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Stability of standing spin wave in permalloy thin film studied by anisotropic magnetoresistance effect

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We have investigated the stability for the resonant spin precession under the strong microwave magnetic field by a specially developed detection method using the anisotropic magnetoresistance effect. The electrically separated excitation and detection circuits enable us to investigate the influence of the heating effect and the nonuniform spin dynamics independently. The large detecting current is found to induce the field shift of the resonant spectra because of the Joule heating. From the microwave power dependence, we found that the linear response regime for the standing spin wave is larger than that for the ferromagnetic resonance. This robust characteristic of the standing spin wave is an important advantage for the high power operation of the spin-wave device. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4937918]

I. INTRODUCTION

Dynamic detection and manipulation of the magnetization properties in a metallic ferromagnetic film have grown rapidly with the development of the physics on spin dynamics.[1–3] Especially, the spatially modulated spin configuration stabilized in the patterned ferromagnetic nanostructures is known to excite the non-uniform coherent spin precession with a spatial periodical modulation, namely, spin wave.[4–7] Owing to its fast time scale in GHz range and high compatibility with a Si-based semiconductor integrated circuits, the spin waves in ferromagnetic thin films are expected to have various potential applications in future telecommunication devices, such as a microwave filter,[8–10] oscillator,[11–13] and fast spin-information transportation.[14,15] In addition, the development of high-performance spin-based telecommunication devices also makes an innovation in military and security applications. Moreover, the fundamental material parameters in ferromagnet, such as the spin polarization and the damping constant, can be deduced from the characteristics of the spin wave propagation.[16] Therefore, the dynamical property of the spin wave and the exploration of their precise manipulation techniques may create important milestones both from fundamental and technological viewpoints.[17] Especially, for seeking the further possibility of spin-based electronic devices, understanding the thermal stability and the non-linear response induced by the large amplitude RF magnetic field are indispensable.

The spin dynamics for the uniform magnetization, namely, ferromagnetic resonance (FMR) has been intensively investigated in nonlinear regime.[18–22] However, the nonlinear dynamics for the spin wave are also important for developing aforementioned telecommunication devices. So far, the spin waves are mainly controlled by using geometrically induced magneto-static interaction.[1,23,24] However, the tunability for such systems is not so high because the modulation magnitude is fixed by their shapes. Instead of the direct patterning of the ferromagnetic film, a patterned periodical electrode is known as an alternative method for controlling the spatial distribution of the spins in a ferromagnetic thin film.[8,10,25] Recent developments for the nano-fabrication techniques made it possible to prepare well-defined patterned electrode with high accuracy. In this method, we can adjust the modulation magnitude and phase. Moreover, since one does not need to consider the deterioration of the ferromagnet during the nano patterning and non-uniformity due to the edge roughness and oxidation, the magnetic properties as high as the bulk values will be expected. The impedance transmission measurements based on the vector network analyzer have been mainly used for characterizing these systems. However, the detectable spin waves are limited by the electrode design because the inter-linkage magnetic flux is canceled out. Moreover, the input power is restricted by the output power of the network analyzer. Here, we demonstrate a sensitive detection method for the spin wave excited by the patterned electrodes. Electrically separated excitation and detection circuits enable us to detect the standing spin waves for various wave lengths sensitively and to investigate their stabilities against the heating and large microwave magnetic field.

II. EXPERIMENT

Our spin-wave device consists of a 40-nm-thick ferromagnetic Permalloy (Py) film and the 200-nm-thick ladder-type nonmagnetic Cu electrode, which are electrically separated by a 100-nm-thick SiO_2 sputtered film. A schematic illustration

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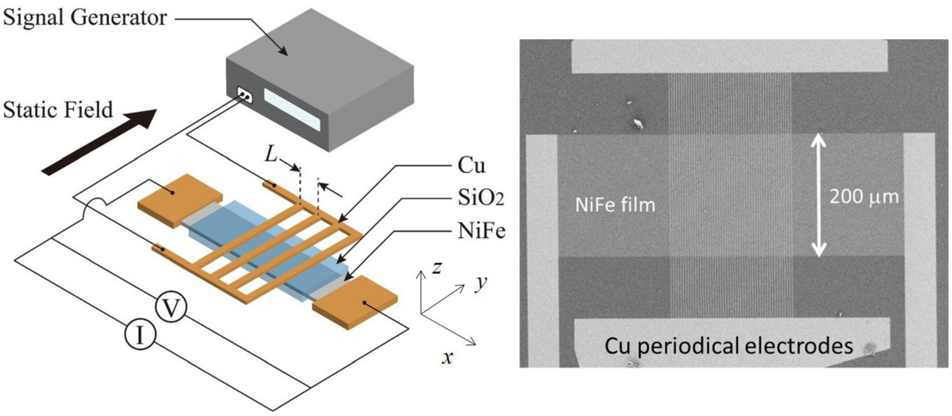

FIG. 1. Schematic illustration of the fabricated spin wave device together with the circuit diagram for the spin-wave excitation and detection and scanning electron microscope image of the representative fabricated device.

for the fabricated device together with a scanning electron microscope (SEM) image of the representative device is shown in Fig. 1. The Py film is grown by a magnetron sputtering at the base pressure of 2×10^{-8} Torr on a conventional Si substrate. Here, the pressure during the sputtering is 2 mTorr, and the deposition rate is 2 nm/s. The Cu narrow wires, 200 nm in width, were fabricated by a conventional lift-off technique with an electron-beam lithography. The center-center interval L between the Cu wires is 8 μm. The width and length for the Py film are 200 μm and 600 μm, respectively. The periodical electrodes were put on the middle part of the Py film (200 micron). The external magnetic field is applied along the Cu wire direction (y direction) in order to fix the precession axis of the magnetizations. The magneto-static surface spin waves (MSSWs) propagating perpendicular to the magnetization were generated by flowing a high frequency ac current with 7 GHz in the nonmagnetic ladder-type electrodes and were detected by monitoring the resistance of the Py film through the AMR. Here, to improve the signal/noise ratio of the detected voltage, we adapt the pulse modulated RF current with the lock-in detection technique.[26,27]

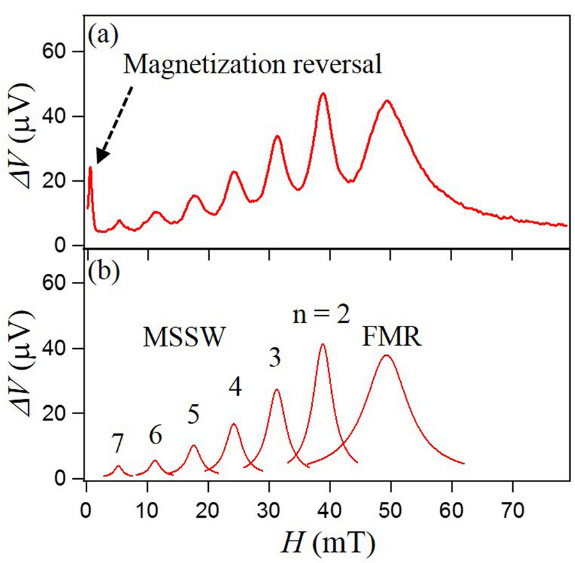

FIG. 2. (a) Field dependence of the resistance for Py film under the microwave magnetic field with the magnitude of 10 mW. (b) Numerical curve reproduced by superimposing several Lorentzian curves with different resonant magnetic fields.

III. RESULTS AND DISCUSSIONS

Figure 2(a) shows the representative result for the field dependence of the voltage induced in the Py film under the RF magnetic field with the power of 10 mW. Here, the DC current for the measurement is 60 mA. The induced voltage clearly exhibits the resonant features consisting of the multiple peaks. We found that each voltage peak is reproduced by several Lorentzian curves with different resonant magnetic field, as shown in Fig. 2(b). To explore the origin of the resonant-like features, we fitted the resonant magnetic fields to the dispersion relationship for the MSSW given by the following equation:[5]

$$f_{\mathrm{MSSW}} = \frac{\gamma}{2\pi}\sqrt{H_0(H_0 + 4\pi M_{\mathrm{S}}) + 4\pi^2 M_{\mathrm{S}}^2(1 - e^{4\pi t/\lambda})}. \quad (1)$$

Here, γ is the gyromagnetic ratio given by 18.4 MHz/Oe, Ms is the saturation magnetization $4\pi Ms = 9.8$ kOe. t and λ are the thickness for the ferromagnetic film and the wavelength, respectively. As shown in Fig. 3(a), the resonant magnetic fields are well explained by the MSSW along the x-axis with assuming that the half wave length of the standing spin wave is given by the fraction of the integer number of the electrode spacing L and the ferromagnetic resonance with the infinite wave length. This means that the present method is more sensitive to the previously developed method based on vector network analyzer because the previous method only can detect the standing spin wave whose wave length is the

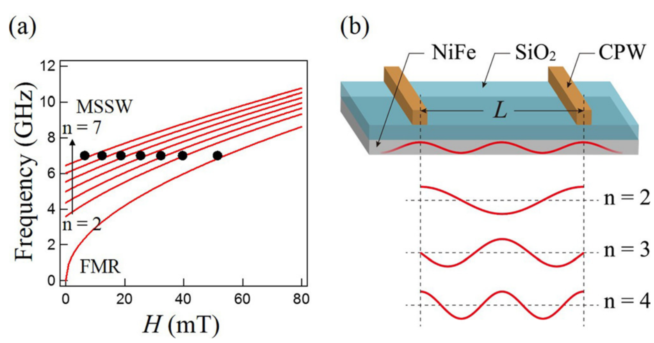

FIG. 3. (a) Theoretical dispersion relationship between the FMR and MSSW frequencies and the external magnetic field together with the experimentally obtained values (Solid circle). Here, we assume $\lambda = 2L/n$. (b) Schematic illustration of standing spin waves with the different n stabilized by periodical Cu electrodes.

fraction of the integer number of the electrode spacing L.[10] We may have to consider the standing spin wave perpendicular to the film place (along z-axis). However, it is difficult to induce such a spin wave by the present frequency range because of its short wave length. The shape of the spectra seems to be broader than those in the vector network analyzer measurements. This is because the signal comes from the whole sample in the present measurement while the signal in the network analyzer measurement mainly comes from the surface of the ferromagnetic film. Since the magnitude of the ac magnetic field induced by present excitation method gradually decreases with increasing z because of the thin SiO_2 thickness, the spin precession perpendicular to the film plane (along z-axis) becomes inhomogeneous. As a result, the spectra obtained from the resistance measurement become broad compared with that by the network analyzer.

Here, we discuss the reason why the present method can induce and detect the standing spin wave with $\lambda/2 = L/n$. Since the methods for exciting the spin wave in both experiments are same, the difference should be caused by the detection scheme. As shown in Fig. 3(b), the standing spin waves for $n = 2$ or other even numbers can be imaged by assuming that the anti-node of the wave is located underneath the electrode. These spin waves can be reproduced by superimposing the wave given by $\cos(kx + \omega t)$ and that given by $\cos(k(x - L) - \omega t)$ with the condition $kL = 2\pi m$, where m is the integer. In these spin waves, the time derivative of the magnetic flux underneath the electrode should be large, leading to the RF voltage generation in the Cu electrode.[3] In the case for $n = 3$ or other odd numbers, the standing wave with the node underneath the electrode satisfies such a condition. This kind of spin wave can be reproduced by superimposing the wave $\cos(kx + \omega t)$ and that given by $\cos(k(x - L) - \omega t)$ with the condition $kL = \pi(2m + 1)$, where m is the integer. In this situation, the magnetic flux around the electrode is always zero, leading to no voltage drop in the Cu electrode. Therefore, the vector network analyzer measurement can detect the standing spin wave with odd numbers but cannot detect that with even numbers.[10] On the other hand, in the present method using the anisotropic magnetoresistance, the signal is not related to the local structure of the spin wave but to the averaged angle of the spins in a whole sample. Therefore, the standing spin waves stabilized in the film are effectively detected. Here, we emphasize that the resonant precessions for the FMR and MSSW occur in the different regions of the Py film. For the FMR, the resonantly precessional motion is excited underneath the Cu electrode while the standing spin wave is formed in the region between the electrodes. This indicates that the total volume for the spin wave becomes much larger than that for the FMR. Indeed, the resistance change due to the MSSW excitation is much larger than the FMR. However, the difference of the resistance change is not so large. This is because the average precession angle for the spin wave is smaller than that for the FMR. We also note that the resistance change due to the spin wave excitation decreases with decreasing the wave length. This is because the average angle decreases with decreasing the wave length due to the increase of the exchange energy. Similar tendency is expected by changing the electrode spacing. However, since the decoherence of the spin wave increases with increasing the electrode spacing, the resistance change also decreases with increasing the electrode spacing. The systematic study on the electrode spacing dependence may provide the dynamical information about the spin wave propagation.

We then investigate the dc dependences of the resonant features. Figure 4(a) shows the resistance spectra of the same device for various dc. The minimum current was 50 mA because the signal-to-noise ratio in the spectra becomes worse below 50 mA. The measurement with smaller current can be performed by further optimization of the sample structure, such as increasing the length or decreasing the thickness of the Py film. In the measurements, the shape of the spectra does not show significant change. However, the resonant fields for the FMR and standing spin waves were found to increase with increasing the bias current. According to Eq. (1), we naively expect that the increase of the resonant fields is related to the modification of the saturation magnetization because it seems to be difficult to change other parameters, such as the wave length, by the dc current. Figure 4(b) shows the dc dependence of the saturation magnetization estimated from Eq. (1). It should be noted that the saturation magnetizations estimated from the standing MSSW for various wave number ($n \geq 1$) show almost same current dependence although that for the FMR shows different signature. The saturation magnetization estimated from MSSW shows a small reduction when the current increases. Since the reduction of the saturation magnetization is caused by elevating the temperature of the ferromagnetic thin film, the observed reduction can be understood by the Joule heating of the detecting dc. Regarding the large difference in the saturation magnetization estimated from FMR, it should be noted that the value is estimated by assuming the uniform precession, meaning infinite wave length. However, in realistic situation, the precession area is only restricted underneath the electrode. Therefore, the saturation magnetization in the FMR was overestimated. The relatively large current dependence in the FMR is also related to the inhomogeneous precession. Since the FMR condition in the pattered

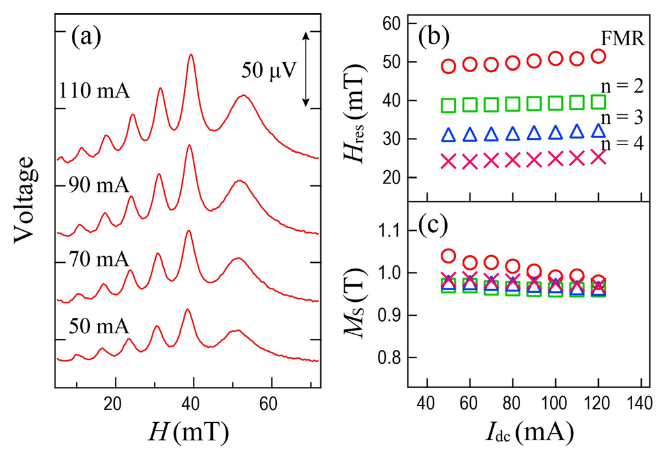

FIG. 4. (a) Voltage spectra for various DC. (b) Resonant fields for FMR and MSSWs as a function of the DC. (c) Saturation magnetizations estimated from the experimental results with Eq. (1) as a function of the dc.

structure is affected by the demagnetizing fields, the dependence of the saturation magnetization becomes large. It also should be noted that we did not see any influence of the spin transfer torque because of the insufficient current density $\sim 10^{10}$ A/cm^2

Finally, we investigate the microwave-power dependence of the resonant properties. Figure 5(a) shows the resistance spectra for various microwave powers. We summarize the resonant field and its relative values as a function of the microwave power in Figs. 5(b) and 5(c), respectively. When the microwave power is smaller than 10 mW, the resonant fields for the FMR and MSSW show a small reduction without significant changes in the resonant properties. However, when the microwave power exceeds 32 mW (15 dBm), the resonant magnetic field for the FMR significantly reduces. Here, it should be noted that the resonant fields for the standing spin waves do not show any large change even the power over 32 mW. These features cannot be explained by the simple heating effect discussed earlier and indicate that, under the high microwave power, the standing spin wave is more stable than the FMR. At the moment, the reason for the poor stability of the FMR is not clear. However, we should be aware of the difference in the excitation regions between the FMR and the standing spin wave. So, one of the possible reasons for the poor power tolerance for the FMR is related to the inhomogeneous excitation of the spin precession. When the large spin precession is locally excited underneath the Cu electrode, the in-plane stray field is induced by the magnetic charge at the border of the electrode. Such a situation may assist the transformation of the spin excitation mode from the FMR into the spin wave with a long wave length, giving rise to the significant reduction of the peak magnetic field for the FMR. Regarding the small reduction of the resonant field for the standing spin wave observed in Figs. 5(b) and 5(c), we may have to take into account the non-sinusoidal distribution of the RF magnetic field. Especially, around the central area of the electrode, the constant magnetic field around the center of electrode significantly prevents to stabilize the standing spin wave in the center of the Cu electrode as shown in Fig. 3(b). As a result, the wave length for the standing spin wave decreases. From Eq. (1), the reduction of the resonant magnetic field can be understood by decreasing the wave length of the standing spin wave.

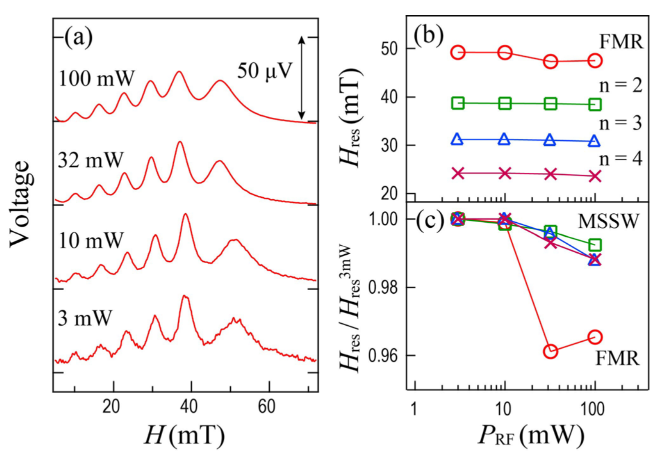

FIG. 5. (a) Voltage spectra for various input microwave powers. (b) Resonant fields for FMR and MSSWs as a function of the microwave power. (c) Relative change of the resonant magnetic fields for FMR and MSSW as a function of input microwave power.

IV. CONCLUSION

We have developed a method for detecting the standing spin wave using electrically separated excitation and detection circuits. By changing the detecting dc and the exciting RF current independently, we investigated the stability of the resonant spin precession. The influence of the detecting current is simply understood by the reduction of the saturation magnetization due to the Joule heating. The microwave-power dependence indicates that the standing spin wave has a superior stability for the strong RF magnetic field compared with the ferromagnetic resonance because the wave length of the spin wave is protected by the patterned electrode. This robust property for the standing spin wave is an advantage for the spin wave application with the high power operation.

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