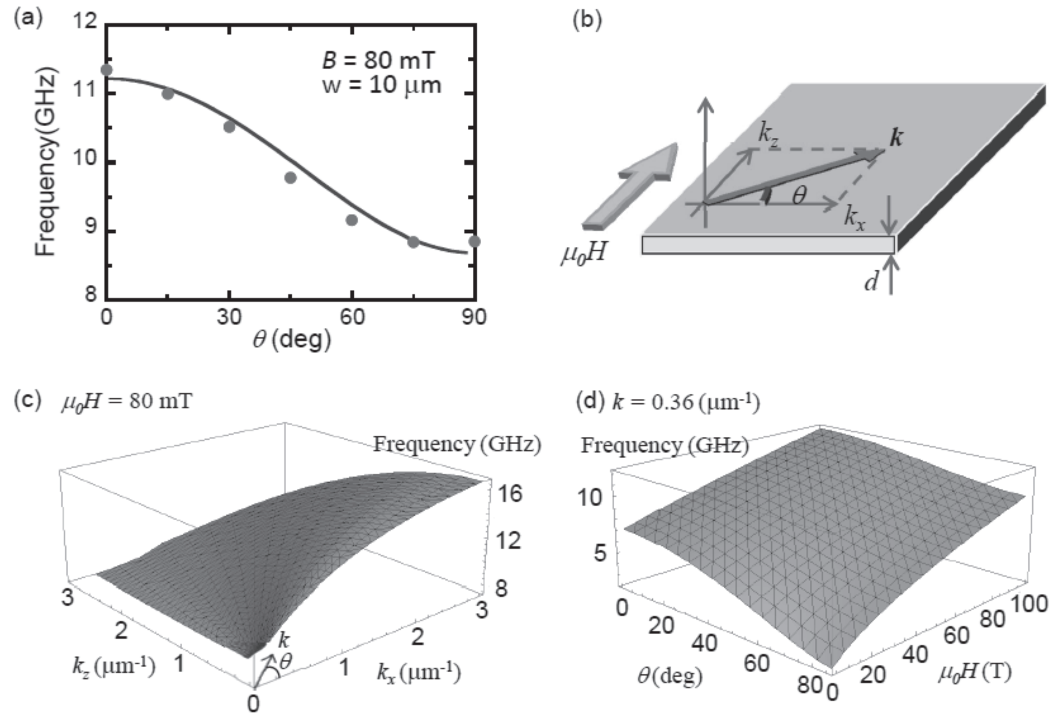

Figure 4 (a) The θ variation of the spin wave resonant frequency at μ_0H = 80 mT. (b) The relationship between the magnetic field direction and wave vector. (c) The surface of the spin wave resonant frequency in k_x and k_z-space for the external magnetic field of μ_0H = 80 mT. (d) The surface of the resonant frequency in θ and μ_0H space.

Numerically solution of the resonant frequency can be obtained by this equation. When $\theta = 0°$, this equation is reduced to the dispersion relation of usual MSSW. The solid line in Fig. 5(a) was the calculated resonant frequency as a function of θ, using the parameters of $k = 0.36\ \mu m^{-1}$ estimated by the experimental results of the MSSW configuration. The curve well explains the experimental results. We also calculated the surface of the spin wave resonant frequency in k_x and k_z-space for the external magnetic field of $\mu_0 H =$ 80 mT in Fig. 5(c). For the k_x direction, usual dispersion relation of MSSW can be seen. For the k_z direction, dispersion relation of MSBVW is obtained, where the frequency decreases with increasing k_z. In the case of the arbitrary θ, the dispersion relation gradually changes from the dispersion relations of the MSSW to that of MSBVW. Figure 5(d) is the surface of the resonant frequency in θ and $\mu_0 H$ space. The frequency decreases with increasing θ as mentioned above, and the frequency variation between $\theta = 0°$ and 90° becomes smaller as the high magnetic field. Thus, the tangential angle dependence of the spin wave was clearly observed, and it is well supported by the dispersion relation derived from the expression of Damon and Eshbach. These results will be useful to design the spin wave devices such as spin wave interferometers.

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