VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Current-Induced Excitations in Single Cobalt Ferromagnetic Layer Nanopillars

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

J. Z. Sun, M. J. Rooks, and R. H. Koch
IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598, USA

(Received 8 March 2004; published 22 October 2004)

Current-induced excitations in Cu/Co/Cu single ferromagnetic layer nanopillars (~50 nm in diameter) have been studied experimentally as a function of Co layer thickness at low temperatures for large applied fields perpendicular to the layers. For asymmetric junctions current-induced excitations are observed at high current densities for only one polarity of the current and are absent at the same current densities in symmetric junctions. These observations confirm recent predictions of spin-transfer torque induced spin-wave excitations in single layer junctions with a strong asymmetry in the spin accumulation in the leads.

DOI: 10.1103/PhysRevLett.93.176604 PACS numbers: 72.25.Mk, 75.30.Ds, 75.75.+a, 85.75.–d

Angular momentum transfer studies in magnetic nanostructures have made tremendous progress during the last few years. Recently, both spin current driven magnetization reversal [1–3] and precession [4,5] have been directly observed in magnetic nanostructures. These experiments confirmed seminal predictions by Berger [6] and Slonczewski [7] that a magnet acting as a spin filter on a traversing current can experience a net torque: (spin-) angular momentum which is filtered out of the current must be absorbed by the ferromagnet. In the presence of an angular momentum component transverse to the magnetization of the ferromagnet this leads to a so-called spin-transfer torque. A transverse spin polarization of the electric current was thought to be necessary for current-induced excitations of the magnetization. Hence most of the experimental and theoretical work on spin-transfer torque concentrated on spin-valve-type structures of ferromagnet/normal metal/ferromagnet layers, in which the layer magnetizations may be noncollinear. Only recently, the necessity of a transverse component of spin polarized current has been relaxed [8,9]. At high enough current densities Polianski and Brouwer [8] and Stiles *et al.* [9] predict spin-wave excitations in thin ferromagnetic layers even when the current is unpolarized.

Polianski and Brouwer [8] have reemphasized the spin-filtering property of a ferromagnet (FM) as the fundamental cause for spin-transfer torque. Spin filtering is present also in normal metal/ferromagnetic metal/normal metal (NM/FM/NM) pillar junctions with only a single FM layer. In the current perpendicular to the plane geometry a current bias results in spin accumulation on either side of the FM. Fluctuations in the magnetization direction combined with spin diffusion parallel to the NM/FM interfaces result in a spin-transfer torque. At each interface these torques act to align the magnetization along the direction of the spin accumulation. In a perfectly symmetric single layer structure the resulting torques are of equal magnitude but of opposite direction and cancel each other. However, if the mirror symmetry is broken the torques acting on each NM/FM interface have different magnitudes. For this case, Refs. [8,9] predict that an unpolarized current can induce spin-wave instabilities and generate spin-wave excitations with wave vectors in the film plane. Instabilities occur when the current bias is such that the direction of the larger spin accumulation is antiparallel to the direction of the magnetization of the FM. Polianski and Brouwer [8] studied the case of a thin FM where the magnetization does not have any spatial variation along the current flow direction. Here, the break in symmetry requires asymmetric contacts. Stiles *et al.* [9] relaxed this requirement and allowed the magnetization to vary along the current flow direction, which also breaks the mirror symmetry. In either case in ideal asymmetric junctions current-induced excitations are predicted to occur for only one current polarity and are expected to be absent in perfectly symmetric structures. Both groups made predictions on how single layer instabilities depend on parameters such as the current bias polarity, the FM layer thickness, the degree of asymmetry of the single layer junction, and the applied field.

In this Letter we report systematic studies of current-induced excitations of the magnetization in both symmetric and asymmetric nanopillar junctions containing only a single FM layer. Measurements were performed in high magnetic fields ($H > 4\pi M$) in the field perpendicular to the plane geometry at 4.2 K. For sufficiently large current densities we observe anomalies in dV/dI for only one current polarity. Current-induced single layer excitations occur in asymmetric pillar devices (PD) and lead to a decrease of the junction resistance [$\Delta R/R \sim O(1\%)$]. They are absent in symmetric PDs. Our results confirm the recent prediction of current-induced excitations in asymmetric PDs.

Pillar junctions have been fabricated by means of a nanostencil mask process [10], which has been used ear-

© 2004 The American Physical Society

lier for spin-transfer torque studies in Co/Cu/Co trilayer spin valves [3,11]. To study the thickness dependence of single layer excitations we combined the nanostencil mask process with an *in situ* wedge growth mechanism. With this approach we have fabricated PDs with a single Co layer of continuously varied thickness across a single wafer. As shown in Fig. 1, structures fabricated by means of an undercut template are intrinsically asymmetric due to the requirement of an inert bottom electrode surface, usually Pt, on top of which the pillar structure is grown. Here, asymmetry refers to the spin-accumulation pattern generated within the PD with respect to the Co layer position. The strong asymmetry due to the choice of Pt as bottom electrode is removed by inserting a second Pt layer. Therefore, the study of spin transfer in symmetric single layer structures requires the "capping" of the pillar with a Pt layer as indicated in Fig. 1. Many junctions with a FM layer thickness varying from 2 to 17 nm and lateral dimensions from 30×60 nm up to 70×140 nm have been studied as a function of bias current and applied field. The range of Co layer thickness covers both the case where the thickness t is smaller than the exchange length l_{ex} of Co and the case where the thickness is comparable to the latter ($t \geq l_{\text{ex}}$). All junctions in this thickness range exhibit single layer excitations. Here we discuss representative data obtained on PDs with $t \approx 8$ nm and $t \approx 17$ nm and lateral dimensions of 30×60 nm and 50×50 nm, respectively. To confirm that the excitations are caused by asymmetric contacts we have repeated experiments with symmetric PDs with a stack sequence of |PtRh15 nm|Cu10 nm|Co10 nm|Cu10 nm|Pt15 nm|.

All measurements reported here were conducted at 4.2 K in a four point-geometry configuration in fields applied perpendicular to the thin film planes. The differential resistance dV/dI was measured by a lock-in technique with a 100 μA modulation current at $f = 873$ Hz added to a dc bias current. As shown in Fig. 1 positive current is defined such that the electrons flow from the bottom electrode of the junction to the top electrode.

A typical magnetoresistance (MR) measurement of a single layer junction at 0 dc bias is shown in Fig. 1. The resistance R has its minimum when the magnetization **M** lies in the thin film plane, i.e., when **M** is orthogonal to $\hat{\mathbf{j}}$. We observe a gradual increase in R as we increase the applied field which tilts the magnetization vector out of the thin film plane. Once the applied field exceeds $4\pi M$, **M** is collinear with $\hat{\mathbf{j}}$ and the resistance saturates at its maximum. From this we conclude that the observed MR is sensitive enough to register (*field induced*) changes of relative orientation of $\hat{\mathbf{j}}$ and **M**. This provides a convenient "*in situ*" tool for detecting *current-induced* changes of the magnetization. It is important to note that for even the thickest layer we observe a *decrease* of the resistance in the field sweeps when **M** and $\hat{\mathbf{j}}$ start deviating from collinear alignment.

A typical $I(V)$ curve for an asymmetric single layer PD is shown in Fig. 2(a). Here dV/dI versus I is plotted for fields $H = 1.5$, 2, and 2.5 T and $H = 3.1$ T for a 30×60 nm junction with $t \approx 8$ nm. At fields above the demagnetization field ($H > 1.5$ T) we observe anomalies in the form of small dips at negative current polarity. The presence of many modes makes it difficult not only to distinguish individual modes but also to find the threshold current for single layer excitations at a particular field value. Note that in the field perpendicular geometry the onset of these excitations always leads to a (small) decrease in resistance, which is opposite to what has been observed in both point contact experiments [12–14] and trilayer PDs.

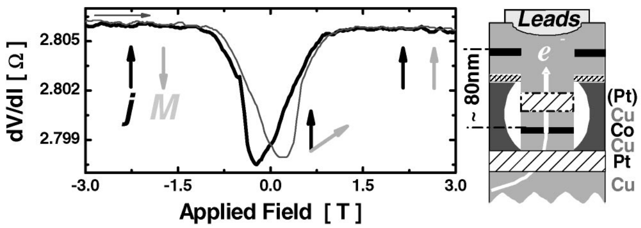

FIG. 1. Left: typical dV/dI vs H measurement at 0 dc bias. The junction size is $50 \times 50\,\text{nm}^2$ and $t \approx 17$ nm. An increase in junction resistance (~0.1%) is observed when **j** and **M** are collinear. Right: schematic of a single Co layer pillar junction fabricated via the nanostencil mask process. Symmetric junctions are fabricated by the addition of a Pt layer (dash-dotted box).

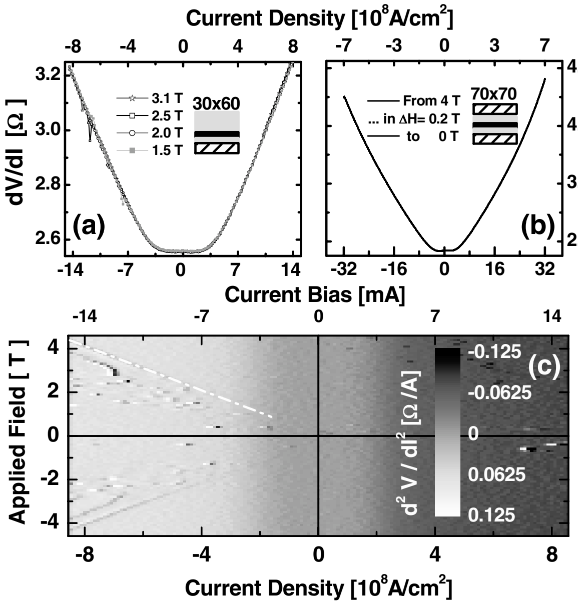

FIG. 2. dV/dI vs I at constant fields. (a) Asymmetric junction (30×60 nm, $t \approx 8$ nm) with Pt as the bottom electrode. For $H > 4\pi M$ dips are observed at negative bias only. (b) Symmetric junction (70×70 nm, $t \approx 10$ nm) with Pt on either side of the Co layer ($t \approx 10$ nm). $I(V)$ curves at different field values overlap fully. (c) Phase diagram for current-induced excitations in single layer junctions; same junction as in (a). d^2V/dI^2 is plotted on a gray scale. The white dash-dotted line indicates the boundary for excitations.

To distinguish these excitations from the parabolic background resistance, we plot d^2V/dI^2, which is sensitive to abrupt features in dV/dI. Plotted on a gray scale as a function of the applied field and the current bias it represents a phase diagram for single layer excitations [Fig. 2(c)]. Here the current is swept from -15 to $+15$ mA while the magnetic field is held constant for each current sweep. For subsequent sweeps the field is stepped from -4.6 to $+4.6$ T in 100 mT steps. The "current bias-applied field" plane segregates into two regions separated by a straight line, which we associate with the threshold current, the critical current I_{crit} for single layer excitations. For fields $H > 4\pi M$ excitations occur only for negative current polarities. At negative current bias excitations are absent below the critical current, whereas above the current threshold many modes are excited. I_{crit} shows a linear dependence on the applied field and can be extrapolated approximately to the origin. Dividing I_{crit} by the *nominal* junction area A, we estimate the field dependence of the critical current density $j_{\mathrm{crit}} = bH$ with $b \approx 1.9 \times 10^8$ (A/cm^2)/T. We obtain a more accurate estimate for j_{crit} by multiplying I_{crit} with the junction resistance $R \approx 2.55\ \Omega$, which is equivalent to dividing by an *effective* junction area: $j_{\mathrm{crit}} \propto I_{\mathrm{crit}}R = \beta H$ with $\beta \approx 8.8 \times 10^{-3}$ (A Ω/T).

A better way to distinguish the small features of current-induced excitations from the varying background resistance is to fix the latter. This can be done by keeping the current constant and sweeping the applied field instead. An example of such a measurement is shown in Figs. 3(a) and 3(c). Field sweeps at fixed negative current bias are shown in Fig. 3(a), whereas Fig. 3(c) shows the MR at fixed positive currents. The strongest evidence for current-induced excitations in single layer junctions comes from the comparison of these two figures. As shown in Fig. 3(c) excitations at fields $H > 4\pi M$ are absent in the field traces. However, high current densities at positive bias gradually increase the applied field at which the differential resistance saturates. This effect cannot be attributed solely to the presence of additional (Oersted) fields related to the charge current and is not yet understood. There is a dramatic change in the field traces if one applies a negative current bias to the junction. For each fixed current value there is now a critical field H_{crit}, above which the resistance remains constant. However, below H_{crit} the observation of peaks and dips indicates the presence of many (current-induced) excitations. H_{crit} is a linear function of the bias current and shifts to higher values as the current increases. As can be seen in Fig. 3(b), the linear fit of the critical fields can once more be extrapolated to the origin. Hence in both field sweeps at fixed currents and current sweeps at fixed fields there is a linear dependence of the critical parameter on the running variable, i.e., $j_{\mathrm{crit}} = bH$ and $H_{\mathrm{crit}} = cj$. For a particular Co layer thickness the slopes b and c are equivalent, i.e., $b \cong c^{-1}$. From Fig. 3(b) and the nominal junction area A we estimate the current density dependence of $H_{\mathrm{crit}} = cj$ with $c \approx 5.2 \times 10^{-9}$ T/(A/cm^2). Using the junction resistance $R \approx 2.80\ \Omega$ as an approximation for the effective junction area we obtain $H_{\mathrm{crit}} \propto \zeta IR$ with $\zeta \approx 73.8$ T/(A Ω). Note that for $H < 4\pi M$ there are large changes in the hysteresis for both current polarities. This effect cannot be explained by the interaction of the Oersted fields with magnetic domain configurations at fields $H < 4\pi M$.

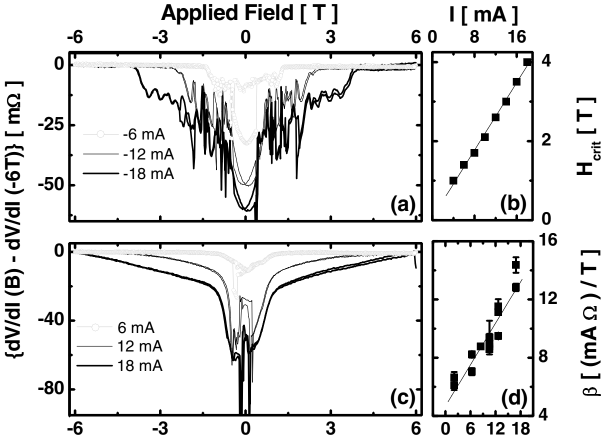

FIG. 3. (a) dV/dI vs H at negative current bias. The zero dc bias field sweep of this junction is shown in Fig. 1. (b) Current bias dependence of the critical fields above which excitations are not observed. (c) dV/dI vs H for positive current bias; excitations are absent. (d) Thickness dependence of the "critical currents." Here the slope β of $I_{\mathrm{crit}}R$ is plotted as a function of Co layer thickness t.

We have also studied the thickness dependence of these excitations and summarize the results in Fig. 3(d). For all thicknesses the observed boundary in the "current bias/applied field plane" can be extrapolated close to the origin. Here we plot only the slope β of the field dependence of $I_{\mathrm{crit}}R$ ($\propto j_{\mathrm{crit}}$) as a function of Co layer thickness t. We observe an *increase* of β with increasing t, $\Delta\beta/\Delta t \approx (0.48 \pm 0.05)$ (mA Ω)/(T nm). The critical currents increase by approximately a factor of 2 as one increases the Co layer thickness t from 2 to 17 nm. Over the same thickness range the junction resistance R increases only by $\approx 25\%$ (not shown).

To clarify the origin of these excitations, we have repeated these experiments in symmetric single layer PDs. An example of current sweeps at fixed fields in these structures is shown in Fig. 2(b). Here the current is swept from $+32$ to -32 mA in a 70×70 nm junction. In magnetic fields up to 4 T features such as dips or peaks are absent in the current-voltage characteristics. Also, field sweeps at fixed current do not exhibit any of the strong polarity dependence observed in asymmetric PDs. To summarize, in symmetric junctions current-induced excitations are absent up to $j \leq 7 \times 10^8$ A/cm^2.

Experimental results and theoretical predictions are in good agreement. Both models give the correct order of magnitude, correct polarity [15], and thickness dependence of j_{crit} in asymmetric structures. Reference [8] studied the case where $\mathbf{M}$ does not have any spatial variation along the direction parallel to the current $\hat{\mathbf{j}}$. Reference [9] also considered the case where $\mathbf{M}$ is allowed to vary along $\hat{\mathbf{j}}$. For this case excitations are expected to occur independent of current polarity even in *symmetric* PDs. However, the predicted critical currents are much larger ($j_{\mathrm{crit}} > 10^{10}$ A/cm^2) than for the asymmetric case [17]. Once $\mathbf{M}$ is allowed to vary along $\hat{\mathbf{j}}$, current-induced excitations are predicted for both current polarities, albeit, with large differences in the magnitude of critical currents. For example, for an asymmetric junction with $t \approx 17$ nm the necessary *positive* current densities ($j_{\mathrm{crit}} > 2.5 \times 10^9$ A/cm^2) far exceed the value which can be sustained by existing PDs. The linear dependence of j_{crit} on H can be explained by both models. The (near) zero intercept of j_{crit} is somewhat peculiar but can also be explained if the influence of the shape and finite size of the PD on the spin-wave modes is properly accounted for in models [17]. Also the increase of the critical current j_{crit} with increasing Co layer thickness t is in agreement with theoretical predictions. An *increase* of j_{crit} with increasing t is expected due to an increase of the (bulk) damping [8,9]. According to Ref. [9] in thicker films ($t \gtrsim l_{\mathrm{ex}}$) the variation of $\mathbf{M}$ along $\hat{\mathbf{j}}$ introduces an additional source of asymmetry. This should activate a competing effect which by itself would *decrease* j_{crit} with increasing t. However, to determine which effect would dominate details of layer structure and junction geometry need to be considered. The direct comparison between experimental results and theoretical predictions is further hampered by the change of asymmetry in spin accumulation as we increase the Co layer thickness [18]. For our device geometry and for Co layer thicknesses up to $t \sim 17$ nm ($t > l_{\mathrm{ex}}$) the dominant source of the current-induced excitations appears to be the asymmetry of the leads. Ultimately, measurement of the high frequency noise and time resolved measurements should lead to a better understanding of the nature of these excitations [4,5].

Finally, we address the possibility of current-induced excitations in multilayered structures caused by an asymmetry in spin accumulation in the leads. For trilayer structures with a stack sequence of |Pt|Cu|Co (thin)|Cu|Co (thick)|Cu| parallel orientation of the magnetization results in a spin-accumulation asymmetry at the thick layer similar to the one in single layer junctions discussed above. Hence, high negative currents should lead to spin-wave instabilities. Also the antiparallel configuration leads to a strong asymmetry in spin accumulation at the thicker layer. However, the asymmetry in spin accumulation at the interfaces of the thick layer is now reversed. Therefore, spin-wave instabilities are now conceivable for positive current bias. Consequently, a strong asymmetry in spin accumulation should lead to spin-wave instabilities in trilayer nanopillars for *both* current polarities at current densities, similar to those at which magnetization reversal is observed.

In conclusion, we have studied current-induced spin-wave excitations in symmetric and asymmetric pillar junctions with only a single ferromagnetic layer. We have confirmed that excitations occur in asymmetric junctions and are absent in symmetric junctions at similar current densities. We have also shown that in asymmetric junctions the critical currents increase with Co layer thickness. Finally, we have discussed implications of an asymmetry in longitudinal spin-accumulation in Co/Cu/Co trilayers.

This research is supported by grants from NSF-FRG-DMS-0201439, NSF-DMR-0405620, and by ONR N0014-02-1-0995.

---

[1] J. A. Katine *et al.*, Phys. Rev. Lett. **84**, 3149 (2000).
[2] J. Grollier *et al.*, Appl. Phys. Lett. **78**, 3663 (2001).
[3] B. Özyilmaz *et al.*, Phys. Rev. Lett. **91**, 067203 (2003).
[4] S. I. Kiselev *et al.*, Nature (London) **425**, 380 (2003).
[5] W. H. Rippard *et al.*, Phys. Rev. Lett. **92**, 027201 (2004).
[6] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[7] J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[8] M. L. Polianski and P.W. Brouwer, Phys. Rev. Lett. **92**, 026602 (2004).
[9] M. D. Stiles, Jiang Xiao, and A. Zangwill, Phys. Rev. B **69**, 054408 (2004).
[10] J. Z. Sun *et al.*, Appl. Phys. Lett. **81**, 2202 (2002).
[11] J. Z. Sun *et al.*, J. Appl. Phys. **93**, 6859 (2003).
[12] E. B. Myers *et al.*, Science **285**, 867 (1999).
[13] Y. Ji, C. L. Chien, and M. D. Stiles, Phys. Rev. Lett. **90**, 106601 (2003).
[14] In Ref. [13] the authors conclude that at high current densities the single layer point contact experiments closely mimic trilayer junctions in which excitations are caused by a spin polarized current and detected via a giant magnetoresistance type of effect. Here the extended film acts as a reference. Hence, excitations lead to a resistance increase and show up as peaks in dV/dI.
[15] We assume that strong spin-flip scattering at the Pt/Cu interface effectively forces the spin accumulation at the Pt/Cu interface to zero [16]. For our sample geometry this leads to a smaller spin accumulation at the Cu/Co interface facing the Pt bottom electrode. Under this assumption the polarity dependence of the single layer excitations is consistent with that predicted in Refs. [8,9].
[16] H. Kurt *et al.*, Appl. Phys. Lett. **81**, 4787 (2002).
[17] M. D. Stiles (private communication).
[18] The total height of the PD is fixed. Therefore, an increase of the Co layer thickness reduces the asymmetry in spin accumulation and hence could increase the critical currents.