Spin-transfer torque in nanoscale magnetic devices

By D. C. Ralph*, Y.-T. Cui, L. Q. Liu, T. Moriyama, C. Wang and R. A. Buhrman

Cornell University, Ithaca, New York, NY 14853, USA

We discuss recent highlights from research at Cornell University, Ithaca, New York, regarding the use of spin-transfer torques to control magnetic moments in nanoscale ferromagnetic devices. We highlight progress on reducing the critical currents necessary to produce spin-torque-driven magnetic switching, quantitative measurements of the magnitude and direction of the spin torque in magnetic tunnel junctions, and single-shot measurements of the magnetic dynamics generated during thermally assisted spin-torque switching.

Keywords: spin-transfer torque; ferromagnetic resonance; magnetic switching; magnetic memory

1. Introduction

The spin-transfer torque effect is a mechanism that can be used to manipulate the magnetic-moment orientation of small ferromagnetic devices, as an alternative to using applied magnetic fields. The mechanism is perhaps easiest to understand and investigate in samples consisting of layers of magnetic and non-magnetic materials with an electrical current passing perpendicularly to the layers; for example, 'spin valve' devices with a ferromagnet–copper–ferromagnet structure or magnetic tunnel junctions with a ferromagnet–tunnel barrier–ferromagnet structure. The idea of the spin-transfer torque effect, as first predicted by Slonczewski [1] and Berger [2], relies on the fact that an electrical current passing through a thin layer of ferromagnetic material becomes partially spin polarized. Spin-up and spin-down electrons have different scattering probabilities within a ferromagnet (and also at ferromagnetic interfaces) so that after transmitting through or reflecting from a ferromagnetic layer a current will have more spins of one type than another. For combinations of materials such as cobalt and copper or permalloy ($Ni_{81}Fe_{19}$) and copper, transmitted electrons are partially polarized in the direction corresponding to majority spins in the ferromagnet, and reflected electrons are partially polarized in the minority direction. When these partially polarized electron currents emerge from the polarizing magnetic layer and pass through the sample, they carry angular momentum in the form of spin with them. When they then interact with another magnetic layer downstream, they

*Author for correspondence (ralph@ccmr.cornell.edu).

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can transfer a portion of their angular momentum to this second magnetic layer in the process of scattering, thereby applying a direct spin-transfer torque. For a sufficiently large current, the magnetic layer can respond by reorienting its magnetic moment.

In optimized devices, the strength of the spin-transfer torque can approach a value on the scale of $\hbar/2$ angular momentum transferred per electron. For samples with sub-micrometre dimensions, this corresponds to a torque per unit current that can be much greater than the torque produced by the more traditional means of using the current to generate a magnetic field, and then having the magnetic field act on the magnet. For example, in the development of magnetic random access memories, the currents required to produce magnetic field-driven switching are presently on the scale of 10 mA, while spin-torque-driven switching can be accomplished with currents of just a few tenths of milliamperes or less. Of added benefit, spin torques act very locally, on essentially atomic length scales, unlike magnetic fields that extend over significant distances with a slow power-law decay in their strength versus distance. This makes it easier to use spin torques than magnetic fields to manipulate one magnetic element within a dense array, without disturbing nearby elements. Spin torque is also of interest because it can be used to generate types of magnetic dynamics that are not easy to produce using magnetic fields alone. In addition to producing simple switching between static magnetic states, of use for example in magnetic memory or logic circuits, samples can be designed so that spin torque from a direct electrical current generates large-angle steady-state precession of the magnetic moment in a ferromagnetic layer, at a frequency that is tunable either by varying the current or by using an applied magnetic field. This type of dynamics is being investigated for use in making nanoscale microwave sources, detectors, mixers and other applications for high-frequency communications and computation. More details about the basic science and initial applications of spin-transfer torques, along with detailed references, can be found in a recent tutorial article [3]. Spin-transfer torques are also important in a different type of device geometry—they can be used to manipulate magnetic domain walls by flowing currents within individual layers of ferromagnetic material. That aspect of spin-torque research is the subject of other articles in this Theme Issue, and has also been discussed in an excellent review [4].

Research relating to spin-transfer torques is a very active field, with many very interesting recent developments achieved by a large number of research groups. Here, we will not attempt to provide a global view, but will focus on three recent projects from our nanomagnetics group at Cornell University, Ithaca, New York: (i) progress in reducing the critical current for spin-transfer-driven magnetic switching [5], (ii) measurements of the bias dependence of the spin torque in magnetic tunnel junctions using spin-torque-driven ferromagnetic resonance (ST-FMR) [6], and (iii) single-shot measurements of the magnetic dynamics during the process of spin-torque switching [7].

2. Reducing the critical current for spin-transfer switching

Progress towards the development of spin-torque-driven magnetic random access memories has been quite rapid in several industrial laboratories, with steadily improving device characteristics and multi-megabit circuits already demonstrated

[8–11]. The primary remaining challenges for commercialization of this technology are to minimize the current required for switching while maintaining sufficient thermal stability for the memory devices and while maximizing the switching speed, demonstrating that the magnetic tunnel junctions used as memory elements can withstand the relatively large current densities needed for spin-torque switching without damage during extended use, and demonstrating sufficient reproducibility in the switching characteristics of the magnetic elements. Whereas magnetic memory elements switched by using current-generated magnetic fields cannot be made to scale to densities less than about $1 \, \mu m^{-2}$ because the torque per unit current possible via magnetic fields is too weak, it is hoped that the stronger torques from spin transfer may enable much denser and hence less expensive memory elements, having also the virtues of fast nanosecond-scale switching and non-volatility. However, in order to scale to the maximum density allowed by fabrication technologies, it is necessary that spin-torque switching should be achieved using the output current of minimum area silicon metal–oxide–semiconductor field-effect transistors (MOSFETs), approximately 0.05–0.1 mA. Until recently, this has been a factor of about three to five beyond the state of the art.

An estimate for the critical current needed for spin-torque switching can be derived by calculating the current required to excite spin-torque excitations in a simple macrospin approximation. For the usual case of a magnetic thin film sample with an equilibrium orientation lying in the sample plane [12],

$$I_c = \frac{2e}{\hbar} \frac{\alpha}{\eta} \left(H_K + \frac{H_d}{2} \right) (M_S \text{Vol}), \qquad (2.1)$$

where α is the Gilbert damping coefficient, η is the efficiency of the spin torque, H_K is the within-plane magnetic anisotropy, H_d is the effective perpendicular demagnetization field for tilting the moment out of plane and $M_S \text{Vol}$ is the total magnetic moment of the switching layer. One can seek to improve all of the parameters α, η, H_K, H_d and $M_S \text{Vol}$ in order to minimize I_c, but one particularly promising strategy is to manipulate H_d. For a typical transition-metal ferromagnet, H_d is comparable to $1 \, \text{T}$, much larger than the within-plane anisotropy $(H_K \sim 0.01 \, \text{T})$, but the thermal stability of the magnetic bit is determined by H_K with no help from H_d. Therefore, the critical current can be reduced without compromising the thermal stability by reducing the demagnetization field. One approach is to choose materials so that the switching layer has perpendicular magnetic anisotropy, with an equilibrium magnetization pointing out of plane rather than in plane so that equation (2.1) does not apply. For this perpendicular case, the critical current and the magnetic stability are both simply proportional out-of-plane anisotropy fields and therefore, all other factors being equal, the critical current should be reduced. Studies of perpendicularly magnetized samples have in fact shown steady progress [13,14]. However, it appears to be a challenge to maintain a low value for the Gilbert damping α for switching layers with perpendicular anisotropy, and it is also a challenge to obtain a high degree of spin polarization (and a large value of the efficiency η) with perpendicularly oriented polarizing layers. Only very recently have samples with out-of-plane anisotropy obtained critical currents competitive with in-plane polarized samples [10]. We have therefore explored an alternative
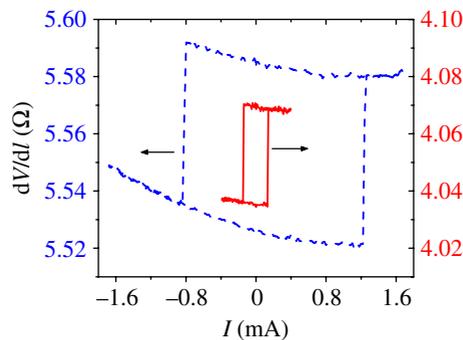
Figure 1. Comparison between the room temperature spin-torque switching characteristics for a low-demagnetization (LD) Co/Ni/Co/Ni/Co sample (solid line) and a high-demagnetization (HD) Co/Ni control sample (dashed line). (Online version in colour.)

approach, choosing materials so as to reduce the value H_d for our switching layer but to not change it so much as to favour a perpendicular orientation. We find that, as predicted by equation (2.1), this reduction in H_d allows a dramatic decrease in I_c while maintaining the convenience of using switching layers and polarization layers that are magnetized in the conventional in-plane orientation.

Our method for decreasing the value of H_d is to use the perpendicular magnetic anisotropy of Co/Ni interfaces, following the work of Mangin *et al.* [13,14]. By testing Co/Ni multi-layers with different thicknesses and repeats, we determined that a switching layer with the composition (thicknesses in nanometres) Co(0.4)/Ni(1.0)/Co(0.4)/Ni(1.0)/Co(0.4) decreases H_d to a value of approximately 0.06 T, more than an order of magnitude less than the value 0.7 T for a simple Ni(2.0)/Co(1.2) bilayer film. After adding an 8 nm Cu spacer layer and a 20 nm permalloy polarizing layer to both the low-demagnetization (LD) multi-layers and high-demagnetization (HD) Ni(2.0)/Co(1.2) control samples and then fabricating nanopillar-shaped samples (cross section approx. $90 \times 190\,\text{nm}^2$), we measured typical room temperature switching characteristics as shown in figure 1. The critical currents for the LD samples are 0.14 mA for both directions of switching, while for comparison the switching currents for the HD control sample are $-0.81\,\text{mA}$ and $+1.24\,\text{mA}$. We do wish to note that these values are affected by thermal fluctuations. More fundamental zero-temperature critical currents (I_{c0}) can be estimated by measuring the switching characteristics as a function of current sweep rate and then extrapolating to the nanosecond scale. This analysis yields $I_{c0} = -0.35$ and 0.39 mA for the LD sample, compared with -1.66 and $+2.54\,\text{mA}$ for the HD sample, giving an overall reduction of about a factor of five on account of the decreased demagnetization field. This is in reasonable quantitative agreement with equation (2.1), taking into account that the spin polarization in the LD samples appears to be reduced by about 30 per cent (as reflected in the smaller magnetoresistance signal upon switching). At the same time, the energy barrier for thermal switching is altered very little by the extra interfaces in the LD sample, decreasing by only 10 per cent. We therefore conclude that manipulating the perpendicular demagnetization field is an effective strategy for reducing I_c while maintaining thermal stability. The

switching currents we have achieved thus far are still somewhat greater than the 0.05–0.1 mA values needed to be compatible with scaling to minimum area MOSFETs, but we are optimistic that this goal can be achieved by incorporating LD switching layers within MgO-based magnetic tunnel junctions to achieve a higher current polarization, and by adding a second polarizing magnetic layer on the other side of the switching layer to increase the strength of the spin torque [15].

3. Measuring the bias dependence of spin torque in magnetic tunnel junctions

Magnetic tunnel junctions are better suited than all-metal spin valves for spin-torque applications because they have larger magnetoresistances and they can be better impedance-matched to silicon-based read-out devices. However, in order to excite spin-torque-driven magnetic dynamics, in general, large biases must be applied to tunnel junctions, and as a function of increasing bias the magnetoresistance decreases significantly. Therefore, it is important to understand how the spin torque depends on bias—whether it decreases significantly at large bias like the magnetoresistance or whether it maintains its strength.

Quantitative measurements of both the magnitude and direction of the spin-torque vector in magnetic tunnel junctions can be achieved using a technique that we call ST-FMR [6,16–19]. When using this technique, one first applies a static magnetic field to initialize the sample in a configuration in which there is a non-zero offset angle between the magnetizations of the two electrodes (approx. a 90° offset gives the maximum signal). A calibrated microwave frequency current is then applied (if desired, simultaneously with a direct current (DC) bias). When the microwave frequency is close to any of the normal modes for magnetic precession in the device, the oscillating spin torque from the microwave current can excite this mode, thereby causing the resistance to oscillate at the same frequency as the drive. The amplitude of the resulting precession can be detected easily by simply measuring an added DC voltage generated by the device owing to mixing between the microwave current and the oscillating resistance. This technique is capable of measuring both vector components of the spin torque (two components since there is no component of torque parallel to the magnetization of the precessing layer) from an analysis of the resonance peak shape and peak height. The analysis of the signal is most straightforward near zero applied DC bias [16,18]. A component of spin torque in the plane defined by the magnetizations of the two samples acts in phase with the resistance oscillations and produces a symmetric Lorentzian lineshape. A component of spin torque in the perpendicular direction acts 90° out of phase from the resistance oscillations, with the consequence that the resonance is antisymmetric about the centre frequency of the resonance, with a lineshape corresponding to the frequency derivative of a Lorentzian. If both vector components are present simultaneously, the response is simply a sum of these frequency-symmetric and -antisymmetric lineshapes. Near zero bias the amplitudes of the symmetric and antisymmetric parts of the resonance are proportional to the in-plane and perpendicular components of the derivative of the spin torque with respect to voltage, $d\tau/dV$, also known as the 'torkance'.
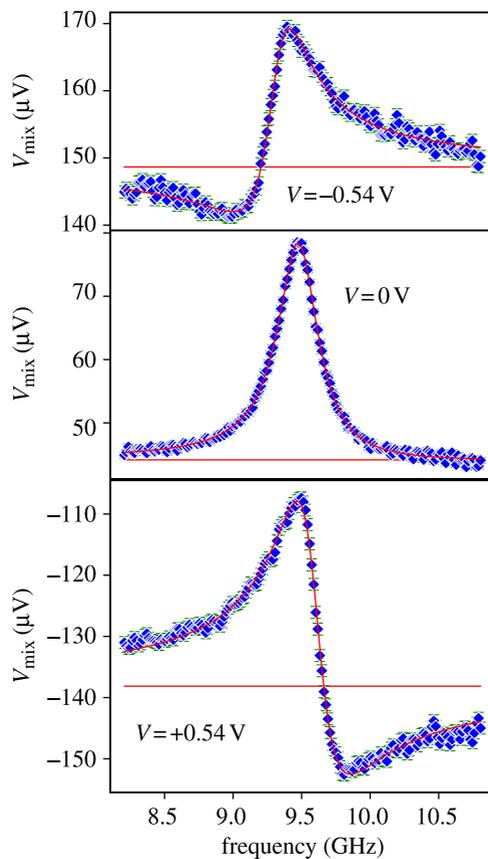
Figure 2. ST-FMR resonance peak shapes for the lowest frequency mode of a CoFeB/MgO/CoFeB magnetic tunnel junction at room temperature. The degree of asymmetry in the peak shape depends on the DC bias V. (Online version in colour.)

Measurements showing typical resonance lineshapes corresponding to the lowest frequency, spatially quasi-uniform normal mode of a CoFeB layer are shown in figure 2. With zero DC bias applied to the tunnel junction, the ST-FMR resonance is to a good approximation symmetric in frequency about the centre frequency, indicating that only the in-plane component of the torkance, $d\tau_\parallel/dV$, is significant. However, when a small DC bias is applied, the peak shape becomes increasingly asymmetric, with opposite signs of antisymmetry for positive and negative bias. This indicates that the perpendicular component of the torkance, $d\tau_\perp/dV$, grows as a function of increasing $|V|$. More detailed analyses [18,19] show that $d\tau_\perp/dV$ is to a good approximation simply linearly dependent on V, so that, after one integration, the perpendicular torque itself is found to have a quadratic dependence on bias: $\tau_\perp(V) = A_0 + A_1 V^2$, with A_0 and A_1 sample-dependent constants. On this point, the first two measurements of the bias dependence of ST-FMR in MgO-based magnetic tunnel junctions [18,19] agreed. This result is also in good accord with *ab initio* calculations [20] and with

symmetry arguments that for a symmetric tunnel junction with negligible inelastic spin-flip scattering $d\tau_\perp/dV$ should be an antisymmetric function of V [3].

The two initial ST-FMR experiments, however, did not agree about the bias dependence of the other, in-plane, component of the spin-transfer torkance, $d\tau_\parallel/dV$. Sankey *et al.* [18] found that this component was approximately constant for $|V| < 0.3\,V$ (a variation less than 16%), with the dependence at higher bias uncertain because of possible artefacts owing to heating. Kubota *et al.* [19] reported that $d\tau_\parallel/dV$ was approximately constant over a smaller bias range ($|V| < 0.1\,V$) and for larger biases was strongly asymmetric, increasing by a factor of 3 for one sign of bias and decreasing to change sign for the other. The reason for the difference in the results was unclear. Two possibilities were that the tunnel junctions measured had different resistance–area (RA) products ($12\,\Omega\mu m^2$ for Sankey *et al.* and $2\,\Omega\mu m^2$ for Kubota *et al.*), and the measurements were conducted using different offset angles between the electrode magnetizations (50–$90°$ for Sankey *et al.* and $137°$ for Kubota *et al.*).

To resolve this disagreement, we have conducted more detailed ST-FMR measurements on samples with different RA products and over a broad range of offset angles, and we analysed for possible additional sources of ST-FMR signal at large biases. We found that all of the CoFeB/MgO/CoFeB tunnel junctions that we measured showed qualitatively similar properties, regardless of their RA value. The origin of the different experimental results reported previously turned out to be the different offset angles. When we took data at offset angles ranging from $90°$ towards $180°$ and analysed them by the same procedure used in the initial experiments of Sankey *et al.* and Kubota *et al.* for $d\tau_\parallel/dV$, the results showed a smooth crossover from the symmetric bias dependence reported by Sankey *et al.* to the strongly asymmetric result of Kubota *et al.* However, we also found that this analysis procedure for extracting the value of $d\tau_\parallel/dV$ from the ST-FMR data became inaccurate at large bias and for offset angles away from $90°$. Our more detailed analysis shows that an applied microwave current can produce a small change in the average resistance of the magnetic tunnel junction because it can change the average offset angle between the magnetizations of the electrodes. When a large DC bias current is applied, this change in average resistance results in a change in DC voltage that adds to the DC voltage measured in the ST-FMR experiment, making the original analyses inaccurate. However, this additional DC voltage artefact can be accounted for within the same theoretical framework as the rectification contribution to the ST-FMR signal discussed above, so that over a reasonably large range of bias around $V = 0$ one can correct for it and still use ST-FMR to extract the true underlying values of the torkances [6]. Our corrected results for the bias dependence of both $d\tau_\parallel/dV$ and $d\tau_\perp/dV$ are shown in figure 3 for an $RA = 12\,\Omega\mu m^2$ tunnel junction. Similar data for a lower RA device and more detailed analysis can be found in Wang *et al.* [6]. The torkances are predicted to be proportional to $\sin(\theta)$, where θ is the offset angle, so in figure 3 we plot the torkances divided by $\sin(\theta)$. We find a good collapse of the data for both components of the torkance, demonstrating good agreement with predicted angular dependence. This agreement is not present before correcting for artefacts at large DC bias. The results for the perpendicular component $d\tau_\perp/dV$ are little changed by the correction for the artefacts at large DC bias, but the bias dependence of the in-plane component $d\tau_\parallel/dV$ is very different from the initial
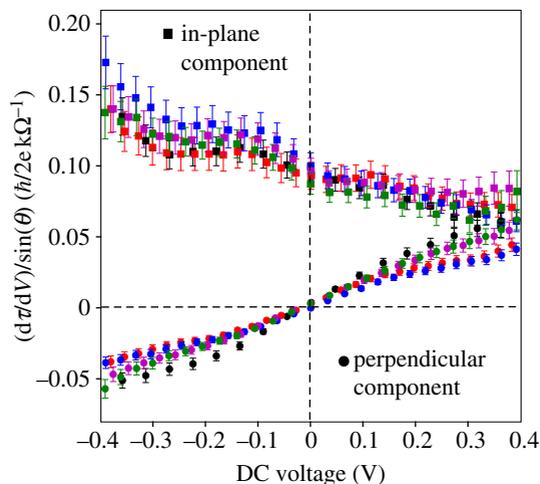
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Figure 3. Measured in-plane and perpendicular components of the spin torkance on the free magnetic layer of a $12\,\Omega\mu m^2$ CoFeB/MgO/CoFeB tunnel junction, for several values of the initial offset angle between the magnetizations of the electrodes, from $58°$ to $131°$. Positive voltage corresponds to electron flow from the free layer to the polarizing layer. (Online version in colour.)

result of Kubota *et al.* [19], and also slightly stronger than the initial report of Sankey *et al.* [18]. We find that $d\tau_\parallel/dV$ decreases by about 30–35% as a function of increasing bias over the voltage range where the correction can be applied. This relatively small variation has not yet been examined in detail theoretically, but a similar change appears to be present in the *ab initio* calculations of Heiliger & Stiles [20].

Several experimental groups have reported other techniques for measuring the bias dependence of the spin torque in magnetic tunnel junctions, finding different results from the ST-FMR experiments. Of the various techniques, we believe that ST-FMR is the most trustworthy because it can be performed near zero bias where heating effects should be least important, heating effects alter the ST-FMR signal only at higher order powers of the microwave frequency and DC currents than the main rectification signal so that they should be negligible for the experimental conditions we employ, and ST-FMR can be performed with sufficiently large applied magnetic fields and sufficiently small-angle magnetic excitations that the macrospin approximation used for analysing the dynamics of the precessing layer should be reasonable. However, we will take this opportunity to cite and discuss the competing experiments. Petit *et al.* [21] measured the centre frequency for thermally excited magnetic precession in aluminium oxide tunnel junctions as a function of applied bias, and by assuming that the frequency changes resulted in part from the perpendicular component of spin torque they inferred a linear dependence for $\tau_\perp(V)$, in contrast to the quadratic dependence seen by ST-FMR. Deac *et al.* [22] used a similar technique with MgO-based tunnel junctions, determining a quadratic bias dependence for $\tau_\perp(V)$ from variations in the precession frequency, but a much more strongly nonlinear bias dependence than in the ST-FMR data for $\tau_\parallel(V)$ based on the bias dependence of the precession linewidth. Our view of these results is shaped by the fact that we

measure the precession frequency as a function of bias during the ST-FMR experiments as well. We find that, in general, the frequency depends on bias much more strongly than would be expected from the effects of $\tau_\perp(V)$ alone (using the value of $\tau_\perp(V)$ determined by the ST-FMR). Our suspicion is that the applied bias simply affects the overall precession frequency more strongly by other mechanisms than by the perpendicular spin torque, perhaps because of heating or because of spin torques from lateral spin diffusion (within the sample plane) that may alter the effective exchange interaction within the precessing layer [23,24]. The linewidths at high bias may also be more sensitive than ST-FMR measurements to heating [25]. In another approach, Li *et al.* [26] argued that the perpendicular torque in MgO-based tunnel junctions has the bias dependence $\tau_\perp(V) \propto |V|V$ at high bias, rather than being $\propto V^2$ as seen by ST-FMR, based on careful measurements of switching currents as a function of magnetic field and current pulse widths. They explained that this bias dependence can result naturally as a consequence of inelastic spin-flip scattering at large bias. However, we believe that their data can be explained instead by a reduction in the within-plane anisotropy H_K at large bias owing to inelastic effects. Independent evidence for a surprisingly strong dependence of H_K on bias has recently been observed by Sun *et al.* [27].

4. Single-shot measurements of the magnetic dynamics during the process of spin-torque switching

The most direct way to study the process of spin-torque switching would be to observe the magnetization dynamics directly in real time. In the past, there have been several approaches to achieving this sort of measurement. In early experiments on all-metal spin-valve devices, the resistance versus time during switching was measured by a sampling oscilloscope technique, but this required averaging over thousands of repetitions of the switching process in order to build up sufficient signal to noise, so that it was sensitive only to the averaged signal, not to individual variations [28]. More recent time-resolved X-ray imaging experiments must likewise average over many repetitions [29]. With the development of MgO-based magnetic tunnel junctions with large magnetoresistance, the resistance signals associated with magnetic precession can now be made large enough that they can be measured using single-shot techniques, without any averaging. Devolder *et al.* [30] and Tomita *et al.* [31] have published initial reports of single-shot measurements in tunnel junctions, in which they were able to resolve event-to-event variations in the switching times, caused by thermal fluctuations. However, they did not achieve the sensitivity to resolve the resistance signals associated with the dynamics leading up to switching. We have developed an experimental technique that significantly improves the dynamic range of single-shot measurements of spin-torque switching, enough so that we can now study the pre-switching magnetic precession in detail and perform comprehensive analyses of how the amplitude of this precession is affected by both thermal fluctuations and spin-transfer torques [7].

The main difficulty we found with the circuits used in previous single-shot measurements of spin-torque switching was their dynamic range. In these techniques, a current step is applied to initiate switching, and the resistance

changes of the sample are detected in the form of small changes in transmitted or reflected voltage coming from the sample following the current step. The dynamic range of the measurement is limited because the output voltage from the sample contains a large initial jump owing to the onset of the current step, so that this signal cannot be amplified by a large gain without saturating the amplifiers either immediately before or immediately after the step. To avoid this problem, we split the initial current step in two before applying it to the sample. One part we apply to the sample, and we amplify the transmitted voltage that emerges from the sample initially with a low-gain inverting amplifier. We then take the second copy of the initial current pulse, suitably attenuated and time-delayed, and recombine it with the signal transmitted from the sample to largely cancel the initial large jump in the transmitted signal that previously prevented further amplification. We can then amplify this combined signal with a much larger gain to provide the dynamic range needed to measure small resistance signals arising from small-angle magnetic precession.

Several single-shot measurements of thermally assisted spin-torque switching for a CoFeB/MgO/CoFeB tunnel junction are shown in figure 4. These data correspond to switching from the antiparallel to parallel state. To eliminate background effects, we have subtracted off signals in which the initial state was the parallel orientation and the samples did not switch. A magnetic field of 100 Oe was applied in the sample plane perpendicular to the easy axis to offset the magnetization of the switching layer approximately 15° from the polarizing layer. In the left-hand panels in figure 4, the initial downward-moving steps in the measured signals at the time labelled 0 correspond to the onset of the current pulse. At later times, we observe clear oscillations in resistance whose amplitudes fluctuate, until eventually the fluctuations are large enough that the sample switches to the parallel state, and the measured voltage signal jumps up. The time required for switching varies from event to event for a given bias applied to the sample because these measurements correspond to a bias less than the zero-temperature threshold for switching, so that thermal fluctuations are needed to assist the switching. The signals for the 2 ns immediately before and after the switching are shown in the right-hand panels of figure 4.

These single-shot measurements enable very detailed analyses of the processes affecting spin-torque switching. We can, for example, observe that the degree of coherence for the precessional oscillations is very different when the switching layer is initially collinear with the polarizing layer, rather than offset by a small angle. We are able to make direct measurements of the correlation times of the thermally induced fluctuations, and, by Fourier transforming the signals, we can achieve measurements of the thermally excited FMR signals of the spin-torque-excited magnetic states that exist within the few tens of nanoseconds prior to switching. These issues are addressed in detail in Cui *et al.* [7]. Here, we discuss a bit of analysis not addressed in that paper—we test predictions [32,33] that under the influence of a spin torque the magnetic fluctuations, although they correspond to a highly non-equilibrium state, are nevertheless described by a Boltzmann distribution, $\propto \exp[-E/k_B T_{eff}(V)]$, where E is the magnetic energy and $T_{eff}(V)$ is an effective temperature.

To test this prediction, we first relate each local maximum in the oscillations of the measured voltage to a maximum in-plane deflection θ by assuming that the conductance of the magnetic tunnel junction varies as $\cos(\theta)$. For data taken
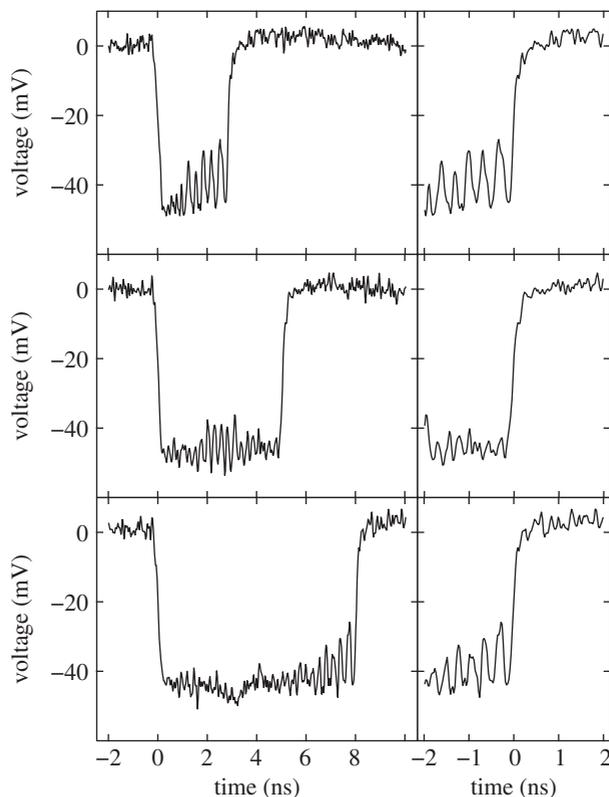
Figure 4. Single-shot measurements at room temperature of the magnetic dynamics associated with switching the free layer of a CoFeB/MgO/CoFeB tunnel junction from the antiparallel to parallel configuration, for a voltage step amplitude $V = -750\,\mathrm{mV}$. Left, full traces. Right, magnified views of the 2 ns immediately prior to switching and the 2 ns immediately after.

with a hard-axis field such as that in figure 4, we can then estimate the magnetic energy per unit volume at each maximum to be

$$E(\theta) = \frac{1}{2} M_S H_K \sin^2 \theta - M_S H_{\text{ext}} \cos\left(\theta - \frac{\pi}{2}\right) + E_0 = \frac{1}{2} M_S H_K \left(\sin \theta - \frac{H_{\text{ext}}}{H_K}\right)^2,$$
(4.1)

where the arbitrary constant $E_0 = M_S H_{\text{ext}}^2/(2H_K)$ is chosen so that the minimum energy is zero. The energy barrier per unit volume for switching is $E_{\text{b}} = M_S H_K (1 - H_{\text{ext}}/H_K)^2/2$. In figure 5$a$, we plot the resulting experimental histograms for $E(\theta)/E_{\text{b}}$ on a semi-log scale for several different values of bias V, using a value $H_K = 280\,\mathrm{Oe}$ determined from the magnetic field switching curve near zero bias. We include only energies corresponding to values of θ well above the background noise level. We find that probability distributions do indeed fall to a good approximation on straight lines, in agreement with the Boltzmann predictions. The slopes of the lines give a measure of $E_{\text{b}}/k_B T_{\text{eff}}(V)$ (figure 5b), which we find decreases as a function of increasing $|V|$ in reasonable agreement with the predicted linear dependence $E_{\text{b}}/k_b T_{\text{eff}}(V) = (1 - V/V_{\text{c0}})E_{\text{b}}/k_b T$ [32,33].
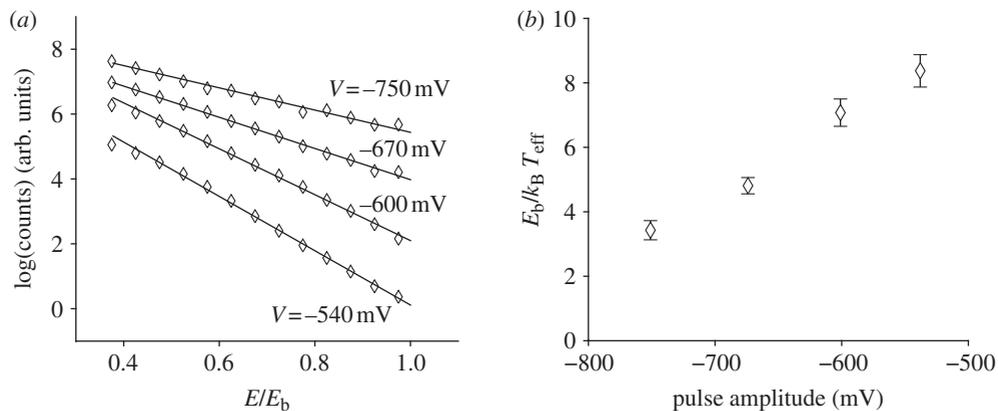
Figure 5. (*a*) Histograms of energy probability distributions for the non-equilibrium magnetic dynamics generated by spin torque and temperature (at room temperature) at several values of applied bias *V*. These energy distributions are determined from the maxima in the resistance oscillations as discussed in the text. Data for the different biases are artificially offset in the vertical direction. (*b*) Bias dependence of the ratio of the effective barrier height to effective temperature, determined from the slopes of the distributions in (*a*).

References

1 Slonczewski, J. C. 1996 Current-driven excitation of magnetic multilayers. *J. Magn. Magn. Mater.* **159**, L1–L7. (doi:10.1016/0304-8853(96)00062-5)

2 Berger, L. 1996 Emission of spin waves by a magnetic multilayer traversed by a current. *Phys. Rev. B* **54**, 9353–9358. (doi:10.1103/PhysRevB.54.9353)

3 Ralph, D. C. & Stiles, M. D. 2008 Spin transfer torques. *J. Magn. Magn. Mater.* **320**, 1190–1216. (doi:10.1016/j.jmmm.2007.12.019)

4 Beach, G. S. D., Tsoi, M. & Erskine, J. L. 2008 Current-induced domain wall motion. *J. Magn. Magn. Mater.* **320**, 1272–1281. (doi:10.1016/j.jmmm.2007.12.021)

5 Liu, L. Q., Moriyama, T., Ralph, D. C. & Buhrman, R. A. 2009 Reduction of the spin-torque critical current by partially canceling the free layer demagnetization field. *Appl. Phys. Lett.* **94**, 122508. (doi:10.1063/1.3107262)

6 Wang, C., Cui, Y.-T., Sun, J. Z., Katine, J. A., Buhrman, R. A. & Ralph, D. C. 2009 Bias and angular dependence of spin-transfer torque in magnetic tunnel junctions. *Phys. Rev. B* **79**, 224416. (doi:10.1103/PhysRevB.79.224416)

7 Cui, Y.-T., Finocchio, G., Wang, C., Katine, J. A., Buhrman, R. A. & Ralph, D. C. 2010 Single-shot time-domain studies of spin-torque-driven switching in magnetic tunnel junctions. *Phys. Rev. Lett.* **104**, 097201. (doi:10.1103/PhysRevLett.104.097201)

8 Hosomi, M. *et al.* 2005 A novel nonvolatile memory with spin torque transfer magnetization switching: spin-RAM. In *Proc. IEDM Technical Digest, Washington, DC, 5–7 December 2005*, pp. 459–462. New York, NY: IEEE. (doi:10.1109/IEDM.2005.1609379)

9 Kawahara, T. *et al.* 2008 2 Mb SPRAM (spin-transfer torque RAM) with bit-by-bit bi-directional current write and parallelizing-direction current read. *IEEE J. Solid State Circ.* **43**, 109–120. (doi:10.1109/JSSC.2007.909751)

10 Kishi, T. *et al.* 2008 Lower-current and fast switching of a perpendicular TMR for high speed and high density spin-transfer-torque MRAM. In *Proc. IEDM 2008, San Francisco, CA, 15–17 December 2008*. New York, NY: IEEE. (doi:10.1109/IEDM.2008.4796680)

11 Beach, R. *et al.* 2008 A statistical study of magnetic tunnel junctions for high-density spin torque transfer-MRAM (STT-MRAM). In *Proc. IEDM 2008, San Francisco, CA, 15–17 December 2008*. New York, NY: IEEE. (doi:10.1109/IEDM.2008.4796679)

12 Katine, J. A., Albert, F. J., Buhrman, R. A., Myers, E. B. & Ralph, D. C. 2000 Current-driven magnetization reversal and spin-wave excitations in Co/Cu/Co pillars. *Phys. Rev. Lett.* **84**, 3149–3152. (doi:10.1103/PhysRevLett.84.3149)

13 Mangin, S., Ravelosona, D., Katine, J. A., Carey, M. J., Terris, B. D. & Fullerton, E. E. 2006 Current-induced magnetization reversal in nanopillars with perpendicular anisotropy. *Nat. Mater.* **5**, 210–215. (doi:10.1038/nmat1595)

14 Mangin, S., Henry, Y., Ravelosona, D., Katine, J. A. & Fullerton, E. E. 2009 Reducing the critical current for spin-transfer switching of perpendicularly magnetized nanomagnets. *Appl. Phys. Lett.* **94**, 012502. (doi:10.1063/1.3058680)

15 Fuchs, G. D., Krivorotov, I. N., Braganca, P. M., Emley, N. C., Garcia, A. G. F., Ralph, D. C. & Buhrman, R. A. 2005 Adjustable spin torque in magnetic tunnel junctions with two fixed layers. *Appl. Phys. Lett.* **86**, 152509. (doi:10.1063/1.1899764)

16 Tulapurkar, A. A., Suzuki, Y., Fukushima, A., Kubota, H., Maehara, H., Tsunekawa, K., Djayaprawira, D. D., Watanabe, N. & Yuasa, S. 2005 Spin-torque diode effect in magnetic tunnel junctions. *Nature* **438**, 339–342. (doi:10.1038/nature04207)

17 Sankey, J. C., Braganca, P. M., Garcia, A. G. F., Krivorotov, I. N., Buhrman, R. A. & Ralph, D. C. 2006 Spin-transfer-driven ferromagnetic resonance of individual nanomagnets. *Phys. Rev. Lett.* **96**, 227601. (doi:10.1103/PhysRevLett.96.227601)

18 Sankey, J. C., Cui, Y.-T., Sun, J. Z., Slonczewski, J. C., Buhrman, R. A. & Ralph, D. C. 2008 Measurement of the spin-transfer-torque vector in magnetic tunnel junctions. *Nat. Phys.* **4**, 67–71. (doi:10.1038/nphys783)

19 Kubota, H. *et al.* 2008 Quantitative measurement of voltage dependence of spin-transfer torque in MgO-based magnetic tunnel junctions. *Nat. Phys.* **4**, 37–41. (doi:10.1038/nphys784)

20 Heiliger, C. & Stiles, M. D. 2008 *Ab initio* studies of the spin-transfer torque in magnetic tunnel junctions. *Phys. Rev. Lett.* **100**, 186805. (doi:10.1103/PhysRevLett.100.186805)

21 Petit, S., Baraduc, C., Thirion, C., Ebels, U., Liu, Y., Li, M., Wang, P. & Dieny, B. 2007 Spin-torque influence on the high-frequency magnetization fluctuations in magnetic tunnel junctions. *Phys. Rev. Lett.* **98**, 077203. (doi:10.1103/PhysRevLett.98.077203)

22 Deac, A. M. *et al.* 2008 Bias-driven high-power microwave emission from MgO-based tunnel magnetoresistance devices. *Nat. Phys.* **4**, 803–809. (doi:10.1038/nphys1036)

23 Polianski, M. L. & Brouwer P. W. 2004 Current-induced transverse spin-wave instability in a thin nanomagnet. *Phys. Rev. Lett.* **92**, 026602. (doi:10.1103/PhysRevLett.92.026602)

24 Lee, K.-J. 2008 Effect of nonlocal spin-transfer torque on current-induced magnetization dynamics. (http://arxiv.org/abs/0811.4649)

25 Slavin, A. & Tiberkevich, V. 2009 Nonlinear auto-oscillator theory of microwave generation by spin-polarized current. *IEEE Trans. Magn.* **45**, 1875–1918. (doi:10.1109/TMAG.2008.2009935)

26 Li, Z., Zhang, S., Diao, Z., Ding, Y., Tang, X., Apalkov, D. M., Yang, Z., Kawabata, K. & Huai, Y. 2008 Perpendicular spin torques in magnetic tunnel junctions. *Phys. Rev. Lett.* **100**, 236602. (doi:10.1103/PhysRevLett.100.246602)

27 Sun, J. Z., Gaidis, M. C., Hu, G., O'Sullivan, E. J., Brown, S. L., Nowak, J. J., Trouilloud, P. L. & Worledge, D. C. 2009 High-bias backhopping in nanosecond time-domain spin-torque switches of MgO-based magnetic tunnel junctions. *J. Appl. Phys.* **105**, 07D109. (doi:10.1063/1.3058614)

28 Krivorotov, I. N., Emley, N. C., Sankey, J. C., Kiselev, S. I., Ralph, D. C. & Buhrman, R. A. 2005 Time-domain measurements of nanomagnet dynamics driven by spin-transfer torques. *Science* **307**, 228–231. (doi:10.1126/science.1105722)

29 Acremann, Y. *et al.* 2006 Time-resolved imaging of spin transfer switching: beyond the macrospin concept. *Phys. Rev. Lett.* **96**, 217202. (doi:10.1103/PhysRevLett.96.217202)

30 Devolder, T. *et al.* 2008 Single-shot time-resolved measurements of nanosecond-scale spin-transfer induced switching: stochastic versus deterministic aspects. *Phys. Rev. Lett.* **100**, 057206. (doi:10.1103/PhysRevLett.100.057206)

31 Tomita, H. *et al.* 2008 Single-shot measurements of spin-transfer switching in CoFeB/MgO/CoFeB magnetic tunnel junctions. *Appl. Phys. Express* **1**, 061303. (doi:10.1143/APEX.1.061303)

32 Li, Z. & Zhang, S. 2004 Thermally assisted magnetization reversal in the presence of spin-transfer torque. *Phys. Rev. B* **69**, 134416. (doi:10.1103/PhysRevB.69.134416)

33 Apalkov, D. M. & Visscher, P. B. 2005 Spin-torque switching: Fokker–Planck rate calculation. *Phys. Rev. B* **72**, 180405(R). (doi:10.1103/PhysRevB.72.180405)