Electrical generation and detection of spin waves in polycrystalline YIG/Pt grown on silicon wafers

Rongxin Xiang \(^1\), Lina Chen \(^{1,2,3}\), Sheng Zhang \(^4\), Haotian Li\(^5\), J Du\(^6\), Y W Du\(^7\) and R H Liu\(^{1,2,3}\)

\(^1\) Shenzhen Research Institute of Nanjing University, Shenzhen 518057, People’s Republic of China
\(^2\) National Laboratory of Solid State Microstructures, School of Physics and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, People’s Republic of China
\(^3\) Authors to whom any correspondence should be addressed.

E-mail: linachen@nju.edu.cn and rhliu@nju.edu.cn

Keywords: spin pumping, magnetron sputtering, polycrystalline YIG film, ferromagnetic resonance, spin current detection

Abstract

We studied the magnetic properties of polycrystalline \(\text{Y}_3\text{Fe}_5\text{O}_{12}\) (YIG) thin films (less than 100 nm) deposited on thermally oxidized silicon wafer by magnetron sputtering and followed by the post-annealing process. Our ferromagnetic resonance (FMR) results demonstrate that sputtering at room temperature combined with the post-annealing treatment can be an efficient method to achieve large-area (inch scale) and highly uniform YIG thin films with a low damping constant \(\alpha \sim 7 \times 10^{-3}\) on cheap oxidized Si wafer. Furthermore, our spin pumping experiments demonstrate that the polycrystalline YIG/Pt system has a good spin mixing conductance, where spin current can be effectively injected into the adjacent Pt layer from YIG through the interface. Then the electrical detection of magnetic properties (e.g., spin waves) of insulating YIG film can be achieved via the inverse spin Hall effect of Pt. The electrical detection of spin waves in the large-area polycrystalline YIG/Pt on silicon wafer may help to develop new spintronic devices (e.g., magnon-based devices) by utilizing the complementary metal-oxide-semiconductor (CMOS) technology.

1. Introduction

Yttrium iron garnet (YIG) material with ultra-low magnetic damping has been widely studied and applied in various microwave devices such as the microwave oscillators, filters, and generators [1, 2]. Additionally, as a ferrimagnetic insulator, YIG is an ideal material of low-power consumption to generate a pure spin current in magnon-based devices without introducing extra charge current. At present, high-quality single-crystal YIG films (thickness < 100 nm) have been successfully achieved on a costly single crystal substrate, e.g., gadolinium gallium garnet (GGG) via epitaxial growth techniques such as liquid phase epitaxy (LPE), molecular beam epitaxy (MBE), pulsed laser deposition (PLD) and magnetron sputtering [3–6], which have been intensively studied in various spintronic researches, such as the spin pumping [7–12], the spin Hall magnetoresistance (SMR) [13–16], and the electrical excitation and detection of spin waves [1, 17].

However, to easily integrate the YIG-based spintronic devices with silicon-based semiconductor electronics on one chip and to reduce the cost, the explorations of the spin-related properties (e.g., spin-wave, spin current) of polycrystalline YIG films deposited on the conventional semiconductor wafers (e.g., silicon wafer) is imperative for the development of multifunctional magnon-based devices. Although a few of previous works studied the magnetic properties and microstructure of the YIG films deposited on Si/SiO\(_2\) or quartz substrates and found that thin YIG films were easy to crack during the post-annealing procedure due to the thermal expansion and the mismatch between YIG film and substrates [18–21], it is still lack of the essential investigations of the electrical generation, detection of spin waves and pure spin-related transport properties in the magnetic heterostructure consisted of polycrystalline YIG and spin Hall materials (e.g., Pt, W) deposited on Si/SiO\(_2\) or quartz substrates.

© 2020 The Author(s). Published by IOP Publishing Ltd
In the present work, the crack-free polycrystalline YIG films thinner than 100 nm were obtained by using the ex-situ post-annealing method to crystallize the amorphous YIG films deposited on thermally oxidized silicon substrate by radio frequency (rf) magnetron sputtering at room temperature. Based on the analysis of the surface morphology, the static and dynamic magnetization of YIG films at different annealing temperatures, the optimal annealing condition was determined. The deterioration of saturation magnetization and the damping coefficient with the decrease of film thickness was also confirmed. Additionally, our spin pumping experiments showed that the magnetization precession excited by the external rf microwave signal in these YIG films could efficiently pump spin current into the adjacent Pt layer and generate a distinct direct current (dc) voltage due to the inverse spin Hall effect (ISHE). The demonstrated electrical detection of spin waves in the polycrystalline YIG/Pt system is an essential step towards integrating YIG-based magnonics and silicon electronics.

2. Experimental procedure

The amorphous YIG films with different thicknesses were firstly deposited on Si/SiO₂ substrates by rf magnetron sputtering with 50 W power at 4 \times 10^{-3} Torr with high purity argon (99.999%), and then crystallized through ex-situ post-annealing procedure in air. The film structures and crystalline phases were characterized by using x-ray diffraction (XRD) with Cu K₀₁ radiation. The thickness, the surface morphology, and saturation magnetization of polycrystalline films were determined by spectroscopic ellipsometry (SE), scanning electron microscope (SEM)/atomic force microscopy (AFM), and vibration sample magnetometer (VSM), respectively. Ferromagnetic resonance (FMR) spectra of the YIG films was performed by using a broadband coplanar waveguide (CPW) with the simultaneous magnetic field and rf excitation under the pulse modulation. All the static and dynamic magnetic properties were performed at room temperature.

3. Results and discussion

To obtain the optimum crystallization condition, we investigated the influence of annealing temperature on the structure and properties of films by ex-situ post-annealing the same batch of as-grown amorphous YIG films in air at different temperatures. After post-annealing, the thickness, the crystal structure, the microstructure, and the morphology of YIG films were characterized by SE, XRD, AFM, and SEM. Figure 1 shows the XRD patterns of the YIG target and the 65 nm YIG films annealed at 800 °C, 850 °C, and 900 °C for 1 h in air, with peaks indexed by Miller indices based on cubic space group (Ia3d). Based on the XRD analysis, the lattice constants of annealing films are obtained: 1.2332 nm (800 °C), 1.2331 nm (850 °C), and 1.2336 nm (900 °C), where the thin films have the smaller lattice constant than the bulk YIG (1.2340 nm), which demonstrates that the substrate has the compressive strain on the thin films.

The surface morphology of the YIG films was further characterized by AFM and SEM. In figures 2(a)–(c), the SEM images (10 μm × 10 μm) show that the YIG films have a relatively smooth surface without any cracks, and all films are dense and contain regular surface grains. With the increase of the annealing temperature up to 900 °C, the film surface shows the enhanced agglomeration of grains, and the grain size gradually increases, which were further confirmed by the AFM. Figures 2(d)–(f) shows the 10 μm × 10 μm AFM images of YIG
films annealed at different temperatures. The root-mean-square (RMS) surface roughness of the annealing films is 10.1 nm (800 °C), 12.7 nm (850 °C) and 13.5 nm (900 °C), respectively, which are about 10 times larger than RMS surface roughness of the as-grown films (1.28 nm). The results of AFM further confirmed the SEM results that the grains grow with increasing annealing temperature. The film quality, such as the crystallization, the composition, and the roughness, can affect the properties of films. To explore the annealing temperature effect on the magnetic properties of the films, we further performed static and dynamic magnetic measurements of the YIG films.

The static magnetic properties of YIG films were characterized by VSM at room temperature. Figure 3 shows the field-dependent magnetization curves ($M-H$) of 65 nm thin YIG films with three different annealing temperatures. The magnetization quickly saturates even at a low field of 200 Oe. Such a small value of the coercive field indicates the soft magnetic properties of all YIG films with fewer defects and inhomogeneities. The coercivity ($H_C$) in the inset of figure 3 was obtained from the $M-H$ hysteresis loops. In figure 3, the saturation magnetization ($M_s$) of YIG films is much smaller than that of the bulk (139.3 emu cm$^{-3}$), consistent with the previous reports [22–24]. For the YIG film annealed at 800 °C, the coercivity $H_C$ and the saturation magnetization $M_s$ are 32 Oe and 73.0 emu cm$^{-3}$, respectively. As the annealing temperature increases to 900 °C, $H_C$ drops to 25 Oe, and $M_s$ increases to 82.4 emu cm$^{-3}$, which can be attributed to the increase of the grain size.

Figure 2. SEM images (a)–(c) 10 μm × 10 μm and AFM surface morphology (d)–(f) 10 μm × 10 μm of the YIG films annealed at 800 °C, 850 °C and 900 °C.

Figure 3. The magnetic hysteresis loops of the 65 nm YIG films annealed at 800 °C, 850 °C and 900 °C. Inset: the coercive field $H_C$ versus the annealed temperature $T_{an}$. 
with the corresponding decrease of the magnetic anisotropy [25], indicating that the higher annealed temperature leads to the better quality of the YIG films. The static magnetic properties show that thin film has a smaller $M_s$ and a higher $H_C$ than that of the bulk ($M_s \sim 140$ emu cm$^{-3}$, $H_C \sim 1$ Oe) [2], which is related to the surface and interfacial effect of thin films. The deterioration of the magnetic properties of thin YIG films may hamper its application in the field of the spintronic devices.

The dynamic magnetic properties of YIG films were further investigated by broadband FMR spectroscopy. The typical differential FMR spectra of YIG films with different annealed temperatures are shown in figures 4(a)–(c). The FMR curve is a combination of symmetric and antisymmetric Lorentzian functions, as following

$$\frac{dP}{dH} = \frac{F_S (\Delta H)^2 - (H - H_{res})^2}{[(H - H_{res})^2 + (\Delta H)^2]^2} + \frac{F_A 2(H - H_{res})\Delta H}{[(H - H_{res})^2 + (\Delta H)^2]^2},$$

where $F_S$ and $F_A$ represent the symmetric and antisymmetric factor, $H$ is the magnitude of the external magnetic field, $H_{res}$ is the resonance field, and $\Delta H$ is the corresponding linewidth of FMR. The coupling between the YIG film and the CPW will cause a partial mixture of the real and imaginary components of the susceptibility, which will induce a symmetric signal $F_S$. By using equation (1), the best FMR fitting gives very small $F_A$, which is over 100 times smaller than the $F_S$. After fitting the FMR spectrum in figures 4(a)–(c), $\Delta H$ and $H_{res}$ were also extracted for films with different annealing conditions in figures 4(d) and (e), respectively.

In figure 4(d), the linewidth $\Delta H$ as a function of the resonance frequency $f$ can be fitted by:

$$\Delta H = \Delta H_0 + \frac{2\alpha f}{\gamma/(2\pi)},$$

where $\gamma/(2\pi)$ (2.8 MHz Oe$^{-1}$) is the gyromagnetic ratio, $\Delta H_0$ and $\alpha$ represent the inhomogeneous broadening and the Gilbert damping coefficient, respectively. Achieving the low damping coefficient $\alpha$ is essential for the application of the YIG thin film. By fitting the data of figure 4(d) by using equation (2), the damping coefficient $\alpha$ was obtained and shown in figure 4(f). As the annealing temperature increases, $\alpha$ decreases from 0.0091 to 0.0072, indicating the better quality of films annealed at a higher temperature.

Figure 4(e) shows the relation between the resonance frequency $f$ and the resonance field $H_{res}$, which can be well fitted by the Kittel equation.
where $M_{\text{eff}}$ is the effective magnetization. For YIG films, $M_{\text{eff}}$ can be obtained by fitting the field dependence of resonance frequency with the corresponding $M_s$ obtained from VSM measurements above. Figure 4(g) shows that, with the increase of the annealing temperature, the saturation magnetization $M_s$ slowly increases, while effective magnetization $M_{\text{eff}}$ rapidly increases. The effective magnetization $M_{\text{eff}}$ can be written as [24]:

$$4\pi M_{\text{eff}} = 4\pi M_s - H_a,$$

where $H_a$ is the magnetic anisotropy field. The obtained $H_a$ is shown in figure 4(h). With the increase of annealing temperature, the $H_a$ of YIG film decreases rapidly, which demonstrates the higher annealing temperature tends to release a part of compression strain from substrate, consistent with structure characterization analysis.

Furthermore, the thickness dependence of the magnetic properties of the YIG film is also investigated. The in-plane magnetic hysteresis loops of YIG films with three different thicknesses (48 nm, 57 nm, and 65 nm) annealed at 900 °C are measured and shown in figure 5. With the thickness increase from 48 nm to 65 nm, $M_s$ increases from 39.8 emu cm$^{-3}$ to 82.4 emu cm$^{-3}$; while $H_a$ decreases from 35 Oe to 25 Oe. Saturation magnetization $M_s$ is deteriorated by reducing the thickness of film due to the appearance of component diffusion/segregation, oxygen vacancies, strains, and the defects at the surface/interface, which has been observed and confirmed by many previous studies on various complex oxides [26, 27]. Therefore, with decreasing thickness, the drop of $M_s$ is related to the degeneration of magnetization at the interface and surface.

We also performed FMR measurements on YIG films with different thicknesses to explore their dynamic properties, as shown in figures 6(a)–(c). Following the previous methods, the resonance field $H_{\text{res}}$ and linewidth $\Delta H$ were extracted from FMR fitting by equation (1), and shown in figures 6(d) and (e). These extracted data can further provide the damping $\alpha$ and the effective magnetization $M_{\text{eff}}$, which were summarized in figures 6(f) and (g). Figure 6(g) shows that $M_s$ and $M_{\text{eff}}$ of the films increase with the increasing of film thickness. The in-plane anisotropy field $H_a$ is determined from $M_{\text{eff}}$ and $M_s$, as shown in figure 6(h). $H_a$ for 65 nm YIG film is about half of that for 48 nm film. Figure 6(f) shows that the Gilbert damping $\alpha$ significantly drops from 0.0138 to 0.0072 when the film thickness increases from 48 nm to 65 nm, consistent with the behavior of the thickness-dependent linewidth for the films in figure 6(d). One can expect that thicker films hold fewer defects and less influence from the interface between YIG and substrate. And thinner YIG films with a larger Gilbert damping is related to defects at the surface and interface, which gives rise to the additional damping due to the two-magnon scattering [26, 28, 29].

Since the spin mixing conductance $g_{\text{eff}}^{11}$ governs various spin-dependent phenomena such as spin pumping, SMR and spin Seebeck effect [30–32], it is essential to experimentally determine $g_{\text{eff}}^{11}$ of polycrystalline YIG/Pt films grown on the silicon substrate. For our Si/SiO$_2$/YIG/Pt samples, the Pt layer was finally deposited at room temperature after the post-annealing of polycrystalline YIG film. Based on the previous theoretical studies [10, 11, 33], spin mixing conductance can be approximately given by

$$g_{\text{eff}}^{11} = \frac{4\pi M_{\text{eff}} t_{\text{YIG}}}{g\mu_B} (\alpha_{\text{Pt}}/\text{YIG} - \alpha_{\text{YIG}}),$$

where $g$ is the Landé factor, $\mu_B$ is the Bohr magneton, $t_{\text{YIG}}$ is the thickness of magnetic material. To quantitatively obtain $g_{\text{eff}}^{11}$, we systematically measured FMR of bare YIG (65 nm) and YIG (65 nm)/Pt (7 nm) at different excitation frequencies and extracted their linewidth using the equation (1), as shown in figure 7(a). Compared with the bare YIG film, the linewidth of YIG/Pt is significantly increased due to spin current generated at the
YIG/Pt interface by spin pumping [inset of figure 7(a)]. Meanwhile, the Gilbert dampings $\alpha$ of the YIG/Pt and YIG were obtained as 0.009 and 0.007, respectively. From equation (5), the spin mixing conductance $g_{\text{mix}}^{1/2}$ of polycrystalline YIG/Pt deposited on Si/SiO$_2$ can be calculated to be $5.2 \times 10^{18} \text{ m}^{-2}$. For direct comparison, we also performed the same FMR measurement to extract Gilbert damping for the 0.92 $\mu$m thick YIG epitaxially grown on GGG substrate GGG/YIG(0.92 $\mu$m) by LPE method with and without Pt (7 nm) layer, and found that the hybrid system of Pt and single-crystal YIG has the higher $g_{\text{mix}}^{1/2} \sim 6.6 \times 10^{19} \text{ m}^{-2}$ as expected, which is also 10 times higher than that of the previously reported thin YIG epitaxial film system GGG/YIG (19 nm)/Pt (20 nm) grown by PLD [34]. There are several reasons for the decrease of $g_{\text{mix}}^{1/2}$ in Si/SiO$_2$/YIG (65 nm)/Pt (7 nm). Based on equation (5), the much lower saturation magnetization $M_S \sim 80$ emu cm$^{-3}$ (less than 60% of $M_S \sim 140$ emu cm$^{-3}$ in GGG/YIG) and the higher spin current loss in the YIG/Pt interface can reduce $g_{\text{mix}}^{1/2}$. Besides, the extrinsic damping enhancement factors such as the strong two-magnon scattering and the spin memory loss induced by the interfacial spin-orbit coupling will directly result in the incorrect evaluation of $g_{\text{mix}}^{1/2}$, which has also been verified by several recent works [35–38].

To directly verify the possibility of the electrical detection of spin-wave and the spin transport in the YIG films on Si/SiO$_2$ substrate, we patterned a 7 nm thick Pt stripe with 5 mm $\times$ 200 $\mu$m size on the top of the 65 nm thick YIG films by a combination of magnetron sputtering and e-beam lithography (EBL). Figure 7(b) shows the schematic illustration of the electrical detection of spin current in YIG/Pt via ISHE based on the spin pumping technique. Figure 7(c) shows the dependence of the obtained dc voltage $V_{dc}$ with the excitation frequency $f = 6$ GHz on the out-of-plane magnetic field angle $\theta$ defined in figure 7(b). One can see that $V_{dc}$ changes its sign when the magnetic field $H$ varies from $\theta = 90^\circ$ (along the $y$-axis positive direction) to $\theta = -90^\circ$, indicating that the dc voltage signal is related to the dc ISHE in Pt layer due to the spin pumping. Field-dependent dc voltage $V_{dc}$ under FMR condition of YIG can be well fitted with the symmetric Lorentzian lineshape given by [12]

$$V_{dc} = V_{sp} \frac{\Delta H^2}{(H - H_{res})^2 + \Delta H^2},$$

where $V_{sp}$ is the peak amplitude of the obtained voltage signal. $V_{sp}$ and linewidth $\Delta H$ can be extracted from the Lorentzian fitting of the experimental data. Based on the previous studies on dc ISHE, $V_{sp}$ signal has the

---

**Figure 6.** Thickness-dependent magnetic properties of YIG films characterized by broadband FMR spectroscopy. (a)–(c) Differential FMR spectra of YIG films with three thicknesses of 48 nm (a), 57 nm (b) and 65 nm (c) from 5 GHz to 12 GHz. (d) Linewidth versus frequency of FMR and (e) frequency versus the external magnetic field $H$ extracted from the FMR spectra of (a)–(c). The solid lines (d) are the linear fittings with equation (2). The solid lines (e) are the fitting curves with the Kittle formula equation (3). (f)–(h) The Gilbert damping constant $\alpha$ (f), the effective and saturation magnetization $g$ (g), and anisotropy field (h) obtained from the fittings of (d), (e) and $M$–$H$ curves of figure 5 as a function of YIG film thickness.
where \( h_{rf} \) is the rf magnetic field, \( P = \frac{4nf[1+4eM_s+\sqrt{(1+4eM_s)^2+4(2nf)^2}]}{2+4eM_s+4(2nf)^2} \) is an ellipticity correction factor, \( R \) the resistance, \( w \) the width, \( \theta_{SH} \) the spin Hall angle, \( \lambda_{SD} \) the spin diffusion length, and \( t_N \) the thickness of Pt stripe, respectively. To better quantify the spin pumping efficiency of the Si/SiO\(_2\)/YIG/Pt system, we further performed the compared experiments on the GGG/YIG(0.92 \( \mu \)m) film with the same 7 nm thick Pt stripe on its top. The \( V_{dc} \) of GGG/YIG(0.92 \( \mu \)m)/Pt(7 nm) and Si/SiO\(_2\)/YIG(65 nm)/Pt(7 nm) at 6 GHz are shown in the inset of figure 7(d). The \( V_{dc} \) of the thick single-crystal GGG/YIG/Pt system shows a very sharp peak with a peak amplitude of 6 \( \mu \)V and a narrow linewidth of 12 Oe due to the ultralow damping constant and high-quality interface. By assuming the same \( \theta_{SH} \) for the Pt stripe on polycrystalline and single crystal YIG films, the ratio of spin pumping voltage \( V_{dc}^{poly} \) and \( V_{dc}^{single} \) can be further obtained as following

\[
\frac{V_{dc}^{poly}}{V_{dc}^{single}} = \frac{R_p}{R_s} \left( \frac{g_{eff}^{poly}}{g_{eff}^{single}} \right)^2 \left( \frac{\alpha^{single}}{\alpha^{poly}} \right)^2
\]

The Pt resistance ratio \( R_p/R_s = 1.31 \) was measured by standard four-probes method. The ellipticity correction factor ratio \( R_p/P_s = 0.976 \) can be calculated from the formula above. Although it is difficult to precisely calculate the absolute value of the interfacial spin mixing conductance due to unknown the actual \( rf \) power on the sample, we can obtain the ratio of the spin mixing conductance \( g_{eff}^{poly} \) of the two systems from the

**Figure 7.** (a) Linewidth versus frequency of FMR extracted from the FMR spectra. The solid lines are the linear fittings with equation (2). Insert: FMR spectra of bare YIG and YIG/Pt films deposited on Si/SiO\(_2\) substrates, respectively. (b) Schematic illustration for the electrical detection of spin current in YIG/Pt via a combination of spin pumping and inverse spin Hall effect. (c) The out-of-plane magnetic field angle \( \theta \) dependence of the ISHE voltage \( V_{dc} \). Insert: the angular dependency of the peak amplitude of \( V_{dc} \). The solid curve is the result of fitting with a sine function. (d) The \( V_{dc} \) obtained at \( \theta = 90^\circ \) (along the y-axis positive direction) and excitation frequency \( f \) varying between 5 GHz and 12 GHz in 1 GHz steps. Insert: the ISHE voltage \( V_{dc} \) obtained at the same conditions \( \theta = 90^\circ \) and \( f = 6 \) GHz in single-crystal GGG/YIG(0.92 \( \mu \)m)/Pt(7 nm) (black line) and polycrystalline Si/SiO\(_2\)/YIG (65 nm)/Pt(7 nm) (red line), respectively. The solid curves in (c) and (d) are the results of fitting by the Lorentzian function equation (6).
measured spin pumping voltage ratio based on equation (6). According to the previous quantitative analysis, the spin pumping experiments indicate that the polycrystalline Si/SiO2/YIG/Pt system has a comparable $g_{\text{eff}}^{1/2}$ with single-crystal GGG/YIG/Pt system, suggesting that the large scale polycrystalline YIG grown on the cheap Si wafer is adequate for developing YIG-based magnonics.

4. Conclusions

We systematically studied thickness and annealing temperature dependence of surface morphology, and static and dynamic magnetic properties of sub-100 nm YIG thin films deposited on Si substrate by magnetron sputtering and post-annealing treatment. 65 nm thick YIG film with the lowest Gilbert damping of $7 \times 10^{-3}$ was achieved at the 900 °C annealing temperature in air. Thickness-dependent experiments show that the magnetic properties strongly degenerate with decreasing the YIG thickness, which indicates that the magnetization deterioration is related to the interfacial effects, including the defect and the composition diffusion. Furthermore, the spin injection across the YIG/Pt interface in the polycrystalline and the high-quality single-crystal YIG films were also studied by FMR and spin pumping measurements. Via the compared experiment of the spin pumping for GGG/YIG/Pt and Si/SiO2/YIG/Pt systems, we found that the spin mixing conductance of Si/SiO2/YIG/Pt is comparable with single-crystal YIG/Pt system. Our results suggest that the polycrystalline YIG/Pt film deposited on a silicon wafer is a promising system to integrate YIG-based magnonics and silicon-based electronics.

Acknowledgments

L. C. and R. H. L. are supported by Shenzhen Basic Research Program (Grant No. JCYJ20170818110402776) and National Natural Science Foundation of China (No. 11774150). R. L. and Y. D. acknowledges support from the National Key Research and Development Program of China (2016YFA0300803).

ORCID iDs

Sheng Zhang https://orcid.org/0000-0003-4487-4132
J Du https://orcid.org/0000-0002-9967-945X
R H Liu https://orcid.org/0000-0002-4053-3923

References

[1] Chumak A V, Serga A A, Jungleisch M B, Neb R, Bozhko D A, Tiberkevich V S and Hillebrands B 2012 *Applied Physics Letters* 100 082405
[2] Serga A A, Chumak A V and Hillebrands B 2010 *Journal of Physics D: Applied Physics* 43 264002
[3] Krichhtsenov B B et al 2017 *Science and Technology of Advanced Materials* 18 351–63
[4] Manuilov S A, Kharitsev S I and Grishin A M 2009 *Journal of Applied Physics* 106 123917
[5] Du C, Himmel P C, Yang F and Wang H 2014 *Physical Review B* 89 134404
[6] Nathan B et al 2018 *IEEE Magnetics Letters* 9 3706005
[7] Wei D, Obstbaum M, Ribow M, Back C H and Woltersdorf G 2014 *Nature Communications* 5 3768
[8] Zhang W, Jungleisch M B, Jiang W, Sklenar J, Fradin F Y, Pearson J E, Ketterson J B and Hoffmann A 2015 *Journal of Applied Physics* 117 172610
[9] Rogdakis K et al 2019 *Physical Review Materials* 3 014406
[10] Haetinger M, Back C H, Lotze J, Weiler M, Gepraegs S, Huebl H, Goennenwein S T B and Woltersdorf G 2015 *Physical Review B* 92 054417
[11] Heinrich B, Burrowes C, Montoya E, Kardasz B, Girt E, Song Y, Sun Y and Wu M 2011 *Physics Review Letters* 107 066604
[12] Zhou H, Fan X, Ma L, Cui L, Jia C, Zhou S, Gui Y S, Hu C M and Xue D 2016 *Applied Physics Letters* 108 192408
[13] de Loubens G, Klein O, Viret M, Naleto V V, Ben Youssef J and Hahn C 2013 *Physical Review B* 87 174417
[14] Vlietstra N, Shan J, Castel V, Ben Youssef J, Bauer G E W and van Wees B J 2013 *Applied Physics Letters* 103 032401
[15] Shan J, Castel V, van Wees B J, Ben Youssef J and Vlietstra N 2013 *Physical Review B* 87 184421
[16] Zhou L, Nie Y, Xia Q, Guo G and Wang X 2018 *Physical Review B* 97 094401
[17] Wang X, Chotorishvili L, Guo G and Berakdar J 2017 *Journal of Applied Physics* D: *Applied Physics* 50 495005
[18] Delgado A et al 2018 *Materials Research Express* 5 026419
[19] Kumar N, Prasad S, Misra D S, Venkataramani N, Bohra M and Krishnan R 2008 *Journal of Magnetism and Magnetic Materials* 320 2233–6
[20] Li K, Zheng H, Zheng P, Xu J, Chen J, Zhou J and Zheng L 2018 *Materials Letters* 2018 228 21–4
[21] Liu J, Chen Y, Liu Z, Zhu M, Wang G, Zhang W and Dong X 2017 *Ceramics International* 43 7477–81
[22] Conca A, Keller S, Mihalceau L, Kejajias T, Dimitrovopoulos G P, Hillebrands B and Papazan-Mou E T 2016 *Physical Review B* 93 134405
[23] Dulal P, Solheid P A, Flammigan D J and Stadler B J 2017 *Materials Research Letters* 5 379–85

8
[24] Popova E, Keller N, Gendron F, Thomas L, Briano M C, Guyot M, Tessier M and Parkin S S P 2001 *Journal of Vacuum Science & Technology A* **19** 2567–70
[25] Rajendran M, Deka S, Joy P A and Bhattacharya A K 2006 *Journal of Magnetism and Magnetic Materials* **301** 212–9
[26] Chumak A V, Kehlberger A, Lauer V, Kim D H, Onbasli M C, Ross C A, Kläui M, Hillebrands B and Jungfleisch M B 2015 *Physical Review B* **91** 134407
[27] Richter T, Paleschke M, Wahler M, Heyroth F, Deniz H, Hesse D and Schmidt G 2017 *Physical Review B* **96** 184407
[28] Haidar M, Ramjbar M, Balinsky M, Dumas R K, Khartsev S and åkerman J 2015 *Journal of Applied Physics* **117** 17D119
[29] Mills D L and Arias R 1999 *Physical Review B* **60** 7395–409
[30] Harii K, Seo Y, Tsutsui Y, Chudo H, Oyanagi K, Matsuo M, Shiomi Y, Ono T, Maekawa S and Saitoh E 2019 *Nature Communications* **10** 2616
[31] Uchida K *et al* 2010 *Nature Materials* **9** 894–7
[32] Jaworski C M, Yang J, Mack S, Awschalom D D, Heremans J P and Myers R C 2010 *Nature Materials* **9** 898–903
[33] Jungfleisch M B, Chumak A V, Kehlberger A, Lauer V, Kim D H, Onbasli M C, Ross C A, Kläui M and Hillebrands B 2015 *Physical Review B* **91** 134407
[34] Sun Y *et al* 2013 *Physical Review Letters* **111** 106601
[35] Rezende S M, Rodríguez-Suárez R L, Soares M M, Vilela-Leão L H, Ley Domínguez D and Azevedo A 2013 *Applied Physics Letters* **102** 012402
[36] Vilela-Leão L H, Salvador C, Azevedo A and Rezende S M 2011 *Applied Physics Letters* **99** 102505
[37] Ralph D C, Buhrman R A and Zhu L 2019 *Physical Review Letters* **123** 057203
[38] Dreher L *et al* 2011 *Physical Review Letters* **107** 046601