(10/16/07) Two Simple Tests for Models of Current-Induced Magnetization Switching

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We describe two simple tests for models of current-induced magnetization switching due to spin-transfer-torque in ferromagnetic/non-magnetic/ferromagnetic (F/N/F) trilayers. The first involves comparing calculated and measured values of the ratio $X = \Delta I(\mathrm{Cu})/\Delta I(\mathrm{CuGe})$, where $\Delta I = I^+ - I^-$, the difference between switching currents for + and – current directions, when only the N-layer is changed from Cu to a dilute CuGe alloy. The Ge in Cu causes a large increase in elastic scattering (large reduction in mean-free-path), but only a smaller increase in spin-orbit scattering (leaving the spin-diffusion length still relatively long). The second involves comparing calculated and measured values of the ratios (I^+/I^-) for both Cu and CuGe. Unexpectedly, the most sophisticated models generally fit the first ratio least well at both 295 K and 4.2 K. None of the models agree with the ratio (I^+/I^-).

Current-Induced Magnetization Switching due to spin-transfer-torque in ferromagnetic/non-magnetic/ferromagnetic (F1/N/F2) trilayers was predicted in 1996 [1,2], and has been studied experimentally since 1998 [3-7]. However, published models [8-14] have still not been quantitatively compared to measured switching currents. In ref. [15], we described a simple new test for models of current-induced magnetization switching. For this conference, we first briefly describe this test, summarize the experimental results presented in [15], and describe how four different models did in fitting those results. Then we focus upon a second related test of the models, their ability to predict the ratio (I^+/I^-) where I^+ is the (positive) current needed to generate switching from the parallel (P) to anti-parallel (AP) ordering of the magnetic moments of F1 and F2, and I^- is the magnitude of the negative current needed to generate switching from AP to P.

The test described in [15] involved comparing predictions with the experimental ratio, $X = \Delta I(\mathrm{Cu})/\Delta I(\mathrm{CuGe})$, where $\Delta I = I^+ - I^-$, for two sets of nanopillars consisting of exactly the same metals and layer thicknesses, except that the 10 nm thick N-metal layer in one set is pure Cu, and while in the other the N-metal is Cu alloyed with 5 % Ge (by atomic number)—hereafter just CuGe. The Ge alloyed into in Cu greatly reduces the mean-free-path, λ, from at least three times *longer* for Cu than the layer thickness of t = 10 nm ('quasi-ballistic' regime), to about 2.5 times *shorter* for CuGe than 10 nm ('quasi-diffusive' regime). But the long spin-diffusion length of Cu, l_{sf}^{Cu} ≈ 290 nm at 295 K, still remains fairly long, l_{sf}^{CuGe} ≈ 55 nm for the CuGe [15], so that spin-flipping in both N-layers is weak and easy to correct for. These properties make X easy to calculate and thus a good test of models.

The values of ΔI (and thus X) in [15] were determined by measuring $R(I)$ on ≈ 70 nm x 130 nm nanopillars of sputtered Py(24)/N(10)/Py(6)—(Py = $\mathrm{Ni}_{1-x}\mathrm{Fe}_x$ with $x \approx 0.2$) multilayers with thicknesses given in nm. To minimize magnetic coupling between the two Py layers, subtractive ion milling was stopped about halfway through the N-layer [16]. The values of ΔI (and thus X) were determined from $R(I)$ measurements such as those in Figs. 1 and 2 for 295 K and 4.2 K. The sharp $R(H)$ switches, with switching occurring only after the magnetic field passes H = 0, are evidence for clean switching and little or no magnetic coupling between the Py layers. Analysis was limited to samples for which the $R(I)$ switching was also sharp, as exemplified in Figs. 1 and 2. Values of X at 4.2 K were determined from data on 8 nanopillars with Cu and 6 with CuGe. The result was X(4.2 K) = 1.1 ± 0.3. Values at 295 K were determined using for the same 8 and 6 samples, which gave X(295 K) = 1.4 ± 0.4, and also an additional 29 Cu samples and 23 CuGe samples, which gave the same result, X(295 K) = 1.4 ± 0.2.

We briefly compare these experimental values with four models.

The first is a ballistic polarization model of Slonczewski [1], supplemented by spin-flipping in the N-metal. With no spin-flipping in either sample, this model predicts X = 1. Correcting for spin-flipping in the Cu and CuGe gives $X = \exp(-t/\ell_{\mathrm{sf}}^{\mathrm{Cu}})/\exp(-t/\ell_{\mathrm{sf}}^{\mathrm{CuGe}}) \approx 1.2$.

The second, based upon results from a prior study [16], assumed that the product $\Delta R \Delta I$ was the same for Cu- and CuGe-based samples, and estimated X by calculating the ratio $\Delta R(\mathrm{CuGe})/\Delta R(\mathrm{Cu})$ from the Current-Perpendicular-to-Plane (CPP) magnetoresistance (MR) model of Valet and Fert [21]. Here $\Delta R = R(\mathrm{AP}) - R(\mathrm{P})$ is the difference in resistance between the AP (maximum R) and P(minimum R)

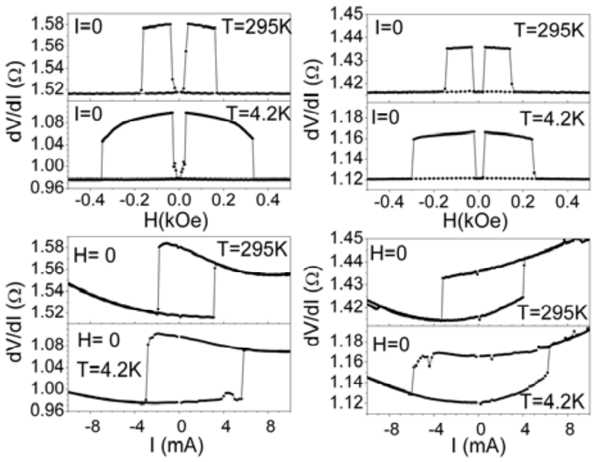

Fig. 1. R(H) (top half) and R(I) (bottom half) for two Cu nanopillars at 295 K and 4.2 K.

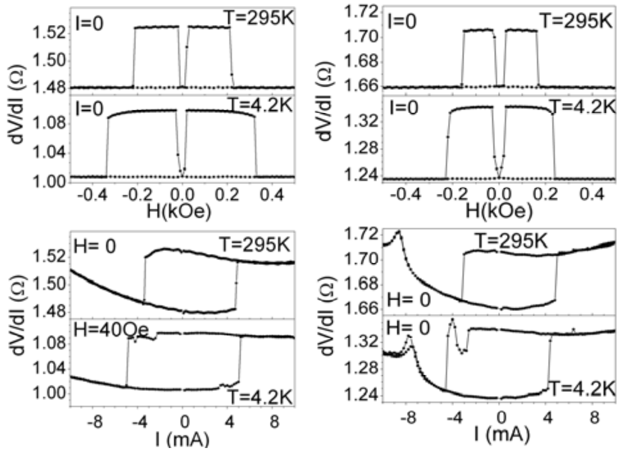

Fig. 2. R(H) (top half) and R(I) (bottom half) for two CuGe nanopillars at 295 K and 4.2 K.

states in Figs. 1 and 2. This model gives $X = 1.6$, mainly due to the larger ρ_N, and shorter ℓ_{sf}^{CuGe}, for CuGe than for Cu.

The third, the spin-torque model of Fert et al. [13], which uses a small angle approximation to calculate the torque in terms of a combination of longitudinal spin currents and spin-accumulations, gives $X \approx 2.2$ [15].

Finally, a Boltzmann model of spin-torque [14], which calculates the torque (per unit current) at all angles by solving numerically the Boltzmann equation in a spin-valve, gives $X = 2.0 \pm 0.12$ [15], due mainly to the much larger ρ_N (shorter mfp) for CuGe.

The values of X predicted by the last three models are generally larger than what we see, especially at 4.2 K. This difference might be due to a number of approximations that are common to the models, as described in detail in [15]. We note here two that might be particularly important. (1) The models assume a uniform nanopillar cross-section throughout, whereas, to minimize magnetic coupling, so that X could be measured at $H = 0$, the actual sample shape is more complex, as noted above. (2) The models calculate the torque, which is most closely related to the onset of instability in an assumed monodomain sample. In contrast to (2), we measure an 'outcome', i.e., a reversal, and hope that any differences between instability and reversal will largely cancel out in our ratio X. As an additional issue, there is evidence that the sample magnetization does not remain monodomain throughout the switching process [26]. In [15] we explain why making the calculations more 'realistic' will not be trivial.

Having reviewed the results in [15], we now turn to the issue of asymmetry in I^+ and I^-. Table I contains the ratios I^+/I^- for our same sets of 62 and 14 samples described above, (in italics) as well as ratios from two independent studies. The one from our laboratory [16] also used Py, and contains both directly comparable data for Cu and related, but not directly comparable, data using strong spin-flipping layers either within the Cu layer (CuPt) or outside of the switching Py layer. The other, from Cornell U. [27], differs in using Co instead of Py. For pure Cu and Py, our 'best average values' of I^+/I^- are 1.34 ± 0.15 at 295 K and 1.5 ± 0.3 at 4.2 K. For CuGe and Py, we find 1.1 ± 0.3 at 295 K and 0.9 ± 0.1 at 4.2 K. For two Py-based nanopillars with strong spin-flipping, Ref. [16] finds $I^+/I^- \approx 1.0$-1.2. For Co-based nanopillars with Cu, [26] finds $I^+/I^- \approx 1.0$ for Cu thickness ≤ 20 nm, but $I^+/I^- \approx 1.5$ for Cu thickness = 50 nm. Essentially all of these values are consistent with a rough average of $I^+/I^- \approx 1.25 \pm 0.3$.

The polarization model of Slonczewski predicts a ratio $I^+/I^-=4.8$ for a polarization P=0.4, reducing to $I^+/I^-=2.0$ in the limit that P goes to zero, neglecting effects of spin-flipping. Our $\Delta R\Delta I$ experimental model does not make a prediction for the ratio of the critical currents. The Fert model predicts $I^+/I^- = 0.9$ for Cu and 2.0 for CuGe. The Boltzmann equation model predicts $I^+/I^- = 2.7 \pm 0.27$ for Cu and 1.8 ± 0.06 for CuGe, both larger than our measured values. For the analysis of X in [15], the Boltzmann uncertainties were most sensitive to the experimental uncertainty in the thickness of the spacer layer, those for I^+/I^- are largely due to the uncertainties in the interface resistances.

The Fert model is too small for Cu, but too large for CuGe, and Slonczewski's simple model and the Boltzmann Equation model are too large for both. We note that a very different technique, on very different samples [28], found an asymmetry in the spin transfer torque that is more consistent with the calculations. A recent study of switching in magnetic tunnel junctions [29] also found closer agreement between experiment and theory.

To summarize, we test models of spin-transfer-torque produced Current-Induced Magnetization Switching in two ways. First, we measured the ratio $X = \Delta I(\mathrm{CuGe})/\Delta I(\mathrm{Cu})$ at 295 K and 4.2 K for samples with Cu giving 'ballistic' transport ($r = \lambda/t \geq 3$) and with CuGe giving 'diffusive' transport ($r \leq 0.4$), with no spin-flipping as electrons transit the Cu, and little spin-flipping for CuGe. We found $X = 1.4 \pm 0.2$ at 295 K and $X = 1.1 \pm 0.3$ at 4.2 K. Surprisingly, these values are roughly consistent with expectations from the original Slonczewski model of ballistic transport. We say surprisingly, because this model cannot correctly describe our full samples, which contain Py and CuGe layers that must involve diffusive scattering. We presume that the deficiencies of the ballistic model fortuitously mostly cancel out of the particular experimental ratio in X. In agreement with this presumption, the ballistic model failed to correctly give the ratio of I^+/I^-. In contrast to the case for the ballistic model, our values of X are smaller than expected from the models of Fert et al. [13] or Xiao-Zangwill-Stiles [15], and smaller at 4.2 K than an experimentally-based model assuming constancy of the product $\Delta R \Delta I$ [16]. We briefly noted some model limitations, which are discussed in more detail in [15]. In the present paper, we also compared the experimental ratio I^+/I^- for Cu and CuGe with the three models that make predictions. In this case, none of the models agree with the experimental results.

Table I. Average values of the ratio (I^+/I^-) at 295 K for a variety of the present samples (in italics) and samples studied by others and at 4.2 K for the present samples (in italics). Numbers in parentheses are the number of samples included in the averages.

Samples	*I+/I-*
295 K	
Cu(29)	1.25±0.12
CuGe(23)	1.03±0.15
Cu(8)	1.22±0.16
CuGe(6)	1.1±0.3
Cu(14)[16]	1.55±0.2
4.2K	
Cu(8)	1.5 ± 0.3
CuGe(6)	0.9 ± 0.1
295K (Other)	
Cu(FeMn)[16]	1.2±0.2
Cu(Pt)[16]	≈ 1.0
Co/Cu(5nm)[26]	1.0±0.2
Co/Cu(20nm)[26]	1.1±0.2
Co/Cu(50nm)[26]	1.5±0.3

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