Giant spin-orbit torque in a single ferrimagnetic metal layer

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Antiferromagnets and compensated ferrimagnets offer opportunities to investigate spin dynamics in the ‘terahertz gap’ because their resonance modes lie in the 0.3 THz to 3 THz range. Despite some inherent advantages when compared to ferromagnets, these materials have not been extensively studied due to difficulties in exciting and detecting the high-frequency spin dynamics, especially in thin films. Here we show that spin-orbit torque in a single layer of the highly spin-polarized compensated ferrimagnet Mn$_2$Ru$_x$Ga is remarkably efficient at generating spin-orbit fields $\mu_0 H_{\text{eff}}$, which approach $0.1 \times 10^{-10}$ T m$^2$/A in the low-current density limit – almost a thousand times the Oersted field, and one to two orders of magnitude greater than the effective fields in heavy metal/ferromagnet bilayers.

We depend on fast, reliable exchange of information across long distances through intercontinental optical fibres, as well as short-distance connections between the central processing unit of a computer and its memory. The latter is the bottleneck to the powerful computing facilities needed in a future where machine learning and algorithms aid our daily lives. This bottleneck is difficult to overcome because electronics lack a practical chip-based solution to produce and detect electromagnetic waves in the spectral range between 0.3 THz and 30 THz known as the terahertz gap.

Slonczewski$^{11}$ realised that angular momentum could be transferred from one magnetic layer (a polariser) to another (the analyser) by a spin polarised current.$^{12}$ This spin-transfer torque has enabled the scaling of devices that depend on the relative magnetic orientation of two ferromagnetic layers.$^{13}$

Spin electronics exploiting the orbital degree of freedom of the electron is a recent development. A major advance was the discovery that the angular momentum could be supplied by a diffusive spin current$^{14,15}$ created via the spin Hall effect$^{16}$ in a non-magnetic heavy metal layer adjacent to the ferromagnet. Devices based on these bilayers require a bare minimum of two layers on a substrate. Earlier, Dresselhaus$^{17}$ and Bychkov and Rashba$^{18}$ had shown that in crystalline or patterned structures lacking inversion symmetry, a current-induced spin polarisation (CISP) is a direct consequence of the symmetry of the band structure. This idea was developed$^{19}$ by Železný et al.$^{20}$ to predict the form of the tensor relating the current to the CISP in crystals of different symmetry. 90° switching of the metallic antiferromagnets CuMnA$_x$ and Mn$_2$Au$_x$ was subsequently observed. These ground-breaking results established the existence of a current-induced, field-like (or reactive) torque, and allow an estimate of the strength of the effective magnetic field by comparing it to the in-plane magnetic anisotropy of the material.

Hitherto there has been no quantitative measurement of the anti-damping (or dissipative) spin-orbit torque in homogeneously magnetised ferrimagnetic or antiferromagnetic single-layer samples. Here we show, via harmonic analysis of the anomalous Hall effect$^{21}$ that in a single layer of the prototype half-metallic compensated ferrimagnet Mn$_2$Ru$_x$Ga with $x = 0.7$ (MRG)$^{15,22}$ both the field- and damping-like components of the torque reach record values, almost two orders of magnitude stronger than those obtained in the bilayer ferromagnet/heavy metal systems, or in metallic ferromagnets and semimagnetic semiconductors$^{23}$. The record values of the single-layer SOT and the dominance of the dissipative torque, open a path to sustaining magnetic oscillations in the terahertz gap.

Thin-film samples of MRG grown on MgO by DC-magnetron sputtering from stoichiometric targets crystallise in a Heusler-like structure, space group $F\bar{4}3m$ illustrated in FIG. 1a, where the conduction bands originate predominantly from Mn in 4c sites$^{24}$ The films are patterned into the micron-sized Hall bar structures shown in FIG. 1b, where the bias current $j$ is parallel to the MRG [010] axis. Further details on sample growth can be found in the supplementary material and$^{19}$. We determine the current-induced effective fields via the anomalous Hall effect (AHE), assuming it is proportional to the $z$ component of the magnetisation of the Mn$^{4c}$ sub-lattice. Due to the substrate-induced biaxial strain, the point group of Mn in this position is reduced from 43m to 42m. Here we restrict our analysis to the effect on one sublattice, as the other will follow via inter-sublattice exchange with a phase-lag. We treat all effective torques as equivalent to external applied fields. For an in-plane applied field $H$, the magnetisation is described by the polar and azimuthal angles $\theta_0$ and $\phi_m$, with the latter taken to be equal to the azimuthal angle $\phi_H$ of the applied field because the four-fold in-plane anisotropy is weak compared with the uniaxial perpendicular anisotropy. The coordinates describing the magnetic state are shown in FIG. 1c. In the presence of a unit charge current density $j \parallel [010]$, the CISP produces a SOT effective field (see...
FIG. 1: (a) MRG crystal structure. The current is carried mainly by electrons in bands originating from Mn in the 4c position, which has point group symmetry 43m. Arrows show the direction of the magnetic moment on each site. (b) Micrograph of a Hall bar with the contacts labelled. (c) Illustration of the coordinate system: \( \theta_0 \) is the polar angle of the magnetisation vector in the absence of the SOT field, and \( \phi_m = \phi_H \) is the azimuthal angle of the magnetisation and applied field vectors, respectively. (d) Illustration of the effective SOT fields acting on the magnetisation with a bias current along MRG [010] || y, the field-like (reactive) component in blue, and the two damping-like (dissipative) components in green.

\[
\mu_0 h_{SOT} = m_z x_{dl} e_x - x_{fl} e_y + m_x x_{dl} e_z
\]

where \( e_i \) are unit vectors, \( m_i \) are the components of the unit magnetisation vector, and \( x_{fl}, x_{dl} \) are the coefficients of the field- and damping-like contributions to the spin-orbit field, respectively. The units of \( \mu_0 h_{SOT}, x_{fl} \) and \( x_{dl} \) are then TA\(^{-1}\)m\(^2\). Henry is an equivalent unit.

When the bias current has an alternating component \( j = j_{dc} + j_{ac}\sin\omega t \), we detect the effect of the CISP on the first and second harmonic responses using lock-in demodulation. The conversion from the voltages detected at the different harmonics to the magnitude of the effective fields is detailed in the supplementary material. In TABLE I we indicate the symmetry of the different contributions to \( V_{xy} \) in the first, second and third harmonic responses. Contributions from the anomalous Nernst effect (ANE) are suppressed by measuring \( V_{xy}^{3\omega} \), or by taking the difference of \( V_{xy}^{2\omega} \) measured with positive and negative DC bias. The contribution from the homogeneous temperature variation \( \Delta T \) oscillating at twice the applied frequency is determined from data in FIG. 2 as explained in the supplementary material.

FIG. 2 shows the temperature dependence of the longitudinal and transverse conductivity of MRG, recorded in the remnant state after saturation in a positive field at room temperature. The conductivity \( \sigma_{xx} \) (FIG. 2a) increases with decreasing \( T \), and its saturation value of 630 kS m\(^{-1}\) or [159 \( \mu \Omega \) cm\(^{-1}\)] corresponds to the minimum metallic conductivity of a bad metal where the mean free path is comparable to the interatomic spacing. The Hall conductivity \( \sigma_{xy} \) (FIG. 2a) closely follows the Mn\(^{4c}\) sublattice magnetisation. The lower panels show the temperature-derivatives of \( \sigma \).

We now turn to the SOT. FIG. 3a and b shows the experimentally observed \( V_{xy}^{3\omega} \) and its calculated values based on the experimental \( \theta_0 \). There is excellent agreement between experiment and the model, which is based only on the site symmetry, the data in FIG. 2 and the first harmonic response (used to determine \( \theta_0 \) and the anisotropy constants). All the features in both the \( \theta_0 \) and \( \phi \) dependencies are well reproduced: two deep minima around \( \mu_0 H_z = \) 450 mT, four maxima that align with the four-fold in-plane anisotropy constant \( K_2 \); as well as a weaker central minimum at small fields. Qualitatively, the field-dependence of the SOT can be understood by comparing the following equation with FIG. 3(a), and noting that the

| Contribution/Harmonic | \( \omega \) | 2\( \omega \) | 3\( \omega \) |
|-----------------------|----------|----------|----------|
| Anomalous Hall Effect: \( \sigma_{xy} \) | \( \circ \) | - | - |
| Anomalous Nernst Effect: \( \partial T/\partial z \) | - \( \wedge \) | - | - |
| Homogeneous \( \Delta T \) oscillating at 2\( \omega \): \( \partial \sigma/\partial T \) | \( \vee \) | \( \wedge \) | \( \circ \) |
| Current-induced fields: \( h_{SOT} \) | \( \vee \) | \( \wedge \) | \( \circ \) |
intrinsic SOT with those recorded on conventional bilayers of a heavy metal (typically Pt, Ta or W) and a 3d ferromagnet (typically Co, Fe, CoFe or CoFeB). For bilayers, the damping-like effective field per current density can be written: $\mu_0 H_{dl}/j = (\theta_{SH} h)/(2eM_s t)$, where $\theta_{SH}$ is the spin-Hall angle of the heavy metal, $h$ is the Planck’s constant, $e$ is the electron charge, $M_s$ the magnetisation of the ferromagnet and $t$ its thickness. For 1 nm of CoFeB ($M_s \approx 1$ MA m$^{-1}$), which has a magnetic moment equivalent to that of $\approx 30$ nm nearly compensated MRG, and $\theta_{SH} = 40\%$ we obtain an effective, damping-like field of $1.3 \times 10^{-13}$ T A$^{-1}$ m$^2$ (0.13 pH). We would need a fictitious spin-Hall angle of 400 % to match the value of the field-like term in MRG and 1200 % to match the damping-like term.

This comparison highlights the inherent advantage of using ferrimagnets in combination with intrinsic SOT. In a bilayer, increasing the thickness of the ferromagnet beyond the spin diffusion length (typically $< 10$ nm), does not produce any additional torque. If the ferromagnet is 2 nm rather than 1 nm thick, the effective field may be reduced to half, whereas the field in single-layer MRG is unchanged with thickness. The volume of MRG can be scaled up or down without changing the torque, providing the current density is constant. The nature of the intrinsic torque is staggered acting directly on the Mn$^{1c}$ sublattice, hence a more correct comparison might be to normalise the spin Hall angle using the sublattice magnetisation, which is approximately ten times greater than the net magnetisation at room temperature for the present sample. Furthermore, the torque is maintained even in the absence of any net magnetisation at the ferromagnetic compensation temperature, thus permitting GMR- and TMR-based device structures to be excited by SOT even in the absence of any net moment of the free layer. This enables targeted control of the dynamics, and the excitation of both in-and out-of-phase resonance modes.

The high effective fields found above assuming small, linear, current-driven variations in $\theta_0$, imply that the action of the SOT should also be observable in the non-linear transfer characteristics of our Hall bar device. We therefore proceeded as follows:

We first recorded a full field-in-plane hysteresis loop from $-14$ T to 14 T to determine the relation between $m_z$ and the applied field and invert this relation numerically, to be able to deduce, from $m_z$, the value of the total effective field at any given applied current. Then, a constant external field $\mu_0 H = 0.4$ T is applied in the sample plane and rotated around $e_z$, changing the azimuthal angle $\phi_H$ from $0^\circ$ to $360^\circ$ while recording $m_z$ (inferred from $V_{xy}$). This measurement is repeated for range of current densities from $0.2 \times 10^{10}$ A m$^{-2}$ to $2.5 \times 10^{10}$ A m$^{-2}$. As the action of the SOT field depends directly on its direction relative to the direction of the magnetisation ($\theta_{MH}$ and $\phi_M \approx \phi_H$), we can subtract any variation that is $\phi$-independent. This $\phi$-independent effective field contains all variations that are due to heating. The result, after

![FIG. 3. (a) Surface plot and its 2D colour map projection of the experimentally observed voltage at the third harmonic $V_{xy}^{(3)}$. (b) Calculated response based on the experimental values of $\cos \theta_0$. (c) and (d) show AC (with $I_{dc} = 3$ mA) and DC ($I_{ac} = 1$ mA) current-dependence of the second harmonic $V_{xy}^{(2)}$ signal. By making the difference and sum of records made with positive and negative DC offset we isolate the SOT (the difference) from the anomalous Nernst effect ANE (the sum).](image)
Subtraction, is shown in FIG. 4, where we give the effective field in terms of the effective, current-induced inductance in pH = 1 × 10^12 T m^2 A^{-1}. A current density of j = 2.5 × 10^10 A m^{-2} can produce an effective inductance L_{eff} ≈ 75 pH, equivalent to an effective in-plane field of 1.9 T. We note that this field is sufficient to magnetically switch ≈ 2% of the sample.

We make two important comments on this analysis. First, by removing the φ-independent part of the signal, we also remove any SOT that behaves the same way. If we again assume the SOT fields can be described by the tensors reported by Železný et al. and Troncoso et al., and expand the relation between h_{eff} and Δθ to second order in Δθ, we find that we have removed a damping-like contribution along e_{z}, which varies as m_{z}^{2} + m_{y}^{2}, which may be considerable. Second, as we are normalising with respect to the action of the external, m-plane field, the SOT effective field directed along e_{z}, remaining after the procedure outlined above, contributes to our signal \( \propto 1 / \cos \theta_{M} \) as seen by the upturn at \( \phi_{H} = 270^\circ \) in FIG. 4.

The strong effective SOT fields in MRG are related to its high anomalous Hall angle. The value is unusual in the sense that MRG does not contain any elements heavier than Ru; in any case the AHE angle does not scale with Ru content. Furthermore, the conduction electrons in MRG are predominantly d-like, although it has been suggested that Ga in the Mn-containing Heuslers lends some p character to the bands at the Fermi-level through hybridisation, increasing the spin-orbit coupling of the conduction electrons. We have already seen above that MRG is at the limit of metallic conductivity. From our measurements of \( \sigma_{xx} \) and \( \sigma_{xy} \), we can deduce the spin-orbit scattering cross-section and find that it corresponds to 60% of the unit cell surface area. The very large scattering cross-section is consistent with the very short mean free path.

So far we have demonstrated high current-induced effective fields as well as a high ratio (~3) of the dissipative (anti-damping) to the reactive (field-like) torques. This will allow for the realization of more efficient magnetic switching, exchange-bias manipulation, as well as low-current control of magnetic textures. The key question is, whether sustained self-oscillation can be driven by SOT. We address this from two different angles, first by considering the results established by Troncoso et al., noting that the effective fields will act distinctly on the magnetisation and the Nel vectors. Using the numerical values of the effective fields found in the linear, low-current regime, self-oscillations will emerge for current densities that provide a reactive torque which is sufficient to overcome the in-plane anisotropy 1 T for MRG, which corresponds to \( j \geq 7 \times 10^{10} \text{A m}^{-2} \). The second necessary condition is that the dissipative torque must overcome the Gilbert damping α. Taking α ≈ 0.01 we find the condition \( j \geq 10 \times 10^{10} \text{A m}^{-2} \). An alternative approach is to compare directly the effective inductance created by the SOT and the self inductance of the oscillating element. In a shorted Hall bar device, a crude estimate of the self inductance for a 500 nm thick film with an active length of 20 μm is 0.1 pH – the dimensions are chosen to enhance impedance matching to free space in a real oscillator. We saw in FIG. 4 that the effective inductance reaches values two orders of magnitude higher than this, ensuring that oscillatory behaviour is possible, even in the low-current-density region. The natural frequency of the oscillator will be determined by the larger of the two effective inductances, that is by the SOT and the magnetic resonance frequency of the material, which we previously estimated as 0.75 THz.

In summary, we find that current-induced spin orbit torque reaches record values in single-layers of the compensated, half-metallic ferrimagnet Mn_2Ru_xGa, well in excess of those achieved in bilayer structures. With realistic values of damping, this should allow sustained magnetic oscillations that could be detected by magneto-resistive effects, or free-space emission using a suitable antenna. A cheap, compact, and tunable oscillator operating in the terahertz gap would break new ground in spin electronics, and could potentially unlock a new realm of information transfer at bandwidths three orders of magnitude higher than those of the present day.

ACKNOWLEDGMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 737038, and from Science Foundation Ireland through contracts 12/RC/2278 AMBER and 16/1A/4534 ZEMS as well as the Research Council of Norway through its Centres of Excellence.
funding scheme, Project No. 262633 “QuSpin”. The authors declare no competing financial interests.

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