Spatial Mapping of Torques within a Spin Hall Nano-oscillator

T. M. Spicer,1 P. S. Keatley,1 T. H. J. Loughran,1 M. Dvornik,2 A. A. Awad,2 P. Dürrfeld,3 A. Houshang,2 M. Ranjbar,2 J. Åkerman,2,3 V. V. Kruglyak,1 and R. J. Hicken1

1Department of Physics and Astronomy, University of Exeter, EX4 4QL, United Kingdom
2Department of Physics, University of Gothenburg, 412 96 Gothenburg, Sweden
3Materials Physics, School of ICT, KTH Royal Institute of Technology, Electrum 229, 164 40 Kista, Sweden

Time-resolved scanning Kerr microscopy (TRSKM) was used to study the precessional magnetization dynamics induced by a radio frequency (RF) current within a Al2O3/Pt(5 nm)/Py(6 nm)/Au(150 nm) spin Hall nano-oscillator structure. The Au layer was patterned so as to form two needle-shaped electrical contacts that concentrated the current in the centre of a Py/Pt mesa of 4 μm diameter. Due to the spin Hall effect, the current passing through the Pt layer generates a spin current that propagates into the Py layer, exerting a spin transfer torque (STT). By injecting an RF current, and exploiting the phase-sensitivity of TRSKM and the symmetry of the device structure, the STT and the torques due to the in-plane and out-of-plane components of the Oersted field have been separated and spatially mapped. TRSKM senses the magnetization directly and is able to probe the torques within measurement configurations for which the magnetoresistive response vanishes. The STT and the torque associated with the in-plane Oersted field are observed to exhibit minima at the centre of the device due to spreading of the RF current that is not observed for a DC current. The torques associated with the RF current are expected to destabilise the position of the self-localised bullet mode excited by a DC current, and to inhibit injection locking.

Spin torque oscillators (STOs)1 are nanoscale magnetoresistive devices of great promise for use in microwave assisted magnetic recording2, microwave frequency telecommunications2, and neuromorphic computing3. Injection of DC current generates spin transfer torque (STT) that excites precessional oscillations of the constituent magnetic moments. The magnetoresistance (MR) therefore leads to an oscillatory voltage across the device. Within spin Hall nano-oscillator (SHNO) devices, charge current is first converted into a pure spin current, by means of the spin Hall effect (SHE)3,8, which then exerts STT upon the active magnetic layer. Decoupling of spin and charge currents provides additional freedom in device design, in the choice of the magnetic materials used8,12 (including electrical insulators13) and the precessional modes excited14. If the charge current flows parallel to the plane, without a top contact obscuring the active region, then optical techniques can probe the magnetization dynamics directly15,16. However it is expected that the spatial current distribution is highly non-uniform, and that thermal effects may modify both the current distribution and the torques15,19. Knowledge of the Oersted torque and STT is critical for understanding the conditions under which auto-oscillations may be excited, or locked to a reference signal, and until now it has not been possible to probe their spatial distribution directly.

STT-ferromagnetic resonance (STT-FMR) is widely used to characterise spintronic devices. Radio frequency (RF) current is injected to excite the magnetisation, and mixes with the oscillatory MR response to generate a DC mixing voltage $V_{mix}$, which is recorded as the applied magnetic field or the frequency of the current is varied. Analysis of the resonance field, or frequency, and linewidth allows the torques acting upon the magnetization to be determined20,27. However, $V_{mix}$ vanishes for certain magnetic field configurations due to the symmetry of the MR mechanism, and represents a spatial average of magnetization dynamics that may in fact be highly inhomogeneous.

In the present study, time resolved scanning Kerr microscopy (TRSKM) is used to determine the torques generated by an RF current injected into an SHNO. The SHNO is formed on an extended magnetic disk, with the intention of concentrating the current and STT within a small central region. The spatial variation of both the STT and Oersted torques was mapped and found to diverge strongly from that expected for the DC current distribution, demonstrating that the reactance of the device geometry strongly modifies the RF current distribution.

The SHNO devices shown in Figure 1 were fabricated on sapphire substrates by a combination of sputtering and electron-beam lithography10. Triangular Au(150 nm) nano-contacts (NCs) with a tip separation of $d = 140 \sim 240$ nm were defined on a 4 μm diameter Py(5 nm)/Pt(6 nm) bi-layer disk. DC current $I_{DC}$ from the gold NCs is concentrated within a small region of the Pt layer between the tips, and generates a spin current, by means of the SHE, that flows into the Py layer beneath. The injected spin polarization lies parallel to the $+ve x$ direction along a horizontal line through the middle of the disk,25 and exerts a STT on the Py magnetization. The charge current also generates an Oersted field with both in and out of plane components. The distributions of the DC electric current and Oersted field plotted in figure11 were calculated using COMSOL29. The STT amplitude is expected to have similar spatial distribution to the charge current within the Pt, while the Oersted...
field has a more complex structure that depends upon the current distribution in both the Pt and Au layers.

Conventional STT-FMR measurements were made by applying audio frequency modulation to an RF current $I_{RF}$ injected through the capacitive arm of a bias-tee, while $V_{mix}$ was measured through the inductive arm using a lock-in amplifier. The out-of-plane component of the dynamic magnetization was also detected directly by means of TRSKM that has been described in detail elsewhere [30].

Both the dynamic magnetization and $V_{mix}$ can be calculated in the macrospin limit. The equation of motion for the magnetization of a thin film driven by an external field and STT is

$$\frac{d\hat{m}}{dt} = -|\gamma|(\hat{m} \times H_{eff}) + \alpha \hat{m} \times \frac{d\hat{m}}{dt} - |\gamma| A \hat{m} \times (\hat{m} \times \hat{d}) + |\gamma| B (\hat{m} \times \hat{d}), \quad (1)$$

where $\hat{m}$ is the normalized magnetization vector, $\gamma$ is the gyromagnetic ratio, $\alpha$ is the Gilbert damping constant, $\hat{d}$ is the injected spin polarisation, and $A$ and $B$ are the amplitudes of the “in-plane” or “anti-damping” STT, and the “out-of-plane” or “field-like” STT respectively. A large in-plane torque is expected due to the SHE. However, since the Py layer is relatively thick and the current is shunted through the Pt layer, negligible torque is expected due to the Rashba effect. $H_{eff}$ is the total effective field acting upon the magnetization, which may be written as $H_{ext} + H_d(\hat{y} \cdot \hat{m})\hat{y} + h_z$, where $H_{ext}$ is the static applied field, $H_d$ is the out of plane demagnetizing field, and $h_z$ is the local Oersted field generated by the RF current. Other anisotropy fields are expected to be small and so have been neglected.

Equation (1) can be linearised to describe small amplitude precession, with the out of plane magnetization component written as $m_y(\varphi) = Re(ae^{i\varphi})$ where $\varphi$ represents the phase of the RF current and $a$ is the complex amplitude. $V_{mix}$ and the real and imaginary parts of $a$ have the forms

$$V_{mix} = I_{RF} \Delta R \sin \theta_H \cos \theta_H \frac{|\gamma|^2 H_{||}(f_0^2 - f^2)(H_{ext} + H_d) + |\gamma|^2 \Delta(\alpha H_{||} + H_{||})}{(f_0^2 - f^2)^2 + f^2 \Delta^2}, \quad (2)$$

$$Re(a) = -|\gamma|^2 H_{ext} H_{||}(f_0^2 - f^2) + f^2 \Delta |\gamma|(H_{||} - \alpha H_{||})(f_0^2 - f^2)^2 + f^2 \Delta^2 \quad (3)$$

$$Im(a) = f |\gamma|(H_{||} - \alpha H_{||})(f_0^2 - f^2) + f \Delta |\gamma|^2 H_{ext} H_{||}(f_0^2 - f^2)^2 + f^2 \Delta^2 \quad (4)$$

where

$$H_{||} = (\sin \theta_H h_x + B \sin \theta_H), H_{||} = \left(\frac{\sin \theta_H}{|\sin \theta_H|} h_y - A \sin \theta_H, \right) \quad (5)$$

$\gamma = \gamma/2\pi, f$ and $I_{RF}$ are the frequency and amplitude of the RF current, $\theta_H$ is the angle between $\hat{m}$ and $\hat{d}$, $H_{||}$ and $H_{\perp}$...
and $H_{||}$ represent effective fields, where the subscripts indicate the direction in which the associated torque acts, and $A$ and $B$ are defined in equation (I). Finally, the line width $\Delta = |\gamma|/\alpha(2H_{\text{ext}}+H_d)$, and the FMR frequency $f_0 = |\gamma|/\sqrt{H_{\text{ext}}(H_{\text{ext}}+H_d)}$. $\Delta R = 0.03 \Omega$ [31] is the change in electrical resistance when the magnetisation is rotated from orthogonal to parallel to the current.

The above expressions yield $m_y$ at different positions within the SHNO when the observed dynamical magnetisation is a response to local torques. This is a reasonable assumption when spin waves excited due to spatially varying STT and Oersted torques are similar in frequency. Dispersion due to dipolar interactions decreases with film thickness. For the 5 nm Py film, the frequency splitting, of the uniform mode and a spin wave with wavelength equal to the diameter of the disk, is no more than 20% and lies within the measured linewidth.

The stroboscopic nature of TRSKM requires that measurements are made at an RF frequency that is a multiple of the laser repetition rate as $H_{\text{ext}}$ and hence $f_0$ are varied. From equations (3) and (4), the expressions for $Re(a)$ and $Im(a)$ are seen to contain a minimum in the denominator at the resonance field, and terms in the numerator that are either slowly varying or antisymmetric (due to the factor $f_0^2 - f^2$) about the resonance field. Hence both expressions consist of parts that are symmetric and antisymmetric about the resonance field. The microwave phase $\varphi$ may be chosen in the experiment, so that $m_y$ is a weighted sum of $Re(a)$ and $Im(a)$, and so $m_y$ also appears as a sum of symmetric and antisymmetric terms. TRSKM measures the polar Kerr rotation that may be written as $Q M m_y$ where the constant $Q$ is of order 0.1 mdeg cm$^3$ emu$^{-1}$. If the value of $Q$ is known then, by recording the dependence of $m_y$ upon $H_{\text{ext}}$ for a number of values of $\varphi$, and fitting $m_y$ to equations (3), (4) and (5), the values $A$ and $B$ can be determined at each position within the sample.

Conventional STT-FMR was first performed to obtain $V_{\text{mix}}$, as shown in figure 2a. The optical probe was then positioned between the NC tips and the polar Kerr signal recorded at three values of RF phase as a function of field, as shown in figure 2b. Both optical and electrical resonance curves are a superposition of components that are either symmetric or antisymmetric about the resonance field. The $V_{\text{mix}}$ data, which does not depend upon $\varphi$, was fitted to equations (2) and (5), yielding values of $H_{||} = -6.1 \pm 0.8$ Oe and $H_{\perp} = 29.7 \pm 3$ Oe, while values of $|\gamma| = 2.94$ MHz/Oe, $\alpha = 0.04$ and $H_D = 8000$ Oe were found to best describe both the $V_{\text{mix}}$ and optical data within the present study [22]. The relatively large value of $\alpha$ has been attributed to spin pumping effects [17]. Since the average out-of-plane Oersted field $h_y$ is small due to the symmetry of the NCs, the large value of $H_{\perp}$ results from the anti-damping torque. From equation (3), if $\theta_H = 150^\circ$, $h_x$ has value of $\sim 12.1$ Oe, which has similar order of magnitude to the 10.2 Oe calculated by

\[ H_{\text{ext}} = 150 \text{ Oe}, \]

\[ f_0 = 240 \text{ nm in (a) and (b), and 140 nm in (c) and (d)} \]

and $H_{||}$.

\[ H_{||} = 90 \text{ Oe.} \]

\[ H_{\perp} = 750 \text{ Oe for } \varphi \text{ values in the range } 0 \text{ to } 180^\circ. \]

The current had frequency of 2 GHz and amplitude of 2.8, 1.3, 3.2 and 4.0 mA in (a), (b), (c) and (d) respectively. The NC separation $d = 240$ nm in (a) and (b), and 140 nm in (c) and (d) at the centre of the disk for a DC current.

Due to the symmetry of the device, one may reasonably assume [22] that the ratio $H_{||}/H_{\perp}$ determined from the optical measurements in figure 2c should be the same as that determined by fitting $V_{\text{mix}}$. Fixing this ratio and fitting the optical resonance curves then yields values for $\varphi$, that have been used to label each curve. The three phase values were found to be offset set by the same amount from the values set on the microwave synthesizer [22], justifying the assumed value of $H_{||}/H_{\perp}$. The fitting also yields an estimate of $Q$, but this is less reliable because the areas sampled by the electrical and optical measurements are different, as will be discussed further.

The dependence of optical and electrical signal strength upon $\theta_H$ is shown in Figure 2d. Maximum optical signal amplitude is observed for $\theta_H = 90^\circ$, due to the sin$\theta_H$ factor in equation (3). In contrast $V_{\text{mix}}$ vanishes for $\theta_H = 90^\circ$ and 180°, and is insensitive to the dynamics.
when $\theta_H = 90^\circ$. Finally, polar Kerr images are plotted in figure 2 for different values of $\varphi$. Due to the symmetry of the current distribution about a vertical line through the centre of the device, $A$, $h_y$ and hence $H_\perp$ are expected to be symmetric about this centre line. On the other hand $h_y$ is antisymmetric so that $H_\parallel$ has mixed symmetry. If terms in $\alpha$ are neglected in equations [3] and [4], then at resonance, when $f = f_0$, $Re(a)$ is symmetric about the centre line, while $Im(a)$ has mixed symmetry. Therefore, the most symmetric image is expected to occur for $\varphi = 0^\circ$. The most striking feature of the images is the minimum between the NC tips, which is unexpected from the DC current calculations in Figure 1.

To further explore the spatial symmetry of the magnetic response, and hence the underlying torques, the field dependence of the polar Kerr rotation was measured at different points on a horizontal line through the middle of the disk, for values of $\varphi = 40^\circ$, $85^\circ$ and $130^\circ$. The extracted values of $H_\perp$ and $H_\parallel$ are plotted as a function of position in figure 3(b). The field values obtained for the three values of $\varphi$ are in good agreement confirming that the absolute phase has been determined correctly.

Since negligible out-of-plane STT is expected, $H_\perp$ should be proportional to $h_x$ and hence spatially symmetric. However, $H_\parallel$ should contain both symmetric and antisymmetric components, (denoted as $Sym(H_\parallel)$ and $Asym(H_\parallel)$) due to the in-plane STT and $h_y$, respectively. These components can be separated by calculating the mirror image (reflection about $x = 0$) of the $H_\parallel$ data, calculating the sum and difference of the original data with its mirror image, and then dividing both by a factor of two. Both components are plotted in figure 3(b), together with convolutions of the Oersted field and current distributions of Figure 1 with a Gaussian function of 870 nm half maximum width (denoted Proc$(h_x,y)$[22]), to account for the finite size of the focused optical spot. In extracting field quantities from the experimental data, a value of $Q = 0.3$ mdeg cm$^3$ emu$^{-1}$ was assumed so that the Oersted fields towards the edge of the disk were in agreement with those from Figure 1. However, the experimental $H_\perp$ and $Sym(H_\parallel)$ curves are seen to exhibit a minimum at $x = 0$ $\mu$m, in strong disagreement with the calculated curves.

As explained above, for $\varphi = 0^\circ$ and $90^\circ$, time resolved images acquired at resonance reveal the spatial variation of $H_\perp$ and $H_\parallel$ respectively. A similar procedure to that applied to the line scan in figure 2(b) was used to extract the symmetric and antisymmetric parts of the image acquired at $\varphi = 90^\circ$. The resulting images of $H_\perp$, $Sym(H_\parallel)$ and $Asym(H_\parallel)$ are plotted next to calculated images of $h_x$, $J$, and $h_y$ in Figure 3(d). Each calculated distribution has been convolved with a 2D Gaussian function of 870 nm half maximum diameter. The form of the $Asym(H_\parallel)$ and $h_y$ images are in reasonable agreement. However the $h_x$ and $J$ images possess a maximum at the centre of the disk, whereas the $H_\perp$ and $Sym(H_\parallel)$ images exhibit a minimum. The convolution with the spot profile takes into account the fact that the NCs partly obscure the underlying Py/Pt bilayer, so that the minimum corresponds to a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field. The observed minimum initially seems at odds with observations of a reduction of the in-plane STT and the torque due to the in-plane Oersted field.
device structure that has the form of a short CPW. The reduction of the torque due to $I_{RF}$ at the centre may explain why the frequency range for injection-locking of auto-oscillations observed in SHNOs is reduced.\cite{18}

In summary, it has been shown that TRSKM can be used to probe the local FMR driven by a combination of STT and Oersted field torques, and comparison has been made with a simple theory. By directly probing the local magnetization, this technique can be applied to magnetic materials or experimental configurations that exhibit weak MR response. Furthermore the phase and spatial symmetry of the different torques allows them to be separated and mapped. The reactance of the device leading to spreading of the RF current so that the spatial distribution of the associated torques is significantly different to that generated by a DC current. The torques due to the RF current exhibit a minimum at the centre of the device, which suggests that the RF current may act to destabilise the position of the self-localised bullet mode, and may explain why the SHNO exhibits a reduced locking range.

We acknowledge financial support from the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, via the EPSRC Centre for Doctoral Training in Metamaterials (Grant No. EP/L015331/1), and grants EP/I038470/1 and EPSRC EP/P008550/1.

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We acknowledge financial support from the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, via the EPSRC Centre for Doctoral Training in Metamaterials (Grant No. EP/L015331/1), and grants EP/I038470/1 and EPSRC EP/P008550/1.
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