

Ballistic versus diffusive transport in current-induced magnetization switching

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We test whether current-induced magnetization switching due to spin-transfer torque in ferromagnetic/nonmagnetic/ferromagnetic (F/N/F) nanopillars changes significantly when scattering within the N metal layers is changed from ballistic to diffusive. Here, ballistic corresponds to a ratio $r = \lambda/t \geq 3$ for a Cu spacer layer, and diffusive to $r \leq 0.4$ for a CuGe alloy spacer layer, where λ is the mean free path in the N layer of fixed thickness $t = 10$ nm. The average switching currents for the alloy spacer layer are only modestly larger than those for Cu. The best available model predicts a much greater sensitivity of the switching currents to diffuse scattering in the spacer layer than we see.

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Current-induced magnetization switching (hereafter referred to as just current-induced switching) due to spin-transfer torque in ferromagnetic/nonmagnetic/ferromagnetic (F1/N/F2) trilayers was predicted in 1996,^{1,2} and has been studied experimentally since 1998.³⁻⁷ However, published models have not yet been shown to quantitatively reproduce measured switching currents.⁸⁻¹⁶ It has been difficult to critically evaluate these models, because comparing calculations with data for samples having several different components is usually complicated. In the present experiments, we simplify by using a test based on a ratio of results from measurements on samples in which only the N layer is modified, with the main effect being just to change the scattering in this layer from ballistic to diffusive. Specifically, we compare the prediction of a Boltzmann equation model¹⁶ to the measured ratio of switching currents [$X = \Delta I(\text{CuGe})/\Delta I(\text{Cu})$], for sample sets that are nominally identical in every way (including the leads), except for changing a fixed 10 nm thickness of the N metal from nominally “pure” Cu to a dilute Cu(5 at. % Ge)—hereafter just CuGe—alloy. Here $\Delta I = I^+ - I^-$ is the difference between the positive (I^+) and negative (I^-) switching currents shown in the upper left panel of Fig. 1, labeled $H=0$. This Boltzmann model has the advantages of interpolating between the ballistic and diffusive limits, and generally including other approaches⁸⁻¹⁵ as limiting cases. We chose CuGe because Ge in Cu: (a) adds a large resistivity per atomic percent Ge [$\approx 3.7 \mu\Omega \text{ cm/at. \%}$ (Ref. 17)], thereby greatly shortening the mean free path λ ; (b) has a small spin-orbit cross section in Cu [$\sigma_{\text{so}} \approx 5.2 \times 10^{-19} \text{ cm}^2$ (Ref. 18)], giving weak spin flipping and thus a long spin-diffusion length $\ell_{\text{sf}}^{\text{N}}$, and (c) is soluble in Cu to $\approx 10\%$.¹⁹

As shown in Table I, with Cu, λ is at least three times the layer thickness of 10 nm (ballistic transport). With CuGe, λ is less than 40% of 10 nm (diffusive transport). We can thus determine, at both 295 and 4.2 K whether (1) just changing the scattering in the N layer from ballistic to diffusive sig-

nificantly affects the switching current ΔI ; and (2) how well the Boltzmann equation model of current-induced switching describes the ratio of switching currents. By using a ratio, we expect that most, if not all, of any systematic errors will cancel.

Our sputtered Cu(80)/Py(24)/N(10)/Py(6)/Au(10)/Cu(20) $\approx 70 \times 130 \text{ nm}^2$ nanopillars were prepared by a combination of optical and e -beam lithography plus subtractive ion milling as described in Refs. 20 and 21. Layer thicknesses are in nanometers, and Py = $\text{Ni}_{1-x}\text{Fe}_x$ with $x \sim 0.2$. To minimize magnetic coupling between the two Py layers, so we can simply measure switching at $H=0$, we left about half of the middle N layer (Cu or CuGe) and all of the bottom Py and Cu layers unpatterned. With fully patterned nanopillars, studying switching would require applying a field to offset the dipolar coupling field, which is not uniform across the sample. Ion-beam etching is done in a chamber with background pressure $\approx 10^{-5} \text{ Pa}$, and we deposit our insulating SiO without breaking vacuum.

Strictly, the calculations in Refs. 8–16 give the torque, which is most closely related to the onset of dynamical instability. Since this onset is hard to determine, we measure the currents at which sharp switching occurs (illustrated at both 295 and 4.2 K for one sample each of CuGe and Cu in Fig. 1), neglecting any “preswitching” structure in the hysteresis curves. This process minimizes ambiguity and is the same for samples with Cu and CuGe. At 295 K, the great majority of our switchings were sharp and complete; at this temperature we include in our discussion data for a total of 36 samples with Cu and 29 with CuGe (see Table II). At 4.2 K, sharp switching was less prevalent; there we include data (bold in Table II) for only seven samples of Cu and six of CuGe.

Crucial to any quantitative comparison of data and theory are checks for possible systematic errors in the data. To make such checks, we include in Table II results for the 13 Cu and

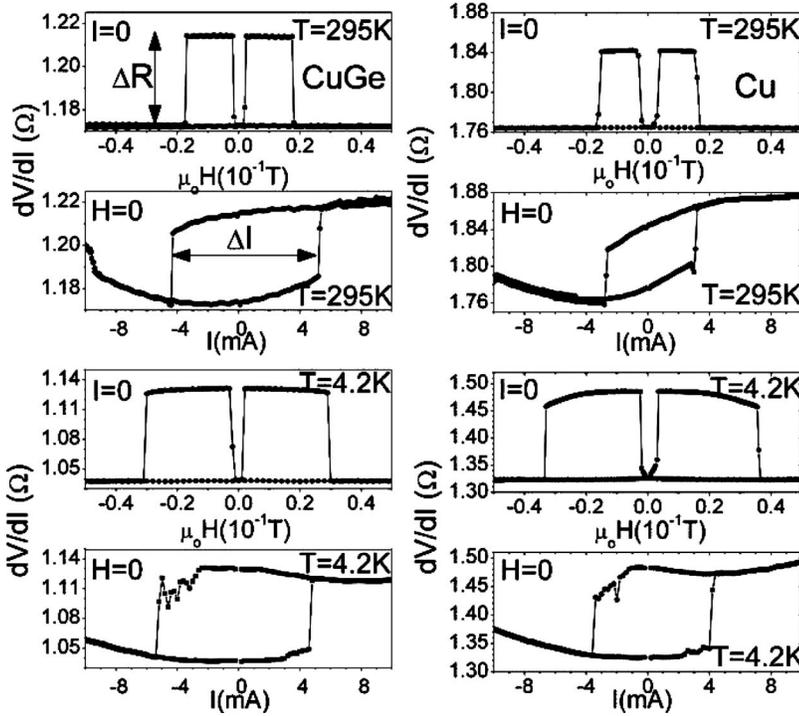


FIG. 1. $R(H)$ and $R(I)$ at 295 (top) and 4.2 K (bottom) for one of the six selected CuGe nanopillars (left) and one of the seven selected Cu nanopillars (right). Arrows in the upper left indicate ΔR and ΔI .

CuGe samples of main interest at both 295 and 4.2 K, and the other 52 samples with Cu and CuGe at 295 K. We discuss the comparisons of these results below.

One of these checks for systematic errors involves results from our previous study at 295 K on samples using $F1=F2=Py$ and $N=Cu$ or Cu alloyed with 5 at. % Pt sandwiched between Cu layers, to test effects of spin flipping within the N layer.²⁰ Pt produces strong spin flipping in Cu,¹⁸ with only modest elastic scattering.¹⁷ For those samples, the inverse critical switching currents ($1/I^+$) or ($1/I^-$) were found to be directly proportional to the change in resistance $\Delta R = R(AP) - R(P)$ between the states with moments of the two F layers antiparallel (AP) or parallel (P) to each other.²⁰ As linear fits to the data of Ref. 20 were compatible with zero intercept for both positive and negative ($1/I$), we recast the data into the form $\Delta R \Delta I = \text{const}$, where $\Delta I = I^+ - I^-$ was defined above (because of uncertainties in the data, we do not claim this recasting as “definitive”—there might be small nonzero intercepts). We used this relationship in two ways: (a) to check if our new values of $\Delta R \Delta I$ with Cu agree with earlier ones^{20–22}—they do; and (b) to check if the values of $\Delta R \Delta I$ for CuGe agree with those for Cu—Table II shows that they do. These agreements at both 295 and 4.2 K give us confidence that any systematic errors in our data should not be large.

To specify the differences between our samples with Cu and CuGe, and to calculate X , we need estimates of the mean free paths λ and spin-diffusion lengths ℓ_{sf}^N for our samples. To estimate λ , we use the free-electron relation between resistivity ρ and λ , in Cu $\lambda\rho = 0.66 \text{ f}\Omega \text{ m}^2$,^{17,23} along with values of ρ measured separately on 200-nm-thick films using the van der Pauw technique.²⁴ Values of ρ , λ , and the ratio $r = \lambda/t$ are given in Table I. To correct for spin flipping, we estimate ℓ_{sf}^N from the Monod and Schultz collection of cross sections σ_{so} measured by electron spin resonance.¹⁸

For Ge in Cu, they list $\sigma = 5.2 \times 10^{-19} \text{ cm}^2$, which yields a spin-flip length for our CuGe alloy of $\lambda_{sf} \approx 4500 \text{ nm}$. We estimate the 4.2 K spin-diffusion length for our CuGe alloy from the Valet-Fert equation $\ell_{sf}^N = \sqrt{(\lambda\lambda_{sf})/6} = \sqrt{[(4.1 \pm 0.2) \times (4500 \pm 450)]/6} \approx 55 \pm 5 \text{ nm}$.²⁵

From data such as those in Fig. 1, we determined values at 295 and 4.2 K of $R(AP)$, ΔI , ΔR , and the product $\Delta R \Delta I$ for nanopillars with both Cu and CuGe. The average values for these quantities are collected together in Table II. In each case, the number of samples measured is given in parentheses. Values of $R(AP)$ are for complete samples, including the wide Cu and Py layers at the bottom and the wide Au and Cu layers at the top. Compared to Cu, the larger resistivity of CuGe should increase $R(AP)$ by $\sim 0.1 \Omega$ at both 295 and 4.2 K, well within our uncertainties.

From the values of ΔI in Table II, we derive the ratios X . At 295 K we find $X = 1.4 \pm 0.4$ for the 13 samples and $X = 1.4 \pm 0.2$ for the other 52 samples. At 4.2 K we find $X = 1.1 \pm 0.3$ for the 13 samples. We take the agreement on $X = 1.4$ at 295 K, as well as those of $\Delta R \Delta I$ in Table II already noted, as evidence that our 13 selected samples are representative of both our larger set of 52 samples and our prior data on Cu.^{20–22}

We calculate X for a Boltzmann equation model,¹⁶ in

TABLE I. Resistivities ρ , mean free paths λ , and ratios $r = \lambda/10 \text{ nm}$ and $r^* = \ell_{sf}^N/10 \text{ nm}$ for $N=Cu$ and CuGe.

Metal	T (K)	ρ ($\mu\Omega \text{ cm}$)	λ (nm)	r	r^*
Cu	295	2.1 ± 0.1	31 ± 2	3.1	~ 29
CuGe	295	18.0 ± 0.9	3.7 ± 0.2	0.37	~ 5
Cu	4.2	0.5 ± 0.1	132 ± 20	13.2	~ 100
CuGe	4.2	16.2 ± 0.7	4.1 ± 0.2	0.41	~ 5

TABLE II. $R(\text{AP})$, ΔI , ΔR , and $\Delta R/\Delta I$ for Cu and CuGe at 295 and 4.2 K. Numbers in parentheses in the first column indicate the number of samples in each data set. Uncertainties are two standard deviations of the mean. Bold font indicates the 13 samples with sharp switching at 4.2 K, and standard font indicates the other 52 samples. The agreements for different sample sets within mutual uncertainties suggests that systematic errors in $R(\text{AP})$, $\Delta R/\Delta I$, and especially ΔI for the 13 new samples are not large.

	$R(\text{AP})$ (Ω)	ΔI (mA)	ΔR (m Ω)	$\Delta R/\Delta I$ (μV)
295 K				
Cu (7)	2.2\pm0.8	5.5\pm1.0	56\pm16	0.31\pm0.11
CuGe (6)	2.2\pm1.0	7.5\pm1.6	41\pm4	0.31\pm0.07
Cu (29)	2.0 \pm 0.4	6.0 \pm 0.8	57 \pm 14	0.34 \pm 0.10
CuGe (23)	1.5 \pm 0.2	8.3 \pm 0.8	35 \pm 6	0.29 \pm 0.06
4.2 K				
Cu (7)	1.9\pm0.8	9.4\pm1.4	114\pm30	1.07\pm0.32
CuGe (6)	1.9\pm1.0	10.2\pm2.0	87\pm14	0.89\pm0.22

which the torque (per unit current) is determined as a function of angle by solving the Boltzmann equation numerically in a spin valve, using independently determined parameters for the nanopillar components.²⁶ The model includes both spin-conserving and spin-flip scattering in all layers, and smoothly changes from a diffusive to a ballistic regime as the mean free path of the spacer layer changes. The critical current is inversely proportional to the slope of the torque curve, giving $\Delta I \propto |d\tau(\text{P})/d\theta|^{-1} + |d\tau(\text{AP})/d\theta|^{-1}$. The values of λ_{N} and $\ell_{\text{sf}}^{\text{N}}$ for Cu and CuGe listed above, together with the standard parameters,²⁶ give $X=2.0\pm 0.13$, due mainly to the much shorter mean free path (much larger ρ_{N}) for CuGe. The uncertainty, most sensitive to the uncertainties in the thickness of the CuGe layer, is computed from the experimental uncertainty in the input parameters and the computed sensitivity of the result to each parameter. As a cross check, we also calculated X using a closely related model by Fert *et al.*¹⁴ with the same input parameters, and found a very similar result, $X=2.2$.

Our calculated value of $X=2.0$ is considerably larger than our experimental values of X at both 295 and 4.2 K. We can identify several possible reasons for this discrepancy, although we do not find any compelling.

One set of complications is due to thermal effects. Both the transport and magnetic dynamics are calculated at zero temperature. We expect any temperature dependence of torque to be weak, because the only variations with temperature in electronic properties should be changes in scattering rates. We also expect the dominant thermal effects to come from thermally activated dynamics, so that, absent complications, the models should be compared with our 4.2 K data.

However, at 4.2 K, magnetic anisotropies in the F layers might lead to more complicated reversal processes where ΔI is not as closely related to the torque as assumed. Also, at 4.2 K, adventitious antiferromagnetic NiO on the surfaces of Py layers in nanopillars was reported to affect switching,²⁷ by producing local exchange biasing that generated both large variations in the switching field H_{s} and occasional mul-

multiple steps. While we do see variations in H_{s} in both Cu and CuGe sample sets, they occur at both 4.2 and 295 K. Since 295 K is well above the Néel temperature of thin NiO layers, variations there cannot be attributed to pinning. We also occasionally see steps at 4.2 K, but we omit any such samples from our analysis. Lastly, as any effects of NiO should be similar for Cu and CuGe, we doubt that their presence would strongly bias our measured ratios. Fortunately, the issue of temperature is not crucial to our conclusions, as our 4.2 and 295 K values of X overlap, with a “common” value of $X=1.3$, to within mutual uncertainties.

One possible cause of the discrepancy between the model and the measurements is that we measure reversal, whereas the model calculates the initial dynamical instability. In addition, the model assumes a macrospin, and the experimental reversal mode may be nonuniform.²⁸ However, we do not expect these complications to differ much for the Cu and CuGe spacers.

Another issue is the geometry. The calculation assumes that the devices are wide wires with uniform current flow. As noted above, so that we could measure switching at $H=0$ (and have it insensitive to H around $H=0$), the actual device structure is more complex, leading to nonuniform current flow and more complicated behaviors of spin accumulation and spin current. Berger²⁹ and Hamrle *et al.*³⁰ have discussed corrections for such nonuniformity, which conceivably might differ for Cu and CuGe. However, since the cross-sectional dimensions of the nanopillars are larger than the layer thicknesses and the mean free paths (except for Cu at 4.2 K), we do not expect a three-dimensional treatment to give very different changes for the two sets of samples.

Finally, there could be other errors in the theoretical approach. The model approximates all Fermi surfaces as spheres with the same radii, idealizes the interfaces as specular, and ignores spin-flip scattering at the interfaces. We do not yet know how much change could be produced by relaxing any of these approximations. Since the nanopillar resistances are comparable to those of the leads, the resistances and magnetoresistances cannot be used to constrain the calculations or independently check the transport parameters, which might not be appropriate for nanopillars. Some of these issues might be addressed in quantum mechanical calculations^{31,32} where, however, it is hard to include diffuse scattering.

To summarize, to see if spin torque differs for ballistic vs diffusive scattering in the N metal, and to test the best available model of spin-transfer-torque-produced current-induced magnetization switching, we measured the simple ratio $X = \Delta I(\text{CuGe})/\Delta I(\text{Cu})$ at 295 and 4.2 K for samples with Cu giving ballistic transport (i.e., ratio $r = \lambda/10 \text{ nm} \geq 3$) and samples with CuGe giving diffusive transport ($r \leq 0.4$), with no spin flipping as electrons transit the Cu, and modest spin flipping for CuGe. At 295 K we find $X=1.4\pm 0.2$ and at 4.2 K $X=1.1\pm 0.3$. These values are not far from unity, indicating that there is not much difference in spin torque for ballistic or diffusive scattering in the N metal. However, they are noticeably smaller than expected from a Boltzmann equation model,¹⁶ or the related Fert *et al.* one.¹⁴ While

experimental issues cannot be ruled out, we think it is more likely that the calculations fail to capture some essential feature of the experiment. The calculations could be improved by adding micromagnetics, more realistic treatment of transport in the sample geometry, and first-principles transport calculations that include diffusive scattering. But each of these advances is computationally intensive and it is very hard to do any two with present computers. It is also not

clear that any will give different results for Cu and CuGe spacers. We hope that our results will provide a benchmark for theoretical analyses to advance understanding of spin-transfer torques.

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