Ultra-low damping insulating magnetic thin films get perpendicular

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A magnetic material combining low losses and large perpendicular magnetic anisotropy (PMA) is still a missing brick in the magnonic and spintronic fields. We report here on the growth of ultrathin Bismuth doped Y3Fe5O12 (BiYIG) films on Gd3Ga5O12 (GGG) and substituted GGG (sGGG) (111) oriented substrates. A fine tuning of the PMA is obtained using both epitaxial strain and growth-induced anisotropies. Both spontaneously in-plane and out-of-plane magnetized thin films can be elaborated. Ferromagnetic Resonance (FMR) measurements demonstrate the high-dynamic quality of these BiYIG ultrathin films; PMA films with Gilbert damping values as low as $3 \times 10^{-4}$ and FMR linewidth of 0.3 mT at 8 GHz are achieved even for films that do not exceed 30 nm in thickness. Moreover, we measure inverse spin hall effect (ISHE) on Pt/BiYIG stacks showing that the magnetic insulator’s surface is transparent to spin current, making it appealing for spintronic applications.

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Spintronics exploits the electron’s spin in ferromagnetic transition metals for data storage and data processing. Interestingly, as spintronics codes information in the angular momentum degrees of freedom, charge transport and therefore the use of conducting materials is not a requirement, opening thus electronics to insulators. In magnetic insulators (MI), pure spin currents are described using excitation states of the ferromagnetic background named magnons (or spin waves). Excitation, propagation and detection of magnons are at the confluence of the emerging concepts of magnonics\cite{12,13}, caloritronics\cite{3}, and spin-orbitronics\cite{4}. Magnons, and their classical counterpart, the spin waves (SWs), can carry information over distances as large as millimeters in high-quality thick YIG films, with frequencies extending from the GHz to the THz regime\cite{5,6,7}.

The main figure of merit for magnonic materials is the Gilbert damping $\alpha_{G}$, which has to be as small as possible. This makes the number of relevant materials for SW propagation quite limited and none of them has yet been found to possess a large enough perpendicular magnetic anisotropy (PMA) to induce spontaneous out-of-plane magnetization. We report here on the Pulsed Laser Deposition (PLD) growth of ultra-low loss MI nanometers-thick films with large PMA: Bi substituted Yttrium Iron Garnet ($\text{Bi}_{x}\text{Y}_{3-x}\text{Fe}_{5}\text{O}_{12}$, or BiYIG) where tunability of the PMA is achieved through epitaxial strain and Bi doping level. The peak-to-peak FMR linewidth (that characterize the losses) can be as low as $\mu_{0}\Delta H_{\text{pp}} = 0.3$ mT at 8 GHz for 30 nm thick films. This material thus opens new perspectives for both spintronics and magnonics fields as the SW dispersion relation can now be easily tuned through magnetic anisotropy without the need of a large bias magnetic field. Moreover, energy efficient data storage devices based on magnetic textures existing in PMA materials like magnetic bubbles, chiral domain walls, and magnetic skyrmions would benefit from such a low loss material for efficient operation\cite{9}.

The study of micron-thick YIG films grown by liquid phase epitaxy (LPE) was among the hottest topics in magnetism few decades ago. At this time, it has been already noticed that unlike rare earths (Thulium, Terbium, Dysprosium …) substitutions, Bi substitution does not overwhelmingly increase the magnetic losses\cite{10,11} even though it induces high uniaxial magnetic anisotropy\cite{12,13,14,15}. Very recently, ultra-thin MI films showing PMA have been the subject of an increasing interest\cite{15,16,17,18}. $\text{TmFe}_{2}\text{O}_{3}$ or $\text{BaFe}_{2}\text{O}_{19}$ (respectively a garnet and an hexaferrite) have been used to demonstrate spin-orbit-torque magnetization reversal using a Pt over-layer as a source of spin current.\cite{14,17,18}. However, their large magnetic losses prohibit their use as a spin-wave medium (reported value of $\mu_{0}\Delta H_{\text{pp}}$ of TIG is 16.7 mT at 9.5 GHz).\cite{19}.

Hence, whether it is possible to fabricate ultra-low loss thin films with a large PMA that can be used for both magnonics and spintronics applications remains to be demonstrated. Indeed, not only low losses are important for long range spin wave propagation but they are also necessary for spin transfer torque oscillators (STNOs) as the threshold current scales with the Gilbert damping.\cite{20}.

In the quest for the optimal material platform, we explore here the growth of Bi doped YIG ultra-thin films using PLD with different substitution; $\text{Bi}_{x}\text{Y}_{3-x}\text{IG}$ ($x = 0.7$, $1$, and $1.5$) and having a thickness ranging between 8 and 50 nm. We demonstrate fine tuning of the magnetic anisotropy using epitaxial strain and measure ultra low Gilbert damping values ($\alpha = 3 \times 10^{-4}$) on ultrathin films with PMA.

### Results

**Structural and magnetic characterizations.** The two substrates that are used are gallium gadolinium garnet (GGG), which is best lattice matched to pristine YIG and substituted GGG (sGGG) which is traditionally used to accommodate substituted YIG films for photonics applications. The difference between Bi and Y ionic radius ($r_{\text{Bi}} = 113$ pm and $r_{\text{Y}} = 102$ pm)\cite{21} leads to a linear increase of the $\text{Bi}_{x}\text{Y}_{3-x}\text{IG}$ bulk lattice parameter with Bi content (Fig. 1a, b). In Fig. 1, we present the (20–0) X-ray diffraction patterns (Fig. 1c, d) and reciprocal space maps (RSM) (Fig. 1e, f) of BiYIG on sGGG (111) and GGG(111) substrates, respectively. The presence of (222) family peaks in the diffraction spectra shown in Fig. 1b, c is a signature of the films’ epitaxial quality and the presence of Laue fringes attests the coherent crystal structure existing over the whole thickness. As expected, all films on GGG are under compressive strain, whereas films grown on sGGG exhibit a transition from a tensile ($x = 0.7$ and 1) towards a compressive ($x = 1.5$) strain. Reciprocal space mapping of these BiYIG samples shown in Fig. 1e, f evidences the pseudomorphic nature of the growth for all films, which confirms the good epitaxy.

The static magnetic properties of the films have been characterized using SQUID magnetometry, Faraday rotation measurements and Kerr microscopy. As the Bi doping has the effect of enhancing the magneto-optical response, the peak-to-peak FMR linewidth (that characterize the losses) can be as low as $\mu_{0}\Delta H_{\text{pp}} = 0.3$ mT at 8 GHz for 30 nm thick films. This material thus opens new perspectives for both spintronics and magnonics fields as the SW dispersion relation can now be easily tuned through magnetic anisotropy without the need of a large bias magnetic field. Moreover, energy efficient data storage devices based on magnetic textures existing in PMA materials like magnetic bubbles, chiral domain walls, and magnetic skyrmions would benefit from such a low loss material for efficient operation.

### Dynamical characterization and spin transparency

The most striking feature of these large PMA films is their extremely low magnetic losses that we characterize using Ferromagnetic Resonance (FMR) measurements. First of all, we quantify by in-plane FMR the anisotropy field $H_{\text{KU}}$ deduced from the effective magnetization ($M_{\text{eff}}$): $H_{\text{KU}} = M_{\text{eff}} - M_{\text{sat}}$ (the procedure to derive $M_{\text{eff}}$ from in-plane FMR is presented in Supplementary Note 3). $H_{\text{KU}}$ values for BiYIG films with different doping levels grown on various substrates are summarized in Table 1. As expected from out-of-plane hysteresis curves, we observe different signs for $H_{\text{KU}}$. For spontaneously out-of-plane magnetized samples, $H_{\text{KU}}$ is...
positive and large enough to fully compensate the demagnetizing field while it is negative for in-plane magnetized films. From these results, one can expect that fine tuning of the Bi content allows fine tuning of the effective magnetization and consequently of the FMR resonance conditions. We measure magnetic losses on a 30 nm thick Bi$_{1}$Y$_{2}$IG//sGGG film under tensile strain with PMA (Fig. 3a). We use the FMR absorption line shape to extract the peak-to-peak linewidth ($\Delta H_{pp}$) at different out-of-plane angle for a 30 nm thick perpendicularly magnetized Bi$_{1}$Y$_{2}$IG//sGGG film at 8 GHz (Fig. 3b). This yields an optimal value of $\mu_0 \Delta H_{pp}$ as low as 0.3 mT for 27° out-of-plane polar angle. We stress here that state-of-the-art PLD grown YIG//GGG films exhibit similar values for $\Delta H_{pp}$ at such resonant conditions$^{28}$. This angular dependence of $\Delta H_{pp}$ that shows pronounced variations at specific angle is characteristic of a two magnons scattering relaxation process with few inhomogeneities$^{29}$. The value of this angle is sample dependent as it is related to the distribution of the magnetic inhomogeneities. The dominance in our films of those two

![Graphs and diagrams related to structural properties of ultra-thin BiYIG films.](image)

Fig. 1 Structural properties of ultra-thin BiYIG films. a and b Evolution of the target cubic lattice parameter of Bi$_x$Y$_{3-x}$IG, the dashed line represents the substrate (sGGG and GGG, respectively) lattice parameter and allows to infer the expected tensile or compressive strain arising for each substrate/target combination. c and d 2θ-ω X-Ray diffraction scan along the (111) out-of-plane direction for Bi$_x$Y$_{3-x}$IG films grown on sGGG (111) and GGG (111), respectively. From the film and substrate diffraction peak position, we can conclude about the nature of the strain. Compressive strain is observed for 1.5 doped films grown on sGGG substrate and for all films grown on GGG whereas tensile strain occurs for films with $x = 0.7$ and $x = 1$ Bi content grown on sGGG. e and f RSM along the evidence the (642) oblique plan showing pseudomorphic growth in films: both substrate and film the diffraction peak are aligned along the $q_{x}/[20-2]$ direction. The relative position of the diffraction peak of the film (up or down) along $q_x$ is related to the out-of-plane misfit between the substrate and the film (tensile or compressive).
Table 1 Summary of the magnetic properties of Bi$_x$Y$_{3-x}$IG films on GGG and sGGG substrates

| Bi doping | Substrate | $\mu_0 M_S$ (mT) | $\mu_0 M_{eff}$ (mT) | $\mu_0 H_{KU}$ (mT) |
|-----------|-----------|----------------|---------------------|---------------------|
| 0         | GGG       | 157            | 200                  | $-43$               |
| 0.7       | sGGG      | 180            | $-151$               | 331                 |
| 0.7       | GGG       | 172            | 214                  | $-42$               |
| 1         | sGGG      | 172            | $-29$                | 201                 |
| 1         | GGG       | 160            | 189                  | $-29$               |
| 1.5       | sGGG      | 162            | 278                  | $-116$              |

The saturation magnetization is roughly unchanged. The effective magnetization $M_{eff}$ obtained through broad-band FMR measurements allow to deduce the out-of-plane anisotropy fields $H_{KU}$ ($H_{KU} = M_S - M_{eff}$) confirming the dramatic changes of the out-of-plane magnetic anisotropy variations observed in the hysteresis curves.

Fig. 2 Static magnetic properties. a Out-of-plane Kerr hysteresis loop performed in the polar mode for Bi$_x$Y$_{3-x}$IG films grown on the two substrates: GGG and sGGG. b Same measurement for Bi$_x$Y$_{3-x}$IG grown on sGGG with the three different Bi doping ($x = 0.7, 1,$ and $1.5$). Bi$_x$Y$_{3-x}$IG//GGG is in-plane magnetized whereas perpendicular magnetic anisotropy (PMA) occurs for $x = 0.7$ and $x = 1$ films grown on sGGG: square shaped loops with low saturation field ($\mu_0 H_{sat}$ about 2.5 mT) are observed. Those two films are experiencing tensile strain. Whereas the inset shows that the Bi$_1Y_2IG$ film saturates at a much higher field with a curve characteristic of in-plane easy magnetization direction. Note that for Bi$_{1-x}Y_xIG$/sGGG $\mu_0 H_{sat} \approx$290 mT > $\mu_0 H_{sat}$=162 mT which points toward a negative uniaxial anisotropy term ($\mu_0 H_{KU}$) of 128 mT which is coherent with the values obtained from in-plane FMR measurement. c Magnetic domains structure imaged on Bi$_1Y_2IG$/sGGG films of three different thicknesses at remanant state after demagnetization. The scale bar, displayed in blue, equals 20 µm. Periods of the magnetic domains structure ($D_{magn}$) are derived using 2D Fast Fourier Transform. We obtained $D_{magn} =$ 3.1, 1.6, and 0.4 µm for $t_{BiY2IG} =$ 32, 47, and 52 nm, respectively. We note a decrease of $D_{magn}$ with increasing $t_{BiY2IG}$ that is coherent with the Kaplan and Gehring model validate in the case $D_{magn} \gg t_{BiY2IG}$.
where $M_i$ and $I_{\text{diam}}$ are the BiYIG magnetization and thickness, $g_{\text{eff}}$ is the effective Landé factor ($g_{\text{eff}} = 2$), $\mu_B$ is the Bohr magneton and $\Delta$ is the increase in the Gilbert damping constant induced by the Pt top layer. We obtain $G_{11} = 3.9 \times 10^{18} \text{m}^{-2}$ which is comparable to what is obtained on PLD grown YIG/GGG systems. Consequently, the doping in Bi should not alter the spin-orbit-torque efficiency and spin-torque devices made out of BiYIG will be as energy efficient as their YIG counterpart. To further confirm that spin current crosses the Pt/BiYIG interface, we measure Inverse Spin Hall Effect (ISHE) in Pt for a Pt/Bi$_{1.5}$Y$_{1.5}$IG(20 nm)/sGGG in-plane magnetized film (to fulfill the ISHE geometry requirements the magnetization needs to be in-plane and perpendicular to the measured voltage). We measure a characteristic voltage peak due to ISHE that reverses its sign when the static in-plane magnetic field is reversed (Fig. 4). We emphasize here that the amplitude of the signal is similar to that of Pt/YIG//GGG in the same experimental conditions.

### Methods

#### Pulsed laser deposition (PLD) growth.

The PLD growth of BiYIG films is realized using stoichiometric BiYIG target. The laser is used is a frequency tripled Nd:YAG laser ($\lambda = 355$ nm), of a 2.5 Hz repetition rate and a fluency varying from 0.95 to 1.43 J cm$^{-2}$ depending upon the Bi doping in the target. The distance between target and substrate is fixed at 44 mm. Prior to the deposition the substrate is annealed at 700 °C under 0.4 mbar of O$_2$. For the growth, the pressure is set at 0.25 mbar O$_2$, pressure. The optimum growth temperature varies with the Bi content from 400 to 550 °C. At the end of the growth, the sample is cooled down under 300 mbar of O$_2$.

#### Structural characterization.

An Empyrean diffractometer with Ka$_1$ monochromator is used for measurement in Bragg-Brentano reflection mode to derive the (111) interplanar distance. Reciprocal Space Mapping is performed on the same diffractometer and we used the diffraction along the (642) plane direction which allow to gain information on the in-plane epitaxy relation along [20-2] direction.

#### Magnetic characterization.

A quantum design SQUID magnetometer was used to measure the films’ magnetic moment ($M_i$) by performing hysteresis curves along the easy magnetic direction at room temperature. The linear contribution of the paramagnetic (sGGG or GGG) substrate is linearly subtracted. Kerr microscope (Evoico Magnetics) is used in the polar mode to measure out-of-plane hysteresis curves at room temperature. The same microscope is also used to image the magnetic domains structure after a demagnetization procedure. The spatial resolution of the system is 300 nm.

A broadband FMR setup with a motorized rotation stage was used. Frequencies from 1 to 20 GHz have been explored. The FMR is measured as the derivative of microwave power absorption via a low frequency modulation of the DC magnetic field. Resonance spectra were recorded with the applied static magnetic field oriented in different geometries (in-plane or tilted of an angle $\theta$ out of the stripine plane). For out-of-plane magnetized samples the Gilbert damping parameter has been obtained by studying the linewidth angular dependence. The procedure assumes that close to the minimum linewidth (Fig. 3a) most of the linewidth angular dependence is dominated by the inhomogeneous broadening, thus optimizing the angle for each frequency within few degrees allows to estimate better the intrinsic contribution. To do so we varied the out-of-plane angle of the static field from 27° to 34° for each frequency and we select the lowest value of $\Delta H_{\text{FWHM}}$.

For Inverse spin Hall effect measurements, the same FMR setup was used, however here the modulation is no longer applied to the magnetic field but to the RF power at a frequency of 5 kHz. A Stanford Research SR860 lock-in was used a signal demodulator.

#### Data availability.

The data that support the findings of this study are available within the article or from the corresponding author upon reasonable request.

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### References

1. Karenowska, A. D., Chumak, A. V., Serga, A. A. & Hillebrands, B. Magnon spintronics. *Handb. Spintron.* 11, 1505–1549 (2015).
2. Chumak, A. V., Serga, A. A. & Hillebrands, B. Magnonic crystals for data processing. *J. Phys. D: Appl. Phys.* 50, 244001–20 (2017).
3. Bauer, G. E. W., Saitoh, E. & Van Wees, B. J. Spin caloritronics. *Nat. Mater.* 11, 391–399 (2012).
4. Li, P. et al. Spin-orbit torque-assisted switching in magnetic insulator thin films with perpendicular magnetic anisotropy. *Nat. Commun.* 7, 12688 (2016).
5. Serga, A. A., Chumak, A. V. & Hillebrands, B. YIG magnonics. *J. Phys. D: Appl. Phys.* 43, 244002–16 (2010).
6. Seifert, T. et al. Launching magnons at the terahertz speed of the spin Seebeck effect. *Prepr. http://arxiv.org/abs/1709.00768* (2017).
7. Onbashi, M. C. et al. Pulsed laser deposition of epitaxial yttrium iron garnet films with low Gilbert damping and bulk-like magnetization. *APL Mater.* 2, 108102 (2014).
8. Zakeri, X. et al. Spin dynamics in ferromagnets: Gilbert damping and two-magnon scattering. *Phys. Rev. B* 76, 104416 (2007).
9. Fert, A., Cros, V. & Sampaio, J. Skyrmions on the track. *Nat. Nanotechnol.* 8, 152–156 (2013).
10. Vittoria, C., Lubitz, P., Hansen, P. & Tollkodorf, W. FMR linewidth measurements in bismuth-substituted YIG. *J. Appl. Phys.* 57, 3699–3700 (1985).
11. Sposito, A., Gregory, S. A., de Groot, P. A. J. & Eason, R. W. Combinatorial pulsed laser deposition of doped yttrium iron garnet films on yttrium aluminium garnet. *J. Appl. Phys.* 115, 53102 (2014).
12. Fratello, V. J., Shasy, S. E. G., Brandle, C. D. & Norelli, M. P. Growth-induced anisotropy in bismuth-rare-earth iron garnets. J. Appl. Phys. 60, 2488–2497 (1986).
13. Popova, E. et al. Magnetic anisotropies in ultrathin bismuth iron garnet films. J. Magn. Magn. Mater. 335, 139–143 (2013).
14. J. Ben Youssef Ph.D Thesis. Characterization and physical study of bismuth substituted thin garnet films grown by liquid phase epitaxy (LPE). (1989).
15. Fu, J. et al. Epitaxial growth of Y$_3$Fe$_5$O$_{12}$ thin films with perpendicular magnetic anisotropy. Appl. Phys. Lett. 110, 202403 (2017).
16. Wang, C. T. et al. Controlling the magnetic anisotropy in epitaxial Y$_3$Fe$_5$O$_{12}$ films by manganese doping. Phys. Rev. B 96, 224403 (2017).
17. Avci, C. O. et al. Fast switching and signature of efficient domain wall motion driven by spin-orbit torques in a perpendicular anisotropy magnetic insulator/Pt bilayer. Appl. Phys. Lett. 111, 072406 (2017).
18. Quindeau, A. et al. Tm$_2$Fe$_5$O$_{12}$/Pt heterostructures with perpendicular magnetic anisotropy for spintronic applications. Adv. Electron. Mater. 3, 1600376 (2017).
19. Tang, C. et al. Anomalous hall hysteresis in Tm$_3$Fe$_5$O$_{12}$/Pt with strain-induced perpendicular magnetic anisotropy. Phys. Rev. B 94, 1–5 (2016).
20. Collet, M. et al. Generation of coherent spin-wave modes in yttrium iron garnet microdics by spin-orbit torque. Nat. Commun. 7, 10377 (2016).
21. Hansen, P., Klages, C.-P., & Witter, K. Magnetic and magneto-optic properties of praseodymium- and bismuth-substituted yttrium iron garnet films. J. Appl. Phys. 60, 721–727 (1986).
22. Robertson, J. M., Wittekoek, S., Popma, T. J. A., & Bongers, P. F. Preparation and optical properties of single crystal thin films of bismuth substituted iron garnets for magneto-optic applications. Appl. Phys. B 2, 219–228 (1973).
23. Hansen, P., Witter, K., & Tolksdorf, W. Magnetic and magneto-optic properties of lead- and bismuth-substituted yttrium iron garnet films. Phys. Rev. B 27, 6608 (1983).
24. Matsumoto, K. et al. Enhancement of magneto-optical Faraday rotation by bismuth substitution in bismuth and aluminum substituted yttrium-iron-garnet single-crystal films grown by coating gels. J. Appl. Phys. 71, 2467 (1992).
25. Chern, M.-Y. & Liaw, J.-S. Study of Bi$_{33}$Y$_{67}$Fe$_5$O$_{12}$ thin films grown by pulsed laser deposition. Jpn. J. Appl. Phys. 36, 1049 (1997).
26. Kahl, S., Popov, V. & Grishin, A. M. Optical transmission and Faraday rotation spectra of a bismuth iron garnet film. J. Appl. Phys. 94, 5688–5694 (2003).
27. Kaplan, B. & Gehring, G. A. The domain structure in ultrathin magnetic films. J. Magn. Magn. Mater. 128, 111–116 (1993).
28. Hamadeh, A. et al. Full control of the spin-wave damping in a magnetic insulator using spin-orbit torque. Phys. Rev. Lett. 113, 197203 (2014).
29. Hurben, M. J. & Patton, C. E. Theory of two magnon scattering microwave relaxation and ferromagnetic resonance linewidth in magnetic thin films. J. Appl. Phys. 83, 4344–4365 (1998).
30. Xiao, J. & Bauer, G. E. W. Spin-wave excitation in magnetic insulators by spin-transfer torque. Phys. Rev. Lett. 108, 217204 (2012).
31. Safranski, C. et al. Spin caloritronic nano-oscillator. Nat. Commun. 8, 117 (2017).
32. Takahashi, R. et al. Electric determination of spin mixing conductance at metal/insulator interface using inverse spin Hall effect. J. Appl. Phys. 111, 07C307 (2012).
33. Heinrich, B. et al. Spin pumping at the magnetic insulator (YIG)/normal metal (Au) interfaces. Phys. Rev. Lett. 107, 66604 (2011).
34. Stigloher, J. et al. Snell’s law for spin waves. Phys. Rev. Lett. 117, 1–5 (2016).

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Author contributions
L.S. performed the growth, all the measurements, the data analysis and wrote the manuscript with A.A., N.B. and J.B.Y. conducted the quantitative Faraday Rotation measurements and participated in the FMR data analysis. L.Q. and fabricated the PLD targets. R.L. supervised the target fabrication and participated in the design of the study. E.J. participated in the optimization of the film growth conditions. C.C. supervised the structural characterization experiments. A.A. conceived the study and was in charge of overall direction. P.B. and V.C. contributed to the design and implementation of the research. All authors discussed the results and commented on the manuscript.

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