Effect of Interlayer Coupling on Current-Assisted Magnetization Switching in Nanopillars

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We show that dipole-field induced antiferromagnetic coupling, or RKKY ferromagnetic coupling, between Co layers can strongly affect the low magnetic field switching behavior of Co/Cu/Co nanopillars. Whereas current-assisted switching at low fields in uncoupled nanopillars is always hysteretic, strong coupling of either kind can change the switching to non-hysteretic (reversible). These differences can be understood with a simple picture of current-assisted thermal activation over a barrier.

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Current-assisted switching in magnetic nanopillars has lately been receiving much theoretical and experimental attention, both to understand the basic physics and because of its potential for technology. Most of the experimental data have been taken on Co/Cu/Co nanopillars that are either magnetically uncoupled or antiferromagnetically (AF) coupled. Initial studies focused upon the similarities in behavior of the two cases. However, we recently showed that at low magnetic field H the dependencies on driving current I of uncoupled and AF coupled nanopillars could be very different: hysteretic for uncoupled samples, but non-hysteretic (reversible) and characterized by telegraph noise for AF coupled ones. In this short paper we provide additional data showing these differences for uncoupled and AF coupled nanopillars, and extend the study to show that low field reversible behavior and telegraph noise occur also in ferromagnetically (F) coupled nanopillars. We show that these differences in behavior can be understood using a simple model of current-assisted thermal activation.

Our samples have the form [Cu(80)/Co(20)/Cu(10 or 2.6)/Co(2.5)/Cu(5)/Au(200)], where thicknesses are in nm. Sample preparation procedures are described elsewhere. In uncoupled samples, only the top Co(2.5) and most of the middle Cu layer were ion milled to nanopillar size (≈70 nm x 130 nm), leaving the rest of that Cu layer and the bottom Co(20)-layer extended. This geometry minimizes dipolar coupling between the two Co layers. AF coupling was achieved by milling about halfway through the Co(20) layer, thereby generating dipolar coupling between the two patterned Co layers. F coupling was achieved by reducing the Cu thickness to Cu(2.6), near the third RKKY magnetoresistance (MR) minimum. There were significant variations in coupling strength among both AF and F coupled samples, presumably due to sample shape variation and roughness of magnetic interfaces.

Differential resistances, dV/dI, were measured with four probes and lock-in detection, adding an ac current of amplitude 20 µA at 8 kHz to the dc current I. Positive current flowed from the extended to the fully patterned Co layer. Fig. 1 summarizes the differences between uncoupled (left), AF-coupled (middle), and F-coupled (right) samples. At I=0, the uncoupled (Fig. 1(a)) and AF-coupled (Fig. 1(d)) samples display the usual changes from a low resistance, high-H state in which the magnetizations of Co layers are aligned parallel (P) to each other, to a high resistance, low field state where the magnetizations are aligned antiparallel (AP). In contrast, in strongly F-coupled samples the magnetizations are simultaneously reversed at small H to stay in the exchange-favored P state, yielding only a small feature in MR at I=0 (Fig. 1(h)). At large enough I > 0, F-coupled samples yielded 5% MR (with no hysteresis), similar to
FIG. 2: Schematics of current driven switching. Dashed lines indicate the effective magnetic temperature. (a) P→AP switching at \( I > 0 \) in the hysteretic regime, at small \( H \) in uncoupled, and intermediate \( H \) in AF-coupled samples. (b) Telegraph noise at small \( H \) and \( I < 0 \) in AF-coupled samples. (c) Telegraph noise at large \( H \) in uncoupled and AF-coupled samples, and at small \( H \) in F-coupled samples.

The values obtained for uncoupled and AF-coupled samples at \( I = 0 \). For uncoupled samples, the change in dV/dI usually occurs in a single step, indicating single domain switching. For AF coupled samples, the nonuniform dipolar field usually leads to a more complex structure. Fig. [1][b,c,i] compares the variations of dV/dI with I for the same three samples. First, we compare the behaviors at small \( H=20-50 \) Oe, applied to fix the magnetization state of the bottom Co layer. The uncoupled sample (Fig. [1][b], solid line) shows the expected asymmetric hysteretic switching \( \delta \) between the same values of dV/dI as in Fig. [1][a]. In contrast, the AF-coupled sample (Fig. [1][c], top curve) shows reversible (non-hysteretic) switching at a negative value of \( I \), and the F-coupled sample (Fig. [1][i]) shows reversible switching at a positive value of \( I \). The dashed line in Fig. [1][b] shows that at larger \( H \) the switching in uncoupled samples becomes nonhysteretic, characterized by a peak similar to that in Fig. [1][i] for an F-coupled sample. In the AF-coupled sample, the switching becomes hysteretic at intermediate \( H \) (Fig. [1][c], middle curve), and nonhysteretic again at large enough \( H \) (Fig. [1][e], bottom curve). These curves are similar to those for the uncoupled sample (Fig. [1][b]), but offset by the dipolar coupling field.

Time-resolved measurements, performed at I, H, close to the nonhysteretic switching peaks, are characterized by telegraph noise switching between the AP and P states. Figs.[1][b,c,g,j] show examples for the uncoupled sample and the AF-coupled sample at high \( H \), and both coupled samples at small \( H \). Note that, at identical I of opposite signs, the average telegraph noise periods in the AF-coupled sample are similar.

The similar high-H behaviors, and different low-H behaviors among the samples shown in Fig. [1][b] can be understood using a simple model of current-assisted thermal excitation over a magnetic barrier separating the AP and P states [17]. We do not rule out alternative interpretations that may lead to similar results [18]. Our model assumes that large enough current \( I > 0 (I < 0) \) generates magnetic excitations in the P(AP) state, that are described by current-dependent effective magnetic temperatures \( T_m^{P(AP)} \). The magnetic barrier between the P and AP states is assumed to vary only through the temperature dependence of magnetization. Fig. [2] shows schematics for the different cases of interest. Fig. [2][a] is for hysteretic transitions, which occur both in uncoupled samples at low \( H \) or in AF-coupled samples when \( H \) balances the dipolar coupling field. The P→AP and AP→P barriers are the same, but \( I > 0 \) results in \( T_m^P > T_m^{AP} \), leading to P→AP switching. Similarly, at \( I < 0 \), \( T_m^{AP} > T_m^P \), leading to AP→P switching. Fig. [2][b] is for AF-coupling at low \( H \). Because the P→AP barrier is small, the P→AP transition is thermally activated at \( I = 0 \). Large enough \( I < 0 \) (causing \( T_m^{AP} > T_m^P \)) also activates the reverse AP→P transition, leading to telegraph noise. Fig. [2][c] shows that, at large enough \( H \), the P→AP barrier is larger than AP→P barrier in all the samples. In this case, both transitions are thermally activated at large enough \( I > 0 \).

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