Asymmetric Spin-Transfer Torque in Single-Crystalline Fe/Ag/Fe Nanopillars

R. Lehndorff, M. Buchmeier, D. E. Bürgler, A. Kákay, R. Hertel, C. M. Schneider
IFF-9: Electronic Properties
CNI: Center of Nanoelectronic Systems for Information Technology

We investigate current-perpendicular-plane giant magnetoresistance (CPP-GMR) and current-induced magnetization switching in single-crystalline Fe/Ag/Fe nanopillars of 70 nm diameter. The interplay between the in-plane, fourfold magnetocrystalline anisotropy of the Fe(001) layers and the spin-transfer torque (STT) gives rise to a two-step switching behavior, which allows an investigation of the angular dependences of CPP-GMR and STT. The results are compared to a theoretical model and contribute to a more fundamental understanding of spin-dependent transport in layered, magnetic nanostructures.

Spin-transfer torque (STT) and its effects of switching the magnetization or exciting steady-state magnetization precessional motions in nanometer-sized magnetic elements attracted a lot of interest since their prediction in 1996. These effects have been demonstrated experimentally and the understanding of STT-driven magnetization dynamics has grown quickly. However, there is still a lack of understanding of the microscopic origin of the STT. We use single-crystalline nanomagnets to gain further insight [1].

Giant magnetoresistance (GMR) and STT are two characteristic magnetotransport phenomena occurring in layered systems consisting of two ferromagnetic (FM) layers separated by a nonmagnetic (NM) interlayer. The common cause for these effects is the fact that the current passing through these layers is spin-polarized. There are two mechanisms giving rise to a spin polarization of the current: (i) The natural spin polarization of the charge carriers in a FM, caused by the imbalance of spin-up and spin-down density-of-states at the Fermi level and (ii) a gradient of the spin accumulation in the NM. For symmetric systems Slonczewski's unified theory [2] for GMR and STT yields for the angular dependences of the GMR $r(\vartheta)$ and the STT $\tau(\vartheta)$:

$$r(\vartheta) = \frac{R(\vartheta)-R(0^\circ)}{R(180^\circ)-R(0^\circ)} = \frac{1-\cos^2(\vartheta/2)}{1+\chi\cos^2(\vartheta/2)} \quad (1)$$

$$\tau(\vartheta) = \frac{\hbar I P \Lambda}{4Ae}\frac{\sin(\vartheta)}{\Lambda\cos^2(\vartheta/2)+\Lambda^{-1}\sin^2(\vartheta/2)} \quad (2)$$

$$\Lambda^2 = \chi + 1 = AG\frac{R^+ + R^-}{2}. \quad (3)$$

$R(\vartheta)$ is the dependence of the resistance on ϑ, G the conductance of the interlayer, A the crossectional area of the nanopillar, $R^{+(-)}$ the total (interface and bulk) resistance for spin-up (spin-down) electrons for one side of the system, and $P = (R^- - R^+)/(R^- + R^+)$ is the spin polarization. The parameter Λ (or χ) is a measure for the deviation from the symmetric behavior, which is given by $\Lambda = 1$. In Fig. 1 we plot $r(\vartheta)$ and $\tau(\vartheta)$ for various values of Λ. The green dotted lines for $\Lambda = 1$ represent the symmetric case. In most cases an asymmetric behavior of both GMR and STT is theoretically expected, but has so far never been observed.

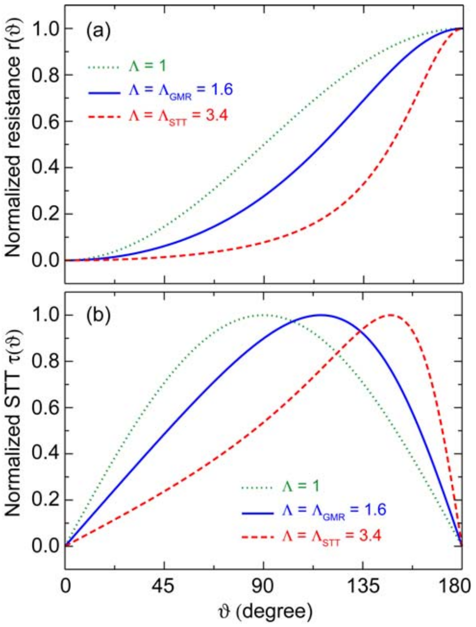

FIG. 1: (a) $r(\vartheta)$ and (b) $\tau(\vartheta)$ for three different Λ values according to Eqs. (1)-(3). The green line shows the symmetric behavior. The blue line results from our GMR data and the red line from our experimental ratio I_{c2}/I_{c1}.

A layer stack of 1 nm Fe, 150 nm Ag, 20 nm Fe (fixed FM), 6 nm Ag (NM), 2 nm Fe (free FM), and 50 nm Au is grown by molecular beam epitaxy onto an annealed GaAs(100) substrate. The free FM is structured into circular nanopillars with diameters of 70 nm by a combination of optical and e-beam lithography and ion beam etching. The 150 nm Ag buffer layer acts as bottom electrode and a bilayer of 5 nm Ti and 200 nm Au is finally evaporated onto the stack as a top electrode (inset of Fig. 3). Preparation and fabrication procedures are described in Refs. [1, 3].

Figure 2 shows the CPP-GMR loop for the field applied along a hard axis of the Fe layers. The maximum GMR value amounts to 3.3%. The curves can be well reproduced by Stoner-Wohlfarth fits (red symbols), which reveal the details of the remagnetization process. An interesting situation occurs at 0 mT, where the two magnetizations rest in two different easy axes of the four-fold crystalline anisotropy of the Fe layers and, thus, include an angle of 90°.

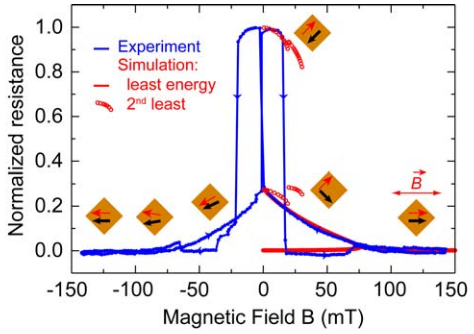

FIG. 2: CPP-GMR data (blue) measured at 5 K with the magnetic field applied along a hard axis of the single-crystalline Fe layers. Red symbols are solutions of Stoner-Wohlfarth fits. The edges of the squares indicate the magnetic easy axis of the Fe layers and the black (red) arrow the magnetization direction of the fixed (free) layer.

For the standard angular dependence of the GMR, $r(\vartheta) = \sin^2(\vartheta/2)$, $r(90°)$ would be 0.5. Instead in Fig. 2 we find a much lower value of 0.3. This deviation originates from spin accumulation at the FM/NM interfaces and yields according to Eqs. (1) and (3) an asymmetry parameter $\Lambda_{GMR} = 1.6 \pm 0.03$.

Figure 3 shows a dc current loop taken at an applied magnetic field of 5.6 mT parallel to a hard axis. Two switching processes can be distinguished upon increasing the current. The first one at +5.8 mA leads to an intermediate resistive state, the second at +7.3 mA to a high resistive state. When the current decreases the system falls back to the intermediate resistive level at +1.9 mA and to the low resistive level at -2.1 mA. The intermediate resistive level is assigned to a perpendicular alignment of the two magnetizations stabilized by the crystalline anisotropy. Obviously, the magnetization switches in two steps from the parallel to the antiparallel alignment *via* an intermediate 90° state. In the following I_{c1} (I_{c2}) denotes the critical current for switching from 0° to 90° (90° to 180°). The behavior in Fig. 3 is representative for magnetic fields of nearly any orientation, but with a magnitude well below the coercive field of the free layer. Under these conditions the anisotropy dominates the switching process. The first critical current value I_{c1} is reached, when the STT overcomes the damping, which is proportional to the effective field $H_{eff} = -dE/dM$. In our case, the anisotropy is the dominant contribution to H_{eff}. The second critical current I_{c2} is determined by the asymmetry of the STT with respect to $\vartheta = 90°$. As confirmed by simulations for this starting condition, a current excites a small-angle precession of the magnetization of the free layer around the easy axis at $\vartheta = 90°$. In this geometry, however, the precession is damped by the STT for one part of the precession trajectory with $\vartheta < 90°$, because then STT and damping are parallel and point towards the easy axis. For other parts of the trajectory with $\vartheta > 90°$ the two contributions are opposing each other and the STT acts as an excitation.

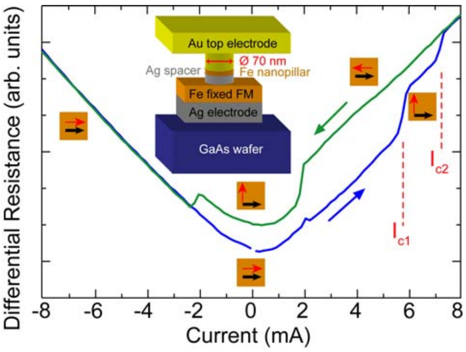

FIG. 3: Two-step current-induced switching of the free layer magnetization at 5 K. I_{c1} and I_{c2} denote the critical currents for the switching from parallel to perpendicular and from perpendicular to antiparallel alignment, respectively. Inset: Schematic sample structure.

The asymmetry of the STT favors excitation over damping. The stronger the asymmetry the lower I_{c2}. In the symmetric case, I_{c2} becomes very large, because the damping and exciting torques along the precession trajectory largely compensate each other. The experiment yields a ratio $I_{c1}/I_{c2} \approx 1.25$. We compare this ratio to results of macrospin simulations because it excludes uncertainties in nanopillar size, anisotropy constant, damping parameter α, or polarization P. We find that we have to increase Λ_{STT} in the simulations to $\Lambda_{STT} = 3.4$ in order to obtain good agreement between experiment and simulation. This value is also in accordance with the theoretical value $\Lambda = 4$ calculated by Eq. (3) using material specific parameters [4, 5].

In conclusion, the angular variation of both CPP-GMR and the critical current density for current induced magnetization switching in single-crystalline Fe/Ag/Fe nanopillars are asymmetric. This feature has been predicted by theory [2], but has not been observed so far. Our work confirms the importance of spin accumulation for GMR and STT.

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