Spin-transfer-induced excitations in bilayer magnetic nanopillars at high fields: the effects of contact layers

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Current-induced excitations in bilayer magnetic nanopillars have been studied with large magnetic fields applied perpendicular to the layers at low temperatures. Junctions investigated all have Cu/Co/Cu/Co/Cu as core layer stacks. Two types of such junctions are compared, one with the core stack sandwiched between Pt layers (Type A), the other with Pt only on one side of the stack (Type B). Transport measurements show these two types of junctions have similar magnetoresistances and slope of critical currents with respect to field, while A samples have higher resistance. The high field bipolar excitation, as was previously reported [Özyilmaz et al. Phys. Rev. B, 71, 140403(R)], is present in B samples only. This illustrates the importance of contact layers to spin-current-induced phenomena. This also confirms a recent prediction on such spin-wave excitations in bilayers.

One geometry to study spin-transfer-induced magnetization excitation in magnetic nanopillars is to have a magnetic field larger than demagnetization field $4\pi M_s$ applied perpendicular to the current-perpendicular (CPP) spin valve layers [1]. In this geometry, the in-plane shape anisotropy of the nanopillar has only a small effect on the magnetization dynamics and resulting phase diagram for current-induced magnetic excitations. Recently, Polianski and Brouwer [2] and Stiles et al. [3] predicted current-induced non-uniform spin wave excitations even in single thin ferromagnetic layer nanopillars, provided that the pillar is asymmetric in the current direction. Özyilmaz et al. observed such excitations in experiments on asymmetric single ferromagnetic layer pillar junctions [4]. As predicted, excitations were absent in more symmetric nanopillars [5]. In later work, high field bipolar excitations were observed in bilayer nanopillars and associated with non-uniform spin-wave excitations, similar to those reported in single layers [6]. It was recently shown theoretically that in bilayers, macrospin and non-uniform excitations can compete, with the favored mode depending on the device structure [6]. Here we compare two types of magnetic nanopillars: one with two Pt layers on both sides of an asymmetric Cu/Co/Cu/Co/Cu bilayer structure (Type A), and one with a Pt layer only on one side of this structure (Type B). Results are compared to theoretical predictions [6].

Using a nanostencil process [7, 8], hundreds of pillar junctions with submicron lateral dimension were fabricated on a 1 cm $\times$ 1 cm Si substrate. Stencil holes with different but accurate lateral dimensions were opened up at the depth of 75 nm, and pillar junctions were deposited through metal evaporation. Type A structures have Pt layers on both sides of the core structure, i.e. || 100 nm Cu | 15 nm Pt$_{70}$Rh$_{30}$ | 3 nm Pt | 10 nm Cu | t Co | 10 nm Cu | 12 nm Co | 10 nm Cu | 3 nm Pt | 200 nm Cu ||. Type B samples have a Pt layer only on the bottom of the magnetic layer sequence: || 100 nm Cu | 15 nm Pt$_{70}$Rh$_{30}$ | 10 nm Cu | t Co | 10 nm Cu | 12 nm Co | 200 nm Cu ||. We investigated approximately 30 junctions of each type. Samples of each type, junctions with $t \approx 1.9$, 3.3, and 4.3 nm and lateral dimensions 50 nm $\times$ 50 nm and 50 nm $\times$ 100 nm were studied in detail.

All measurements reported here were made at 4.2 K with a 4-point geometry. Both DC resistance $V/I$ and differential resistance $dV/dI$ for each junction were measured. A 0.2 mA AC current at 802 Hz was added to the DC current bias. Junction resistances were found to scale inversely with their lateral areas. Positive currents are defined such that electrons flow from thin Co layer to thick Co layer.

Magnetoresistances (MR) were measured with magnetic field applied in the film plane. Typical hysteresis loops are shown in the insets of Fig. 1. These two junctions have identical 50 nm $\times$ 100 nm lateral areas and similar thin Co layer thickness ($t \approx 3.3 \, nm$), with the loop of the Type A in Fig 1(a) and that of Type B in Fig 1(b). Due to the additional Cu/Pt interface and Pt bulk scattering, junctions on sample of Type A are more resistive than those on sample of Type B. But their MR values are roughly the same, 2.2% and 2.3% for junction of Type A and Type B respectively.

$I(V)$ measurements were conducted with magnetic field applied perpendicular to the sample surfaces. When the field is higher than the demagnetization field $4\pi M_s$, the magnetic layers are aligned along the field direction. When positive current is applied to the junction, the spin transfer torque $a_J\hat{m} \times (\hat{m} \times \hat{m}_P)$ [9,10] can drive the thin layer into instability. Here $a_J$ is the torque factor which is proportional to applied current density $J$, and $\hat{m}$, $\hat{m}_P$ are the magnetic moment unit vectors of the thin layer and the thick layer respectively. When the torque is large enough, it may switch the thin layer into the anti-parallel (AP) state. The differential resistance $dV/dI$ versus $I$ at 7 T is shown in Fig. 1, for the same two junctions as in the insets. A resistance change close to in-plane MR was observed from both curves. In Fig 1(a), the $I(V)$ curve of Type A junction shows a $\sim 1.3 \, mA$ hysteresis and the switching was accompanied by a step in $dV/dI$ in both directions of current sweep. The majority of the junctions of Type A show hysteresis. However, most junc-
tions of Type B (Fig 1(b)) do not have hysteresis, and their switching is accompanied by a peak in \(dV/dI\). Furthermore, DC resistance \(V/I\) versus I curves are smooth except that there is a sharp step at the switching current. The step can be used to determine the critical current.

In order to emphasize small features on top of the background which is associated with Joule heating, the contour plots of \(d^2V/dI^2\) are shown in Fig. 2. Here the current is swept from positive to negative with magnetic field perpendicular to the sample surface. Above the demagnetization field \((\sim 1.5 T)\), the critical current increases with applied magnetic field as shown in Fig. 2, which is consistent with theoretical calculations of the threshold current for a macrospin instability \([6, 11, 12, 13]\), numerical modeling \([1]\) and previous experimental results \([1]\). The derivatives of critical current density with respect to high field at 7 T \(dJ_c/dH\) for these two junctions are similar: \((3.1 \pm 0.5) \times 10^7 A/(cm^2 T)\) for the one of type A, and \((3.9 \pm 0.6) \times 10^7 A/(cm^2 T)\) for that of type B.

In addition to the boundary of critical currents for switching, there are more small features distributed in the contour plots shown in Fig. 2. When positive current is applied to junctions of Type A, there is another boundary which is weaker than the main switching peak and is associated with Joule heating, and also located at slightly lower current bias. Between these two boundaries, there are some even more complicated structures. Those structures can even be seen on \(dV/dI\) plots if the part of the \(dV/dI\) curve right before the switching is magnified, like in Fig 3(a). Usually those excitations appear like multiple peaks in \(dV/dI\) for junctions of Type A. However the excitations in Type B junctions at positive currents behave differently. After switching, small features which look like a “comb” could be seen beyond a certain current boundary as can be seen in Fig 2(b). Those excitations are multiple dips in \(dV/dI\) as shown in Fig 3(b). All junctions of Type B studied exhibited this feature. The type of excitations in junctions of Type B were also studied in experiments before \([5]\), while those in junctions of Type A were not. All Type A junctions studied do not show additional excitations beyond the main peak in \(dV/dI\).

Furthermore, at negative currents, additional excitations are found in Fig. 2(b). Such kind of excitations are absent below a certain current boundary which is indicated as a black line in the contour plot of Fig. 2(b) and extends linearly to zero field zero current. This was also revealed in the previous study \([5]\). But in Fig. 2(a), no such excitations were found at negative current polarity when \(H > 1.5 T\).

Theoretical studies of excitations in magnetic nanopillars go back to Berger, who calculated an onset of spin wave excitations \([10]\), and Slonczewski, who considered a coherent rotation of the whole magnet spin \([9]\). Recently, Brataas et al. \([6]\) calculated the onset of macrospin precession versus non-uniform spin-wave excitations in bi-layer magnetic nanopillars. Using the two-spin-channel circuit theory, they deduced the spin torque on a ferromagnet by considering its small transverse instabilities \(\delta \mathbf{m}\) as the function of wavevector \(\mathbf{q}\). Both the uniform macrospin \((\mathbf{q} \rightarrow 0)\) excitations and non-uniform spin-wave \((\mathbf{q} \rightarrow \infty)\) excitations have been discussed. As an example, they computed the phase diagram for bilayer junctions without Pt on top. At negative currents, they predicted a spin-wave instability for the thick ferromag-
FIG. 3: $dV/dI$ current sweep curves of 50 nm $\times$ 50 nm junctions with the regions of excitations at positive currents magnified. (a): Type A sample with $t \simeq 4.3$ nm, $H = 5$ T; (b): Type B sample with $t \simeq 1.9$ nm, $H = 2.3$ T

net. At positive currents starting from P state, there is a macrospin instability of the thin layer, and after switching of the thin layer a further increase in current leads to a spin-wave instability of the thick layer. These predictions are consistent with our results in junctions of Type B and previous experimental work.

One of the results of [4] is that the layer contacts are important in determining the resulting instabilities, i.e. whether it is a uniform or non-uniform mode and the critical current. For simplicity, if the resistances of the two Co layers are mainly due to the Cu/Co interfaces, then their effective resistances in the circuit are close to each other. In this case, the spin torque on the thin/thick magnetic layer in the short wavelength limit can be written as:

$$\tau_{\text{thin/thick}} = \mp (P/2) \delta m_{\text{thin/thick}}^{(c)} \times (R_m - 2R_b/t)/R_{\text{thin/thick}}^{(c)}$$

(1)

where $P$ is the total polarization of the current, $R_m$, $R_b/t$ are the resistances of normal metal contact layers located between Co layers and outside Co layers close to bottom/top respectively, $R_{\text{thin/thick}}^{(c)}$ is the mixing resistance of the thin/thick Co layer and $j^{(c)}$ is the charge current density in the junction. This shows that the thickness of the top Cu contact layer adjacent to thick Co affects the magnitude of the short wavelength spin torque on the thick Co layer: increasing the resistance asymmetry $|R_m - 2R_b|$, increases the torque.

We applied this result to our junctions. Parameters given by MSU group [14] were used to calculate Co resistances. For Co layer with $t = 3.3$ nm, the bulk contribution is 24% of interface counterpart. In this case, the thin layer resistance is 33% lower than that of thick layer, and Eq (1) is a reasonable approximation. In Type A samples, the Pt layers on both sides of the pillar create a good zero spin accumulation boundary so that the effective resistance of $R_b$ does not extend over the Pt layers. In our Type A junctions, $|R_m - 2R_b| \simeq R_m$. Whereas in Type B samples the top Cu lead is considerably longer (35 to 50 nm) and $|R_m - 2R_b| \geq 6R_m$. In this case the short wavelength spin torque is considerably larger and excitations should occur for lower current densities. This is consistent with our experimental results that show excitations at positive currents beyond the main peak and negative currents only in Type B samples. Similar excitations in Type A samples are predicted to occur only at much larger current densities.

In summary, we compared spin transfer effects, especially the current induced excitations, in bilayer magnetic nanopillars with two types of layer stacks, one with Pt on both sides (Type A) and one with Pt only on one side (Type B). In contrast to the junctions of Type B, no excitations were observed on the junctions of Type A. Both at positive currents higher than switching threshold and negative currents, which confirms a prediction of Ref. [4]. In this sense, the contact layers in bilayer magnetic nanopillars are of great importance in spin-transfer devices.

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