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# Balancing interlayer dipolar interactions in multilevel patterned media with out-of-plane magnetic anisotropy

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Nanostructures consisting of a stack of two magnetic multilayers with out-of-plane anisotropy and distinct coercivities hold great promises in spintronics devices. Yet their miniaturization leads to interlayer dipolar coupling, which results in detrimental asymmetrical behaviors of magnetization reversal or even in the loss of intermediate antiparallel configuration. In this letter, we take advantage of Ruderman–Kittel–Kasuya–Yosida interactions in order to compensate for this coupling and restore symmetry. The study has been performed on an array of square dots of 200 nm lateral size, each dot consisting of two [Co/Pt] multilayers antiferromagnetically coupled through a thin Ru spacer. © 2009 American Institute of Physics. [DOI: 10.1063/1.3078523]

The density of information stored on computer disk drives has steadily increased for more than 50 years. This was made possible by a number of breakthroughs concerning both read heads as well as media. Regarding media, a significant advance has been recently achieved with the introduction of perpendicular media in commercially available drives since 2006.<sup>1</sup> Discrete track media are now appearing, which should be followed within few years by bit-patterned media.<sup>2</sup> Furthermore, a strong interest is now brought by the emergence of multilevel magnetic recording.<sup>3–5</sup> This approach consists in increasing the number of remanent states per elementary storage cell by stacking several ferromagnetic layers with distinct coercive fields. The most advanced technological implementation in the field of magnetic recording might thus rely on the combination of multilevel recording and patterned media with out-of-plane anisotropy.<sup>4,5</sup>

Interlayer magnetostatic interactions are no longer negligible when the lateral size of the device is reduced.<sup>5–7</sup> For “soft-hard” bilayer structures with out-of-plane anisotropy and submicrometric dimensions, interlayer coupling manifests itself as a shift ( $H_F$ ) from zero field of the minor hysteresis loop of the magnetically softest layer.<sup>5,6</sup> As an illustration, Fig. 1(a) shows a typical hysteresis loop of an array of  $400 \times 100 \text{ nm}^2$  dots spaced by 100 nm and covered with two Pt/Co multilayers of different coercivities.<sup>5</sup> Such a loop shift leads to asymmetrical behavior of the magnetization reversal of the soft layer, which is detrimental in the perspective of applications. For magnetic recording notably, (i) it implies the need for inconvenient asymmetrical positive and negative writing fields, (ii) it reduces the gap between the switching fields of the layer; and (iii) it may even result in a loss of the intermediate remanent states if this shift is larger than the coercive field of the soft layer, as is the case in Fig. 1(a).<sup>5</sup>

The coexistence of Ruderman–Kittel–Kasuya–Yosida (RKKY) and dipolar interlayer interactions has been observed in continuous films with out-of-plane magnetic

anisotropy.<sup>8,9</sup> However, the case of such interactions in structures with reduced lateral dimensions and out-of-plane anisotropy has not been considered up to now. We report in this letter how antiferromagnetic RKKY coupling and ferromagnetic interlayer dipolar interactions can be advantageously balanced in magnetic structures with out-of-plane anisotropy and submicron lateral dimensions.

$S_S/\text{Pt}(0.15 \text{ nm})/\text{Ru}(t_{\text{Ru}})/\text{Pt}(0.15 \text{ nm})/S_H$  sheet film structures with perpendicular anisotropy, consisting of a bottom soft  $S_S$ : [Pt(1.8 nm)/Co(0.6 nm)]<sub>2</sub> and a top hard  $S_H$ : [Co(0.6 nm)/Pt(1.8 nm)]<sub>4</sub> multilayer stack, were dc-magnetron sputtered onto thermally oxidized silicon wafers.<sup>5</sup> The ruthenium thickness  $t_{\text{Ru}}$  ranges here from 0.35 to 0.5 nm, thus covering the first antiferromagnetic peak of the well known oscillatory RKKY interactions.<sup>10,11</sup> Such a choice will be justified later in the manuscript. The two Pt(0.15 nm) intermediate spacer layers in contact with the Ru layer have a twofold role: (i) they both stabilize the out-of-plane anisotropy of the last cobalt layer of  $S_S$  and first cobalt layer of  $S_H$  and (ii) they considerably reduce the strength of the RKKY interaction, which can amount to tens of kilo-oersted for such small Ru thicknesses.<sup>10,11</sup>

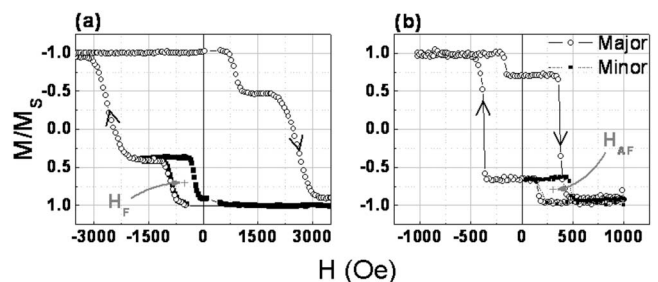


FIG. 1. (a) Major and minor hysteresis loops as measured by polar Kerr (a) for an array of  $S_S/\text{Pt}(4 \text{ nm})/S_H$  dots of  $400 \times 100 \text{ nm}^2$  spaced by 100 nm as reproduced from Fig. 4(b) in Ref. 5 (manifestation of the sole intradot dipolar interactions) and (b) for a continuous film of  $S_S/\text{Pt}(0.15 \text{ nm})/\text{Ru}(0.45 \text{ nm})/\text{Pt}(0.15 \text{ nm})/S_H$  film (manifestation of the sole RKKY interactions), where  $S_S$  and  $S_H$  stand for [Pt(1.8 nm)/Co(0.6 nm)]<sub>2</sub> and [Co(0.6 nm)/Pt(1.8 nm)]<sub>4</sub>. In order to ease the comparison between (a) and (b), the Y axis in (a) is inverted. The black arrows on the loops indicate the scan directions.

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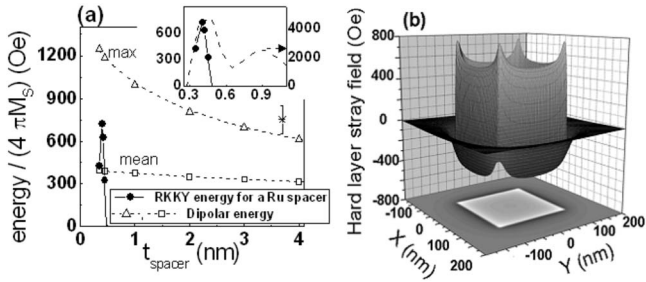


FIG. 2. (a) Dependence with  $t_{\text{spacer}}$  of the antiferromagnetic RKKY shift  $[|H_{\text{AF}}| = (\text{RKKY energy}) / (4\pi M_S)]$ , as deduced from experimental hysteresis loops for the case of a Ru spacer, and calculated dependence of the dipolar energy normalized to  $4\pi M_S$  ascribed to the stray field ( $\sim H_F$ ) created by  $S_H$  on  $S_S$  for square dots  $200 \times 200 \text{ nm}^2$ . The star indicates the experimental value from Ref. 5. The inset is a zoom of our RKKY data, compared with data from Ref. 11 (dotted line). (b) Mapping of the stray field emanating from  $S_H$  at the upper interface of  $S_S$  for  $t_{\text{spacer}} = 0.75 \text{ nm}$ .

Figure 1(b) shows room temperature hysteresis loops for a continuous film with  $t_{\text{Ru}} = 0.45 \text{ nm}$ . The loops are measured via magneto-optical Kerr rotation using an optical wavelength ( $\lambda$ ) of  $632.8 \text{ nm}$ . Coming from positive fields, the transition at  $160 \text{ Oe}$  corresponds to the magnetization reversal of  $S_S$ , and the transition at  $-375 \text{ Oe}$  corresponds to the magnetization reversal of  $S_H$ . As indicated on the figure, the minor loop is shifted by  $H_{\text{AF}} = 310 \text{ Oe}$  as a consequence of the preferred antiparallel alignment of both soft and hard layers in that Ru thickness range. For these macroscopic films, there are no magnetostatic interactions. The corresponding experimental absolute values of the RKKY shift  $H_{\text{AF}}$  are plotted in Fig. 2(a) for various Ru thicknesses. It is expressed in terms of RKKY energies over  $4\pi M_S$ , with  $M_S$  the saturation magnetization  $[|H_{\text{AF}}| = (\text{RKKY energy}) / (4\pi M_S)]$ . The comparison with data from Ref. 11 is shown in the inset. The differences in amplitude and period of the oscillations are a consequence of the addition of our Pt intermediate spacers.

This graph also shows for comparison the calculated dependence of the dipolar energy created by  $S_H$  on  $S_S$  as a function of the thickness of a spacer layer  $t_{\text{spacer}}$  independently of the RKKY coupling for square dots with lateral dimension of  $200 \text{ nm}$ . This calculation uses a simplified model that considers facing charged surfaces. The derived potential  $V(x, y, z, t_{\text{Co}}, L)$  is a function of the cobalt layer thickness  $t_{\text{Co}}$ , lateral dimension  $L$ , and positions  $x$ ,  $y$ , and  $z$ .<sup>12</sup> For given cobalt thicknesses and lateral dimensions (here  $0.6$  and  $200 \text{ nm}$ , respectively), the resulting stray field for one cobalt sublayer along the perpendicular  $z$  direction is given by  $H_Z(x, y, z) = -4\pi M_S dV(x, y, z) / dz$ . Following superconducting quantum interference device measurements, we find that  $1400 \text{ emu cm}^{-3}$  stands as a good approximation of the saturation magnetization of the Co sublayers of our Co/Pt multilayers. We sum the contributions of the stray fields emanating from the four sublayers of  $S_H$ . A typical profile  $H_Z(x, y)$  is plotted in Fig. 2(b) and shows that the field is maximum at the dot edges. Figure 2(a) gives the variation with  $t_{\text{spacer}}$  of (i) the maximum stray field averaged over the thickness of the two cobalt sublayers of  $S_S$  and (ii) the mean stray field averaged over their volume.

In Ref. 5, we reported experimental results for arrays of dots with various dimensions and for layers of  $S_S/\text{Pt}(4 \text{ nm})/S_H$ . Without RKKY interactions, the calculated

maximum stray field is in satisfactory agreement with the experimentally determined shift field [Fig. 2(a)]. For the more complex stack reported in Ref. 6, we obtained a maximum stray field of  $680 \text{ Oe}$ , which also compares well with the experimental shift of  $-650 \text{ Oe}$ . We note however that the magnetization reversal process most likely results from the convolution of the mapping of the dipolar energy provided by  $S_H$  on  $S_S$  with the mapping of the energy barriers in  $S_S$ . This involves complicated nucleation events that cannot all be considered in our simple calculations. For a single multilayer, it was previously showed that the magnetization reversal is initiated at the dots edges,<sup>13</sup> confirming that the energy barriers for reversal nucleation are lower at these locations. The RKKY antiferromagnetic coupling through the ruthenium spacer in dots with reduced dimensions is also likely to be inhomogeneous. Indeed, a reduction in the layer thickness at the edges of the dots with respect to its center is inferred from the bending of the layers at the edges, which can be seen in the transmission electron microscopy (TEM) images from Fig. 5 of Ref. 14. We can hence qualitatively infer that RKKY interactions will increase from the center to the edges of the dots. We can take advantage of such a variation in order to compensate for the larger stray field at the edges of the dots and the lower stray field elsewhere [see Figs. 2(a) and 2(b)]. To do so, we choose  $t_{\text{Ru}} = 0.45 \text{ nm}$ , i.e., for which the absolute value of the RKKY energy is of the order of the mean dipolar energy and for which a small thickness reduction (i.e., in the vicinity of the dots edges) results in a large enhancement in the RKKY energy. Following these qualitative arguments, and as will be experimentally confirmed in the following, the mean stray field is now the relevant field to be considered.

Such structures were deposited onto prepatterned wafers,<sup>13</sup> forming a  $1 \times 1 \text{ mm}^2$  pattern of silicon square dots with lateral dimensions, height, and edge to edge spacing of  $200 \text{ nm}$ . The deposit covers the top of the pillars (dots) and the interdots region (trenches). The height of the pillars ensures magnetic decoupling between the dots and the trenches.<sup>12</sup> Figure 3(a) shows a typical room temperature Kerr hysteresis loop measured with  $\lambda = 405 \text{ nm}$  and a magnetic circular reflection configuration (i.e., without analyzer and with the photoelastic modulator at an angle of  $45^\circ$  with respect to the polarizer). Four magnetization reversals can be distinguished for each branch of the loop. Owing to the quasi-vertical incidence of the laser spot during the measurements, both signals from the dots and trenches are probed, resulting in two superimposed hysteresis loops.

Coming from positive fields, the two abrupt transitions, at  $140$  and  $-390 \text{ Oe}$ , correspond to the magnetizations reversals in the trenches for the soft and hard layers, respectively. These values are comparable to those measured on the continuous film (Fig. 1). The soft layer transition in the trenches is significantly broadened compared to that of the continuous film. It results from larger domain wall pinning potentials for the trenches, likely at the base of the silicon dots. The sharper hard layer switching indicates that these pinning potentials are negligible with respect to the external Zeeman energy above  $-390 \text{ Oe}$ .<sup>7</sup> The two other broad transitions in Fig. 3(a), at around  $-100$  and  $-1000 \text{ Oe}$ , are attributed to the magnetization reversals of the soft and hard layers on the dots, respectively. The switching field distribution for the dots is ascribed to intrinsic dot to dot structural<sup>14</sup> or microstructural<sup>15,16</sup> distributions. On the other hand, the

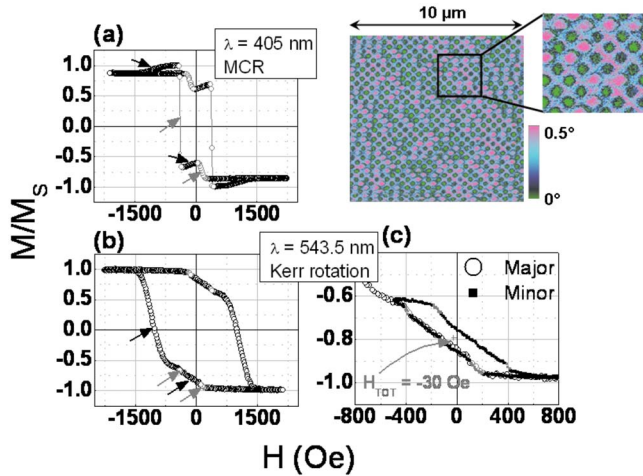


FIG. 3. (Color online) Hysteresis loop for an array of  $200 \times 200 \text{ nm}^2$  dots spaced by  $200 \text{ nm}$  measured via polar magneto-optical Kerr effect experiments with different optical wavelengths ( $\lambda$ ) and configurations (a) and (b). The signal from the dots is highlighted in black with respect to the signal from the trenches, which is in gray. (c) Minor hysteresis loop (closed squares) for the same sample and conditions as those of (b). The scan directions for (a)–(c) are the same as those labeled in Fig. 1. The inset is the corresponding MFM image after demagnetization by rotation at  $180 \text{ rpm}$  under a decreasing steady magnetic field ( $\sim 0.2 \text{ Oe s}^{-1}$ ). The scale gives the correspondence between the color code of the image and the phase shift in the resonance frequency of the MFM tip.

increased switching field of the hard layer on the dots can be attributed to the reduced number of effective nucleation centers in comparison to continuous films.<sup>14</sup> In Fig. 3(a), the opposite sign of the Kerr signals between the dots and trenches allows us to discriminate both contributions. Varying  $\lambda$  and/or configuration of measurement is a way to tune the sign and relative amplitudes of the contributions of dots and trenches.<sup>16</sup> For particular wavelengths, the signal coming from the dots or that coming from the trenches can be almost suppressed.<sup>5,17</sup> By choosing  $\lambda = 543.5 \text{ nm}$  and a Kerr rotation configuration we mostly suppressed the signal of the trenches, as shown in Fig. 3(b). This allows us to safely interpret the minor hysteresis loop for the soft layer on the dots, which is shown in Fig. 3(c) for these last same experimental conditions. It is shifted toward negative fields by about  $H_{\text{tot}} = -30 \text{ Oe}$ . This shows that RKKY interactions almost perfectly compensate the dipolar energy provided by the stray field from the patterned hard layer onto the soft one. Since  $H_{\text{AF}}$  is  $310 \text{ Oe}$  (Fig. 1),  $H_F$  is of the order of  $340 \text{ Oe}$  ( $H_{\text{tot}} = H_{\text{AF}} - H_F$ ), in satisfactory agreement with our estimate of  $400 \text{ Oe}$  [Fig. 2(a)].

We additionally observe that the minor loop in Fig. 3(c) is broad and exhibits low remanence. From the magnetic force microscopy (MFM) image shown in the inset of Fig. 3, we observe single-domain dots. The image is made of  $20 \times 20 \text{ nm}^2$  pixels, which is the largest accuracy precision that one can get given the typical spatial resolution of the

MFM tip. This proves that the low remanence is not due to a low remanence configuration of all individual dots (e.g., vortex states). It rather shows that the minor loop in Fig. 3(c) results from the summation of minor loops over all dots. This means that perfect compensation of interactions is only effective for a given number of dots. This is a result of structural inhomogeneities among dots, leading to a broad switching field distribution. We also remark that the MFM seems to display three different contrasts. The green and pink contrasts correspond to dots for which the soft and hard layers point in the same direction: both upward and both downward, respectively. An intermediate black contrast is seen on dots for which the soft and hard layers point in opposite directions. This is a further proof that at least for some of the dots, the hysteresis loop has been recentered toward zero field.

To conclude, this letter proposes a way to compensate for the detrimental interlayer dipolar coupling, arising from the reduced size of nanodevices based on soft-hard bilayers with out-of plane anisotropy. By a proper choice of  $t_{\text{Ru}}$ , antiferromagnetic RKKY coupling balances ferromagnetic dipolar interactions in such a way that the minor loop of the soft magnetic layer can be recentered toward zero field, thus restoring the symmetrical behavior of the magnetization reversal of the soft layer. Full compensation is demonstrated for only part of the dots' array because of the distribution of the magnetic properties of the different dots.

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