

Perpendicular magnetization in sputtered YIG thin films for spin wave propagation and spin-orbit torque switching

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ABSTRACT

Yttrium iron garnet (YIG) is known for its extremely low magnetic damping, making it a key material for magnon-based spintronic devices. Although perpendicular magnetic anisotropy (PMA) has been reported in rare-earth-substituted or Bi-doped YIG thin films, its realization in pure YIG remains limited. In this work, we demonstrated the YIG thin films grown on the substituted gadolinium gallium garnet substrates that exhibit PMA and a low damping constant. X-ray diffraction measurements revealed an in-plane tensile strain relative to bulk YIG, suggesting that the strain-induced lattice distortion plays an important role in the emergence of PMA. Spin wave propagation with forward volume configuration was investigated using two separated coplanar waveguides and network analyzer. The measured propagating spin wave spectra show a coherent propagation over several micrometers with a group velocity of approximately 0.2 km/s. Furthermore, in a heterostructure with a heavy metal layer of Pt, current-induced spin-orbit torque successfully switches the perpendicular magnetization. These results establish sputter-deposited YIG thin films with perpendicular magnetization as a promising platform for studying low-damping spin-wave transport and current-driven magnetization dynamics.

I. INTRODUCTION

Yttrium iron garnet (YIG) has long served as a cornerstone material in magnonics owing to its exceptionally low magnetic damping and its ability to support long-distance spin-wave propagation[1]. These characteristics have enabled diverse advancements in magnon-based information transport, logic functionalities, and magnon–spintronic devices[2–4]. However, most YIG thin films used to date possess in-plane magnetization[5–9], which limits the accessible spin-wave modes and constrains device architectures that require perpendicular magnetization. Realizing perpendicular magnetic anisotropy (PMA) in YIG is therefore essential for expanding the degrees of freedom in spintronics / magnonics applications and enabling devices based on spin-orbit-torque- (SOT) induced magnetization dynamics, e.g. magnetization switching and the fast motion of magnetic textures, and out-of-plane spin-wave configuration[10–21].

Previous efforts to induce PMA in garnet systems have primarily relied on chemical substitution with elements such as Bi, Dy, Tm or Tb to engineer the strain between the substrates and garnet thin films[10,16,21–26]. While these strategies can produce PMA, chemically substituted garnets often introduce undesirable side effects such as increased magnetic damping or structural complexity, making them less suitable for applications requiring low-loss spin-wave transport. In contrast, achieving PMA in *pure* YIG without compositional modification remains a significant challenge.

Strain engineering has recently emerged as a promising route to tailor magnetic anisotropy by exploiting substrate-induced lattice distortions. Gadolinium gallium garnet (GGG) is widely used as a substrate for the growth of YIG thin films due to its close lattice constant with YIG, resulting in a lattice mismatch of only 0.06%. As a result, YIG films grown on GGG typically exhibit in-plane magnetization. In contrast, PMA has been reported in YIG films grown on substrates with larger lattice mismatch, such as quartz[27], Si[28], and other garnet substrates[13,18,29–35], where strain-induced magnetoelastic effect can lead to PMA. In particular, substituted gadolinium gallium garnet (SGGG) substrate, which has a larger lattice constant than YIG, enables the realization of perpendicularly magnetized YIG thin films without sacrificing their intrinsically low magnetic damping[33]. Meanwhile, sputtering provides a scalable and industry-compatible method for producing YIG thin films, and recent progress has shown that sputtered YIG can achieve damping parameters approaching those of films grown by pulsed laser deposition or liquid-phase epitaxy[31,32,36–38].

In this work, we demonstrate that sputter-deposited YIG thin films grown on SGGG substrates exhibit PMA together with a low damping constant below 1×10^{-3} . Structural analysis via X-ray diffraction reveals the presence of in-plane strain relative to bulk YIG, indicating that strain-induced lattice distortion plays an important role in the emergence of PMA. We show that these perpendicularly magnetized YIG films support coherent spin-wave

propagation over micrometer distances in the forward-volume configuration. Furthermore, by integrating a Pt layer, we demonstrate that current-induced SOT can switch the perpendicular magnetization, establishing perpendicularly magnetized YIG as a promising platform for SOT-driven control in insulating magnets.

II. FILM GROWTH AND CHARACTERIZATION

Single-crystal (111)-oriented $(\text{GdCa})_3(\text{GaMgZr})_5\text{O}_{12}$ (SGGG) substrates were used for YIG film growth. The lattice constant of SGGG substrate is $a_{\text{SGGG}} = 1.2504$ nm, which is slightly larger than that of bulk YIG $a_{\text{YIG}} = 1.2376$ nm, resulting in the lattice mismatch ratio $(a_{\text{SGGG}} - a_{\text{YIG}})/a_{\text{YIG}} = 1.03\%$. A commercial YIG target was used to fabricate the YIG thin films by a radio-frequency magnetron sputtering system. The deposition process was carried out at room temperature with an argon pressure of 0.07 Pa. The sputtering power and time was 200 W and 1 hour, respectively. After the deposition, the samples were annealed in air at various temperatures between 550 °C and 800 °C for 1 hour. Figure 1(a) shows the X-ray reflectivity of the YIG thin films after annealing. From the oscillation period, the film thickness was determined to be 28-29 nm for all samples, indicating that the annealing temperature does not affect the film thickness.

Figure 1(b) presents the out-of-plane X-ray diffraction patterns measured around the (444) diffraction. For the sample annealed at 550 °C, no discernible YIG (444) peak is observed. This indicates that the film remains predominantly amorphous at this annealing temperature. Once the annealing temperature exceeds 600 °C, a clear YIG (444) peak emerges, and pronounced Laue oscillations appear. Moreover, the YIG (444) peaks are located at higher diffraction angles than the bulk YIG (444) peak and shift further toward higher angles as the annealing temperature increases, indicating an increase of out-of-plane lattice compression in YIG thin films. To further evaluate the crystallinity of the YIG films, reciprocal space maps around (486) diffraction were measured. From Fig. 1(c), for all samples annealed above 600 °C, the in-plane reciprocal-lattice coordinate of the YIG peak coincides with that of the SGGG substrate. This observation implies that the lattice mismatch between the YIG film and the SGGG substrate is accommodated predominantly as an in-plane tensile strain imposed on the YIG thin films. Such strain-induced magnetoelastic anisotropy is expected to contribute to the emergence of PMA in the YIG thin films, as discussed later. In addition, the out-of-plane reciprocal-lattice coordinate shifts to higher values compared with bulk YIG, corresponding to a reduced out-of-plane lattice constant. This shift increases with increasing annealing temperature, consistent with the results shown in Fig. 1(b). The out-of-plane lattice shrinkage, especially for the films annealed at high temperatures may originate from the formation of point defects and dislocations in the YIG lattices, which possibly influence the magnetic properties.

To characterize the static magnetic properties of YIG films, magnetic hysteresis loops under the out-of-plane magnetic field are measured as shown in Fig. 2(a). Except for the sample annealed at 550 °C, finite remanent magnetization was observed in all samples, indicating that the magnetic easy axis is oriented perpendicular to the film plane. The sample annealed at 650 °C shows the largest saturation magnetization M_s , while the M_s values at higher annealing temperatures decrease slightly, as shown in Fig. 2(b). From Fig. 2(c), the coercive field H_c monotonically increases with annealing temperature. However, the hysteresis loops become less square for annealing temperatures of 750 °C and above. This degradation of loop squareness indicates increased dispersion in magnetic domain nucleation at high annealing temperatures.

To further examine the dynamic magnetic properties of the perpendicular YIG films, we measured field-modulated magnetic resonance spectra under the out-of-plane magnetic field. The sample for the measurement was placed on a coplanar waveguide, and an rf diode and lock-in amplifier were used for the measurements. The microwave transmission signals were recorded by sweeping the magnetic field while fixing the microwave frequency. Figure 3(a) shows the ferromagnetic resonance (FMR) spectra measured at 16 GHz for YIG films annealed at different temperatures. The resonance peak shifts to lower fields as the annealing temperature increases up to 750 °C, reflecting the enhancement of PMA, and moves to higher fields once the annealing temperature exceeds 800 °C. The linewidth, on the other hand, increases monotonically with annealing temperature. To obtain the resonance field H_{res} and half-width-at-half-maximum FMR linewidth ΔH , the measured signal is fitted with the derivative of the sum of symmetric and antisymmetric Lorentzian function. Figures 3(b) and 3(c) summarize the extracted parameters as a function of microwave frequency for the sample with different annealing temperatures. The solid lines in Figs. 3(b) and 3(c) are the fits to

$$f = \frac{\mu_0 \mu_B g}{2\pi \hbar} (H_{\text{res}} + H_k^{\text{eff}}), \quad (1)$$

$$\Delta H = \Delta H_0 + \frac{2\pi \hbar}{\mu_0 \mu_B g} \alpha f, \quad (2)$$

respectively, where μ_0 , μ_B , and $\hbar$ are the vacuum permeability, Bohr magneton constant, and reduced Planck constant, and we obtained the Landé g-factor g , effective PMA field H_k^{eff} , Gilbert damping constant α and inhomogeneous broadening ΔH_0 as a function of annealing temperature, as shown in Figs. 3(d) – 3(g). The Landé g-factor shows no clear dependence on annealing temperature and remains nearly constant across all samples. In contrast, H_k^{eff} increases with annealing temperature up to 750 °C. However, H_k^{eff} is reduced for the sample annealed at 800 °C, likely due to structural degradation at elevated annealing temperatures. While the ΔH_0 increases monotonically with annealing temperature, the lowest α was obtained for the sample annealed at 650 °C, with $\alpha = 9.8 \times 10^{-4}$. Although the obtained damping constant is larger than

the extremely low values reported for optimized YIG films grown on GGG substrate (on the order of 10^{-4} or lower) [39], it remains sufficiently small to support coherent spin wave propagation over micrometer distances, as described below.

Combining the magnetometry and magnetic resonance results, we conclude that annealing at 650 °C provides the optimal condition in terms of overall magnetic performance, as it simultaneously yields the highest saturation magnetization, the sharp magnetization switching, the lowest damping constant, and small inhomogeneous broadening. This annealing condition therefore provides the optimal balance between crystallinity, strain, and magnetic uniformity in sputter-deposited YIG thin films with perpendicular magnetization.

III. SPIN WAVE PROPAGATION

Perpendicularly magnetized systems enable the realization of forward-volume spin-wave (FVSW) mode, which propagates isotropically in the film plane and intrinsically preserve reciprocity. Therefore, this mode is an attractive platform for the development of scalable magnonics circuits.

Motivated by the successful realization of low-damping perpendicularly magnetized YIG films under optimized annealing conditions, we next investigate spin-wave propagation in this system. For this purpose, a YIG thin film with a thickness of 20 nm was fabricated using the optimized growth and annealing conditions, and FVSW mode was examined under an out-of-plane magnetic field.

Figure 4(a) shows an optical microscope image of the device after microfabrication together with a scanning electron microscopy image of the antenna region. Two coplanar waveguide antennas were patterned on the YIG film, with a separation D of 1.5 μm , enabling the excitation/detection of spin waves propagation. For the measurement, each antenna is connected to the vector network analyzer by the microwave probes. The excitation power is fixed at -10 dBm and the external magnetic field is applied in the out-of-plane direction.

Figure 4(b) presents the magnetic field dependence of the spin wave transmission spectra $|\Delta S_{12}|$ measured between the two antennas. The signal at each magnetic field was obtained by subtracting the spectrum measured at a high magnetic field, where no resonant features appear within the measured frequency range. Clear resonance peaks originated from the spin wave transmission are observed over the entire magnetic field range investigated, including at zero magnetic field. This behavior highlights a key advantage of perpendicularly magnetized YIG, where forward-volume spin waves can propagate without an external magnetic field. As shown in Fig. 4(e), the magnetic field dependence of the peak frequency in $|\Delta S_{12}|$ are well reproduced by using the theoretical FVSW dispersion relation[40,41]

$$f_{\text{FVSW}} = \frac{\mu_0 \mu_B g}{2\pi \hbar} \sqrt{(H_{\text{ext}} + H_k^{\text{eff}}) \left(H_{\text{ext}} + H_k^{\text{eff}} + M_s \left(1 - \frac{1 - e^{-kt_{\text{YIG}}}}{kt_{\text{YIG}}} \right) \right)} \quad (3)$$

where $M_s = 85$ kA/m obtained from magnetometry measurement and $\mu_0 H_k^{\text{eff}} = 53$ mT obtained from FMR measurement. The slightly reduced values compared to those reported in Fig. 2(b) and 3(e) can be attributed to the smaller film thickness. The k and t_{YIG} are a wavevector and a film thickness, respectively. The experimentally observed peaks are well fitted using Eq. (3) with $k = 2.04 \mu\text{m}^{-1}$, which is in good agreement with the efficiently excited spin wave wavevector calculated from a spatial distribution of microwave current in the antenna [inset of Fig. 4(e)].

To examine the propagation symmetry, Fig. 4(c) shows the comparison of the transmission spectra measured in the two propagation directions, S_{21} and S_{12} . The overlap between two spectra indicates the absence of nonreciprocity. This behavior is characteristic feature of FVSW modes and contrasts with the nonreciprocal propagation observed in surface spin wave geometries.

Figure 4(d) shows the real and imaginary part of the transmission signal, from which the phase evolution of the propagating spin wave is extracted as shown in the inset. The phase delay φ_{12} is given by $\varphi_{12} = -kD$, and we can estimate the group velocity v_g as follows[41,42]:

$$|v_g| = -2\pi D \left(\frac{d\varphi_{12}}{df} \right)^{-1}. \quad (4)$$

The extracted v_g from the antenna distance D and the slope of the phase variation as a function of the microwave frequency is shown in Fig. 4(f) with the calculated spin wave group velocity

$$v_{g,\text{cal}} = 2\pi \frac{df_{\text{FVSW}}}{dk} \approx \frac{\mu_0 \mu_B g}{4\hbar} M_s t_{\text{YIG}}. \quad (5)$$

In the low-magnetic field region, the spin-wave transmission signal was too weak to observe a sufficient phase variation for reliable evaluation of the group velocity. Nevertheless, the experimentally obtained spin-wave group velocity was found to be approximately 0.2 km/s and showed no discernible dependence on the magnetic field strength, as expected from $v_{g,\text{cal}}$. This value is about a factor of two larger than that obtained from theoretical calculation. Such discrepancies between experimentally evaluated and calculated group velocities have also been reported in perpendicularly magnetized thin film and are likely due to spatial inhomogeneities in the magnetic parameters[43].

In the present experiment, the antenna geometry excites micrometer-scale wavelength spin waves in dipolar regime, which leads to relatively small group velocities. In contrast, when nanometer-scale wavelength spin waves in exchange regime are excited, group velocities on the order of several km/s can be achieved [39]. Because exchange spin waves possess nearly isotropic dispersion relations that are independent of the magnetization configuration, similar group velocities are expected even in perpendicularly magnetized YIG. Therefore, excitation of shorter-

wavelength spin waves could potentially enable both higher group velocities and longer propagation distances in this system.

IV. SPIN ORBIT TORQUE SWITCHING

The realization of perpendicularly magnetized YIG with low damping opens an opportunity to explore SOT-driven magnetization dynamics in an insulating magnetic system. Motivated by this perspective, we investigate SOT-induced magnetization switching in perpendicularly magnetized YIG films with a heavy metal overlayer. The experiments were performed on the same YIG films used in the spin wave propagation measurements, onto which a Pt (5 nm) layer was deposited by the magnetron sputtering to generate SOT via the spin Hall effect.

The Hall cross devices were fabricated as shown in Fig. 5(a). The YIG/Pt bilayer was patterned into a Hall-bar structure with 8- μm -wide channel width and 1- μm -wide Hall probe width are defined by electron-beam lithography and Ar ion milling. The contact pads are defined by photolithography, followed by suppering deposition of Ti/Au and lift-off. The electric current was applied along the x -direction and the magnetization state of the YIG layer was detected through the Hall resistance of the Pt layer, which is sensitive to the magnetization direction via spin-Hall magnetoresistance[44–46]. All electrical measurements were performed using a lock-in technique. As shown in Fig. 5(b), the Hall resistance R_H as a function of out-of-plane magnetic field shows full remanence and sharp magnetization switching at a coercive field $\mu_0 H_c = 6.0$ mT, confirming the perpendicular magnetic easy axis of YIG after device fabrication. The linear background is due to the ordinary Hall effect in Pt.

To demonstrate the current-induced magnetization switching, a 100- μs -long pulse current was applied under the presence of an in-plane magnetic field along the current injection axis. The in-plane magnetic field acts as a symmetry-breaking term that lifts the degeneracy between the two perpendicular magnetization states and therefore enables deterministic switching[47,48]. Figure 5(c) show the R_H as a function of applied pulse current density J . Clear switching of the Hall signal and the polarity reversal depending on the magnetic field direction are observed, indicating deterministic magnetization switching driven by SOT. The magnitude of the Hall resistance change corresponds to that observed for full magnetization reversal. Therefore, the complete switching between the two perpendicular magnetization states is achieved.

To quantitatively evaluate the SOT efficiency in the perpendicularly magnetized YIG/Pt heterostructure, harmonic Hall measurements were performed[49]. This technique allows the separation of the current-induced effective fields arising from SOT by analyzing the first- and second-harmonic Hall responses under an AC current. When the magnetization is saturated along the direction of the applied magnetic field, the following relation is used in the analysis of the harmonic Hall measurement:

$$R_H^{1\omega} = R_{\text{PHE}} \sin 2\phi_H, \quad (6)$$

$$R_H^{2\omega} = -\left(R_{\text{AHE}} \frac{H_{\text{DL}}}{H_{\text{ext}} - H_k^{\text{eff}}} + R_{\text{VT}}\right) \cos \phi_H + 2R_{\text{PHE}} \frac{H_{\text{FL}} + H_{\text{Oe}}}{H_{\text{ext}}} (2 \cos^3 \phi_H - \cos \phi_H) \\ = -R_{\text{DL+VT}} \cos \phi_H + R_{\text{FL+Oe}} (2 \cos^3 \phi_H - \cos \phi_H), \quad (7)$$

where, R_{PHE} , R_{AHE} , and R_{VT} are planer Hall resistance, anomalous Hall resistance, and thermal-induced second-harmonic resistance, and H_{DL} , H_{FL} , and H_{Oe} are the effective fields with damping-like (DL) and field-like (FL) SOTs and Oersted field, respectively. The ϕ_H is the in-plane field angle with respect to the x -axis.

Figure 6(a) shows the ϕ_H dependence of the first- and second-harmonic Hall resistance under the AC current with an amplitude of 2 mA (0.5×10^{11} A m⁻²) and a frequency of 17 Hz. The measurements were performed under the external magnetic fields larger than the effect PMA field, ensuring that the magnetization was aligned with the applied field direction. We then extracted $R_{\text{DL+VT}}$ and $R_{\text{FL+Oe}}$ from the fitting of $R_H^{2\omega}$ vs ϕ_H using Eq. (7), as shown in Figs. 6(b) and 6(c). The estimated $R_{\text{DL+VT}}$ and $R_{\text{FL+Oe}}$ show a linear dependence on $1/(\mu_0 H_{\text{ext}} - \mu_0 H_k^{\text{eff}})$ and $1/(\mu_0 H_{\text{ext}})$, respectively. The corresponding effective fields, H_{DL} and $H_{\text{FL}} + H_{\text{Oe}}$, were also obtained from the slope of linear fits, and $\mu_0 H_{\text{DL}}/J$ and $\mu_0 (H_{\text{FL}} + H_{\text{Oe}})/J$ are estimated to be 2.2 mT/(10^{11} A m⁻²) and -0.059 mT/(10^{11} A m⁻²). Therefore DL-SOT is the dominant contribution in our YIG/Pt bilayer systems. Finally we evaluate the efficiency of the DL-SOT via $\xi_{\text{DL}} = (2e/\hbar)(\mu_0 M_s t_{\text{YIG}} H_{\text{DL}}/J)$ using appropriate material parameters, where e is the elementary charge. We find $\xi_{\text{DL}} = 0.018$, which is comparable to those reported for YIG/Pt systems[45], demonstrating efficient spin-current generation and transfer across the YIG/Pt interface. These results further corroborate that the sputter-deposited perpendicularly magnetized YIG serves as a viable platform for quantitative studies of SOT and for current-controlled magnetization dynamics in insulating magnetic systems.

V. DISCUSSION

One of the central implications of the present work lies in the simultaneous realization of efficient spin-wave propagation and spin-orbit-torque-driven magnetization switching within the same perpendicularly magnetized YIG material. These two functionalities impose inherently conflicting requirements on the magnetic layer thickness. On the one hand, the group velocity of spin waves scales with $M_s t_{\text{YIG}}$, as described by Eq. (5), favoring thicker magnetic films for efficient spin-wave transport. On the other hand, the threshold current density required for SOT-induced magnetization switching also scales with $M_s t_{\text{YIG}}$, implying that thinner films are advantageous for reducing the switching current[50]. Reconciling these competing requirements within a single material platform is therefore highly nontrivial.

The key enabling factor in our system is the low magnetic damping achieved in YIG films

with perpendicular magnetization. The spin-wave propagation length is given by the product of the group velocity and the magnon relaxation time, and is therefore inversely proportional to the magnetic damping constant. Consequently, the small damping constant allows coherent spin-wave propagation to be sustained even in relatively thin films. In this sense, the present work demonstrates that perpendicularly magnetized YIG occupies a unique parameter space where both spin-wave transport and current-driven magnetization control can be realized without compromising either functionality.

The relatively small bias field (~ 4.5 mT) observed in the present YIG/Pt bilayer suggests the possibility of non-volatile control of magnonics circuits. Since forward-volume spin waves exhibit isotropic dispersion in the film plane, magnetization switching could enable reconfigurable magnonics functionalities without significantly affecting spin-wave propagation. Beyond magnetization switching, SOT can also enable the amplification and active control of spin waves in magnetic heterostructures. Such effects have been demonstrated in several ferromagnetic systems and could potentially be realized in the perpendicularly magnetized YIG/Pt structures investigated here, providing a route toward active magnonics devices [51–53]. This combination of efficient spin-wave transport and current-driven magnetization control highlights the potential of the YIG system studied here as a versatile platform for integrated magnonic and spin–orbitronic devices.

VI. SUMMARY

In summary, we have demonstrated the realization of perpendicularly magnetized YIG thin films grown by magnetron sputtering on substituted gadolinium gallium garnet substrates. By optimizing the post-annealing conditions, perpendicular magnetized YIG thin films were successfully fabricated while maintaining an exceptionally low magnetic damping constant. Structural analysis revealed epitaxial growth with in-plane lattice clamping, indicating the presence of strain-induced lattice distortion that contributes the emergence of perpendicular magnetic anisotropy. Using optimized perpendicularly magnetized YIG films, we demonstrated coherent forward-volume spin wave propagation over micrometer distances even at zero magnetic field and exhibiting fully reciprocal behavior. Furthermore, by integrating a Pt overlayer, we achieved the SOT-induced switching of the perpendicular magnetization in YIG. Harmonic Hall measurements enabled a quantitative evaluation of SOT efficiency, confirming efficient spin-current generation and transfer across the YIG/Pt interface. These results establish sputter-deposited perpendicularly magnetized YIG as a promising and versatile platform for low-dissipation spin-wave transport and current-driven magnetization control in insulating magnetic systems.

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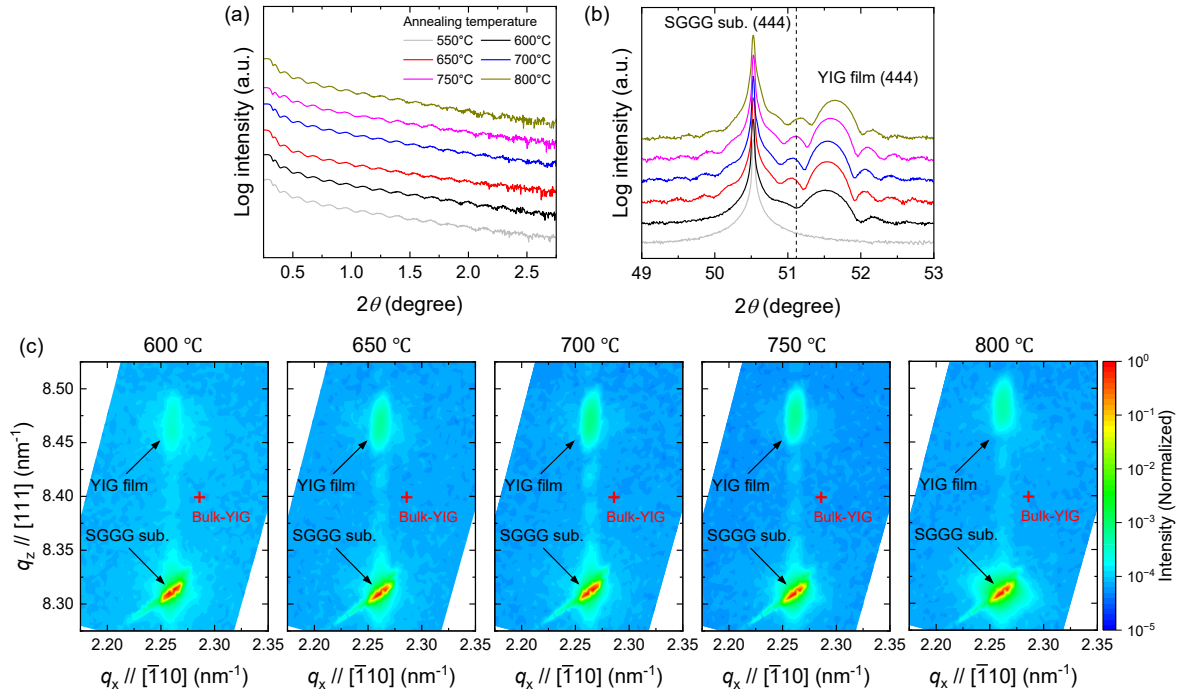


FIG. 1. (a) X-ray reflectivity of YIG thin films annealed at different temperatures. (b) Out-of-plane X-ray diffraction measured around (444) diffraction. The dashed line indicates the (444) peak position of bulk YIG. (c) Reciprocal space maps around the (486) diffraction.

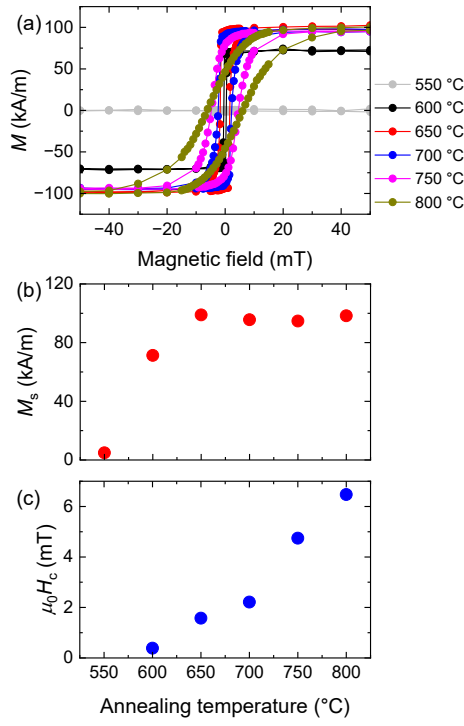


FIG. 2. (a) Magnetic hysteresis loops along out-of-plane magnetic field with the YIG thin films annealed at different temperatures. (b) Saturation magnetization and (c) coercive field as a function of annealing temperature.

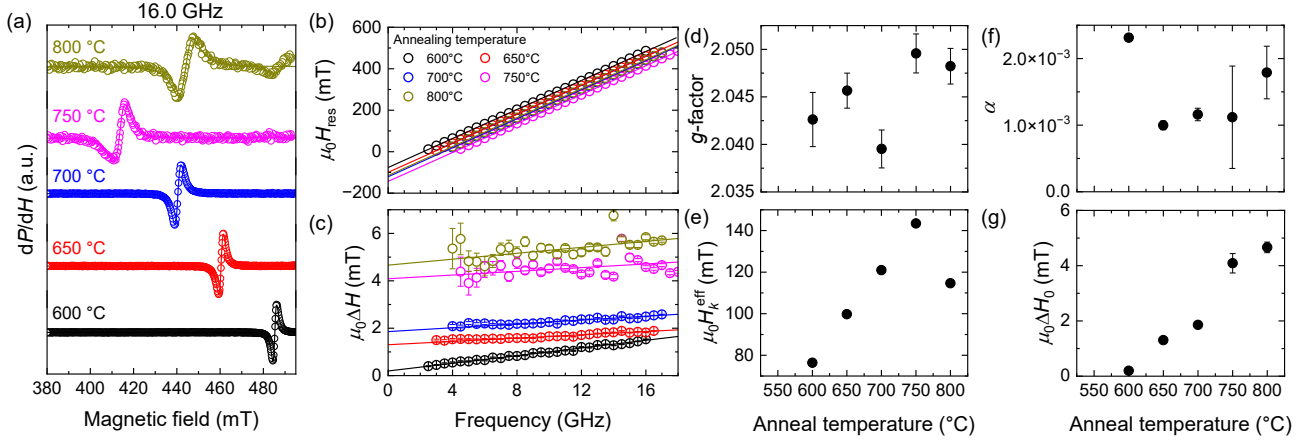


FIG. 3. (a) Ferromagnetic resonance (FMR) spectra measured at 16 GHz under out-of-plane magnetic field for YIG thin films annealed at different temperatures. (b)(c) Frequency dependence of the resonance field H_{res} (b) and linewidth ΔH (c), obtained from fitting the FMR spectra with the derivative of the sum of symmetric and antisymmetric Lorentzian function. (d-g) Annealing temperature dependence of the extracted magnetic parameters: (d) Landé g-factor, (e) effective magnetic anisotropy field H_k^{eff} , (f) Gilbert damping constant α , and (g) inhomogeneous linewidth broadening ΔH_0 .

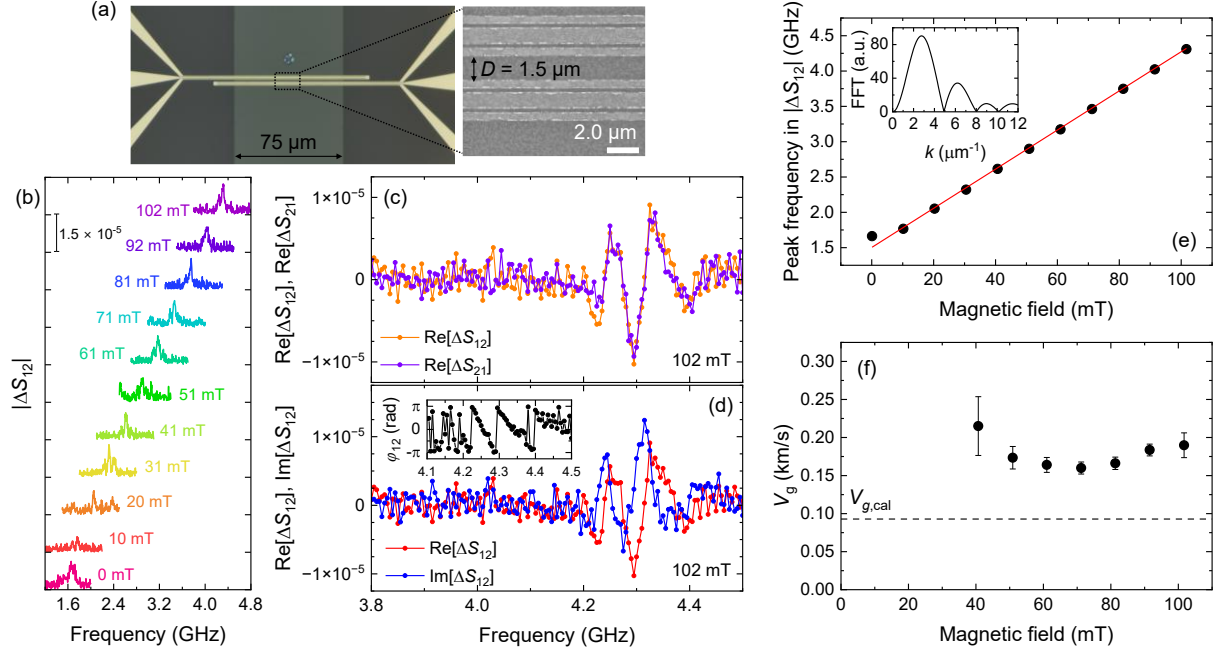


FIG. 4. (a) Optical microscope image of the spin wave device with perpendicularly magnetized YIG waveguide and a scanning electron microscope image of the antenna region. (b) Spin wave transmission spectra $|\Delta S_{12}|$ measured at various out-of-plane magnetic fields. (c) Comparison of the transmission spectra ΔS_{12} and ΔS_{21} and (d) real/imaginary part of the transmission signal $\text{Re}[\Delta S_{12}]$ and $\text{Im}[\Delta S_{12}]$ measured under the magnetic field of 102 mT. Inset in (d) shows the phase of the transmission signal as a function of microwave frequency. (e) Spin wave resonance frequency as a function of magnetic field with the fitting using Eq. (3). Inset shows the Fourier transform of the current distribution in the microwave antenna. f) Spin wave group velocity as a function of magnetic field.

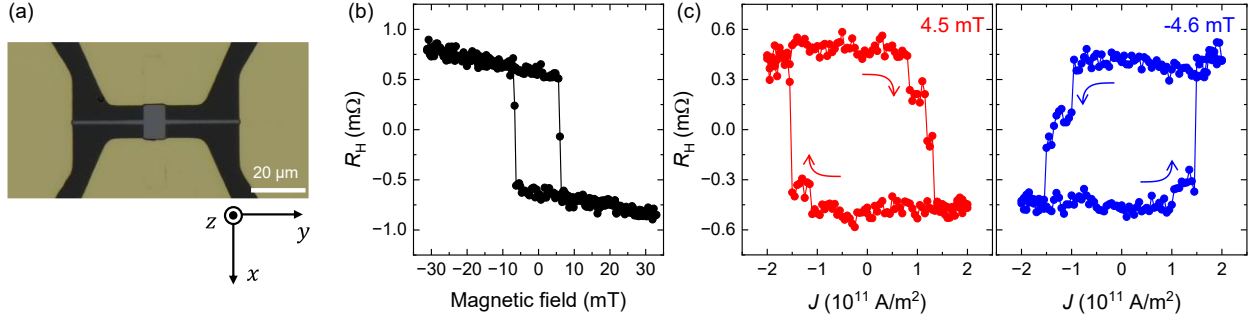
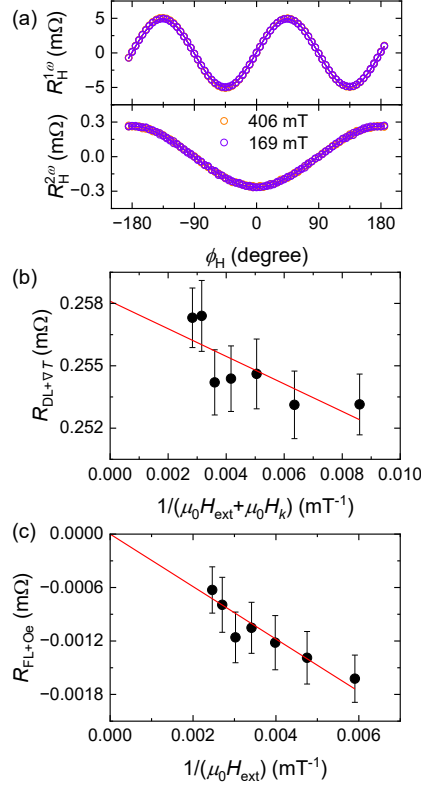


FIG. 5. (a) Optical microscope image of the YIG/Pt Hall-bar device used for spin-orbit torque switching experiments. (b) Out-of-plane magnetic field dependence of the Hall resistance R_H . (c) R_H measured after the pulse current to the Pt layer under fixed in-plane magnetic fields of 4.5 mT and -4.6 mT.



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494 FIG. 6. (a) First-harmonic Hall resistance $R_H^{1\omega}$ (upper panel) and second-harmonic Hall resistance $R_H^{2\omega}$
 495 (lower panel) measured at in-plane magnetic field of 169 mT and 406 mT under AC current with the amplitude
 496 of 2.0 mA. (b) The $R_{DL+\nabla T}$ as a function of $1/(\mu_0 H_{ext} + \mu_0 H_k)$ and (c) the R_{FL+Oe} as a function of
 497 $1/(\mu_0 H_{ext})$. The solid lines are linear fits to the experimental data.