Tunable exchange bias-like effect in patterned hard-soft two-dimensional lateral composites with perpendicular magnetic anisotropy


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Patterned magnetic media have been the focus of an intense research during the last decade due not only to fundamental physical interest but also because of their potential for technological applications.1–7 Usually, these systems consist in arrays of structures, where the magnetic behavior is studied as a function of shape and/or structures density without changing the intrinsic magnetic properties. The use of magnetic lateral multilayers, i.e., extended films with a 1D lateral modulation of intrinsic magnetic properties, such as magnetic anisotropy,8 saturation magnetization,9 or exchange bias,10 introduces an extra freedom degree, which should be useful in the development of forefront magnetic devices. The combination of different exchange coupled materials gives rise to many interesting phenomena in standard vertical multilayers such as standard exchange bias in antiferromagnetic/ferromagnetic systems11,12 or isothermal field induced exchange bias effects in coupled ferromagnetic bilayers with orthogonal anisotropies.13–16 A lateral exchange coupled configuration could be used to reproduce these phenomena. For example, exchange-spring behavior has been demonstrated in soft-magnetic films with laterally modulated saturation magnetization9 and misfit strain has been shown to take a central role in the magnetic configuration of stripe domains in weak perpendicular magnetic anisotropy lateral multilayers.17 This lateral approach can be taken a step further with the design of 2D lateral structures on continuous magnetic films: ordered 2D arrays of hard magnetic elements (Co and CoPt) coupled to soft permalloy films have been used to modify its magnetization reversal process through magnetostatic interactions;16,19 also, out-of-plane exchange bias effects have been demonstrated in arrays of CoPt platelets coupled to a continuous CoPt film with strong perpendicular magnetic anisotropy.20

In this work, we report the fabrication of soft 2D NdCo5-based magnetic lateral hard/soft composites as sketched in Fig. 1(a). The samples consist in patterned microstructure arrays of NdCo5 discs with 3 μm diameter and 60 nm of thickness, arranged in a square lattice geometry and exchange-coupled to a NdCo5 etched film with 30 nm of thickness. This highly symmetric 2D design allows us to take advantage of rotatable anisotropy to control the magnetic response of these systems by the orientation of the last saturating magnetic field.24 Thus, lateral thickness variations provide a simple way to create a pattern of exchange coupled hard/soft regions within the sample.17 Even more, the in-plane easy axis of rotatable anisotropy is determined by the direction of the last saturating magnetic field.24 Thus, in-plane magnetic anisotropy in the hard regions can be tuned through magnetic history, which adds to the flexibility of the design of the final hard/soft composite.

In this work, we report the fabrication of soft 2D NdCo5-based magnetic lateral hard/soft composites as sketched in Fig. 1(a). The samples consist in patterned microstructure arrays of NdCo5 discs with 3 μm diameter and 60 nm of thickness, arranged in a square lattice geometry and exchange-coupled to a NdCo5 etched film with 30 nm of thickness. This highly symmetric 2D design allows us to take advantage of rotatable anisotropy to control the magnetic response of these systems by the orientation of the last saturating magnetic field. Actually, we observe an “exchange bias-like” shift ($H_b$) of few Oe in the in-plane magnetization hysteresis cycles $[M(H)]$ of the NdCo5 etched film tunable through magnetic history.
The samples have been fabricated by the combination of electron beam lithography (EBL), sputtering deposition, and ion milling techniques similar to the process described in Ref. 25. The patterned microstructures consist of rectangular 300 × 1000 μm² magnetic frames, where the central square area of 300 × 300 μm² is filled with 3 μm diameter discs, in a square lattice with different lattice parameters L (6, 7.5, and 9 μm) and different thicknesses regarding to the rest of the layer [Fig. 1(a)]. First of all, a first EBL process defines a positive resist mask of Poly(methyl methacrylate) (PMMA) 950 K A4 from Microchem™ with thickness of ~200 nm. After sputtering deposition and lift-off processes, the desired magnetic frames with the following layer structure: Si(100)/Al (10 nm)/NdCo₅ (60 nm)/Al (3 nm) are obtained. Then, a second EBL process is performed to create an array of 12 nm thick Nb discs, again by sputtering deposition and lift-off, over the center of the magnetic frame, which will act as a protective mask during an Ar⁺ ion milling. In this way, we get, after the milling of the complete Nb layer, an exchange coupled system of 60 nm thick NdCo₅ discs within 30 nm thick NdCo₅ etched layer [Fig. 1(b)]. Finally, a 3 nm Al protective layer is sputter deposited over the whole sample to prevent oxidation. During this process, continuous control samples have been fabricated within the microstructures following all fabrication steps mentioned above. These unpatterned samples consist, after an Ar⁺ ion milling process, in full films of NdCo₅ with 60 and 30 nm of thickness. In the former case, the sample was coated with 12 nm Nb protective layer.

Figure 1(c) shows the resulting hysteresis loops in the control continuous layers sputter deposited at the same time that the 2D micro-composite, measured by transverse magneto-optical Kerr effect (T-MOKE),26 where the applied magnetic field direction is parallel to the in-plane E.A. Depending on the thickness of the magnetic layer, the magnetic hysteresis loop of the system can change from a clear transcritical loop (a reduced in-plane remanent magnetization followed by an almost linear reversible region as the magnetization approaches to saturation) with remarkable PMA (Nb protected layer), to an in-plane uniaxial loop (etched layer) with a reduction in coercivity from 300 Oe to 50 Oe in agreement with previous results.25,27,28 The reason for the in-plane uniaxiality comes from the co-sputtering deposition method29 and its magnetic easy axis (E.A.) is parallel to the short side of the magnetic frames [Fig. 1(a)]. In the patterned sample, the behavior indicated by the control films is confirmed, as can be observed from the remanence magnetic force microscopy image of a disc and its surrounding etched film [Fig. 1(d)]. The signal from the disc shows magnetic stripe domains and the etched film around it not, thus we have fabricated an exchange coupled 2D hard-soft system, where the discs present a PMA magnetic material behavior with weak magnetic stripe domains and the rest of the layer exhibits an in-plane uniaxial magnetization behavior. The magnetic differences between the discs and the etched layer allow us to perform the following experiment to control the magnetization reversal in this last one: first, by the application of an in-plane saturating field (H ≥ 1500 Oe) we can orient the weak magnetic stripe domains in the discs along the field direction and second, measure the hysteresis loops of the etched layer in the in-plane E.A. direction with a field amplitude smaller than 150 Oe which, according to the hysteresis loops of the control layers shown in Fig. 1(c), should be enough to reverse the etched layer keeping the discs magnetization orientation unchanged. The selected saturation senses are positive (→) and negative (←), both parallel to E.A., and also perpendicular (⊥).

In Figure 2, the hysteresis loops of the sample with a lattice parameter L = 7.5 μm are presented with domain images taken simultaneously to the acquisition of the loops by Kerr Microscopy (KM).22 Images and loops are measured
following the previous method: after positive E.A. [Fig. 2(a) (1–6)], perpendicular to E.A. [Fig. 2(b) (7–12)] and negative E.A. [Fig. 2(c), images not shown] saturations. Dark and bright grey contrasts in KM images indicate in-plane magnetization domains pointing to the left (→, white arrows) and right (←, black arrows), respectively, and the magnetic field direction applied during the loop measurement is parallel to the etched layer E.A., which is parallel to the arrows in the images. The jump on the Kerr signal has been normalized between the positive and negative saturation senses of the etched layer. The NdCo discs keep their image color (same orientation of the in-plane M component) during the whole $M(H)$ loop of the etched layer, which should introduce a vertical shift in the $M(H)$ cycle, as reported in Ref. 16.

An asymmetry in the backward and forward branches of the hysteresis loops and an “exchange bias-like” field shift (this last one calculated as half the difference between the coercive fields of the loops) can be observed in the positive [Fig. 2(a)] and negative [Fig. 2(c)] E.A. orientations, respectively, while in the perpendicular one, no bias-field shift is observed and the loop keeps its symmetry [Fig. 2(b)]. Thus, the system exhibits a tunable “exchange bias-like” effect, which is a very interesting feature in exchange bias standard vertical multilayers.11,31 Our results show a similar behavior than those reported in Refs. 12 and 16 but with external applied magnetic fields needed to tune the exchange bias effect at least one order of magnitude lower (10^3 Oe) than those used (10^4–10^5 Oe) in Refs. 12 and 16.

The observed tunable exchange bias-like effect can be linked to coupling effects between the discs and the etched layer. In general, the coupling in laterally patterned structures is caused by exchange at the interfaces and magneto-static charges created by the lateral modulation of in-plane magnetization.30 In the present case, KM images indicate significant differences in the magnetization reversal of inter-disc areas [labeled as I in Fig. 2(d)] and of the linear regions in between the rows of discs [labeled as II in Fig. 2(d)]. In the case of positive E.A. orientation, regions II reverse first, while regions I remain with the original magnetization orientation [Fig. 2(a) (1–2)]. A field of ~100 Oe is needed to completely remove these inter-disc domains. The second magnetization reversal shows the opposite behavior: the first reversed domains appear at regions I [Fig. 2(a) (4)] and, then, expand into regions II [Fig. 2(a) (5)], and the final field to saturate the etched layer is reduced to 70 Oe. The same behavior is observed in the negative E.A. orientation of the
discs in-plane magnetization, but in the opposite order. These different magnetic domains behaviors are responsible of the asymmetries observed in the branches of the $M(H)$ loops. In the case of perpendicular to E.A. orientation, no inter-disc domains are observed during the whole magnetization reversal process [Fig. 2(b) (7–12)]. Regions I and II are directly connected with the configuration of the stray field created by the array of discs. We have performed micromagnetic simulations by using Mumax 3.5 (Ref. 32) of the magnetic configuration of the array of discs ($L = 6 \mu$m) after saturating them in-plane and along the positive E.A. direction. The simulation was done using an exchange stiffness of $10^{-18}$erg/cm, a PMA energy density of $10^6$erg/cm$^3$ and a saturation magnetization of $10^3$ emu/cm$^3$. Figure 2(d) shows a map of the calculated stray field ($H_{\text{stray}}$) along the E.A. created by the discs in regions I and II at remanence after saturating them at the positive direction. Region I corresponds to a positive stray field, whereas in regions II, $H_{\text{stray}}$ changes between positive and negative values. The local stray field in the center of region I has positive values of $40$ Oe at discs remanence and $17 \ (22)$ Oe at forward (backward) coercive field ($H_c$). Therefore, we have always a significant positive bias field in region I, indicating that magnetostatic interactions alone can introduce a shift in the hysteresis loop. However, in the presented system, the exchange interaction between the discs and the etched layer should also play a role in the observed exchange bias-like effect. In Table I, the experimental forward ($H_c^F$) and backward ($H_c^B$) coercive fields and bias field ($H_b$) as a function of sample lattice parameters ($L$) are presented for the three different disc’s in-plane magnetization orientations: parallel (positive ($\rightarrow\rightarrow$) and negative ($\leftarrow\leftarrow$)) and perpendicular ($\uparrow\downarrow$) to E.A. The applied magnetic field amplitude during the measurement of the hysteresis loops is $150$ Oe for the sample with $L = 6 \mu$m and $120$ Oe for the others.

The existence of a switchable bias field shift is observed in all the fabricated samples due to the same magnetic domain’s behavior during the magnetization reversal processes. This shift can be understood in terms of exchange and magnetostatic interactions between the discs and the surrounding etched layer, mainly because of the in-plane magnetization discontinuities at the discs edges. $^{30}$ The discs act as nucleation points for the domains in the etched layer with the same orientation as the discs in-plane magnetization ($\rightarrow\rightarrow$ or $\leftarrow\leftarrow$), and because of the stray field generated at the edges, a faster (stronger) growth (pinning) of reversed (original) inter-disc domains takes place. Due to its magnetostatic origin, we can tune the magnitude of the bias field by changing the lattice parameter of the system as illustrated in Table I, where the sample with $L = 9 \mu$m shows a $H_b$ of $4.5$ Oe, which is smaller than the bias field of the $L = 7.5 \mu$m sample (7.0 Oe). However, not only the lattice parameter controls the strength of $H_b$, but also the maximum amplitude of the applied magnetic field during the measurement of the hysteresis loop of the etched layer seems to play an important role. In the case of the sample with $L = 6 \mu$m, a field amplitude of $150$ Oe has been used to completely saturate the etched layer (because of the higher strength of the bias field). We think that the effect of this higher applied field amplitude induces a different minor loop in the discs so that the recorded in-plane magnetization component is reduced, originating a smaller stray field that contributes to the bias field decrease. This phenomenon was also observed in Refs. 13 and 16 for a system consisting of two perpendicularly coupled ferromagnets.

In summary, we have fabricated patterned 2D NdCo$_5$ based magnetic lateral hard-soft composites with PMA, where the thickness of the NdCo$_5$ layer is laterally modulated so that soft (hard) regions are below (above) the critical thickness for nucleation of weak stripe domains in the system. This spatial modulation of the magnetic behavior leads to an exchange coupled system, which exhibits a tunable “exchange bias-like” shift in the $M(H)$ hysteresis loops of the thin NdCo$_5$ etched layer, switchable (on/off) by the orientation of the weak stripe domains of the thick NdCo$_5$ discs that are controlled by the last saturating magnetic field.

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TABLE I. Forward ($H_c^F$) and backward ($H_c^B$) coercive and bias ($H_b$) fields obtained from the hysteresis loops for different disc’s in-plane magnetization orientations, namely, parallel (positive ($\rightarrow\rightarrow$) and negative ($\leftarrow\leftarrow$)) and perpendicular ($\uparrow\downarrow$) to E.A, for different lattice parameters ($L$). Applied magnetic field amplitudes during the measurement of the loops are $150$ Oe for $L = 6 \mu$m and $120$ Oe for $L = 7.5 \mu$m and $L = 9 \mu$m.

<table>
<thead>
<tr>
<th>$L$ ($\mu$m)</th>
<th>6.0</th>
<th>7.5</th>
<th>9.0</th>
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<tr>
<td>$H_c^F$ ($\rightarrow\rightarrow$)</td>
<td>$70 \pm 1$</td>
<td>$62 \pm 1$</td>
<td>$61 \pm 1$</td>
</tr>
<tr>
<td>$H_c^F$ ($\leftarrow\leftarrow$)</td>
<td>$-81 \pm 1$</td>
<td>$-76 \pm 1$</td>
<td>$-70 \pm 1$</td>
</tr>
<tr>
<td>$H_b$ ($\uparrow\downarrow$)</td>
<td>$-5.5 \pm 1$</td>
<td>$-7.0 \pm 1$</td>
<td>$-4.5 \pm 1$</td>
</tr>
<tr>
<td>$H_c^F$ ($\uparrow\downarrow$)</td>
<td>$82 \pm 1$</td>
<td>$76 \pm 1$</td>
<td>$70 \pm 1$</td>
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<tr>
<td>$H_c^F$ ($\leftarrow\leftarrow$)</td>
<td>$-70 \pm 1$</td>
<td>$-62 \pm 1$</td>
<td>$-61 \pm 1$</td>
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<tr>
<td>$H_c^F$ ($\rightarrow\rightarrow$)</td>
<td>$6.0 \pm 1$</td>
<td>$7.0 \pm 1$</td>
<td>$4.5 \pm 1$</td>
</tr>
<tr>
<td>$H_c^B$ ($\uparrow\downarrow$)</td>
<td>$67 \pm 1$</td>
<td>$64 \pm 1$</td>
<td>$62 \pm 1$</td>
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<tr>
<td>$H_c^B$ ($\leftarrow\leftarrow$)</td>
<td>$-69 \pm 1$</td>
<td>$-66 \pm 1$</td>
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<tr>
<td>$H_c^B$ ($\rightarrow\rightarrow$)</td>
<td>$-10 \pm 1$</td>
<td>$-10 \pm 1$</td>
<td>$-0.5 \pm 1$</td>
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</table>


See supplementary material at http://dx.doi.org/10.1063/1.495571 for more details about the magnetic properties of weak PMA materials.