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Cite as: Appl. Phys. Lett. **114**, 172404 (2019); https://doi.org/10.1063/1.5090205 Submitted: 25 January 2019 . Accepted: 16 April 2019 . Published Online: 30 April 2019

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Appl. Phys. Lett. **114**, 172404 (2019); https://doi.org/10.1063/1.5090205 © 2019 Author(s). 2017 Journal Impact Factor:

2.894

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ABSTRACT

We report on the switching of the in-plane magnetization of thin yttrium iron garnet (YIG)/Pt bilayers induced by an electrical current. The switching is either field-induced and assisted by a dc current, or current-induced and assisted by a static magnetic field. The reversal of magnetization occurs at a current density as low as 10^5 A/cm² and magnetic fields of ~40 μ T, two orders of magnitude smaller than in ferromagnetic metals, and consistent with the weak uniaxial anisotropy of the YIG layers. We use the transverse component of the spin Hall magnetoresistance to sense the magnetic orientation of YIG while sweeping the current. Our measurements and simulations reveal that the current-induced effective field responsible for switching is due to the Oersted field generated by the current flowing in the Pt layer rather than by spin–orbit torques, and that the switching efficiency is influenced by pinning of the magnetic domains.

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The possibility of manipulating the magnetization of planar structures using electrical currents opens up exciting prospects in spintronics. Electrical currents can affect the magnetization of thin films through the Oersted magnetic field,¹⁻⁵ spin transfer torques,⁶ and spin-orbit torques.⁷ Previous works have focused on magnetization switching and domain wall dynamics induced by spin-orbit torques in metallic ferromagnets adjacent to a heavy metal layer.^{8–15} Recently, investigations were extended toward insulating ferrimagnetic garnets, which, owing to low magnetic damping, are particularly appealing for generating and transmitting spin-waves¹⁶⁻¹⁹ as well as for magnetization switching.^{20–22} The most prominent component of this material class is yttrium iron garnet (YIG). Extensive work on the interplay of current-induced effects and magnetization dynamics in YIG/Pt bilayers demonstrated efficient spin-wave excitations,²³⁻²⁷ spin-wave amplification,^{28,29} and the control of magnetization damping.³⁰ So far, however, no attempt at current-induced magnetization switching of YIG has been reported. Two plausible reasons for the scarcity of results in this area are the extreme sensitivity of YIG to magnetic fields, which makes it difficult to control the intermediate magnetization states, as well as the need to utilize YIG films with uniaxial in-plane anisotropy, which is required to achieve binary switching. Indeed, the electrical switching of garnet insulators has been reported only for thin films with relatively large perpendicular anisotropy, such as thulium iron garnet layers in combination with either Pt or W.²⁰

In this paper, we investigate the reciprocal effects of the current and the magnetic field on the switching of YIG/Pt bilayers with inplane magnetic anisotropy. We demonstrate field-induced switching assisted by a dc current as well as current-induced switching assisted by a static magnetic field at extremely low current densities (~10⁵ A/ cm²) and bias fields (40–60 μ T). We further show that the magnetization reversal can be sensed electrically by measuring the transverse component of the spin Hall magnetoresistance (SMR)^{31–33} and adding an ac modulation to the dc current inducing the switching. Current and thickness dependent measurements reveal that the effective switching field is consistent with the Oersted field generated by the current flowing in the Pt layer. No significant effect of spin–orbit torques was detected in the current range from 1 to 8×10^5 A/cm² investigated in this work. Our results are relevant for the operation of YIG-based spintronic devices at very low current density in the thin film regime.

YIG layers with thicknesses between 6 and 7 nm were grown epitaxially by pulsed laser deposition on (111)-oriented gadolinium gallium garnet substrates, followed by *in-situ* magnetron sputtering of a 3 nm thick polycrystalline Pt film with a sheet resistance of 160 Ω . For electrical measurements, the samples were patterned into Hall bars using optical lithography followed by Ar-ion milling [Fig. 1(a)]. The current line is 50 μ m wide and is oriented along the [110] crystal direction of the substrate. The separation between two consecutive Hall arms is 500 μ m. The YIG layers have in-plane magnetization with the saturation value $M_s = (1.0 \pm 0.2) \times 10^5$ A/m, which is smaller by about 30% compared to the M_s of bulk YIG. This reduced M_s , typical for very thin YIG, is assigned to the diffusion of Gd atoms from the



FIG. 1. (a) Schematics of the YIG/Pt Hall bar with the coordinate system. (b) R_{xy} of YIG(6 nm)/Pt(3 nm) measured as a function of φ_B at $B_{ext} = 7 \text{ mT}$ (green line) and 60 μ T (black line). The blue and red lines are measured at $B_{ext} = 60 \ \mu$ T in the presence of a dc offset of 8 and $-8 \times 10^5 \text{ A/cm}^2$, respectively. (c) Macrospin simulations of the data shown in (b). (d) Diagram showing the combined effect of B_I and B_{ext} on magnetization switching in proximity to the hard axis (HA). (e) Details of the shift of R_{xy} as a function of dc offset and (f) macrospin simulations.

substrate into YIG.³⁴ In addition to the shape anisotropy, the layers have a rather strong easy plane anisotropy, corresponding to an effective isotropic anisotropy field of about 75 mT, and a weaker in-plane uniaxial anisotropy, corresponding to an in-plane anisotropy field $B_{\rm K} \approx 40-50 \ \mu$ T, which is not correlated to a specific crystal direction. The origin of the uniaxial in-plane anisotropy in the epitaxial YIG(111) layers is attributed to local strain variations introduced during the microfabrication process. Detailed structural and magnetic characterization of our samples is reported in Ref. 34.

To sense the magnetic orientation and the current-induced effective fields, we performed harmonic Hall voltage measurements,^{7,35} whereby an ac current with a frequency of 10 Hz and current density $j = 10^5$ A/cm² is sent through the Hall bar, while the transverse resistance is acquired and decomposed into its harmonic components. To derive the orientation of the in-plane magnetization, it is sufficient to consider the first harmonic Hall resistance R_{xy} as a function of the direction of the external magnetic field B_{ext} . The azimuthal angles of B_{ext} and magnetization are $\varphi_{\rm B}$ and φ , respectively, defined with respect to the current direction. The corresponding polar angles are $\theta_{\rm B}$ and θ [see Fig. 1(a)]. $B_{\rm ext}$ is measured using a calibrated Hall sensor placed next to the sample, without correction for the earth's magnetic field. All experiments are performed at room temperature.

Figure 1(b) shows the R_{xy} of YIG(6 nm)/Pt(3 nm) measured as a function of φ_B for $B_{ext} = 7 \text{ mT}$ (green curve) and 60 μ T (black curve). As $\theta = \theta_B = \pi/2$, the Hall resistance is determined by the planar Hall-like contribution from the SMR as^{31,32}

$$R_{\rm xy} = R_{\perp} \sin\left(2\varphi\right),\tag{1}$$

where R_{\perp} denotes the transverse SMR coefficient. If the magnetization is saturated parallel to the field, we have $\varphi = \varphi_{\rm B}$ and $R_{\rm xy} = R_{\perp} \sin(2\varphi_{\rm B})$, in agreement with the measurement performed at $B_{\rm ext} = 7 \,\mathrm{mT}$. Conversely, for $B_{\rm ext} = 60 \,\mu\mathrm{T}$, that is comparable to or smaller than $B_{\rm K}$, we observe significant deviations from the saturated behavior. These deviations consist of a reduction of the signal amplitude due to $\varphi \neq \varphi_{\rm B}$ and two abrupt jumps separated by 180°. We attribute these jumps to the sudden switch of the magnetization from the positive to the negative direction (relative to the easy axis) as $B_{\rm ext}$ crosses the hard axis (HA), consistent with the uniaxial in-plane anisotropy of our films.

In order to support this hypothesis and quantify $B_{\rm K}$, we performed macrospin simulations based on the magnetic energy functional

$$E = -\mathbf{M} \cdot \mathbf{B}_{\text{ext}} + M_{\text{s}} B_{\text{K}} \sin^2(\varphi - \varphi_{\text{EA}}) - \mathbf{M} \cdot \mathbf{B}_{\text{I}}, \qquad (2)$$

where the first two terms on the right hand side correspond to the Zeeman energy and the uniaxial in-plane anisotropy energy, respectively, and the last term represents the interaction between the magnetization M and the current-induced magnetic field B_1 , which we will discuss later on. Minimization of E for a given set of φ_B at constant B_{ext} and $B_1 = 0$ yields B_K and a set of values of φ , which we use to simulate R_{xy} using Eq. (1). The best fit between simulations and data is achieved for $B_K = 40 \ \mu\text{T}$ and an easy axis $\varphi_{\text{EA}} = 63^\circ$. The R_{xy} curves calculated using these parameters are shown in Fig. 1(c) for different values of B_{ext} . The simulations reproduce fairly well the main features of the Hall resistance measurements, namely the lineshape, the amplitude and the position of the jumps, and their separation by 180°. We thus conclude that the macrospin model is appropriate to describe the behavior of the magnetization, at least in the Hall cross region probed by R_{xy} .

Since B_{ext} and B_{K} are in the range of tens of μ T, we expect that any additional current-induced field B_{I} should have a pronounced impact on the orientation of the magnetization, even for very small current densities. To prove this point, we added a dc offset to the ac current and measured R_{xy} at a low field as a function of φ_{B} . For a dc offset of 8×10^5 A/cm², we observe that the angle φ_{B} at which the magnetization switches shifts by an amount $\Delta \varphi$. The sign of $\Delta \varphi$ depends on the polarity of the dc current, as shown by the red and blue curves in Fig. 1(b). Such a shift is attributed to the action of a dc field B_{I} , which assists B_{ext} so as to favor or hinder the switching of the magnetization in proximity to the hard axis [Fig. 1(d)]. Accordingly, in the first hemicycle ($0^{\circ} \leq \varphi_{\text{B}} < 180^{\circ}$), a negative (positive) current shifts the magnetization reversal toward smaller (larger) φ_{B} , whereas, in the second hemicycle ($180^{\circ} \leq \varphi_{\text{B}} < 360^{\circ}$), the opposite effect occurs. In order to quantify $B_{\rm I}$, we performed a series of measurements for positive and negative dc offsets, shown in Fig. 1(e). We then fitted the $R_{\rm xy}$ curves using the energy functional from Eq. (2), while keeping $B_{\rm K}$ and $\varphi_{\rm EA}$ equal to the values determined in the absence of a dc current and $B_{\rm I}$ as the only free parameter. The simulations, shown in Fig. 1(f), reproduce well the current-dependent switching observed in Fig. 1(e). Overall, the model supports the presence of a field $B_{\rm I} \parallel \pm y$ for a dc current $j_{\rm dc} \parallel \pm x$, which has the same symmetry as the Oersted field expected from the current flowing in the Pt layer. The current dependence of $B_{\rm I}$, reported in Fig. 2, further shows that $B_{\rm I}$ scales linearly as a function of $j_{\rm dc}$ and that its amplitude is comparable with the Oersted field calculated from Ampère's law as $B_{\rm Oe} = \mu_0 j_{\rm dc} t_{\rm Pt}/2 \approx 0.19$ mT for $j_{\rm dc} = 10^7$ A/cm² (thin black line), where $t_{\rm Pt}$ is the thickness of Pt and μ_0 denotes the vacuum permeability.

The presence of uniaxial in-plane anisotropy and finite $B_{\rm I}$ allows us to switch the YIG magnetization by ramping the dc current in Pt. To enable the current-induced switching, we select a configuration in which the magnetization is bistable, namely the hysteretic region of R_{xy} shown by the red curve in Fig. 3(a). We thus fix $B_{ext} = 34 \ \mu\text{T}$ at $\varphi_{\rm B} = 160^{\circ}$ when sweeping from 360° to 160° which corresponds to the point indicated by the dashed line in Fig. 3(a). In this configuration, the magnetization is tilted toward the hard axis. We then ramp the dc current toward positive values and simultaneously record R_{xy} [red curve in Fig. 3(b)]. From our former analysis, we expect that $B_{\rm I}$ induces a tilt $\Delta \phi$ that will eventually lead to switching. Indeed, when reaching $j_{dc} = 5 \times 10^5$ A/cm², we observe a step-like decrease of R_{xy} indicating the reversal of the magnetization, followed by a paraboliclike increase of R_{xy} at higher current, which we assign to the tilt of the magnetization in areas close to the Hall cross that have not switched. When sweeping the current back to zero, R_{xy} remains in the low resistance level (black curve). Moreover, the resistance switches back to the initial value at $j_{dc} = -2 \times 10^5$ A/cm². This behavior is similar to that reported for the current-induced switching of strained GaMnAs layers, with the difference being that B_I in GaMnAs originates from spin-orbit coupling rather than from the Oersted field.³

Figures 3(c) and 3(d) further show that the switching is reproducible for a sequence of positive and negative current pulses. In particular, the high and low levels of R_{xy} reproduce the full excursion of the R_{xy} signal at $B_{ext} = 34 \ \mu T$ [red curve in Fig. 3(a)] and persist at



FIG. 2. Current dependence of $B_{\rm I}$ in YIG(6 nm)/Pt(3 nm) for positive and negative dc offsets. The red and blue lines are linear fits to the data. The thin black lines show the Oersted field calculated from Ampère's law.



FIG. 3. (a) R_{xy} of YIG(7 nm)/Pt(3 nm) as a function of $\varphi_{\rm B}$ at $B_{\rm ext} = 4.8$ mT (black line) and $B_{\rm ext} = 34~\mu$ T (red line). The dashed line indicates the value of $\varphi_{\rm B}$ used for current-induced switching. (b) R_{xy} during a forward (red curve) and a backward dc current sweep (black curve). [(c) and (d)] Current sequence and R_{xy} measured at $\varphi_{\rm B} = 160^{\circ}$ and $B_{\rm ext} = 34~\mu$ T.

zero dc current confirming the remanent character of the switching. Moreover, applying two consecutive pulses with the same current polarity does not lead to an additional increase or decrease of R_{xy} , suggesting that the switching occurs between well-defined magnetization states, suggesting that the reversal process involves a majority and reproducible portion of the magnetic layer in proximity to the Hall cross. Additional effects due to Joule heating are neglected, since the temperature increase derived from measurements of the resistivity during current injection is lower than 1 K.

Before concluding, we discuss the origin of the current-induced field $B_{\rm I}$. As is seen in Fig. 2, $B_{\rm I}$ is only slightly smaller than $B_{\rm Oe}$, suggesting that $B_{\rm I}$ is dominated by the Oersted field, with possibly a small opposing spin-orbit effective field at the interface with Pt.⁷ This conclusion is consistent with earlier work on the current-induced ferromagnetic resonance of YIG/Pt bilayers.³⁷ As the Oersted field acts on the entire magnetic volume of YIG, we also expect that $B_{\rm I}$ does not depend on the YIG thickness ($t_{\rm YIG}$). Measurements of the angular shifts $\Delta \varphi$ as a function of t_{YIG} , however, give values of B_{I} that vary significantly between $t_{\rm YIG} = 3.5$ nm and 7 nm, and finally saturate to about $0.05 \text{ mT}/(10^7 \text{ A cm}^{-2})$ for $t_{\text{YIG}} \ge 9 \text{ nm}$ (dotted circles in Fig. 4), which is much smaller than $B_{\rm Oe} \approx 0.19 \,\mathrm{mT}/(10^7 \,\mathrm{A \ cm^{-2}})$ (gray line in Fig. 4). Whereas the increase of $B_{\rm I}$ between $t_{\rm YIG} = 3.5$ nm and 4.5 nm can be attributed to a reduction in the interfacial spin-orbit effective field, which has an opposite direction relative to B_{Oe} and scales as $1/t_{\rm YIG} M_s$, the monotonic decrease of $B_{\rm I}$ observed at $t_{\rm YIG} > 4.5$ nm has apparently no explanation. Furthermore, harmonic Hall voltage measurements^{7,35} of $B_{\rm I}$ performed on thick YIG samples yield values of $B_{\rm I}$ that are consistent with B_{Oe} (dotted triangles in Fig. 4), in clear



FIG. 4. Thickness dependence of the current-induced effective field $B_{\rm I}$ measured by the angular shift method (dotted circles) and harmonic Hall voltage measurements (dotted triangles). The data are shown for a current density $j_{\rm dc} = 10^7$ A/cm².

contrast with $B_{\rm I}$ determined from the angular shifts of the hysteretic $R_{\rm xy}$ curves. This apparent discrepancy can be reconciled by taking into account the pinning of domain walls, which influences the magnetization reversal and hence the values of $B_{\rm I}$ determined using the angular shift method. Indeed, x-ray photoelectron emission microscopy shows that the domain morphology of YIG undergoes a transition around $t_{\rm YIG} = 9$ nm, changing from an irregular elongated pattern to 100 μ m-wide pinned zigzag domains.³⁴ We therefore conclude that $B_{\rm I}$ originates mostly from the Oersted field, and that its effect on the magnetization is highly sensitive to the local pinning field, which depends strongly on $t_{\rm YIG}$. Finally, we note that the harmonic Hall voltage measurements were not feasible in thinner samples due to additional effects overlapping with the Oersted field and spin–orbit torques, which are likely due to the small coercivity of the layers and prevent a reliable analysis of the data.

In summary, we have shown that the current-induced effective field $B_{\rm I}$ is sufficient to reversibly manipulate the direction of magnetization in YIG/Pt bilayers with in-plane anisotropy in the presence of a weak static external field. In YIG films thicker than 4 nm, B_I is consistent in sign and magnitude with the Oersted field generated by the current flowing in the Pt layer. Current-induced switching is achieved at an extremely small current density $(2 \times 10^5 \text{ A/cm}^2)$, which is two orders of magnitude smaller compared to the dc current switching of metallic ferromagnets such as Pt/Co,38 ferrimagnets such as Pt/ GdCo,³⁹ and even thulium iron garnet/Pt.²⁰ We attribute this difference to the extremely small uniaxial anisotropy and the depinning field of YIG compared to ferro- and ferrimagnets with perpendicular anisotropy. The switching efficiency decreases in films thicker than 7 nm, which we attribute to a change in the domain morphology and increased pinning of the magnetic domain walls.³⁴ Strain engineering of YIG thin films may be used to further tailor the magnetic anisotropy,⁴⁰ and hence the switching behavior of YIG in response to current-induced fields of either Oersted or spin-orbit origin. Our results should also be taken as a cautionary warning about the possible undesired switching of YIG at current densities commonly used to excite and sense the magnetization of YIG/Pt bilayers.

We acknowledge financial support by the Swiss National Science Foundation under Grant No. 200020-172775. We thank Can Onur Avci for valuable discussions.

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