Current-Driven Excitations in Symmetric Magnetic Nanopillars

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We study experimentally the current-driven magnetic excitations in symmetric Co/Cu/Co nanopillars. In contrast with all the previous observations where the current of only one polarity is capable of exciting a multilayer system saturated by an externally applied magnetic field, we observe that both polarities of the applied current trigger excitations in a symmetric multilayer. This may indicate that in symmetric structures the current propels high-frequency magnetic oscillations in all magnetic layers. We argue, however, that only one layer is excited in our multilayers but, interestingly, currents of opposite polarities excite different layers. This hypothesis is supported by modeling the spin accumulation in symmetric magnetic multilayers.

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The magnetic state of a ferromagnet can be altered by an electrical current [1–3]. For instance, current-induced generation of spin waves, precession, and reversal of magnetization have all been observed [4–7]. It is generally believed that the current transfers spin angular momentum and generates a torque on a ferromagnet, thus offering a new method of magnetization control, which may lead to smaller and faster spintronic devices [8]. However, a rigorous understanding of this new phenomenon is still evolving [9–20], thus increasing the need for more elaborate experiments [21–33]. A typical experiment on current-driven excitation of a ferromagnet usually involves two single-domain thin film magnets separated by a nonmagnetic spacer. One magnet is "hard" and used to polarize the current while the spacer is thin enough for the polarized current to get through and excite the second "free" magnet. The free magnetic layer is generally thin compared to the hard one thus marking an intrinsic asymmetry of the phenomenon [9]—for initially parallel magnetizations of the two magnets the current-driven excitation occurs only when electrons flow from the free magnet to the fixed one [1–33].

In the present Letter we study the current-driven excitations in symmetric nanopillars. Here the fixed and free magnets have comparable layer thicknesses. We find that dc currents of both polarities produce excitations. Therewith we argue that for a given polarity of the exciting current only one of the two magnets is excited: namely, the one through which the electron flow enters the nanopillar. In agreement with previous observations the threshold current for such excitations was found to increase linearly with the applied magnetic field [4–7,21–33] and with the thickness of the excited layer [22]. We use our new results to test the various models of spin transfer proposed to date [1–3,9–20].

A schematic view of the multilayer pillar device is shown in the inset to Fig. 1. The trilayer sequence Co(t_{bottom})/Cu(7.5–10 nm)/Co(t_{top}) was sputtered through a submicron stencil mask [28] to form a pillar with lateral dimensions from 50 to 240 nm. Top and bottom contacts to the pillar were made with Cu electrodes. The bottom Co layer thickness t_{bottom} was fixed at ~2–3 nm. The top Co layer thickness t_{top} was varied from 12 nm down to 2 nm. At low bias currents (< 1 mA) such samples give usual current perpendicular-to-plane magnetoresistances (MRs) of $\approx 3\%$. Squares and circles in Fig. 1 show two independent MR sweeps for magnetic field **B** applied parallel ($B_{\parallel}$) and perpendicular ($B_{\perp}$),

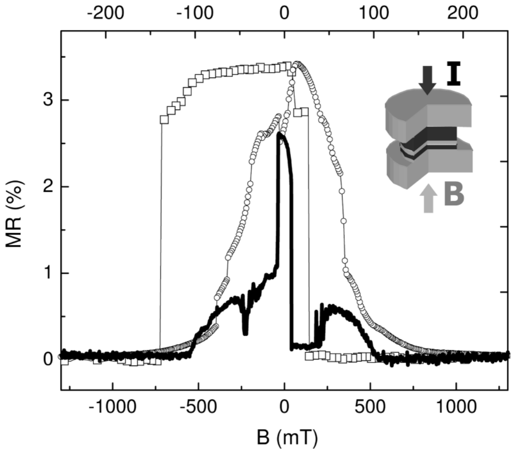

FIG. 1. Squares and circles show examples of pillar MRs for magnetic field **B** applied parallel (squares, upper scale) and perpendicular (circles, lower scale), respectively, to the layers of a sample with thick (12 nm) top and thin (3 nm) bottom Co layers. For comparison the solid trace shows a MR in perpendicular field (lower scale) for a sample with Co layers of equal thickness (2 nm). Only down MR sweeps ($+B - B$) are shown for clarity. The inset shows a schematic drawing of our experimental geometry: pillar sequence—two Co layers (black) are separated by a Cu spacer; the arrows indicate the directions of the applied magnetic field B and bias current I.

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respectively, to the layers of a sample with thick (12 nm) top and thin (3 nm) bottom Co layers. For comparison the solid trace shows a MR sweep ($B_\perp$) for a sample with Co layers of equal thickness (2 nm). Easy-axis MR ($B_\parallel$) reveals sharp transitions between resistive-high and -low states, suggesting that uniformly magnetized Co layers switch between parallel and antiparallel configurations. A nonzero MR for a sample with two equal Co magnets (top and bottom layers) may indicate that dipolar coupling between the Co layers is strong enough to induce an antiparallel alignment between them at low fields and/or the two layers are not identical (i.e., pinning and/or anisotropies are different for different layers).

At room temperature (287 K) and in magnetic fields $B_\perp$ up to 6 T we have measured the current-voltage (I-V) characteristics of pillars with various thickness ratios $\Gamma = t_{\rm top}/t_{\rm bottom}$. Note that we apply magnetic fields B larger than the saturation field B_S of the pillar from shape anisotropy $4\pi M_S$, which is about 1.4 T for $B_\perp$ in cobalt. For $B_\perp \gg 4\pi M_S$, magnetic moments of both layers are aligned parallel to $\mathbf{B}_\perp$ [34]. Figures 2(a)–2(c) show typical variations in the pillar resistance $R = V/I$ as a function of the bias current I (solid trace) for three different samples. Here positive current flows from the top to the bottom layer. Figure 2(a) shows the usual step increase in R at a certain critical bias current $I_c(B)$ for a sample with a high $\Gamma = 4$ ($t_{\rm top} = 12$ nm, $t_{\rm bottom} = 3$ nm). Such an increase in R is associated with the onset of current-induced magnon excitations [4,7,21,23,25,32] and occurs only at positive bias. The inset to Fig. 2(a) shows that $I_c(B)$ increases linearly with B. Figures 2(b) and 2(c) show that the step increase in $R(I)$ occurs both at positive $I_c^+(B)$ and negative $I_c^-(B)$ bias currents for samples with low $\Gamma = 1.5$ ($t_{\rm top} = 4.5$ nm, $t_{\rm bottom} = 3$ nm) and $\Gamma = 1$ ($t_{\rm top} = t_{\rm bottom} = 2$ nm), respectively. The increase in $R(I)$ at negative bias in Fig. 2(c) is very broad; the corresponding peak in the derivative resistance dV/dI makes it easy to trace the changes in $R = V/I$. We do not observe any peak structure in $dV/dI(I)$ at high (> 50 mA) positive biases from data in Fig. 2(b) (not shown). Here the dV/dI resistance shows a usual monotonic and nonlinear increase at larger currents, which is a familiar effect in small metal junctions due to electron scattering by emission of phonons [35].

Note that variations in both nanopillar sizes and contact resistances to the electrodes usually lead to scatter in pillar resistances. In Figs. 2(a)–2(c) variations in pillar resistances can be largely accounted for by variations in pillar sizes: 50×200, 80×240, and 70×70 nm^2, respectively. However, an additional contact resistance to the electrodes is poorly controlled and makes questionable a direct comparison between results obtained from different junction devices. Instead, we focus on data analysis of the same junction but excited by currents of different polarity. The insets to Figs. 2(b) and 2(c) show that both $I_c^+(B)$ and $I_c^-(B)$ increase roughly linearly with B. Moreover, for a given sample the ratio $I_c^-(B)/I_c^+(B) = 1.7$ in Fig. 2(b) [1.1 in Fig. 2(c)] is very close to the corresponding $\Gamma = 1.5$ (1). In agreement with previous observations by Albert *et al.* [22] that the critical switching current increases linearly with the thickness of the free layer, the latter suggests that at positive bias the

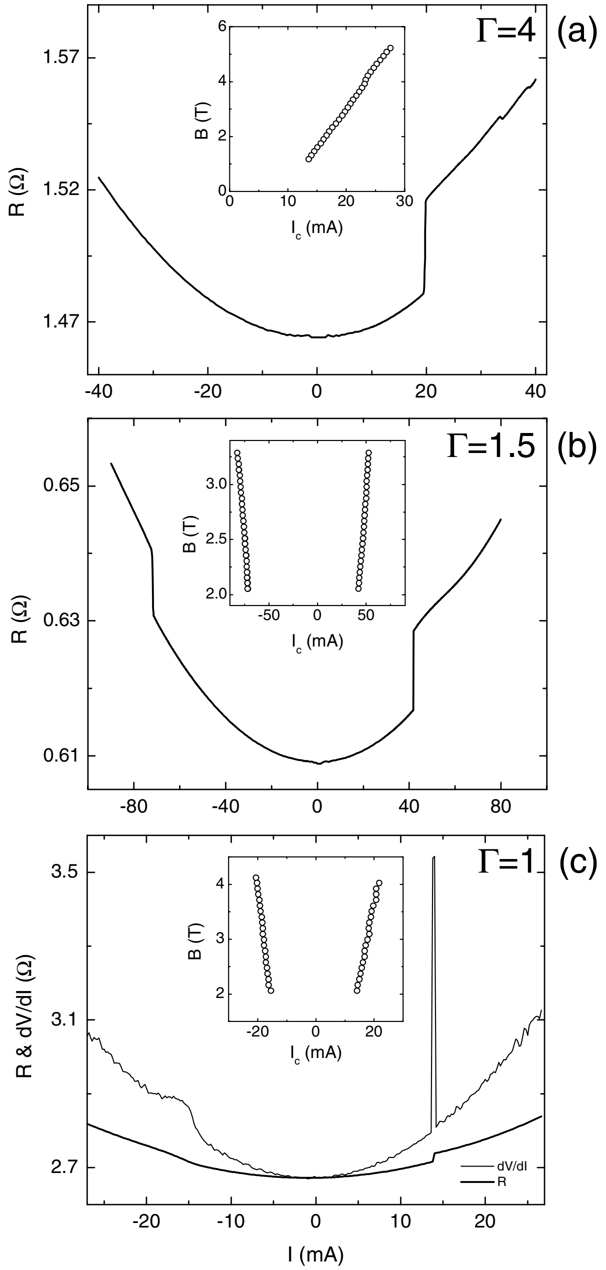

FIG. 2. Variation of the pillar resistance $R = V/I$ as a function of dc bias current I for three different samples with $\Gamma = 4$ (a), 1.5 (b), and 1 (c) at constant $B_\perp = 2.6$ T (a) and 2.1 T (b),(c). Step increases in R at a certain critical bias current $I_c(B)$ (positive and/or negative) correspond to the onset of the current-induced excitations. Open symbols in the corresponding insets show I_c vs B. Measurements are done at room temperature (287 K). In (c) $dV/dI(I)$ is shown along with $R(I)$ to spotlight variations in R.

bottom layer is excited, while at negative bias we excite the top layer.

We analyze our observations in view of the existing models [1–3,9–20]. According to model Ref. [1], an electrical current traversing a $F_1/N/F_2$ trilayer sandwiched between thick nonmagnetic (N) electrodes [see Fig. 3(b)] exerts torques on two magnetic layers. The sign conventions [1,10] for torques L_1 and L_2 acting on layers F_1 and F_2, respectively, are shown in Fig. 3(a); here F_1 (F_2) corresponds to the bottom (top) Co layer in our pillars. Usually, one of the layers (e.g., F_2) is fixed and the other (F_1) is free to execute a general precession. To induce excitations in F_1 torque L_1 must overcome damping, measured by the Gilbert damping parameter α_G [10]. The latter, along with other material parameters [1,10] defines the threshold current $I_c(B)$ for the excitation. In a perfectly symmetric system (identical F_1, F_2, and symmetrical N-electrode arrangement) torques L_1 and L_2 are equal and a sufficiently high current should trigger magnetic excitations in both F_1 and F_2 layers. This may account for what we observe in Fig. 2(c) where both positive and negative bias currents of similar magnitudes induce an increase in the sample resistance. However, there are several questions. First of all, in a perfectly symmetric system an electrical current flowing in either direction would excite similar combined motions in the two layers. In contrast, Fig. 2(c) shows that at negative bias the onset of the excitation is significantly broader than that at positive bias. Second, for a slightly asymmetric $F_1/N/F_2$ trilayer (e.g., with $\Gamma = 1.5$), one would expect somewhat different threshold currents I_c^{F1} and I_c^{F2} for F_1 and F_2 layers, respectively. Exploiting a linear dependence of I_c on the thickness of the excited layer [22] gives $|I_c^{F2}/I_c^{F1}| = \Gamma$. Therefore, our observation of $|I_c^-/I_c^+| \approx \Gamma$ [see Fig. 2(b)] strongly suggests that positive bias excites F_1, while negative bias excites F_2. Note that we neglect any finite temperature effects; its impact on I_c is discussed in detail elsewhere [36].

We analyze possible excitations in our trilayer ($\Gamma = 1.5$) as a function of the bias current I assuming $L_1 = L_2$ for a given I [10]. At low currents $|I| < |I_c^{F1}|$, neither F_1 nor F_2 can be excited. For $|I_c^{F1}| < |I| < |I_c^{F2}|$ the thinner layer F_1 is excited only at positive biases, i.e.; the step increase in R at $I \approx 42$ mA in Fig. 2(b) corresponds to the onset of excitations in F_1. Finally, at high currents $|I| > |I_c^{F2}|$, both F_1 and F_2 can be excited; i.e., the step increase in R at $I \approx -72$ mA [Fig. 2(b)] corresponds, in this interpretation, to the onset of a joint excitation of F_1 and F_2. However, we do not observe any singularities in R at positive $I = |I_c^{F2}| \approx 72$ mA [see Fig. 2(b)], indicating that at high positive biases F_2 stays intact.

We explain our observations using a simple model, where spin accumulation acts as the driving force for the current-induced excitations [2,4,9,13]. A current flow across a $N/F_1/N/F_2/N$ structure [Fig. 3(b)] involves a redistribution of the current over spin-up and spin-down electrons near N/F interfaces. Such a 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 [37], so that an electron flipping its spin releases 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 possible only when $\Delta\mu$ ($\sim I$) [2,4] is larger than the energy $\hbar\omega$ of spin-wave excitations, where ω is spin-wave frequency and $\hbar$ is the Planck constant. This energy relation defines the threshold current I_c for the excitation.

We have calculated $\Delta\mu$ in $N/F_1/N/F_2/N$ structures [Figs. 3(b)–3(d)] similar to those used in our experiments; here F_1 (F_2) corresponds to the bottom (top) Co layer in our pillars; current flows from F_2 to F_1 across a 7.5 nm thick N spacer. Figure 3(c) [Fig. 3(d)] shows spatial variation of $\Delta\mu$ across a structure with F_1 and F_2 layer thicknesses 2 and 2 nm (2 and 3 nm),

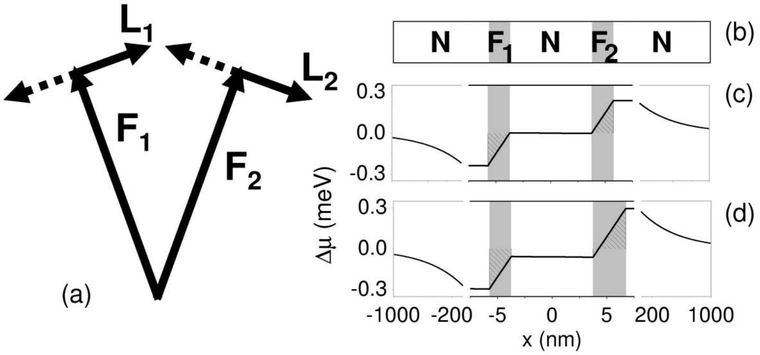

FIG. 3. (a) Sign conventions for torques L_1 and L_2 acting on magnetic moments of F_1 and F_2, respectively, shown in the common plane of the moments. (b) Schematic representation of a $N/F_1/N/F_2/N$ multilayer structure with F layers shown in gray. (c),(d) Spatial variations of $\Delta\mu$ across $N/F_1/N/F_2/N$ structures corresponding to those from Figs. 2(b) (d) and 2(c) (c) in our experiments. Hatched areas measure the current-induced torques acting on magnets.

respectively, corresponding to the pillar from Fig. 2(c) [Fig. 2(b)]. An explicit analytical expression for $\Delta\mu$ can be found elsewhere [38]. We have used realistic parameters for Co (i.e., F) and Cu (i.e., N)—resistivities $\rho_N = 5\ \mathrm{n}\Omega\,\mathrm{m}$ and $\rho_F = 50\ \mathrm{n}\Omega\,\mathrm{m}$, bulk spin-asymmetry coefficient $\beta = 0.5$ in F, and spin-diffusion lengths $\Lambda_N \approx 500$ nm and $\Lambda_F \approx 50$ nm [39]. The current density $j = I/A \approx 2.5 \times 10^{12}\ \mathrm{A/m^2}$ was estimated using $I = 20$ mA and pillar cross section $A = 8000\ \mathrm{nm}^2$. The resulting maximum $\Delta\mu \approx 0.3$ meV is consistent with previously observed spin-wave energies [4,21,25,32].

For the given current direction $\Delta\mu$ is <0 in F_1 and > 0 in F_2 (this sign convention is reversed for the opposite current). Conservation of angular momentum implies that only when $\Delta\mu < 0$ is the emission of spin waves possible [4], i.e., only one (e.g., F_1) layer can be excited for a given polarity of I. The reversal of I would lead to excitation of F_2 in place of F_1. These predictions correlate well with our observations (see Fig. 2) where only one singularity in R is observed for a given direction of I. The latter supports energy, rather than a simple torque, threshold for the current-induced excitations.

Finally we want to address the difference in shapes of R increases associated with the onset of current-induced excitations at positive and negative biases in Fig. 2(c). Previous experiments in various layered structures [4–7,21–33] revealed many different shapes of resistance anomalies tentatively attributed to variations in the local magnetic order. Current-driven excitation of different layers (top or bottom) in our pillars would necessarily involve somewhat different onsets of such excitations because the layers are not identical.

In summary, we have presented a detailed measurement of the current-induced excitations in symmetric multilayer nanopillars. Both polarities of the applied bias current produce magnetic excitations in such structures, in contrast to previous observations in asymmetric structures, where current of only one polarity produces the excitations. We use this feature of symmetric pillars to test various models of the current-induced excitations proposed to date. The observed behavior suggests an energy threshold for the excitation that can be qualitatively explained on the basis of spin accumulation in symmetric trilayer structures, where currents of different polarities excite different magnetic layers.

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