Switching Current vs. Magnetoresistance in Magnetic Multilayer Nanopillars.

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We study current-driven magnetization switching in nanofabricated magnetic multilayers, varying the magnetoresistance in three different ways. First, we insert a strongly spin-scattering layer between the magnetic trilayer and one of the electrodes, giving increased magnetoresistance. Second, we insert a spacer with a short spin-diffusion length between the magnetic layers, decreasing the magnetoresistance. Third, we vary the angle between layer magnetizations. In all cases, we find an approximately linear dependence between magnetoresistance and inverse switching current. We give a qualitative explanation for the observed behaviors, and suggest some ways in which the switching currents may be reduced.

Our samples were made with a multistep process described elsewhere. Below, all thicknesses are in nm. The basic samples had structure Cu(80)/Py(30)/N(15)/F, where N was Cu(13.5-d)/Cu(2)/Au(150). The bottom Cu(80)/Py(30) layers were extended leads.

FIG. 1: (a) \(\frac{dV}{dI}\) vs. \(I\) for a sample of type 1 (as defined in the text) at \(H = 0\). Inset: \(\frac{dV}{dI}\) vs. \(H\) at \(I = 0\). (b) Same as (a), for a sample of type 2.

FIG. 2: (a) Variation of \(\Delta R\) with \(t_{CuP}\). Dashed line is a fit with \(\Delta R = \Delta R_0 \exp(-t_{CuP}/t_{CuP}^{SF})\), \(\Delta R_0 = 0.06 \pm 0.004\Omega\), \(t_{CuP}^{SF} = 6.1 \pm 0.8\) nm. (b) \(I_s^{AP\rightarrow AP}\) (upward triangles) and \(I_s^{AP\rightarrow AP}\) (downward triangles) vs. \(t_{CuP}\).

N, F, and Cu(2) were patterned into an elongated shape with dimensions \(\approx 130 \times 70\) nm, and Au(150) was the top lead. Leaving \(F_1\) extended minimizes the effect of dipolar coupling on the current-driven switching. \(N\) was Cu(13.5-\(d\))/Cu(2)/Pt(6)/Cu(1.5), with \(d = 0, 0.4, 8, 12\) in sample types 1 through 5, respectively. In sample type 2, the Cu(2) layer was replaced with a Cu(2)/Fe50Mn50(1)/Au(2) sandwich. We measured \(dV/dI\) at room temperature (295 K) with four-probes and lock-in detection, adding an ac current of amplitude 20–40 \(\mu\)A at 8 kHz to the dc current \(I\). At least 7 samples of each type were tested. Typical sample resistances were 1 to 3 \(\Omega\). Variations in resistances are attributed to scatter in both nanopillar sizes and contact resistances to the electrodes. Positive current flows from the extended to the patterned Py layer. \(H\) is in the film plane and (except for the angular dependence studies) along the nanopillar easy axis.

Fig. 1 compares typical results for a sample of type 1 (Fig. 1a) vs. a sample of type 2, (Fig. 1b). In both cases, negative current \(I\) leads to transition from the antiparallel (AP) state with high resistance \(R_{AP}\) to the parallel (P) state with low resistance \(R_P\) at \(I = I_s^{AP\rightarrow P}\). A reverse transition occurs at positive \(I = I_s^{P\rightarrow AP}\). In the

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$H$ sweep at $I = 0$ (insets Fig. 1a,b), the extended $F_1$ layer reverses at $H \approx 20$ Oe, and $F_2$ reverses at the field $H_s \approx 100 - 200$ Oe, determined by the shape anisotropy of $F_2$. The average $H_s$ in samples of type 1 and type 2 were similar, insets of Fig. 1 only illustrate scatter among samples. There was no systematic correlation between $I_s$ and $H_s$. Since the high resistivity $\rho \approx 100\Omega \mathrm{cm}$ of Fe$_{50}$Mn$_{50}$ contributes only $\approx 0.25 \Omega$ to the resistance of samples of type 2, the contact resistance in Fig. 1(b) must be $\approx 1\Omega$ larger than that in Fig. 1(a). For 14 samples of type 1, $\Delta R = R_{AP} - R_P = 0.060 \pm 0.002\Omega$, $I^{AP\rightarrow P}P = -2.45 \pm 0.2\ mA$, and $I^{P\rightarrow AP}P = 3.8 \pm 0.2\ mA$. For 12 samples of type 2, $\Delta R = 0.085 \pm 0.012\Omega$, $I^{AP\rightarrow P}P = -1.5 \pm 0.2\ mA$, and $I^{P\rightarrow AP}P = 1.85 \pm 0.2\ mA$. For uncertainties, we give twice the standard deviations of the mean. The main result of this experiment is the higher $\Delta R$, and lower $I_s$, in the nanopillars with the inserted Fe$_{50}$Mn$_{50}$ layer.

Fig. 2 shows data for sample types 1, 3, 4, 5. Fig. 2a) ($\Delta R(t_{CuP})$) gives a spin-diffusion length of 6.1 $\pm$ 0.8 nm in Cu$_{94}$Pt$_{6}$ at 295 K, shorter than $\approx 10$ nm at 4.2 K [9]. Fig. 2b) shows that both $I^{P\rightarrow AP}P$ and $I^{AP\rightarrow P}P$ increase with increasing $t_{CuP}$. Interestingly, the ratio $I^{P\rightarrow AP}P/I^{AP\rightarrow P}P$ decreases from $\approx 1.5$ at $t_{CuP} = 0$ to $\approx 1.0$ for $t_{CuP} = 8$. This decrease with increase of spin-flipping within the N-layer is opposite to that reported in [8] for a similar measurement with varied thickness of N=Cu, and is inconsistent with the explanation proposed there. All 8 samples of type 5 showed hysteretic field-driven switching, similar to other sample types. However, none showed reproducible hysteretic current-switching. Such a qualitative change at sufficiently large $t_{CuP}$ is expected.

When the Py layers are nearly decoupled due to spin-flip scattering in a thick Cu$_{94}$Pt$_{6}$ layer, the effect of current becomes independent of the mutual orientations of these layers. This effect is similar to that for a single magnetic layer, and cannot lead to hysteretic switching between P and AP states.

Fig. 3 shows the results for varied non-collinear orientations of magnetic layers in sample type 1. Before each measurement, a pulse of $H = 60$ Oe at the desired in-plane angle $\theta$ was applied to rotate the magnetization $M_1$ of $F_1$ parallel to $H$, then the current-switching was measured at $H = 10$ Oe, needed to fix $M_1$. The data in Fig. 3 confirm results reported in [8], but with a larger magnetoresistance $\Delta R/R$.

In Fig. 3, we collect together the data of Figs. 1a,b in a plot of average values of $1/I_s$ vs. average $\Delta R$. The variations among different samples lead to uncertainties of the average values, close to the symbol sizes in Fig. 3a). The overall agreement of the data for three different types of measurements suggests a general inverse relationship between $I_s$ and $\Delta R$, independent of the particular way in which $\Delta R$ was varied. The switching is determined by the current density, so both $1/I_s$ and $\Delta R$ are inversely proportional to the nanopillar areas; their variation only leads to scaling along the approximately linear dependence in Fig. 3a).

To qualitatively describe the inverse relationship in Fig. 3a), we use the simplest plausible ballistic model, in which the electrons polarized by $F_1$ are scattered in $F_2$, generating magnetic excitations. Fig. 3b) shows a cartoon of this model, where a spin-up electron coming from $F_1$ is either transmitted or reflected by $F_2$. In either case, it can flip its spin, exciting (or de-excitng) the $F_2$ layer.

We introduce a parameter $p$, describing the polarization of current if $F_2$ is removed. We define the sign of $p$ with respect to the direction of magnetization $M_2$ of $F_2$. For Py (sample type 1), we expect $p \approx 0.45 - 0.6$ [2,9]. When $F_1$ is absent, $p = 0$. The current polarization in the diffusive transport model [11] is different: it depends both on $F_1$ and $F_2$, and does not disappear when $F_1$ is absent.

In our model, $\Delta R$ is determined by the spin-dependent resistance of the interfaces and bulk of $F_2$ and is proportional to $p$. We can interpret the variations of $\Delta R$ in terms of a change in polarization $p$. When
Cu_{94}Pt_{6} is inserted between F_{1} and F_{2}, spin-flip scattering in this layer decreases \( p \) according to \( p(\theta_{CaPt}) = p(0)exp[-I_{CaPt}/I_{sf}^{eff}] \), consistent with Fig. 2(a). The angular dependence of Fig. 3(a) can be understood similarly in terms of the projection of spin current onto the direction of the magnetization of F_{2}, giving \( p(\theta) = p(0)\cos(\theta) \). Finally, the Fe_{50}Mn_{50} inserts outside F_{2} have very short spin-diffusion length. Although the resulting increase of MR involves spin-diffusion outside the magnetic trilayer, and cannot by described by our ballistic model, it is also reasonable to approximate the effect of the Fe_{50}Mn_{50} inserts as an increase of \( p \).

The current-driven switching is also expected to be determined by \( p \). Electrons with spin opposite to \( M_{2} \) can generate magnetic excitations when they flip their spins, while electrons with spins along the magnetization can absorb the excitation when they spin-flip, as follows from the conservation of angular momentum along \( M_{2} \). Thus, we may expect the rate of magnetic excitation by current to be given by the difference between spin-down and spin-up electron currents, i.e. approximately proportional to \( p \cdot I \). \( p \cdot I \) is then determined by the level of magnetic excitation, needed for the magnetization switching, i.e. \( 1/I_{s} \propto p \). The data and linear fits (solid lines) in Fig. 4(a) are consistent with this analysis. Our data are also generally consistent with the more quantitative analyses of current-driven switching based on the popular spin-torque model \[2, 11\], and the recently proposed effective temperature model \[12\]. These models differ from each other in details, which need further experimental testing.

Our data, and the simple model, suggest that one might reduce \( I_{s} \) by using a more highly polarizing ferromagnet for F_{1}, or by being more clever in designing the layers outside the F_{1}/N/F_{2} trilayer. Independent evidence that the current-driven switching is determined by the N/F_{2} interfaces \[7\] suggests that modifying those interfaces (e.g. by varying their roughness or local composition) should be worth exploring. At room temperature, the current-driven switching is thermally activated \[11, 14\]. An obvious way of decreasing the switching current is then to lower the switching barrier. But a smaller switching barrier also leads to thermal activation at room temperature without applied current, thus reducing the effectiveness of the nanopillars for information storage.

To summarize, we measured the changes in resistance upon switching, \( \Delta R \), and the switching currents, \( I_{s} \), in Permalloy (Py)-based trilayer nanopillars with: a) strong spin-flipping between the nanopillar and one of the leads, b) spin-flipping in the spacer between the Py layers, c) varying angle between the magnetizations of the Py layers. We find a linear relation between \( I_{s}^{-1} \) and \( \Delta R \). We describe the data in terms of a qualitative ballistic model.

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