

Spin-torque diode effect in magnetic tunnel junctions

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There is currently much interest in the development of ‘spin-tronic’ devices, in which harnessing the spins of electrons (rather than just their charges) is anticipated to provide new functionalities that go beyond those possible with conventional electronic devices. One widely studied example of an effect that has its roots in the electron’s spin degree of freedom is the torque exerted by a spin-polarized electric current on the spin moment of a nanometre-scale magnet. This torque causes the magnetic moment to rotate^{1–19} at potentially useful frequencies. Here we report a very different phenomenon that is also based on the interplay between spin dynamics and spin-dependent transport, and which arises from unusual diode behaviour. We show that the application of a small radio-frequency alternating current to a nanometre-scale magnetic tunnel junction^{20–22} can generate a measurable direct-current (d.c.) voltage across the device when the frequency is resonant with the spin oscillations that arise from the spin-torque effect: at resonance (which can be tuned by an external magnetic field), the structure exhibits different resistance states depending on the direction of the current. This behaviour is markedly different from that of a conventional semiconductor diode²³, and could form the basis of a nanometre-scale radio-frequency detector in telecommunication circuits.

We performed experiments on a magnetic tunnel junction (MTJ) in the structure Si (substrate)/PtMn (15 nm)/CoFe (2.5 nm)/Ru (0.85 nm)/CoFeB (3 nm)/MgO (0.85 nm)/CoFeB (3 nm); see Fig. 1a. This multi-layered film was further patterned into oval-shaped pillars of dimension 200 nm × 100 nm, using electron-beam lithography and ion milling techniques. The bottom anti-ferromagnetically coupled CoFe and CoFeB layers (the synthetic antiferromagnetic layer) act as a pinned layer, while the top CoFeB layer acts as a free layer, whose magnetization can be changed. The resistance of the MTJ depends on the relative orientations of the pinned and free layers. The present MTJ shows a giant tunnelling magnetoresistance (TMR) due to the crystalline MgO (001) tunnelling barrier. A current passing through the MTJ gets spin-polarized by the pinned layer, and exerts a torque on the free layer.

The experimental arrangement to measure the diode effect is shown in Fig. 1a. A bias T is used to pass high-frequency current (200 MHz to 15 GHz) through the MTJ and to measure the d.c. voltage simultaneously. For all the experiments described here, the external magnetic field was applied at an angle of 30° from the pinned-layer magnetization axis within the film plane (see inset of Fig. 1b). In this geometry the sample showed a giant TMR of ~100%, as shown in Fig. 1b. We also measured microwave power from the MTJ arising from the thermal fluctuations of the free-layer

magnetization^{24,25}. The power was measured by a spectrum analyser, by passing a d.c. current of 1 mA using a bias T .

The radio frequency (r.f.) response of the MTJ was first tested using a network analyser. The results obtained showed evidence of magnetic resonance excited by r.f. current (results not shown).

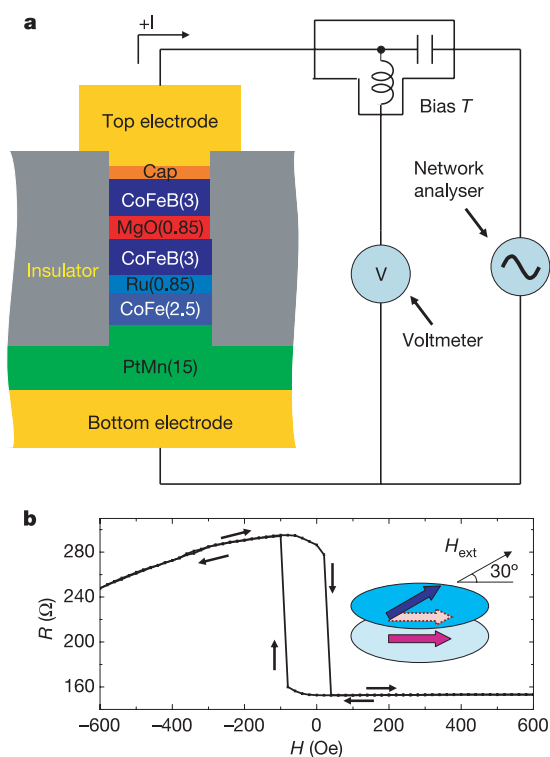


Figure 1 | Experimental set-up and magnetoresistance. **a**, Schematic diagram of the experimental set-up and cross-sectional view of the magnetic tunnel junction (MTJ) device. The thicknesses of various layers of the device in nanometres are given in brackets. The bottom CoFeB and CoFe layers, coupled anti-ferromagnetically through the Ru layer, act as a pinned layer. The top CoFeB layer acts as a free layer, the magnetization of which can be changed. The pinned and free layers are separated by a tunnelling MgO barrier. The experimental set-up measures the d.c. voltage produced across the device on applying the r.f. current. **b**, The magnetoresistance of the device, by applying magnetic field at 30° from the pinned-layer magnetization. The arrows indicate the sweeping direction of the magnetic field.

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Current-induced resonance has recently been observed also in a magnetic domain wall in the megahertz frequency range²⁶. The signal is, however, small, and its phase determination is prone to errors in the calibration of the network analyser. In contrast, we found that the MTJ produces d.c. voltage because of its nonlinear behaviour and this diode-effect measurement offers phase-problem-free results. The effect of alternating current (a.c.) on the precession of magnetization induced by large d.c. current has recently¹⁹ been studied. However, in the present experiment, we excite the magnetization only with alternating current, without applying a d.c. bias. The d.c. voltage response measured by passing 0.55 mA of r.f. current is plotted in Fig. 2. The response shows a large resonance structure, whose position depends on the magnetic field. Figure 3a shows the noise power spectra having a large peak, along with a small side peak, the positions of which also depend on the magnetic field.

The working principles of the spin-torque diode and the semiconductor p–n junction diode are compared in Fig. 4a. As shown in Fig. 4a, when current flows from the n side to the p side, the space charge region around the p–n junction is enlarged, and so the resistance of the p–n junction is higher in this case. For the opposite direction of current, the space charge region is shrunk, which gives lower resistance. In the case of the spin-torque diode, the alternating current passing through it exerts a torque on the free-layer spin moment. When the frequency of the alternating current nears the precession frequency of the free-layer spin-moment, the spin is tilted towards the pinned-layer magnetization during the negative (or positive) half of the alternating current. This configuration has low resistance. During the next half of the alternating current, spin is tilted in the opposite direction, which is a high-resistance state. The difference in resistance during positive and negative currents produces d.c. voltage, in the case of both the diodes. In contrast to the semiconductor diode, the spin-torque diode is resistant to the noise because it produces d.c. voltage only in a narrow frequency range around the resonance frequency, which can be tuned by applying a magnetic field.

Furthermore, the spin-torque diode effect is phase-sensitive. A small r.f. current ($I = I_{\text{a.c.}} \sin(2\pi ft)$) passing through MTJ exerts a torque on the free-layer spin. As a result, the z component (parallel to the pinned-layer magnetization) of the spin oscillates as

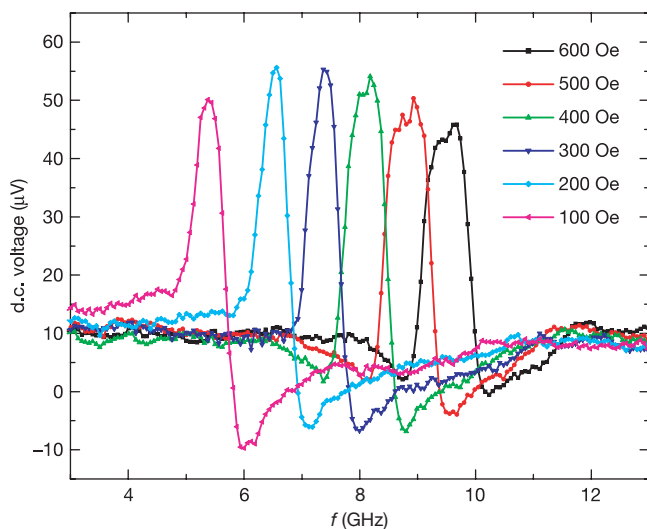


Figure 2 | Direct-current voltage generated by the device in response to the alternating current. The d.c. voltage is plotted as a function of the frequency of the a.c. current (0.55 mA). The external magnetic fields are as shown. The d.c. voltage results from the resonant oscillation of the magnetic moment of the free layer by current-induced spin-transfer and effective-field torques.

$S_z = \cos(\theta) + A \sin(2\pi ft) + B \cos(2\pi ft)$, where A and B are respectively the in-phase and 90° -phase components of the motion of the spin, S_z denotes the direction cosine of the spin and θ is the angle between the free and pinned layers. The resistance of the MTJ depends on S_z as follows: $R = R_0 + 0.5 \Delta R (1 - S_z)$, where R_0 is the resistance of the sample when the free layer is parallel to the pinned layer, and ΔR is the increase in the resistance when the free layer is anti-parallel to the pinned layer. The d.c. voltage given by the time-averaged value of I^*R is $V_{\text{d.c.}} = -A \Delta R I_{\text{a.c.}} / 4$. Thus alternating current passing through the MTJ produces d.c. voltage, which is sensitive to the in-phase part of the oscillation of the magnetic moment. Because this is an intra-sample detection, it gives a phase-error-free spectrum, and a new method for performing ferromagnetic resonance experiments, for which at present an oscillating magnetic field is usually applied.

A torque exerted on the free-layer spin can in general be decomposed into two directions orthogonal to it, that is, $\hat{s}_{\text{free}} \times (\hat{s}_{\text{free}} \times \hat{s}_{\text{pin}})$ and $(\hat{s}_{\text{free}} \times \hat{s}_{\text{pin}})$, where \hat{s}_{free} and \hat{s}_{pin} are unit vectors along the magnetizations of the free and pinned layers respectively. The torque from the spin-transfer effect^{1,2} lies in the first direction. The torque along the second direction is called the field-like term, and has been predicted in different ways^{3,4}. Owing to the symmetry differences between these terms (when the free- and pinned-layer magnetizations are in-plane), the d.c. voltage produced by the spin-transfer torque shows a peak, whereas the d.c. voltage produced by an effective field shows a dispersion curve, as shown in Fig. 4b. If both torques act on the spin, by superposition, we get d.c. voltage, as shown in the bottom panel of Fig. 4b. For small and uniform oscillation of the magnetic moment, the d.c. voltage is given approximately by (see Supplementary Discussion):

$$V_{\text{d.c.}} \approx \frac{1}{4} \Delta R \sin^2(\theta) I_{\text{a.c.}}^2 \operatorname{Re} \left[\frac{if\gamma' \text{ST} - \gamma' H_d \gamma' \text{FT}}{(f_0^2 - f^2) - if\alpha\gamma' H_d} \right] \quad (1)$$

where ST is the spin transfer and FT is the effective field term, per unit current. γ is the gyromagnetic ratio ($\gamma' = -\gamma/2\pi > 0$), α is the Gilbert damping factor, H_d is the demagnetization field perpendicular to the free-layer plane, f_0 is the resonant frequency and f is the frequency of the applied alternating current, $I_{\text{a.c.}}$. (We have neglected the stray field effect for a uniform mode.)

The comparison of the d.c. voltage and thermal noise power spectrum at 300 Oe is shown in Fig. 3b. Each spectrum is composed of a large resonance centred at about 7.5 GHz and a small resonance at lower frequency. Here we consider only the dominant resonance (larger peak in the noise) as the uniform oscillation of the free layer (see Supplementary Fig. 1). The d.c. voltage from this mode corresponds to a combination of spin-transfer and effective-field torques (compare with the bottom trace in Fig. 4b). The resonance frequency obtained from fitting to a superposition-type spectrum coincides with the main peak position in the thermal noise spectrum. The frequency of the resonance position as a function of magnetic field is plotted in Fig. 3c. For small θ , and neglecting the marginal influence of d.c. bias current, the resonance frequency is approximately given by Kittel's equation²⁷: $f = \gamma' [(H_c + |H_{\text{dip}} + H_{\text{ext}}|)(H_c + H_d + |H_{\text{dip}} + H_{\text{ext}}|)]^{1/2}$ where H_c is the coercivity and H_{dip} is the dipolar field from the pinned layer. The fitting to this equation gives $H_c + H_{\text{dip}} = 176$ Oe and $H_d = 12.8$ kOe.

As mentioned above, because d.c.-measurement is phase-sensitive detection, we can decompose the spectra into two sources of torque—spin transfer and effective field—by using equation (1); see Supplementary Fig. 2. Further, we also measured the d.c. response by changing the r.f. current (see Fig. 3d), and found that the d.c. voltage decreased linearly with the square of the current, as expected from equation (1).

The d.c. voltage output of an ideal semiconductor diode is given by $V_{\text{d.c.}} \approx eV_{\text{r.f.}}^2/k_B T$, where $V_{\text{r.f.}}$ is the high-frequency voltage applied to the diode, k_B is Boltzmann's constant and T is the temperature. The

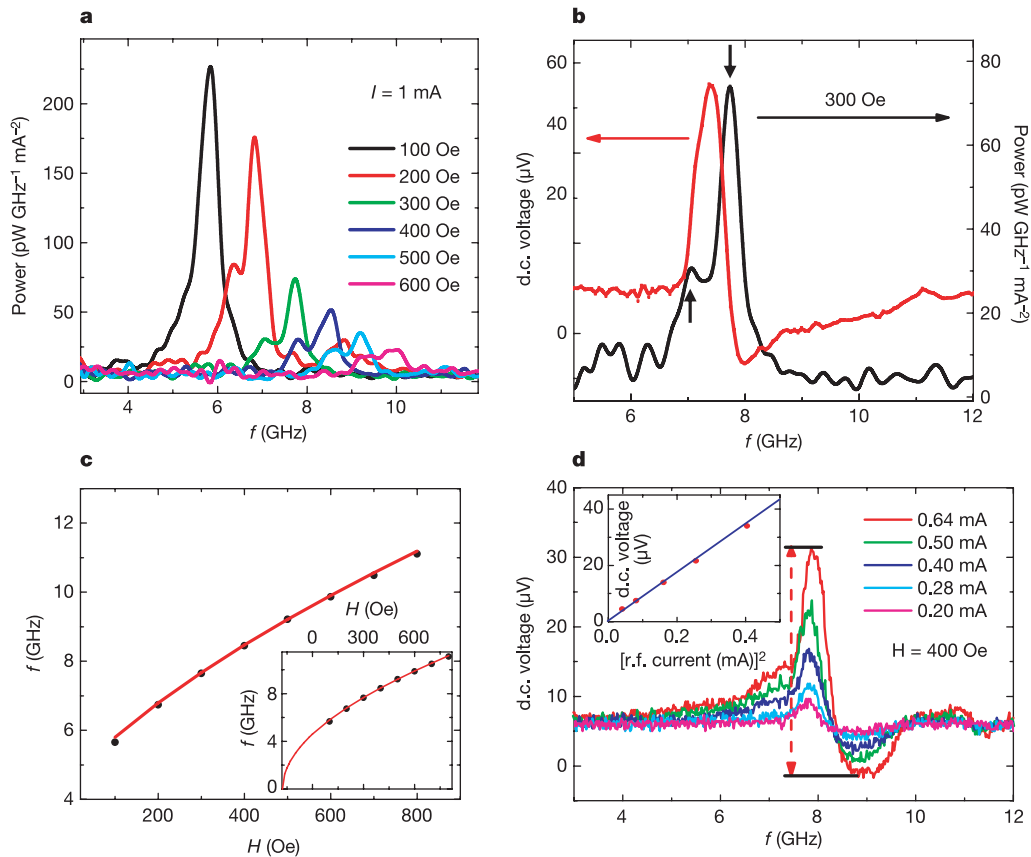


Figure 3 | Magnetic-field dependence of microwave power and a.c. current dependence of d.c. voltage. **a**, Microwave power spectra of the device measured by spectrum analyser, using a d.c. bias current of 1 mA. The power spectra with zero d.c. current are taken as background and subtracted from the data. The external magnetic fields are as shown. **b**, Comparison of the d.c. voltage spectrum and microwave power spectrum at 300 Oe. The arrows mark the positions of two peaks in the microwave power. The d.c. spectrum also has two corresponding resonance frequencies. The shape of the d.c. spectrum is a combination of peak and dispersion curves (also see Fig. 4b).

Thus, the resonance positions do not match with the maxima in the d.c. voltage. **c**, The magnetic-field dependence of resonant frequency corresponding to the larger peak in the microwave power spectra. The black points represent the experimental data points, while the red curve is the fit to the data using Kittel's equation. The inset shows the extrapolation of the fitted curve to zero frequency. **d**, Direct-current voltage from a different sample for the given a.c. currents. The inset shows the linear power dependence of the d.c. voltage measured from peak to valley, as marked by the arrow in the main panel.

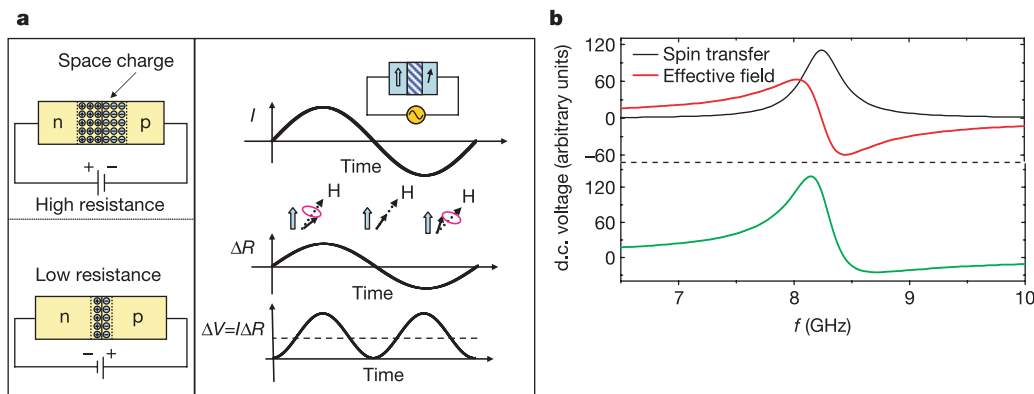


Figure 4 | Principle of the spin-torque diode. **a**, Comparison of the functioning of the semiconductor p-n diode (left panel) and the spin-torque diode (right panel). In the semi-conductor diode, if positive voltage is applied to the n side, the space charge region around the p-n junction is enlarged, and the resistance is high. For the opposite polarity, the space charge region is shrunk and the resistance is low. In the case of the spin-torque diode, the free-layer magnetization (shown by thin black arrows) oscillates owing to the current-induced torque. The resistance of the diode is less when the a.c. current is negative, because the free layer makes a smaller angle with the pinned layer (shown by the thick blue arrow). When the alternating current is positive, the resistance is larger, owing to the larger

angle. The bottom trace in the right panel of **a** shows the schematic variation of the product of the current and the change in resistance. The dotted line shows the average value of this product, which appears as d.c. voltage across the spin-torque diode. **b**, Theoretical plot of the d.c. voltage spectrum obtained from equation (1). The d.c. voltage shows a peak if the torque induced by the a.c. current is due to the spin-transfer effect only. This is shown by the black curve in the top panel. But if the torque is due to the effective-field effect only, the d.c. voltage shows a dispersion curve, as shown by the red curve. If both the torques apply, the d.c. voltage shows a superposition of peak and dispersion, as shown by the green curve in the bottom panel.

spin-torque diode can perform r.f. detection better than the semiconductor diode if the magnetization of the pinned layer lies 45° out-of-plane. In this geometry, by increasing the ratio (H_d/H_c) of free-layer magnetization, we can squeeze the elliptical trajectory of the precession of the magnetic moment to lie in-plane. This enhances the amplitude of in-plane oscillation, and produces large d.c. voltage. The maximum d.c. voltage produced by spin-transfer in this case is given by (see Supplementary Discussion):

$$V_{\text{d.c.}} \approx \text{TMR} \frac{V_{\text{r.f.}}^2}{V_c} \sqrt{\frac{H_d}{H_c}}$$

where V_c is the critical voltage required to flip the magnetization¹. Thus, by increasing the H_d/H_c ratio as well as by increasing the magnetoresistance (as we have done here using a high-quality crystalline MgO barrier), the spin-torque diode can be a sensitive power detector. The sensitivity can also be enhanced by increasing the spin-transfer efficiency^{28,29}, which decreases the critical voltage.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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