Spin wave modulation by topographical perturbation in $\text{Y}_3\text{Fe}_5\text{O}_{12}$ thin films

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Spin wave modulation by topographical perturbation in Y$_3$Fe$_5$O$_{12}$ thin films

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ABSTRACT
We present a comparison of the spin wave propagation in Au/Y$_3$Fe$_5$O$_{12}$ and Pt/Y$_3$Fe$_5$O$_{12}$ bilayers. Microwave technique with a co-planner waveguide arrangement was used to excite and detect the spin wave. We observed a suppression in the propagating spin wave intensity when a metal stripe is placed on the surface of Y$_3$Fe$_5$O$_{12}$ in the spin wave propagation path due to the spin pumping from Y$_3$Fe$_5$O$_{12}$ to nonmagnetic metal stripe. However, a significant difference in the suppression property was observed with the Au and Pt electrode layers, which cannot be explained by the enhancement of the damping constant induced by spin pumping alone. The significant suppression of the spin wave propagation in the Au/Y$_3$Fe$_5$O$_{12}$ bilayer system is attributed to the spin backflow and two magnon scattering.

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I. INTRODUCTION
A collection of magnetic moments precessing around their equilibrium axes can propagate through a magnetic material in the form of waves, which are known as spin waves (SW). SW offer data transmission capability without joule heating for post CMOS data processing. Moreover, in the case of SW, data can be encoded in both amplitude and phase, providing an additional degree of freedom compared with the electronic counterparts. Using the phase information of the SW, the interferometer-based devices such as magnetometer and SW majority gate have been reported. However, the data processing application requires an active control or modulation of the SW by the external fields similar to the gating mechanism of a conventional electronic transistor.

For active controlling of SW, one of the fewer reported methods employs laser light for gating purpose. However, the necessity of a bulky laser arrangement and difficulty in confining the laser light restrict its application on-chip device. Another approach has been reported to modulate the SW using electric current; however, it can eventually generate joule heating in the source inhibiting the advantage of SW.

To comply with the existing technology, the study of electric field modulation of SW is required. Although the coupling between the spin and the electric field is very weak, the electric field dependent phase modulation has been proposed. Another approach utilizes the electric field to produce mechanical effect such as piezoelectric effect. For such field dependent phenomena, the electrodes of gold (Au) and platinum (Pt) are often placed on SW media. However, the ferromagnetic (FM)/metal bilayer tends to absorb the propagating SW, and this behavior needs to be investigated. Recently, there has been an increased interest in the SW propagation in FM/FM and FM/NM bilayer structures; however, only a few reports discuss the relative comparison between various FM/NM bilayers.

In this study, we investigate the propagation of SW through Y$_3$Fe$_5$O$_{12}$ (YIG) thin films. Au and Pt stripes were placed on the propagation path of SW to investigate the suppression effect in Au/YIG and Pt/YIG bilayer structures. This study was performed to select an appropriate combination of electrodes for SW modulating field.
II. EXPERIMENT

For the sample preparation, 80 nm-thick YIG film was grown on a single crystalline (100)-oriented Gd$_3$Ga$_5$O$_{12}$ (GGG) substrate by the pulsed laser deposition (PLD) technique. During the growth, the substrate temperature, the oxygen pressure, and the pulse rate were maintained at 750°C, 0.1 Pa, and 5 Hz, respectively. After the growth, the sample was annealed at 800°C for 3 hours in air to improve the crystalline quality. The crystallinity of the YIG film was investigated by X-ray diffraction using a PANalytical Empyrean diffractometer in 2θ-θ mode as shown in Figure 1(a). The 2θ-θ scan displays the (100)-aligned peaks from YIG film and GGG substrate. The film peak is surrounded by the Laue oscillations (see the inset of Figure 1(a)), which is typical for a highly epitaxial film. The lattice constant of the YIG film was found to be 12.60 Å, which is larger than the reported bulk YIG lattice constant of 12.38 Å. The lattice expansion may be due to the non-stoichiometry of Fe and O sites. As shown in Figure 1(b), the atomic force microscopy (AFM) image of the YIG film demonstrates an excellent step terrace structure, revealing an atomically flat YIG surface. Figure 1(c) is the extended view of the step size along the blue line shown in Figure 1(b), which shows that the average height is approximately 1.3 nm, corresponding to the YIG lattice constant. The root mean square (RMS) roughness of the film was estimated to be 0.6 nm. Subsequently, two 100 nm-thick metallic co-planer waveguides (CPWs) were integrated on the YIG film by electron beam lithography and sputtering techniques. The metallic co-planer waveguides (CPWs) were integrated on the YIG (GGG) substrate.

III. RESULTS AND DISCUSSION

Firstly, we investigated the single layered SW device to confirm SW excitation and detection. Microwave probes from VNA were connected to CPWs. The RF current in CPW creates an oersted field around its signal wire, which excites the SW in the magnonic material. The SW propagates by transferring magnetic momentum to the nearest neighbors. The propagating SW creates a perturbation in the local magnetization, causing a change in the magnetic flux and inducing a voltage in the detecting CPW. In our experimental setup, a dc magnetic field is applied in the plane of the film but perpendicular to the direction of SW propagation to excite magnetostatic surface SW (MSSW). We obtained the FMR spectra for different bias fields ($\mu_0H_{ext}$) by measuring the scattering parameters. As an example, the real part of $\mathbf{S}$ at $\mu_0H_{ext}$ = 150 mT is shown in Figure 2(a). The clear dip in Re($\mathbf{S}$) indicates the ferromagnetic resonance. From the FWHM of the resonance spectra, we determined the effective Gilbert damping constant $\alpha$ = $\Delta f/\gamma f_{res}$, where $f_{res}$ is the resonance frequency. We measured the $\alpha$ from Re($\mathbf{S}$) at $\mu_0H_{ext}$ = 150 mT. The value of $\alpha$ is comparable with the PLD grown YIG films summarized in previous reports. $\text{Im}(\mathbf{S})$ is shown in Figure 2(b), which also exhibits a peak at similar resonance frequency. The $\mu_0H_{ext}$ dependence of the $f_{res}$ is plotted in Figure 2(c). As the $\mu_0H_{ext}$ is varied in the range of 7–125 mT, the $f_{res}$ shifts from 1.1 to 5.4 GHz. Fitting this data with Kittel equation $\Delta f = \gamma/2\pi \sqrt{H_{ext}(H_{ext} + 4\pi M_{eff})}$, we obtained $4\pi M_{eff}$ = 1760 G and $\gamma/2\pi$ = 28.08 GHz, and these values are comparable with the previously reported values in PLD grown YIG film.20 Figure 2(d), representing the Re($\mathbf{S}$) component shows the envelope-like oscillating SW signals with characteristics wave vectors $k_i(i=1,2,3,\ldots)$ at $\mu_0H_{ext}$ = 32 mT. In this work, along with detailed characterization. To confirm the spin pumping parameters including mixing conductance, standard ferromagnetic resonance measurements (JES-FA300, JEOL) is carried out for YIG single layer, and Pt/YIG, and Au/YIG bilayers.

![FIG. 1](image_url)

FIG. 1. (a) 2θ-θ scan for epitaxial YIG film on GGG (100) substrate, (b) AFM image of the YIG surface, and (c) extended image of the region indicated by the blue line in (b). Optical image of (d) the single layered (reference) SW device and (e) SW device with Pt or Au stripe in the SW propagation path.
The main mode ($k_1$), we observed six additional modes ($k_2$–$k_7$) in Re($S_{21}$). This multiple frequency modes can be attributed to the current distribution of the meandering CPW structures.\textsuperscript{26} The Im($S_{21}$) also displays an oscillating behavior, as shown in Figure 2(e). From Im($S_{21}$), we calculated the group velocity ($v_g$) using the following formula:

$$v_g = \Delta f \times l,$$

where $\Delta f$ is the frequency difference between two oscillating maxima in highest intensity mode of Im($S_{21}$).

We calculated the $v_g$ of the $k_1$ mode under the magnetic field of 7.8–125 mT, as shown in Figure 2(f). The highest $v_g$ of 5.08 km/s was observed for the lowest field and has been reduced gradually with higher field.

Further, we investigated the SW transmission properties of the Pt/YIG and Au/YIG bilayer devices, as depicted in Figure 1(e). Figures 3(a) shows the Re($S_{11}$) spectra of Pt and Au striped SW devices for $\mu_0 H_{ext}$ = 32 mT. As compared with the single layered device, the $S_{11}$ spectra of the Au (Pt) stripe SW device shows a decrease (increase) of 1.5 MHz (6.9 MHz) in the $f_{res}$, (Inset of

![FIG. 2. (a) Real and (b) imaginary parts of $S_{11}$ spectra of the reference SW device. (c) Applied bias field dependence of the resonance frequency. (d) Real and (e) imaginary parts of the $S_{21}$ spectra of the reference device. (f) Bias field dependence of the SW group velocity, $v_g$. Figure 3(a), (b), (d), and (e) were recorded at 32 mT bias field.](image-url)
Fig. 3(a) shows clear difference. The $f_{res}$ shift are due to the negative and positive susceptibilities of the diamagnetic Au and paramagnetic Pt, respectively, which can be explained by the following equation:

$$\chi = M + \chi_0 \cdot H,$$

where $\chi$, $M$, and $\chi_0$ are the susceptibility, net magnetization, and the spontaneous magnetization, respectively. The negative (positive) $\chi$ of Au (Pt) weakens (strengthens) the bias magnetic field and decrease (increase) the value of $M$. Since the magnetic susceptibility of Pt (192 cm$^{-1}$ mol$^{-1}$) is approximately 6.5 times larger than that of Au (−28.3 cm$^{-1}$ mol$^{-1}$), the shift in the $f_{res}$ can be attributed to this difference.

Figure 3(b) represents the $S_2$ for the Pt and Au striped devices with $d = 45 \mu$m. In the Pt-striped device (top block of Figure 3(b)), five envelope-like modes still exist with a minor reduction, whereas the Au striped device (bottom block of Figure 3(b)) exhibits only two of these modes with a significant reduction in the SW intensity. The signal suppression for $k_1$ and $k_2$ modes as a function of the Pt and Au stripe widths are summarized in Figure 3(c). Only 20% reduction of SW intensity was observed in the 85 μm-wide Pt stripe in $k_1$ mode, whereas greater than 50% reduction was observed in the Au stripe of the same width. In the $k_2$ mode, an additional signal loss of nearly 50% was observed in the Au striped device than the Pt striped device. The other modes are completely disappeared in the case of Au striped device.

In previous report, the suppression behaviors are mostly attributed by spin pumping (SP). However, the difference in the suppression behavior in our Au/YIG and Pt/YIG bilayer SW devices cannot be explained in the similar manner. According to the previous spin current injection model, Pt/FM bilayer shows higher $\alpha$ than that of the Au/FM bilayer. According to this, the Pt/YIG bilayer should have a higher suppression than the Au/YIG bilayer; however, the scenario is opposite in our case. Hence, we explain the difference in the SW suppression using the non-adiabatic SP model in FM/NM bilayer and the two-magnon scattering (TMS). The spin precession in YIG layer injects the spin current in the NM layer adjacent to the surface. Depending on the spin flipping capability of the NM layer, the injected spin current either relaxes in the NM layer or scatters back to the YIG layer. Since Pt has $d$-electron in the conduction band and possess a large spin-orbit coupling $\epsilon \geq 10^{-4}$, it can act as a perfect spin sink. For confirming the spin injection in Pt layer, we have performed the ESR measurements as shown in Figure 3(d) and calculated the spin mixing conductance ($g_{11}$) for Pt/YIG and Au/YIG bilayer. For this purpose, we have used similar YIG film with 10 nm-thick Pt and Au film. The $g_{11}$ is experimentally evaluated by comparing the FMR linewidth of bare YIG film ($\Delta H_{YIG}$), Pt/YIG ($\Delta H_{Pt/YIG}$), and Au/YIG ($\Delta H_{Au/YIG}$) bilayer respectively. The $g_{11}$ for Pt/YIG layer is given by:

$$g_{11} = \frac{4\pi M_y YIG}{g_{B} B_{0} \omega} \left( \Delta H_{Pt/YIG} - \Delta H_{YIG} \right)$$

where $g$, $\mu_B$ and $\omega$ are Lande factor with value 2, Bohr magneton and microwave angular frequency, respectively. From the equation (3), we obtained $g_{11} = 2.2 \times 10^{15}$ m$^{-2}$, which is in the range of the previous report. Sufficiently high $g_{11}$ indicates the efficient SP through well-ordered Pt/YIG interface. However, owing to large spin flipping capability of Pt, the spin current injected in the Pt-layer gets relaxed inside it. As a result, the additional magnetic damping is introduced in the YIG layer, causing a minor reduction in SW intensity. According to previous report, for sufficiently thick YIG film ($\geq 20$nm) the interfacial effect or TMS is quite negligible. On the other hand, Au...
possesses the conduction electrons in its s-orbital and exhibits a relatively small spin-orbit coupling $\epsilon \geq 10^{-2}$ with a weak spin flipping capability.\textsuperscript{19} According to our FMR measurement, Au/YIG bilayer does not show any linewidth broadening (minor linewidth sharpening is observed due to error bar). Therefore, it does not have any SP and cannot act as a spin sink. As a result, the spin accumulation at the Au/YIG interface occurs, which induces a spin backflow into the YIG layer. The backflow interferes with the propagating SW by the TMS, which strongly suppresses the SW propagation in the Au/YIG bilayer. Previously reported micromagnetic simulations for Au/YIG bilayer also suggest strong absorption of the SW.\textsuperscript{26}

The metallic layers are used as the control electrodes in SW devices. These electrodes are often placed in the SW propagation path. Therefore, it is crucial to select the layer elements that do not impact the SW propagation significantly. Based on our study, Pt is a better candidate for an electrode than Au. Other heavy metals with similar electronic configuration such as Pd may also be a good choice for this purpose. Conversely, metals with similar electron configuration as Au, such as Ag, Al or Cu, will also suppress the SW significantly; therefore, such materials may not be suitable for the control electrode.

IV. SUMMARY

We fabricated CPW based SW devices using a ferrimagnetic YIG thin films with low damping constant. The SW suppression behavior of the Au/YIG and Pt/YIG SW devices was investigated and compared with a single layered YIG device. First, we confirmed the SW propagation in the reference device. For this purpose, we measured the field dependent $S_1$ parameter and fitted its shifting with Kittel equation. Total seven envelope-like transmission modes ($k_1$–$k_7$) were observed in Re($S_1$) at $\mu_0H_{\text{ext}} = 32$ mT. Moreover, the field-dependent group velocities were observed to be reduced gradually with higher field. Additionally, we investigated the transmission behavior of the Au/YIG and Pt/YIG bilayer devices. We varied the width of the Pt and Au stripe in the steps of 15, 25, 45 and 85 $\mu$m. For the 85 $\mu$m-wide stripe, we observed approximately 50% intensity suppression of the $k_1$ mode in Au, whereas only 20% in Pt. Moreover, Pt showed only 30% suppression for the $k_2$ mode, whereas it was observed to be nearly 80% for Au. The significance suppression of SW propagation in the Au/YIG bilayer system is attributed to the spin backflow and TMS.

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