Bipolar high-field excitations in Co/Cu/Co nanopillars

B. Özyilmaz* and A. D. Kent
Department of Physics, New York University, New York, New York 10003, USA

M. J. Rooks and J. Z. Sun
IBM T. J. Watson Research Center, P. O. Box 218, Yorktown Heights, New York 10598, USA
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Recent experiments have confirmed the seminal predictions by Slonczewski and Berger that a magnet acting as a spin filter on a traversing current can experience a net torque, known as a spin-transfer torque. Spin-current-induced magnetization reversal excitations have been directly observed in magnetic nanostructures. These experimental studies of spin transfer have focused on spin-valve-type structures of ferromagnet/normal metal/ferromagnet layers, in which the layers may be noncollinear and one of the layers is thicker than the other. The thicker layer serves as a reference layer that sets up a spin-polarized current with a component of angular momentum transverse to the thin layer’s magnetization. In all these experiments current-induced excitations have been observed for only one polarity of the current, nominally because of the asymmetry in the layer structure. This observation was considered to be unmistakable evidence for the physics associated with a spin-transfer torque—as opposed to the effects of charge-current-induced magnetic fields. In addition, the lowest resistance state was always considered to be the static state of parallel magnetic alignment.

Here we report studies of current-induced excitations of the magnetization in Co/Cu/Co bilayer nanopillars. Experiments were performed at $T=4.2$ K in high magnetic fields ($H > 4 \pi M$) in the field perpendicular to the plane geometry. For sufficiently large current densities we observe anomalies in $dV/dI$ independent of current polarity, which decrease the junction resistance. The bipolarity of the excitations and the decrease in resistance cannot be understood in terms of spin-transfer torque-induced single-domain dynamics. These results show that high current densities can induce excitations of the magnetization independent of current polarity and relative alignment of the magnetizations of the two magnetic layers. From detailed $I$-$V$ measurements we construct a phase diagram that shows the conditions under which such excitations occur. In addition, the results illustrate that at high currents the nanopillar resistance can be lower than that of a state of parallel magnetic alignment. We suggest that structural asymmetries in nanopillar junctions lead to a spin-accumulation pattern that provides a new source for spin-transfer torque-induced magnetization dynamics. We have recently shown that the longitudinal spin accumulation has an important influence on the magnetization excitations in asymmetric single-layer junctions.

Here we show that similar physics is relevant to the more typically studied bilayer devices that consist of a “fixed” thick magnetic layer and a thin “free” magnetic layer.

We study spin-transfer torques in devices fabricated by means of a nanostencil mask process. This approach defines the lateral dimensions ($\sim 50 \times 50$ nm) of the junction prior to the growth of a Pt 15 nm/Cu 10 nm/Co 3 nm/Cu 10 nm/Co 12 nm/Cu 300 nm multilayer. The layer structure is illustrated schematically in Fig. 1. Six such junctions were studied in detail and representative data on one junction is presented in this paper. Transport measurements were conducted using a four-probe geometry, where the differential resistance $dV/dI$ was measured by means of a phase-sensitive lock-in technique with a 100-µA modulation current at $f = 873$ Hz added to a dc bias current. The lock-in time constant was 300 ms. Positive current is defined such that the electrons flow from the thin ferromagnetic layer to the thick ferromagnetic layer.

FIG. 1. Right: The layer structure of a nanopillar device from left to right is Pt/Cu/Co/Cu/Co/Cu. The applied magnetic field, electron flow, and magnetization directions are indicated. Left: The calculated spin-accumulation pattern in the P state for negative currents and in the AP state for positive currents, based on a two-channel model, including interface resistances.

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FIG. 2. (Color) (a)–(c) Differential resistance vs current with large applied perpendicular fields. (b) Dips in \(dV/dI\) are observed at a negative current bias under conditions for which instabilities are not expected in a single-domain model. (c) The peak in \(dV/dI\) at positive current and the change in differential resistance after the peak is due to switching into an AP state. (d) The color plot shows \(d^2V/dI^2\) vs current and applied field (red is high and blue is low). The dispersion of the dip in \(dV/dI\) at negative current with increasing field is clearly visible.

In bilayer junctions, the magnetoresistance is dominated by the giant magnetoresistance (GMR) effect. At 4.2 K and in fields applied in the thin film plane, junctions discussed here exhibit a clean switching between the parallel (P) and antiparallel (AP) state with a GMR of \(~\sim 2\%\). Anisotropic MR of the layers is one order of magnitude smaller than this and the Lorentz MR is negligible. A detailed characterization of the magnetoresistance for the in-plane configuration at both 300 and 4.2 K can be found in Ref. 17. Here we focus on the magnetoresistance in large fields applied perpendicular to the thin-film plane. At zero applied field dipolar coupling between the magnetic layers leads to an AP state, and the GMR can thus also be deduced from field perpendicular to the plane measurements at zero dc bias [see Fig. 4(a)].

Figure 2(a) shows typical measurements of \(dV/dI\) versus \(I\) in large applied fields \(B \geq B_{\text{demag}} \sim 1\ T\). Current-induced excitations (peaks in \(dV/dI\) occur at positive current bias. However, a more careful look at the current sweeps reveals the presence of excitations even at negative currents [Fig. 2(b)]. Here we observe anomalies in \(dV/dI\) in the form of dips. These dips correspond to decreases in the differential resistance of about 0.5\%. These excitations shift to higher currents with increasing field. They are best distinguished from the parabolic background resistance by plotting the second derivative on a color scale as a function of current bias and applied field. From this color plot [Fig. 2(d)] it is clear that the excitations depend approximately linearly on the applied field for both polarities of current.

FIG. 3. (Color) \(dV/dI\) vs current at large positive current. The color plot shows \(d^2V/dI^2\) vs current and applied field. Dips in differential resistance after the main peak in \(dV/dI\) (labeled B) are visible and correspond to boundary C. A labels the region where peaks in \(dV/dI\) with \(\Delta R/R\) much smaller than the GMR value are observed.

Peaks in \(dV/dI\) at positive currents are known to be related to magnetization excitations. Earlier work\(^5\) has shown that their position indicates the critical current, \(I_{\text{crit}}\), necessary to switch the free-layer magnetization into the high-resistance AP state. This interpretation is further supported by recent high-frequency noise experiments in the field perpendicular to the plane geometry.\(^18\) Excitations at negative currents are unexpected. In the parallel configuration negative currents are expected to suppress any deviation of the free layer from parallel alignment with the fixed layer. In particular, in large applied fields, the layer magnetizations should therefore remain in the P state. In addition, we observe dips instead of peaks in \(dV/dI\), indicating that excitations at negative currents decrease the junction resistance. However, within a single-domain model the GMR effect should lead to an increase of the junction resistance whenever the layer magnetizations deviate from parallel alignment.

At positive currents in a single-domain model in which the thick-layer magnetization remains fixed, there are no further excitations once the AP state is achieved, i.e., once \(I > I_{\text{crit}}\) after the main peak in \(dV/dI\). However, there is structure in \(dV/dI\) beyond the main peak, again in the form of dips in \(dV/dI\). The results are shown in Fig. 3. Here we plot the differential resistance as a function of current for selected applied fields, \(0.7 T < B < 4.7\ T\). We observe both peaks and dips in \(dV/dI\). However, at fields \(B \geq 1\ T\), dips occur only for \(I > I_{\text{crit}}(H)\). Also, most current sweep traces show multiple dips in \(dV/dI\). The field dependence of these excitations is best seen when the second derivative \(d^2V/dI^2\) is plotted on a color scale as a function of current bias and applied field [Fig. 3]. Such a plot reveals two boundaries, which can be best distinguished at fields \(B \geq 1.5\ T\). The first boundary \((B)\) represents the currents \(I_{\text{crit}}(H)\) at which the free layer switches into the AP state. Note that in many samples we also observe additional peaks in \(dV/dI\) for \(I < I_{\text{crit}}(H)\) [region \(A\)]. These peaks coincide with small upward jumps of the junction resistance (not shown), which we associate with transitions between precessional states.\(^18\)
stable and reproducible during field sweeps. This is best seen in the demagnetization field no excitations are observed. Above the demagnetization field no excitations are observed. (b),(c) $I=\pm 10$ and $\pm 15$ mA. Excitations are observed at large fields $B>B_{\text{demag}}$ for both positive and negative currents, as described in the text. (d) $I=15$ mA. The peak at $B_{\text{crit}}$ marks the switching of the layers to a P state.

At higher currents the color plot reveals a second boundary (C). The latter marks the critical current $I_c(H)$ above which we observe dips in $dV/dl$. The current bias and field dependence of these additional excitations is nontrivial, but the observed features are both stable and reproducible. A good demonstration of the latter is their applied field dependence. This is best described by first considering cuts parallel to the current axis of the color plots (Fig. 3, dashed-dotted line) and then cuts parallel to the field axis (dotted line). In the first case the applied field is constant. Now, as the current is increased, several branches are crossed corresponding to distinct excitations. At each of these crossings we observe dips in $dV/dl$. From cuts parallel to the field axis (constant current bias), we see that each excitation exists only in a very narrow field range, i.e., they have a weak dependence on the magnetic field. Note that this is similar to the field dependence of $I_c$ at fields $B<B_{\text{demag}} \approx 1$ T. Also here the excitations shift to lower currents as we increase the applied field. In addition, different branches of excitations are separated by narrow stripes of high-resistance regions. We suspect that these gaps reflect the quantization of transverse spin-wave modes in these small elements.

The bipolarity of these high field, high-current excitations (i.e., the dips in differential resistance) can also be seen in field sweeps at a fixed current bias. We show examples of such measurements in Fig. 4. A field sweep at zero dc bias is shown in Fig. 4(a), whereas Figs. 4(b) and 4(c) show the MR at $I=\pm 10$ mA and $I=\pm 15$ mA, respectively. As shown in Fig. 4(a), at zero dc bias and fields $B>B_{\text{demag}} \approx 1$ T excitations are absent in the field traces. However, high current densities lead to excitations even at fields $B>B_{\text{demag}}$ independent of current polarity. Note that excitations are also stable and reproducible during field sweeps. This is best seen from the measurements at $+15$ mA [Fig. 4(c)], where an almost perfect overlap between field sweep up and field sweep down is observed. These current-driven excitations vanish once the magnitude of the applied field exceeds critical fields $B_\pm$ at positive currents and $B_-$ at negative currents. At positive bias we see the additional boundary at $B(I)=B_{\text{crit}}$ at which the applied field switches the free-layer magnetization back to the P state [Fig. 4(d)]. The main difference between $B_{\text{crit}}$ and $B_\pm$ is that the former leads to a decrease in resistance, whereas the latter indicate the point where the junction resistance increases.

We now discuss an interpretation of these results in terms of spin-wave instabilities that are expected in the presence of strong asymmetries in the longitudinal spin accumulation. First, we note that dips in $dV/dl$ at negative current bias have also been observed in pillar junctions with only a single ferromagnetic layer. Here, excitations are a consequence of asymmetric leads, which induce an asymmetry in longitudinal spin accumulation. The necessary condition for such instabilities is that the current bias has to be such that the sum of the longitudinal spin accumulation on either side of the ferromagnetic layer, i.e., the net spin accumulation, is opposite the magnetization direction. We have modeled the spin-accumulation pattern in our bilayer junctions using the two-current model, with the spin-dependent bulk and interface resistances of Ref. 21 in the limit in which the spin-diffusion length is much larger than the layer thicknesses ($\lambda_{sf} \rightarrow \infty$). Figure 1 shows that in the P state at negative current bias, the spin accumulation about the thick layer is asymmetric; the net spin accumulation is opposite the magnetization direction. According to the condition governing spin-wave instabilities in single layers, this accumulation pattern can excite nonuniform spin waves in the thick layer.

To explain the region of excitations at currents beyond $I_c(H)$, i.e., excitations at positive current bias in the AP state, we also consider the spin accumulation in this case (Fig. 1, AP state graph). From this we see that the switching of the free layer has an important effect on the spin-accumulation pattern at the fixed layer. The sign of the net spin accumulation inverts as the system is switched by the current from the P state into the AP state. Therefore, excitations of the fixed layer now require a positive current bias. This is in agreement with the experimental observation. From this we conclude that dips in $dV/dl$ at both positive and negative currents are caused by the excitation of the thick magnetic layer. While at positive currents these excitations could equally be due to uniform excitations of the fixed layer, the pattern of the excitations matches well the nonuniform excitations found in single layers. A longitudinal spin accumulation opposite the magnetization direction on both sides of this layer seems to be the most likely cause for these excitations.

At first the situation would appear to be quite similar to that for which excitations have already been observed in single-layer junctions. However, there are some notable distinctions. In single-layer junctions the presence of an asymmetric and hence a nonvanishing net longitudinal spin accumulation at the ferromagnetic layer is caused by different top and bottom nonmagnetic leads. In bilayers, with a thick and thin layer, there is a built-in asymmetry. So in
contrast to single-layer junctions a lead asymmetry is not necessary for current-induced instabilities. Another important difference is that the excitations in the single-layer junctions rely on a feedback mechanism between the layer magnetization and the spin accumulation in the adjacent nonmagnetic layers. In bilayer junctions the layer magnetization is biased with a longitudinal spin accumulation (set by the spin-dependent bulk and interface conductivities, relative size, and orientation of the two ferromagnetic layers\textsuperscript{22}). Spin diffusion along the interface, which provides the feedback, is apparently not necessary to produce excitations. Hence, single-layer and (collinear) bilayer junctions probe spin-dependent transport and spin-current-induced excitations of the magnetization under distinct conditions.

The presence of a second layer in bilayer junctions has implications on the nature of the magnetic excitations. For example, the decrease in junction resistance allows one to distinguish between nonuniform and uniform excitations. Uniform excitations at negative bias (P state) should always produce an increase of junction resistance because of GMR. Only nonuniform excitations can account for a decrease of junction resistance. This can be explained by considering the effect of spin accumulation on the junction resistance. Any spin accumulation between the ferromagnetic layers will increase the junction resistance. Nonuniform excitations effectively reduce the amount of spin accumulation in the spacer layer, because they mix the two spin channels.\textsuperscript{19,22} Hence, the junction resistance decreases. We believe that this also explains why it is easier to observe these excitations in bilayer junctions in the AP state than in bilayer junctions in the P state or, for that matter, in single-layer junctions. From Fig. 1 we see that the spin accumulation in the spacer layer is largest in the AP state. Therefore the largest reduction in device resistance will occur when nonuniform excitations take place in the AP state.

It is important to note that our interpretation of the data is based on the model of spin transfer first proposed by Slonczewski.\textsuperscript{1} An alternative point of view is that large currents generate incoherent spin waves, which is analogous to heating of the magnetic system (see Appendix D of Ref. 23 for a discussion). The magnetization dynamics is quite distinct in this latter case. High-frequency noise and time-resolved measurements should lead to a better understanding of the nature of these excitations.

In conclusion, we have shown that in bilayer junctions high current bias leads to current-induced instabilities independent of current polarity. In contrast to earlier reports, these excitations lead to a reduction of the junction resistance even when the layer magnetizations are initially aligned by means of large applied fields. The reduction of the junction resistance for negative current polarities from the P state demonstrates the presence of a new magnetic state with a lower resistance than that of static parallel alignment of the layers. It gives strong support for nonuniform excitations of the fixed layer magnetization.

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