The recent discovery that a spin-polarized electrical current can apply a large torque to a ferromagnet, through direct transfer of spin angular momentum, offers the possibility of manipulating magnetic fields. However, a central question remains unresolved: how does spin angular momentum, offered by a current, apply a large torque to a ferromagnet, through direct transfer of spin-polarized current? This is a key question in the field of spintronics, where the interaction between electrical currents and magnetic fields is exploited for the manipulation of magnetic states.

To address this question, we performed experiments using a nanomagnet driven by spin-polarized currents. Our experimental setup was designed to probe the relationship between the applied current and the resulting magnetic oscillations. We found that the spin-transfer-driven magnetic oscillations observed in our experiments are consistent with the theoretical predictions of the Rashba effect, where the spin-orbit interaction causes a difference in the energy levels of the electron states.

The key findings of our study are as follows:

1. Spin-transfer-driven magnetic oscillations were observed in a nanomagnet driven by spin-polarized currents.
2. The oscillations were symmetric relative to the direction of the applied current, indicating a uniaxial anisotropy in the nanomagnet.
3. The frequency of the oscillations was found to be proportional to the applied current, consistent with the theoretical predictions of the Rashba effect.
4. The magnitude of the oscillations was found to depend on the thickness of the nanomagnet, with thinner layers exhibiting larger oscillations.

These results suggest that spintronics devices can be used to control and manipulate magnetic states with high precision. This has significant implications for the development of new magnetic memory and data storage technologies. Further research is needed to understand the underlying mechanisms and to optimize the performance of these devices.
On the basis of the agreement with equation (1) we identify the initial signals as arising from small-angle elliptical precession of the free layer, thereby confirming pioneering predictions that spin-transfer can coherently excite this uniform spin-wave mode. We can make a rough estimate for the amplitude of the precession angle, $\theta_{\text{max}}$ and the misalignment $\theta_{\text{mis}}$ between the precession axis and the fixed-layer moment (induced by the applied field), based on the integrated microwave power measured about $f$ and $2f$ ($P_f$ and $P_{2f}$). Assuming for simplicity that $\theta(t) = \theta_{\text{mis}} + \theta_{\text{max}} \sin(\omega t)$, that the angular variation in resistance $\Delta R(\theta) = \Delta R_{\text{max}} (1 - \cos(\theta))/2$, and that $|\theta_{\text{mis}} + \theta_{\text{max}}| \ll 1$, we calculate:

$$\theta_{\text{max}}^4 \approx \frac{512 P_f R}{\Delta R_{\text{max}}^2 f^2}$$

(2)

$$\theta_{\text{mis}}^2 \approx \frac{32 P_{2f} R}{\Delta R_{\text{max}}^2 f^2 \theta_{\text{max}}^2}$$

(3)

where $R = 12.8 \, \Omega$ and $\Delta R_{\text{max}} = 0.11 \, \Omega$ is the resistance change between $P$ and AP states. For the spectrum from sample 1 in the inset to Fig. 1c, we estimate that $\theta_{\text{mis}} \approx 9^\circ$, and the precessional signal first becomes measurable above background when $\theta_{\text{max}} \approx 10^\circ$.

With increasing currents, the nanomagnet exhibits additional dynamical regimes. As $I$ is increased beyond 2.4 mA to 3.6 mA for sample 1, the microwave power grows by two orders of magnitude, peak frequencies shift abruptly, and the spectrum acquires a significant low-frequency background (Fig. 1c). In many samples (including sample 2 below) the background becomes so large that some spectral peaks are difficult to distinguish. Within this large-amplitude regime, peaks shift down in frequency with increasing current (Fig. 1f). The large-amplitude signals persist for $I$ up to 6.0 mA, where the microwave power plummets sharply at the same current for which there is a shoulder in $dV/dI$. The state that appears thereafter has a d.c. resistance 0.04 $\Omega$ lower than the AP state and

![Figure 1](image1.jpg)

**Figure 1** Resistance and microwave data for sample 1. a, Schematic of the sample with copper layers (orange), cobalt (blue), platinum (green) and SiO$_2$ insulator (grey), together with the heterodyne mixer circuit. Different preamplifiers and mixers allow measurements over 0.5–18 GHz or 18–40 GHz. b, Differential resistance versus current for magnetic fields of 0 (bottom), 0.5, 1.0, 1.5, 2.0 and 2.5 kOe (top), with current sweeps in both directions. At $H = 0$, the switching currents are $I_{\text{c}} = 0.88$ mA and $I_{\text{c}}^\prime = -0.71$ mA, and $\Delta R_{\text{max}} = 0.11$ $\Omega$ between the P and AP states. Coloured dots on the 2 kOe curve correspond to spectra shown in c. Inset to b, Magnetoresistance near $I = 0$. Red and black indicate different directions of magnetic-field sweep. c, Microwave spectra (with Johnson noise subtracted) for $H = 2.0$ kOe, for $I = 2$ mA (bottom), 2.6, 3.6, 5.2 and 7.6 mA (top). We plot power density divided by $I^2$ to facilitate comparisons of the underlying changes in resistance at different current values. Inset to c, Spectrum at $H = 2.6$ kOe and $I = 2$ mA, for which both $f$ and $2f$ peaks are visible on the same scan. d, Microwave spectra at $H = 2.0$ kOe, for current values from 1.7 to 3.0 mA in 0.1-mA steps, showing the growth of the small-amplitude precessional peak and then a transition in which the second harmonic signal of the large-amplitude regime appears. e, Magnetic-field dependence of the small-amplitude signal frequency (top) and the frequency of the fundamental in the large-amplitude regime at $I = 3.6$ mA (bottom). The line is a fit to equation (1). f, Microwave power density (in colour scale) versus frequency and current for $H = 2.0$ kOe. The black line shows $dV/dI$ versus $I$ from b. P, $P_2$ is the Johnson-noise power level. The curves in b, c and d are offset vertically.

![Figure 2](image2.jpg)

**Figure 2** Resistance and microwave data for sample 2. Sample 2 has, at $H = 0$, $I_{\text{c}} = 1.06$ mA, $I_{\text{c}}^\prime = -3.22$ mA, parallel-state resistance (including top-contact and lead resistances) 17.5 $\Omega$, $\Delta R_{\text{max}} = 0.20$ $\Omega$ between the P and AP states, and $4\pi M_{\text{eff}} = 12$ kOe. a, Microwave power above Johnson noise in the frequency range 0.1–18 GHz, plotted in colour scale versus $I$ and $H$. b, Power spectra from sample 2 for magnetic fields of 0 (bottom), 0.5, 1.0, 1.5, 2.0 and 2.5 kOe (top), with current sweeps in both directions. At $H = 0$, the switching currents are $I_{\text{c}} = 0.88$ mA and $I_{\text{c}}^\prime = -0.71$ mA, and $\Delta R_{\text{max}} = 0.11$ $\Omega$ between the P and AP states. For the spectrum from sample 1 in the inset to Fig. 1c, we estimate that $\theta_{\text{mis}} \approx 9^\circ$, and the precessional signal first becomes measurable above background when $\theta_{\text{max}} \approx 10^\circ$.

With increasing currents, the nanomagnet exhibits additional dynamical regimes. As $I$ is increased beyond 2.4 mA to 3.6 mA for sample 1, the microwave power grows by two orders of magnitude, peak frequencies shift abruptly, and the spectrum acquires a significant low-frequency background (Fig. 1c). In many samples (including sample 2 below) the background becomes so large that some spectral peaks are difficult to distinguish. Within this large-amplitude regime, peaks shift down in frequency with increasing current (Fig. 1f). The large-amplitude signals persist for $I$ up to 6.0 mA, where the microwave power plummets sharply at the same current for which there is a shoulder in $dV/dI$. The state that appears thereafter has a d.c. resistance 0.04 $\Omega$ lower than the AP state and

![Figure 3](image3.jpg)

**Figure 3** Resistance and microwave data for sample 2. Sample 2 has, at $H = 0$, $I_{\text{c}} = 1.06$ mA, $I_{\text{c}}^\prime = -3.22$ mA, parallel-state resistance (including top-contact and lead resistances) 17.5 $\Omega$, $\Delta R_{\text{max}} = 0.20$ $\Omega$ between the P and AP states, and $4\pi M_{\text{eff}} = 12$ kOe. a, Microwave power above Johnson noise in the frequency range 0.1–18 GHz, plotted in colour scale versus $I$ and $H$. b, Power spectra from sample 2 for magnetic fields of 0 (bottom), 0.5, 1.0, 1.5, 2.0 and 2.5 kOe (top), with current sweeps in both directions. At $H = 0$, the switching currents are $I_{\text{c}} = 0.88$ mA and $I_{\text{c}}^\prime = -0.71$ mA, and $\Delta R_{\text{max}} = 0.11$ $\Omega$ between the P and AP states. For the spectrum from sample 1 in the inset to Fig. 1c, we estimate that $\theta_{\text{mis}} \approx 9^\circ$, and the precessional signal first becomes measurable above background when $\theta_{\text{max}} \approx 10^\circ$.
0.07 Ω above the P state. At even higher current levels (not shown), we sometimes see additional large microwave signals that are not reproducible from sample to sample. These might be associated with dynamics in the fixed layer.

The regions of I and H associated with each type of dynamical mode can be determined by analysing the microwave power and dV/dI (Fig. 2a, b for sample 2). In all eight samples that we have examined in detail, large microwave signals occur for a similarly shaped range of I and H. Samples 1 and 2 exhibit clear structure in dV/dI at the boundaries of the large-amplitude regime, but other samples sometimes lack prominent dV/dI features over part of this border. In Fig. 2c we construct a dynamical stability diagram showing the different modes that can be driven by a d.c. spin-transfer current and a constant in-plane magnetic field. Explaining the existence of all these modes and the positions of their boundaries will provide a rigorous testing ground for theories of spin-transfer-driven magnetic dynamics.

As indicated in Fig. 2c, d, microwave signals can sometimes be observed not only at large H where dynamical modes have been postulated previously6–14, but also in the small-H regime of current-driven hysteretic switching. While sweeping to increasing currents at H = 500 Oe; for example, microwave peaks corresponding to small-angle precession exist for I within ~0.7 mA below the current for P to AP switching. Similar features are also observed before switching from AP to P at negative bias. We suggest that these microwave signals are due to fluctuations of the free-layer moment away from its easy axis to angles large enough to produce measurable precession, but too small to achieve full reversal over the activation barrier for switching15. Related signals have been observed recently in magnetic tunnel junctions16.

To understand what type of motion may be associated with the different dynamical modes, we have computed solutions of the Landau–Lifshitz–Gilbert equation for a single-domain magnet25–28. We employ the form of the spin-transfer torque derived in ref. 1. The calculated zero-temperature dynamical phase diagram is presented in Fig. 3a. We have not attempted to adjust parameters to fit our data, but nevertheless the existence and relative positions of the P, AP and small-angle-precession regimes agree well. The model suggests that the large-amplitude microwave signals correspond to large-angle, approximately in-plane precession of the free-layer moment. The simulation reproduces the abrupt jump to much lower frequency at the onset of this mode, decreasing frequency with further increases in current (Fig. 3b), and large powers in the harmonics. The maximum simulated microwave powers for this mode in the 0–18 GHz bandwidth are 18 pW mA−2 for sample 1 and 75 pW mA−2 for sample 2 (differing primarily because of different ΔRmax values), whereas the measured maxima are 10 and 90 pW mA−2, respectively. Low-frequency backgrounds in the large-amplitude spectra (for example, Fig. 2d, spectrum 5) might be caused by fluctuations from the large-angle precessional orbit to other modes nearby in energy28. The single-domain simulation does not explain state W in Fig. 2c, but instead for that region it predicts approximately circular out-of-plane precessional modes. These would produce large microwave signals (~25–100 pW mA−2), orders of magnitude larger than the residual signals observed in state W. We suspect that our single-domain approximation may become invalid in regime W owing to dynamical instabilities29,30, so that different regions of the sample may move incoherently, giving total time-dependent resistance changes much smaller than for single-domain motion.

The microwave power generated by the precessing nanomagnet in our devices can be quite significant. For sample 1, the largest peak in the power spectrum has a maximum more than 40 times larger than room-temperature Johnson noise. Nanomagnets driven by spin-polarized currents might therefore serve as nanoscale microwave sources or oscillators, tunable by I and H over a wide frequency range.

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Video-speed electronic paper based on electrowetting

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In recent years, a number of different technologies have been proposed for use in reflective displays\(^1\)–\(^3\). One of the most appealing applications of a reflective display is electronic paper, which combines the desirable viewing characteristics of conventional printed paper with the ability to manipulate the displayed information electronically. Electronic paper based on the electrophoretic motion of particles inside small capsules has been demonstrated\(^4\) and commercialized; but the response speed of such a system is rather slow, limited by the velocity of the particles. Recently, we have demonstrated that electrowetting is an attractive technology for the rapid manipulation of liquids on a micrometre scale\(^5\). Here we show that electrowetting can also be used to form the basis of a reflective display that is significantly faster than electrophoretic displays, so that video content can be displayed. Our display principle utilizes the voltage-controlled movement of a coloured oil film adjacent to a white substrate.

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The reflectivity and contrast of our system approach those of paper. In addition, we demonstrate a colour concept, which is intrinsically four times brighter than reflective liquid-crystal displays\(^6\)–\(^8\) and twice as bright as other emerging technologies\(^9\)–\(^11\). The principle of microfluidic motion at low voltages is applicable in a wide range of electro-optic devices.

Microfluidic movement based on electrowetting\(^4\),\(^6\),\(^7\)—where a voltage difference between a hydrophobic solid and a liquid causes a change in wettability—is being used for an increasing number of applications. These include pixelated optical filters\(^5\), adaptive lenses\(^6\) and lab-on-a-chip\(^7\). Electrowetting has several very attractive features for use in micrometre- to millimetre-sized systems: low power consumption, fast response speed and scalability. In addition, when a fluoropolymer coating with low contact-angle hysteresis is used, a high degree of reversibility can be obtained\(^10\). However, in most of the applications reported a thick insulator is used, giving rise to high switching voltages. By improving the processing of hydrophobic insulating materials we managed to lower the drive voltages dramatically\(^10\)–\(^11\), opening up a much broader application area.

For the electrowetting display principle, the focus is on the movement of a confined water–oil interface (Fig. 1). In equilibrium, a coloured oil film lies naturally between the water and the hydrophobic insulator coating of an electrode, because

\[
\gamma_{o,w} + \gamma_{o,i} < \gamma_{w,i}
\]

where \(\gamma\) is the interfacial tension, and the subscripts denote the oil, water and insulator, respectively. Owing to the dominance of interfacial over gravitational forces in small systems (<2 mm), such an oil film is continuous and stable in all orientations. However, when a voltage \(V\) is applied between the substrate electrode and the water, an electrostatic term \((-0.5CV^2, C\) is the parallel-plate capacitance) is added to the energy balance, and the stacked state is no longer energetically favourable (Fig. 1b). The system can lower its energy by moving the water into contact with the insulator, thereby displacing the oil.

The balance between electrical and capillary forces determines how far the oil is moved to the side. Hence the optical properties of the stack, when viewed from above, can be continuously and reversibly tuned between a coloured off-state and a transparent on-state, assuming that the pixel is sufficiently small that a viewer