PHYSICAL REVIEW B **69**, 100406(R) (2004)

Current-driven excitations in magnetic multilayer nanopillars from 4.2 K to 300 K

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(Received 16 January 2004; published 18 March 2004)

We report direct experimental evidence of an energy threshold for spin-transfer-induced magnetic excitations in Co/Cu/Co nanopillars from temperature dependent measurements of current-induced excitations. The current threshold of excitations decreases when the temperature is increased from 4.2 to 300 K. However, the product of the current threshold and the pillar resistance stays almost temperature independent up to a temperature of ~150 K. This behavior supports the energy-threshold mechanism for spin-transfer-induced magnetic excitations.

DOI: 10.1103/PhysRevB.69.100406 PACS number(s): 75.30.Ds, 72.25.−b, 73.40.Jn, 85.75.−d

A sufficiently high electrical current can affect the magnetic state of a ferromagnet. For example, current-induced generation of spin waves and magnetization reversal have been predicted[1–3] and observed experimentally.[4–7] These so-called ''spin transfer'' phenomena have attracted much attention in the last few years because they form a fascinating combination of fundamental science with technological potential in magnetic storage and logic.[8] Today a variety of experimental techniques[4–7,9–22] have provided clear evidence that large enough current density can perturb the magnetic state of a ferromagnet. However, a rigorous theoretical understanding of the basic mechanisms by which the current affects the magnetic state of a ferromagnet is still evolving, thus posing a challenge for experimentalists. Most of the experiments on spin transfer to date have been carried out at constant temperature, typically 4.2 K or room temperature. However, detailed temperature-dependent measurements of the current-induced excitations are highly desirable, since they would provide an experimental probe into the detailed nature of the excitation mechanism and, thereby, test the various models of spin transfer that have been proposed.[1–3,23–25] The original model[1,3] associates current-induced excitations with a threshold current that is proportional to magnetic damping, and which therefore would generally increase with temperature.

In this communication we report detailed measurements of the current-induced excitations in magnetic multilayer nanopillars for temperatures varying from 4.2 to 300 K. Our measurements reveal that for temperatures between 4.2 and 150 K, the threshold behavior can be best described by a constant threshold voltage, while both the junction resistance and threshold current vary with temperature by about 20% in opposite directions. Such a voltage threshold lends support to models involving an energy and not a current density threshold.

A schematic view of the multilayer pillar device is shown in the inset to Fig. 1. The pillar sequence Co(3 nm)/Cu(10 nm)/Co(12 nm) was sputtered onto the bottom electrode through a submicron stencil mask, and the top was contacted by a second electrode. Details of the stencil process and sample characterization are described elsewhere.[15,16] A variety of pillars with both circular and elliptical shapes and lateral dimensions varying from 50 to 200 nm were studied. At low bias currents (<1 mA) such samples give usual current perpendicular to the plane magnetoresistaces (MR) of ≈3%. Figure 1 shows two independent MR sweeps for magnetic field **B** applied parallel (open squares and lower scale) and perpendicular (filled circles and upper scale) to the layers of a 50×200-nm sample. The corresponding experimental geometries are shown in the inserts to Fig. 1. Easy-axis MR (**B** parallel) reveals sharp transitions between resistive-high and -low states, thus suggesting that uniformly magnetized Co layers switch between parallel and antiparallel configurations. In the following we focus on measurements of the pillar's current-voltage (I-V) characteristics at different **B** applied perpendicular to the layers for temperatures ranging from 4.2 to 300 K. Note that the applied B is larger than the saturation field B_S of the pillar from shape anisotropy, which is about 1 T for **B** applied perpendicular to the layers. In this region the magnetic moment of the layer is

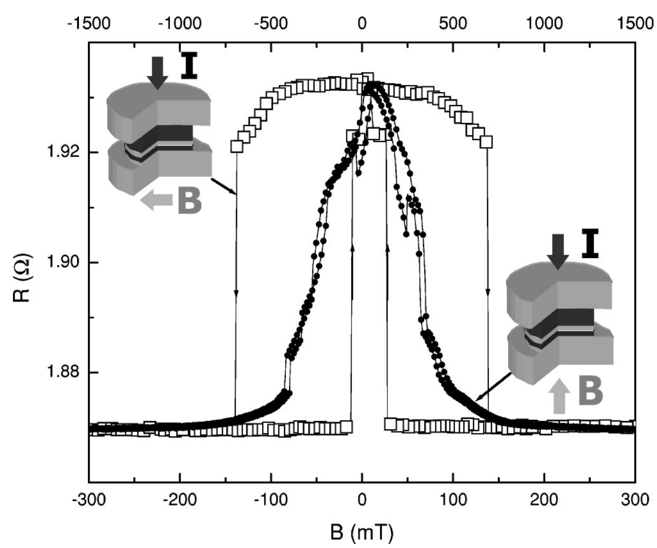

FIG. 1. Examples of pillar MRs for magnetic field oriented in the plane of the layers (open symbols and lower scale) and perpendicular to the plane (solid symbols and upper scale). Insets show schematic drawings of the corresponding experimental geometries: pillar sequence—two Co layers (black) 3 and 12 nm thick are separated by 10 nm of Cu; arrows indicate directions of the applied magnetic field B and bias current I.

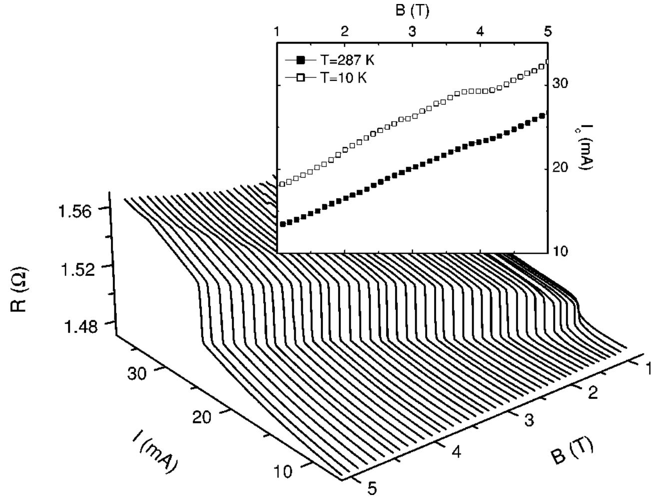

FIG. 2. Variation of the pillar resistance $R=V/I$ as a function of dc bias current I for a series of magnetic fields. Solid lines show R vs I for a series of magnetic fields in the range 1–5 T at $T=287$ K. Step increases in R at a certain critical bias current $I_c(B)$ correspond to the onset of the current-induced excitations. The solid and open squares in the inset show I_c vs B at 287 and 10 K, respectively.

essentially aligned parallel to **B**. Similar behavior was found for fields applied in the plane of the layers with a lower saturation field, of about 0.1 T.

Figure 2 shows typical variations in the pillar resistance $R=V/I$ as a function of the bias current I (solid lines) for a series of magnetic fields B. These data were taken at room temperature, 287 K. For a given field B (given trace), the resistance has the usual step increase in R at a certain critical bias current $I_c(B)$ previously associated with the onset of current-induced magnon excitations.[4,7,9,10,12,19,22] Such step increases in R occur only at positive bias, but not at negative bias (not shown). Solid squares in the inset (b) to Fig. 1 show that $I_c(B)$ increases roughly linearly with B. Deviations from the linear dependence are tentatively attributed to the resonant excitation of magneto-acoustic modes.[19] We have performed similar measurements at different temperatures. For comparison open squares show I_c vs B at 10 K. The inset to Fig. 2 shows that at low temperature I_c varies with B in the same way as at room temperature. The I_c at 287 K is smaller than that at 10 K by about 6 mA for the same B.

Next we show how the threshold current I_c varies with temperature. At a given value of magnetic field $B=4$ T applied perpendicular to the layers, we have measured the current-voltage (I-V) characteristics of the pillar at temperatures ranging from 4.2 to 300 K. Solid lines in Fig. 3 show the variation of the pillar resistance $R=V/I$ as a function of the bias current I at different temperatures. For a given temperature T, the resistance has a step increase at a critical bias current $I_c(T)$. Open squares in the inset to Fig. 3 show that the critical current I_c decreases with increasing temperature T. Also shown are values of the pillar resistance R before (solid circles) and after the step (open circles) as a function of T.

The current-driven excitation of a thin film nanomagnet

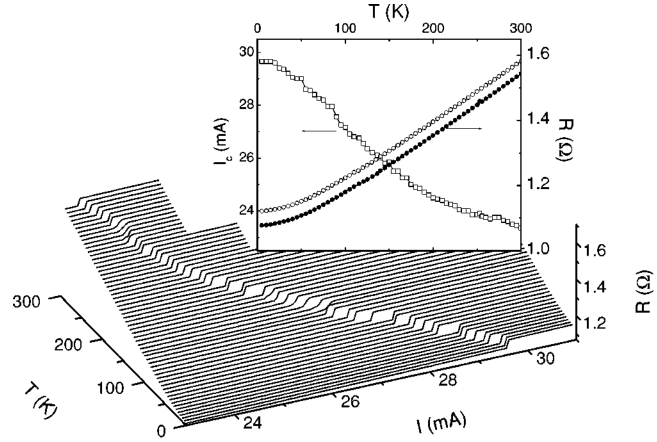

FIG. 3. Variation of the pillar resistance $R=V/I$ as a function of dc bias current I for a series of temperatures. Solid lines show R vs I for temperatures in the range 4.2–300 K at constant $B=4$ T. Open squares in the inset show that the critical current I_c where we observe the step increase in R decreases with increasing temperature T. Also shown are values of the pillar resistance R before (solid circles) and after (open circles) the step as a function of T.

can be described by the Landau-Lifshitz-Gilbert (LLG) equation. In the original model[1,3] the spin-polarized current exerts a torque on the nanomagnet. To induce excitations this torque must overcome damping, measured by the Gilbert damping parameter α_G.[1] The latter thus defines the critical current I_c for the excitation.[26] However, typical temperature variations in α_G for various ferromagnetic materials[27,28] cannot explain what we observe in $I_c(T)$. Moreover, a strong correlation between magnetization relaxation and electrical resistivity $\alpha_G \propto \rho$ has recently been observed,[29] which would suggest a simple relation $I_c \propto \rho$. In contrast, our data exhibit quite opposite behavior. Figure 4 shows that at temperatures

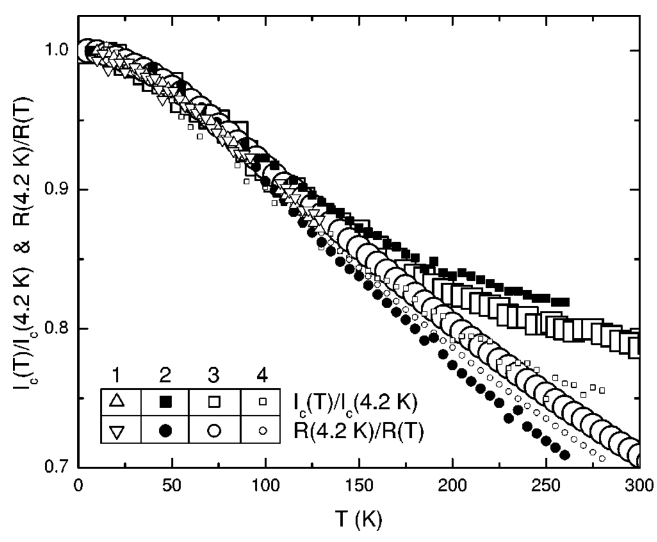

FIG. 4. Temperature dependence of the normalized critical current $I_c(T)/I_c(4.2\text{ K})$ (squares and up triangles) and inversed pillar resistance $R(4.2\text{ K})/R(T)$ (circles and down triangles) for four different $50\times200\text{-nm}^2$ samples ($B=4$ T). For $R(T)$ we have used the value just before the transition (solid circles in Fig. 3).

below $\sim$150 K the critical current for the excitations (open squares) is inversely proportional to the resistance of our device.

The decrease in I_c with increasing temperature T (see Figs. 3 and 4) can be explained within a simple model, where spin accumulation acts as the driving force for the current-induced excitations.[2,4] A current flow from a nonmagnetic metal N into a ferromagnetic metal F involves a redistribution of the current over spin-up and spin-down electrons near the N/F interface. Such redistribution results in spin accumulation, i.e., a splitting ($\Delta\mu$) between electrochemical potentials of the spin-up ($\mu\uparrow$) and spin-down ($\mu\downarrow$) electrons.[30–32] An electron crossing the N/F interface and flipping its spin will release the energy corresponding to $\Delta\mu$; this process was initially proposed[4] as a source of energy for the current-induced spin-wave excitations. Note that the emission of spin waves is only possible above a critical current where $\Delta\mu(I)\geqslant\hbar\omega$. That is, it defines the *energy threshold* for current-induced magnetic excitations.

We can obtain an expression of $\Delta\mu$ for a simple case corresponding to our experimental geometry. Here a thin ($\ll$spin diffusion length) nonmagnetic spacer N_s separates two ferromagnetic layers F_1 and F_2 sandwiched between thick nonmagnetic (N) electrodes. When a current density j flows across such a $N/F_1/N_s/F_2/N$ structure, $\Delta\mu$ at the interface N/F_1 is given by

$$\Delta\mu\approx\frac{ej}{\beta}[r_{SI}+t(\rho_F(1-\beta^2)-\rho_N)], \tag{1}$$

where r_{SI} is the spin-coupled interface resistance of Johnson and Silsbee[31] or van Son, van Kempen, and Wyder,[32] t is the sum of F_1 and F_2 thicknesses, ρ_N and ρ_F are N and F resistivities, β is the bulk spin asymmetry coefficient in F, and e is the electron charge. An expression of $\Delta\mu$ for an arbitrary N_s thickness can be found elsewhere.[33]

Assuming that at low temperatures and a constant applied field B the excitation of magnons in F_1 requires $\Delta\mu=\hbar\omega(B)=$const, and $\rho_F\gg\rho_N$ and $1\gg\beta^2$ we find the critical current for the excitation

$$j_c\approx\frac{\beta\Delta\mu}{e(r_{SI}+r_F)}, \tag{2}$$

where $r_F=t\rho_F$ is the F-layer resistance. Note that in Eqs. (1) and (2) we neglect interface resistances, which were shown by CPP-GMR experiments[34,35] to be sufficiently small in Co/Cu systems at least at low temperatures. Choosing realistic parameters for Co/Co (Refs. 34 and 35)—$\rho_N=5\ \mathrm{n}\Omega\,\mathrm{m}$, $\rho_F=50\ \mathrm{n}\Omega\,\mathrm{m}$, $\beta=0.5$, $r_{SI}=0.3\times10^{-15}\ \Omega\,\mathrm{m}^2$, $r_F=0.5\times10^{-15}\ \Omega\,\mathrm{m}^2$, we find $j_c\approx2.5\times10^{12}\ \mathrm{A/m}^2$ ($I=20$ mA) for $\Delta\mu\approx4$ meV. The relatively high value of $\Delta\mu$ may indicate that in laterally constrained magnetic layer (F_1) we are exciting a resonance spin-wave mode with higher energy then that of the uniform precession.[4,12] The sum $r_{SI}+r_F$ in the denominator of Eq. (2) is essentially the resistance R_t of $F_1/N_s/F_2$ trilayer in our device, i.e., $I_c\propto R_t^{-1}$. The actual value of device's resistance $R\sim1\Omega$ in our experiments differs significantly from $R_t\sim0.1\Omega$. This may be because our simple one-dimensional model does not take into account the constriction resistance[4,36] and resistances of the two (N) contact electrodes. However, temperature variations of R and R_t are closely related, suggesting $I_c\propto R^{-1}$.

Figure 4 shows that relation $I_c\propto R^{-1}$ is consistent with our data at temperatures below 150 K. Large open squares and circles show the temperature dependences of the normalized critical current $I_c(T)/I_c(4.2\ \mathrm{K})$ and inversed resistance $R(4.2\ \mathrm{K})/R(T)$ for a 50×200-nm pillar, respectively. For comparison, small open squares (circles), filled squares (circles), and up (down) triangles show $I_c(T)/I_c(4.2\ \mathrm{K})$ $[R(4.2\ \mathrm{K})/R(T)]$ for three different samples. All of the data show reasonable agreement with Eq. (2) at low temperatures. Deviations from $I_c\propto R^{-1}$ at $T_s>150$ K can have a number of reasons, for example, variations in ρ_N/ρ_F, $\hbar\omega$, spin diffusion lengths, and/or more significant interface scattering at higher T_s.

Recently Myers *et al.*[17] and Urazhdin *et al.*[20] have measured the current-driven magnetic switching in a narrow temperature range 180–220 K and for two temperatures 4.2 and 295 K, respectively. Both of these studies are consistent with our data but are, however, insufficient to establish a close link between the critical current for the excitations and the device's resistivity. Our results suggest that the threshold for current-induced magnetic excitations is not likely to be related to magnetic damping, but rather can be described as an energy threshold for spin-transfer-induced magnetic excitations.[2,4,23]

In summary, we have presented detailed measurements of the temperature dependence of current-induced excitations in magnetic multilayer nanopillars. We find that the current threshold for the excitations decreases by $\sim$20% when the temperature is increased from 4.2 to 300 K. At temperatures below $\sim$150 K the threshold current is inversely proportional to the resistance of the nanopillar, thus resulting in a temperature-independent threshold voltage (current-resistance product). The observed variations in the current/voltage threshold at low temperatures can be explained on the basis of the energy-threshold mechanism for spin-transfer-induced magnetic excitations.

We thank R. Carruthers, J. M. E. Harper at IBM Thomas J. Watson Research Center, and T. S. Kuan at SUNY Albany for part of sample preparation and structural analysis. This work was supported in part by DARPA and NEDO.

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