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Tuning Spin Wave Modes in Yttrium Iron Garnet films with Stray Fields

Ushnish Chaudhuri\textsuperscript{a}, Navab Singh\textsuperscript{b}, R. Mahendiran\textsuperscript{a*}, Adekunle O. Adeyeye\textsuperscript{c,d*}

\textsuperscript{a}Physics Department, National University of Singapore, 117551, Singapore.
\textsuperscript{b}A*STAR Institute of Microelectronics, 2, Fusionopolis Way, 138634, Singapore.
\textsuperscript{c}Department of Electrical and Computer Engineering, National University of Singapore, 117576, Singapore.
\textsuperscript{d}Department of Physics, Durham University, South Rd, Durham, DH1 3LE, UK

Nanopatterning of Yttrium Iron Garnet (YIG) has proven to be a non-trivial problem even with advances in modern lithography techniques due to non-compatibility with conventional complementary metal oxide semiconductor platform. In an attempt to circumvent this problem, we demonstrate a simple and reliable method to indirectly pattern YIG films on a Gadolinium Gallium Garnet (GGG) substrate. We fabricated exchange-coupled arrays of Py dots unto an underlying YIG film using nano stencil lithography. The stray fields generated from the Py dots were used to transfer patterned magnetic information unto the underlying YIG films. The static and dynamic properties of the fabricated hybrid YIG/Py dots structure and reference YIG film were characterized using a focused magneto-optic Kerr effect and broadband ferromagnetic resonance spectroscopy. For the reference YIG film, as expected, a single field-dependent resonance mode with a narrow linewidth was observed in contrast with the splitting into three distinct resonance modes for the YIG/Py dots structure as predicted by micromagnetic simulations. We have thus shown that it is possible to utilize stray field effects from easily patternable magnetic materials for the development of future YIG based magnonic devices.
Introduction

Yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) and other ferro/ferrimagnetic insulators which exhibit lower Gilbert damping, are ideal materials for efficient spin-wave propagation over long distances\textsuperscript{1,2}. High-quality crystalline YIG films on lattice-matched substrates such as Gadolinium Gallium Garnet ($Gd_3Ga_5O_{12}$, GGG)\textsuperscript{3}, by using liquid phase epitaxy (LPE)\textsuperscript{4}, pulsed laser deposition (PLD)\textsuperscript{5}, and magnetron sputtering\textsuperscript{6,7} have been grown by various groups. Moreover, investigations into the properties of YIG revealed exciting spin-wave properties that can be utilized for various applications in magnonics\textsuperscript{8}. Ferromagnetic nanostructures form the building blocks in the development of magnonic or spintronic devices. Permalloy (Ni\textsubscript{80}Fe\textsubscript{20} alloy, Py) nanostructures have already demonstrated great potential and versatility in developing devices used for logic, data storage\textsuperscript{9}, and biological sensing\textsuperscript{10}. Py and other ferromagnetic metals, however, exhibit plasmon-magnon interactions that heavily damp spin wave propagation through in them. Unfortunately, nanofabrication of YIG based devices have been difficult due to the high cost of integration of epitaxial YIG films and compatibility issues with current Complementary Metal Oxide Semiconductor technology. Several groups have tried various methods of pattern YIG. One route involves the ion etching of sputtered YIG films using resist masks to define the patterned structures\textsuperscript{11}. However, high energy Ar ions can damage the film quality which may lead to high damping in YIG films\textsuperscript{12}. Ion milling of YIG thin films can also change the magnetic properties of the film\textsuperscript{11}, making this process less suitable. Another alternate route involves the etching of the GGG substrate itself\textsuperscript{13} followed by sputter deposition of YIG. The most common method to fabricate YIG nanostructures involves electron beam lithography (EBL) and lift-off process\textsuperscript{14}. However, to overcome electron charging effects that makes EBL taxing, since high-quality
epitaxial YIG films can only be grown on an insulating GGG substrate, a thin gold layer is deposited on GGG before the electron beam resist is coated which is followed by a high voltage electron exposure and subsequent gold etching. Subsequently, YIG film is deposited by magnetron sputtering followed by a final lift-off. This multi-stage fabrication process makes EBL expensive and cumbersome. Another interesting technique employed to pattern YIG on silicon substrates makes use of anodic Alumina oxide (AAO) membranes which are used for masking purposes. This technique however is limited to specific geometry and lacks uniformity. High quality YIG films with Gilbert damping less than $10^{-4}$ can also be grown using liquid phase epitaxy (LPE), however they are usually above 100 nm thick because LPE-YIG quality starts to degrade for ultra-thin YIG samples. For ultra-thin YIG films, pulsed laser deposition (PLD) is preferred however magnetron sputtering is more compatible with the industry.

To circumvent these problems associated with nano-patterning of YIG films on GGG substrates, we propose a simple method that involves the use of stray fields to virtually transfer magnetic information from Py dot arrays through exchange coupling unto the underlying YIG film. Since, spin wave information generated in either layer can be transferred to each other and local stray fields from the Py structures can alter the propagation of spin waves inside YIG. Various studies have also attempted to tune spin waves in YIG thin film by depositing a Py layer adjacent to it. Py nanostructures on top of YIG were also previously investigated to demonstrate a microwave magnonic transducer, however, the effects of the stray fields from Py nanostructures have not been investigated. Our fabrication process will make use of resistless nano stencil lithography to deposit high-quality Py dots on YIG films. Compared to conventional nanostructure fabrication processes, which comprises of multiple resist processing, dispositions and chemical processes, nanostencil lithography is nondestructive which is crucial to prevent any parasitic spin wave
excitations due to non-uniformity in edges. Up till now, stencil lithography has been used to fabricate contacts on graphene since it prevents any surface contaminants during the process\textsuperscript{21}. Nano magnetic logic devices\textsuperscript{22} and nanostructured antenna arrays\textsuperscript{23} have also been fabricated using stencil lithography.

In this paper, we fabricate hybrid Py nanodots/YIG structures by first depositing a high-quality YIG film on a GGG substrate by magnetron sputtering and post-deposition annealing process. This was followed by the deposition of Py nanodots using nanostencil lithography\textsuperscript{24}. Nanostencil lithography is resistless and requires no prior coating with toxic solvents or prior treatment of the substrate. Nanostencil lithography is a parallel process which can be used to pattern large area in a single step deposition compared with a multi-level EBL process\textsuperscript{25}. In our fabrication process, nanopatterned stencils are placed over the substrates while the material is evaporated in a vacuum chamber. The evaporated material passes through the apertures in the stencils and are deposited on the substrate placed over it. Later the stencils are removed and can be used again. Micromagnetic simulations were performed to understand both the static and dynamic behavior of the hybrid Py nanodots/YIG structure.

**Experimental Details**

**Sample Fabrication:** 20 nm YIG films were sputter deposited on (111)-oriented gadolinium gallium garnet (Gd\textsubscript{3}Ga\textsubscript{5}O\textsubscript{12}, GGG) single crystal substrates at room temperature (RT) from a commercial YIG sputter target. The chamber partial pressure and sputtering power were kept at 3 mTorr and 150 W respectively, which is the optimal deposition environment for RT growth. The films were subsequently subjected to an ex-situ post annealing at 800 °C for 12 hours in a furnace. Heating and cooling were performed at 1 °C per minute. After the samples were annealed, XRD
and FMR spectroscopy was performed on a sample from the same batch to determine crystallinity and film quality. A stencil membrane with regularly spaced holes was placed on top of the YIG thin film grown on GGG and Py was evaporated to fabricate the Py dots on the YIG film. The chamber pressure was about 8 x 10^{-8} Torr during the evaporation process.

**FMR measurements:** A typical microstrip line FMR setup was used for the dynamic magnetization measurements. The sample was placed flipped down on the stripline. The external magnetic field was swept from 5000 Oe to 200 Oe at a constant frequency (f) supplied by a Vector Network Analyzer to generate the dynamic magnetic field. A lock-in detection technique was used to measure the absorbed power (dP/dH) by the sample for discrete frequencies from 2 GHz to 15 GHz.

**Simulation details:** Micromagnetic simulations at T = 0 K using the OOMMF software were performed. We list the simulation parameters used for the Py and the YIG layers: The saturation magnetization $M_\text{Py}^{S} = 800 \text{ emu/cm}^3$ and $M_\text{YIG}^{S} = 160 \text{ emu/cm}^3$, the exchange constant $A_\text{Py} = 13 \times 10^{-7} \text{ erg/cm}$ and $A_\text{YIG} = 4 \times 10^{-7} \text{ erg/cm}$. For both the layers, the magnetocrystalline anisotropy $K_1 = 0 \text{ erg/cm}^3$. The magnetocrystalline anisotropy of the bulk Py film was assumed to be negligible when compared with the shape anisotropy of the patterned nano dots. The most important parameter for our simulation is the exchange parameter between the YIG and Py layer which represents the strength of the ferromagnetic interaction between the layers. Periodic boundary conditions were also used. This interaction can be described by a bilinear exchange constant ‘J’. In the simulations we have used $J= 0.18 \text{ erg/cm}^2$. A unit cell size of $5 \times 5 \times 5 \text{ nm}^3$ was used for simulating the static magnetization. To simulate the magnetization reversal process the damping coefficient of $\alpha$ for both were taken as 0.5 for rapid convergence. To simulate the dynamic magnetization response, time (t) dependent simulations were performed using a sinc wave function.
excitation field: \( h_{\text{sinc}} = h_0 \frac{(\sin(2\pi f t))}{t} \), where \( h_0 = 50 \) Oe, with a gyromagnetic ratio \( \gamma/2\pi = 2.8 \) GHz/kOe. The damping coefficient for YIG and Py were taken as \( \alpha^{\text{YIG}} = 0.001 \) and \( \alpha^{\text{Py}} = 0.008 \).

The sinc wave was used in the simulation to yield a uniform excitation in the frequency domain. The dynamic simulation results were analyzed in the frequency domain after Fast Fourier Transform (FFT) processing.

**Results and Discussions**

To fabricate these structures, Py dots were deposited on the 20 nm YIG continuous film using stencil lithography. As shown in Fig. 1a a membrane with the desired pattern was placed on top of the YIG film grown on GGG by magnetron sputtering. This membrane allowed only evaporated Py to pass through the nanosized apertures. After removing the membrane, an atomic force microscopy (AFM) analysis was performed to measure the surface morphology of the fabricated samples. Regularly spaced dots were observed and are presented in Fig. 1b. The AFM results show Py dots of diameter 500 nm, arranged with a center-to-center distance of 1000 nm. The thickness of the dots was found to be 50 nm. A longitudinal magneto-optical Kerr effect (MOKE) setup was used to obtain the normalized \( M-H \) loop from the sample of Py dots on YIG as shown in Fig. 1c. The \( M-H \) loop shows regions of saturation, nucleation, and vortex which were in good agreement with the simulated results in Fig. 4a. Before deposition, a YIG film grown under the exact conditions was used to characterize the YIG film for its damping and crystallography. The inset in Fig. 1c shows the \( 2\theta \) scan for the sample. The result reveals the existence of the YIG phase with no other phases, suggesting that the YIG thin film is well crystallized along with the (111) orientation. The ferromagnetic resonance (FMR) spectra were recorded in the frequency range...
from 2 GHz to 15 GHz and magnetic field was swept from 200 Oe to 5 kOe therefore magnetization dynamics were studied only in the saturated region.

In Fig. 2a the normalized FMR response at 12 GHz from a 20 nm continuous film of YIG is presented in the top panel while the response from a 50 nm Py dot array deposited on GGG is presented in the middle panel and the response from the Py dots grown on the YIG film is presented in the bottom panel. A plot of the resonance frequencies of the continuous YIG film and the two strongest modes observed in the Py dot array on GGG are shown in Fig. 2b using solids symbols. At 1000 Oe, the resonance for the YIG film occurred at 4.3 GHz while the strongest mode for the Py dots occurred at 8 GHz. The resonance frequencies from the continuous YIG film were analyzed by fitting the data to the Kittel equation:

\[
f_r = \frac{\gamma}{2\pi} \left[ \left( H + (N_x - N_x)4\pi M_x \right) \left( H + (N_y - N_x)4\pi M_x \right) \right]^{1/2}
\]

Where, \( M_x \) is the magnetization along the applied field direction, \( H \) is the external applied magnetic field, \( N_x, N_y, N_z \) are the demagnetizing factors of the area along the \( X-Y \) and thickness (\( Z \)) directions of the film. \( \gamma \) is the gyromagnetic ratio. \( 4\pi M_s \) and \( \gamma/2\pi \) values were found to be 1196.1 Oe and 2.88 MHz/Oe respectively. The linewidth (\( \Delta H \)) of the spectra was obtained by measuring the peak-to-peak distance as shown in the inset of Fig. 2b. \( \Delta H \) was also observed to increase linearly with frequency and was analyzed using the relationship: \( \Delta H = \Delta H_0 + 1.16 \alpha (2\pi f / \gamma) \). Here \( \Delta H_0 \) is the inhomogenous line width and \( \alpha \) is the gilbert damping factor which was found to be \( 1.72 \times 10^{-4} \). This low damping confirmed the quality of the fabricated YIG thin film and thus it can be used for spin wave propagation. The FMR response from the Py dot array on GGG at 12 GHz showed multiple modes at a lower field region far away from the mode observed for the YIG sample. In the sample with the Py dots grown on YIG two group of modes were distinctly observed.
at 12 GHz. The high field modes displayed narrow line widths while the low field modes were broader with lower signal strength. The signal strength for the Py dots is lower since the volume of Py contributing to the FMR signal was less than the YIG continuous film. A zoomed in view of the low field modes is shown in the inset of Fig. 2a.

The FMR response from the sample of Py dots grown on YIG is presented as a function of resonance frequency in Fig. 3a. Three distinct narrow modes were observed moving to higher fields as the frequency increased. Similarly, a group of broad resonance modes were observed at lower magnetic fields for 10, 12 and 15 GHz. The frequencies corresponding to the resonant fields are plotted in Fig. 3b. The modes occurring at the high field values were labeled as \( Y_1 \), \( Y_2 \), \( Y_3 \) depending on field value they occurred at, with \( Y_1 \) occurring at the highest field and \( Y_3 \) occurring at the lowest field. Similarly, the two most prominent modes occurring at the lower fields were labelled as PyD\(_1\) and PyD\(_2\). The FMR signals from these modes were very small as compared to the modes observed in the YIG layer therefore, we focus primarily on the YIG modes. Comparing these modes with the modes in Fig. 2, mode \( Y_1 \) occurred around the same field as the fundamental mode observed in the YIG film. At 12 GHz, the three high field modes occurred at 3396 Oe, 3538 Oe and 3615 Oe with line widths of 27 Oe, 26 Oe and 24 Oe respectively. The FMR mode for the continuous YIG film occurred at 3613 Oe with a line width of 24 Oe. We can infer that the continuous YIG film mode is present in the YIG/Py(dots) sample and occurs along with additional modes due to the influence of the Py dots. \( Y_1 \) appears to be the mode originating from the continuous YIG film while \( Y_2 \) and \( Y_3 \) are the distinct modes due to an increased contribution of stray fields\(^\text{27}\) from Py dots. From the linewidth analysis, the damping parameter for the three modes \( Y_1 \), \( Y_2 \) and \( Y_3 \) were found to be \( \alpha_{Y_1} = 2.31 \times 10^{-4} \), \( \alpha_{Y_2} = 4.19 \times 10^{-4} \) and \( \alpha_{Y_3} = 2.97 \times 10^{-3} \).
the increase in damping parameters can be attributed to additional loss channels due to the coupling of spin wave modes. Thus, there was no decrease in the quality of the YIG film due to the deposition of Py using stencil lithography.

To understand the experimental results further, in Fig. 4a we present simulated magnetization ($M$) versus field ($H$) curve for our fabricated YIG/Py (nanodots) sample. In the simulation, YIG thickness was fixed at 20 nm and Py thickness was fixed at 50 nm. The Py dots were 500 nm in diameter and the edge-to-edge distance was kept also at 500 nm (center to center distance was 1000 nm). The magnetization of the sample was simulated from -5kOe to 5kOe (presented by red dots) and from 5kOe to -5kOe (presented by black dots). The $M-H$ loop is similar to the $M-H$ loops of Py dot arrays as previously reported investigating the vortex state (VS) in Py dots\textsuperscript{28,29}. The magnetization in both the Py dots as well as the YIG layer have been presented in Fig. 4b- Fig. 4e for -1000Oe, 0Oe, 600Oe, and 1000Oe respectively. At -1000 Oe, the magnetic moments in the Py dots and YIG layer are saturated along the applied field direction. As the field is decreased, the magnetic moments in the Py dots relax following the circumference of the dot and a sharp decrease in magnetization corresponds to nucleation of the VS. Due to the exchange interaction of the Py dots to the YIG film, the YIG underneath the Py dots also nucleate to form a VS. The vortex is at the center of the Py dots at 0 Oe. The VS in the YIG layer has the same polarity as the Py dots due to the ferromagnetic exchange coupling between the layers. As the field is further increased, the vortex core moves perpendicular to the applied magnetic field and is annihilated when it reaches the top/bottom. The YIG region directly below the Py dots follow the magnetization states of the Py dots. Qualitatively, we observe two distinct regions in the YIG layer. One corresponding to the region underneath the Py dots which behave like YIG nanodots but follow the magnetization of Py dots, and the other region corresponding to the rest of the YIG film. There are sharp domains
seen near the edge of the Py Dots on the YIG film, these can be explained as due to the interaction of the induced vortex magnetization in the YIG film with the surrounding magnetization of in the YIG film. Further simulations were done by increasing the Py dot diameter D = 250, 500, 800nm while keeping center to center distance the same, and similar stray field effects were observed. The magnetic states of the Py dots were transferred to the underlying YIG film. With increase in diameter the nucleation starts to occur earlier while annihilation is at a higher magnetic fields as show in the inset of Fig. 4a. Thus the simulations show considerable agreement with our proposal to tune a continuous YIG film to form pseudo-YIG nanostructures.

To understand the magnetization dynamics of the structure, dynamic simulations were also carried out. In the simulations, the Py dots were perfect and completely cylindrical. The simulated spectra for the structure are presented in Fig. 5a along with the simulated spectra for Py dots, continuous film of YIG, YIG dots, and YIG antidots at 1000 Oe applied magnetic field. The resonance modes and their corresponding mode profiles have also been presented in the Fig. 5b. The simulated results from Py dots as well as the YIG continuous film exhibited a single resonance mode. Resonance in the Py dots occurred at 8.20 GHz showing a central mode in each dot which has been labeled as PyD-1 and the resonance for the continuous YIG film occurred at 4.78 GHz labeled as YIG-a. The simulations for the YIG antidot and YIG dot structures exhibited two resonance modes at 4.69 GHz and 4.10 GHz. Three distinct modes were observed for the combined structure of Py dots on the YIG film. Mode YIG/PyD-1 occurred at 8.79 GHz and modes YIG/PyD-a and YIG/PyD-b occurred at 5.27 GHz and 4.49 GHz respectively. The mode profiles for these modes are given in Fig. 5c with the contours of the Py dots overlaid on the spin-wave intensity map of the YIG layer.
In the mode YIG/PyD-1 occurring at 8.79 GHz, the YIG layer exhibits no distinct spin-wave mode while the Py dots on top of the YIG exhibit intense central modes similar to the mode PyD-1 in the sample of only Py dots. The lower frequency modes correspond to spin-wave excitations predominantly in the YIG film. The spin wave intensity is along the applied field direction for the mode YIG/PyD-a and perpendicular to the applied field in YIG/PyD-b. Comparing with experimental data $Y_3$ corresponds to YIG/PyD-a and $Y_2$ corresponds to YIG/PyD-b.

Interestingly, for both, the modes YIG/PyD-a and YIG/PyD-b do not run throughout the parallel strips below the Py dots which is in contrast with what was observed by Duerr et al.\textsuperscript{31} in an antidot lattice of Py with Co nanodisks. For the YIG/PyD-b mode, the spin waves are localized along the perpendicular direction of applied magnetic field and in-between the dot contour overlays. Spin wave modes are also localized near the edges of the Py dots and can be observed in both the YIG layer as well as in the Py layer. In the YIG layer, this is similar to the mode observed in the YIG dots (YIG-D-b). Therefore, this proposed structure has the potential to show interesting properties in terms of both its static and dynamic properties.

**Conclusions**

We have demonstrated a simple and reliable method to indirectly pattern YIG films on a GGG substrates. We fabricated exchange-coupled Py dots array unto the underlying YIG film using nano stencil lithography. The stray field generated from the Py dots array is used to communicate patterned magnetic information unto the underlying YIG films. For the reference YIG film, as expected, a single field-dependent resonance mode with a narrow linewidth was observed. In contrast, for the hybrid YIG/Py dots structure three distinct YIG resonance modes were observed.
as predicted by micromagnetic simulations. Thus, we have demonstrated the use of the stray fields to pattern YIG films, opening up a new route for the development of future YIG based magnonic devices.

Conflicts of interest

There are no conflicts to declare.

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Fig. Captions:

Fig. 1. (a) Schematic diagram of the deposition method. Py dots were fabricated on top of a YIG thin film grown on GGG using a stencil membrane. (b) AFM images of the Py dots. (c) Normalized $M-H$ loop obtained from the longitudinal MOKE setup which is agreement with the simulated $M-H$ loop. Inset: the XRD pattern of the continuous YIG film on GGG.

Fig. 2. (a) Resonance spectra at 12 GHz for a continuous YIG film on GGG (top panel), Py dots deposited on GGG (middle panel), and Py dots on the YIG film (bottom panel). Inset in the bottom panel: Zoomed view of the low field resonance modes. (b) The resonance frequencies corresponding to their resonance fields for the sample of YIG continuous film (red squares) and Py dots grown on GGG (green symbols). The solid line represents the Kittel fit of the resonance frequencies observed for the YIG continuous film. The lines joining the resonance frequencies for the Py dots are provided to identify the different modes. Inset: Zoomed view of the spectra obtained from the continuous YIG film at 12 GHz. The linewidth ($\Delta H$) of resonance was taken as the peak to peak distance.

Fig. 3. (a) Resonance spectra for the sample of Py dots grown on YIG thin film at 5, 8, 10, 12, 15 GHz. (b). Resonance frequencies corresponding to the resonance fields for the same sample. The solid lines $Y_1$, $Y_2$, and $Y_3$ and the low field modes $PyD_1$ and $PyD_2$ are connected by dotted lines to aid the eye.
Fig. 4. (a) Simulated hysteresis loop for the sample of Py dots on YIG. The dot were placed 1000 nm (center to center distance) away from each other with diameter D = 500nm. Red color depicts sweep from -5 kOe to +5 kOe, black curve is the reverse sweep. (i)-(iv) Magnetization states of the bilayer structure corresponding to the locations in the $M-H$ loop when taken from negative saturation to positive saturation. Inset: Simulated hysteresis loop for Py dots with D= 250nm, 500nm and 800nm.

Fig. 5. (a) Simulated dynamic spectra for a sample of only Py dots (50 nm thick, 500 nm in diameter with a spacing of 1000 nm between the dots), a 20nm thick continuous film of YIG, a sample of YIG film with empty holes (YIG antidots), a sample of 20nm thick YIG dots and a sample of Py dot array on YIG (b) (i)-(v) are the mode profiles of the PyD-1, YIG-D-a, YIG-D-b, YIG-AD-a, and YIG-AD-b modes identified in the simulated dynamic spectra in the $m_z$ direction. (c) (i)-(iii) are the mode profiles of the YIG/PyD-1, YIG/PyD-a, and YIG/PyD-b modes -AD-b modes identified in the simulated dynamic spectra for the Py dot array on YIG. The yellow circles are used to indicate the position of the Py dots on top of the YIG layer.

Fig. 1. Chaudhuri et al.
Fig. 2. Chaudhuri et al.

Fig. 3. Chaudhuri et al.
Fig. 4. Chaudhuri et al.

Fig. 5. Chaudhuri et al.
References


