Relevance of length scales in exchange biased submicron dots

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Strong dot-size dependence of the positive exchange bias onset with the cooling field was found in Ni/FeF_2 exchange biased nanostructures. With increasing cooling field, the sign of the exchange bias field changes from negative to coexistence of positive and negative, and eventually to positive. As the structure size decreases, the lower limit of cooling fields necessary for only positive exchange bias also decreases and is one order of magnitude smaller than that of unpatterned films. This behavior is attributed to comparable Ni dot size with the antiferromagnet "domain" size estimated to be about 500 nm. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3114372]

Exchange biased nanodots have attracted much attention lately both due to the technological interest in enhancing the thermal stability of magnetic dots and the interest in physical systems of reduced dimensions.[1] When a ferromagnet/antiferromagnet (FM/AF) bilayer is cooled below the Néel temperature (T_N) of the AF in a magnetic field (H_{FC}), exchange bias (EB) effect arises.[2,3] This is characterized by a shift of the hysteresis loop along the magnetic field axis by the EB field H_{EB}. Besides the technological significance of EB in magnetic recording, it also raises important questions on the relevance of lateral length scales of two dissimilar magnetic materials. This was most clearly demonstrated in the H_{FC} dependence of the sign of H_{EB} in some EB systems such as FeF_2/FM bilayers.[4] FeF_2/FM bilayers show negative (positive) EB for a small (large) cooling field H_{FC} and double hysteresis with coexistence of both biasing directions for intermediate H_{FC}.[4,5] This was attributed to the much larger AF "domain" size than the FM domain wall width, where the FM is independently biased on top of different AF domains. When the AF domain size is much smaller, the FM averages over both biasing directions and results in the usual single hysteresis loop.[6] Note that in connection with EB, the AF domain is not what is conventionally defined by the AF order parameter; rather it is defined by the sign of pinned uncompensated AF moments. In this manuscript, we use this definition for "AF domains" since it is the relevant one for EB. In EB nanostructures, the dot size dependence of H_{EB} may also be connected to the AF grain size.[7–14] In this work, we patterned the FM on top of a continuous AF thin film. By varying the FM dot size, we find that the H_{FC} dependence of EB sign can be strongly modified, while $|H_{EB}|$ remains unchanged. This is attributed to a crossover from dot sizes larger to smaller than the AF domain size. From this dependence the AF domain size was estimated.

Ni (30 nm)/FeF_2 (30 nm) bilayer capped with 4 nm thick Al was deposited on a MgF_2 (110) single crystal substrate by e-beam evaporation.[6] FeF_2 grows epitaxially untwinned in (110) orientation, whereas the Ni layer is polycrystalline. FeF_2 is an AF with T_N=78 K. Subsequent e-beam lithography followed by Ar^+ milling patterned the Ni layer into circular submicron dot arrays. Two groups of arrays were made. For the first group, the dot diameters are d=400 and 700 nm with periodicities D=600 and 1200 nm, respectively, measured by atomic force microscope. The second group keeps the periodicity constant D=300 nm while varying the dot diameters d=110, 170, and 180 nm. Double hysteresis loops for intermediate H_{FC} were observed in unpatterned samples on MgF_2 substrates by superconducting quantum interference device (SQUID) magnetometer.[4] Magnetic measurements of the patterned array were made using magneto-optical Kerr effect at T=10 K below T_N after cooling from 150 K at various H_{FC}.

SQUID measurement of the Ni/FeF_2 unpatterned thin film shows negative and positive EB for $H_{FC}<10$ kOe and $H_{FC}>60$ kOe, respectively, with $H_{EB}=\pm1.1$ kOe [Figs. 1(a) and 2(a) inset]. Coexistence of negative and positive EBs was observed when 10 kOe$\le H_{FC}\le$60 kOe. For patterns of all sizes and periodicities, the sign of H_{EB} can be similarly tuned by H_{FC} with $|H_{EB}|$ similar to that of the unpatterned film. For example, Fig. 1(a) shows the hysteresis loops of the dots with d=110 nm and D=300 nm with $|H_{EB}|=1.2\pm0.1$ kOe for H_{FC}=2, 3, and 5 kOe. Previously in the literature, either enhancement[10,12,13] or suppression[8,9,11,13,14] of H_{EB} was observed when the dot size

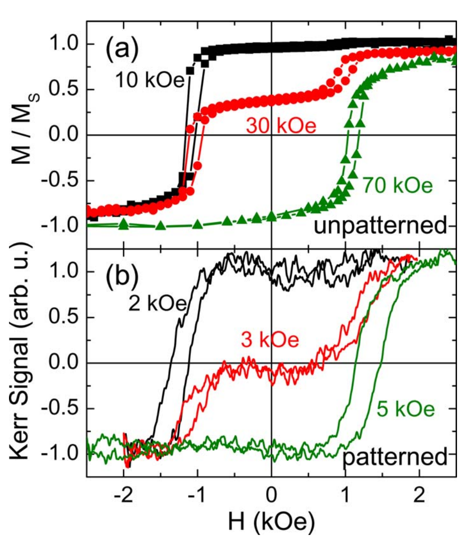

FIG. 1. (Color online) (a) Hysteresis loops for the unpatterned film at T=10 K with cooling fields H_{FC}=10 kOe (black), 30 kOe (red), and 70 kOe (green). (b) Hysteresis loops for dots with diameter d=110 nm and periodicity D=300 nm measured at T=10 K with cooling fields H_{FC}=2 kOe (black), 3 kOe (red), and 5 kOe (green).

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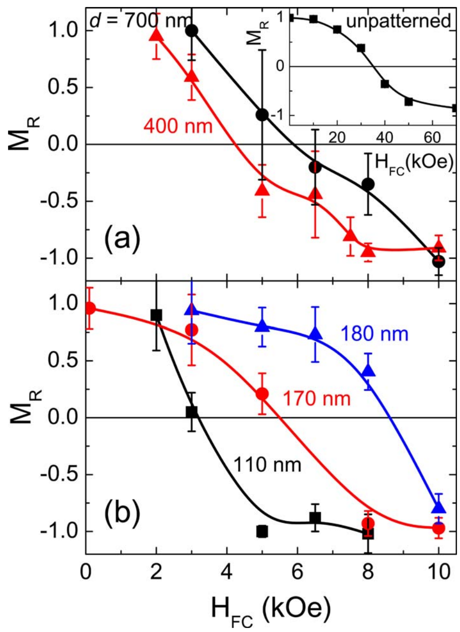

FIG. 2. (Color online) Normalized remanent magnetization $M_R=M(H=0)/M_S$ at $T=10$ K vs cooling field H_{FC}. $M_R=1$ or -1 at $T=10$ K correspond to fully negative or positive EB, respectively. (a) Results for dots with $d=700$ (black circles) and 400 nm (red triangles). Inset shows the results for the unpatterned film. (b) Results for dots with $d=110$ (black squares), 170 (red circles), 180 nm (blue triangles). Lines are guide to the eyes.

decreases. The fact that H_{EB} is insensitive to the dot size here is possibly connected to the large AF domain size, as will be shown later.

More importantly, comparison of the H_{FC} dependence in the nanodot and unpatterned film in Fig. 1 shows that much smaller H_{FC} is necessary for positive EB in patterned than unpatterned structure. Positive EB is found in dots of $d=110$ nm with $H_{FC}\geq 5$ kOe, an order of magnitude smaller than that for the unpatterned film. Figure 2 shows the dependence of normalized remanent magnetization $M_R=M(H=0)/M_S$ at $T=10$ K versus cooling field H_{FC}. Since $H_{EB}\gg H_C$, the coercivity of the dots and film M_R is a single-valued function of H_{FC} and $M_R=1$ or -1 corresponds to fully negative or positive EB, respectively. Figure 2 shows the dependence of M_R on H_{FC} for the unpatterned film and both groups of dot arrays. Here we define a characteristic H_{FC0} for the M_R versus H_{FC} dependence as the H_{FC} that induces equal amount of positive and negative EB in the sample, or $M_R=0$. For the unpatterned film, $H_{FC0}^{film}=35$ kOe, much larger than that of dots of all sizes and periodicities. When the dot size increases from 400 to 700 nm, H_{FC0} increases from about 4.2 to 6.2 kOe. Similar trend was also found in the second group of patterns. When fixing the periodicity $D=300$ nm while increasing the dot size from $d=110$ to 170 and 180 nm, H_{FC0} also increases [Fig. 2(b)].

It is worth noting that the magnetic dipole energy of each dot and the interdot interaction does not play an important role in determining the sign of H_{EB}. The dipole energy is important in establishing various micromagnetic states and relative orientation of neighboring dots in the magnetization reversal process, but it does not change the sign of H_{EB}, which is determined by the sign of the pinned uncompensated AF moments. The orientation of uncompensated AF moments is established in the cooling process when H_{FC} overcomes the dipolar interaction and saturates the magnetization of all FM dots.

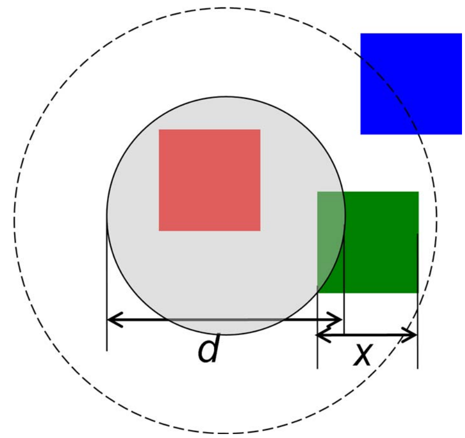

FIG. 3. (Color online) A schematic of AF domains (denoted by squares), either not covered (blue), partially covered (green), or fully covered (red) by a FM dot (gray). AF uncompensated moments inside the dashed-line circle are effectively involved in the competition with the interfacial coupling (see text).

The sign of EB was originally attributed to the competition between the Zeeman energy of uncompensated AF moments and the antiferromagnetic interfacial coupling.[5] For a small H_{FC}, the antiferromagnetic interfacial coupling dominates the AF Zeeman energy. Therefore, uncompensated AF moments preferably orient antiparallel with positive FM moments and lead to negative EB. A large H_{FC} aligns the AF uncompensated moments in the positive direction and results in positive EB.[15] Below, we will call the energy contribution from the AF "AF energy" either due to the Zeeman energy of AF moments in the original model or due to the AF domain wall energy in the extended model. In both cases, the AF energy is assumed to be proportional to H_{FC} without loss of generality.

In case of a patterned FM the competition becomes more complicated since AF domains may not be fully covered by FM dots (Fig. 3). For AF domains not covered by the FM, the uncompensated AF moments are aligned by H_{FC} without being subject to the interfacial coupling. For AF domains partially covered by the FM, the interfacial coupling contributes less to the competition with the AF energy. Therefore, a lower H_{FC} would be expected to align the uncompensated AF moments with the field in these domains than to align with those fully covered by FM. Since these partially covered AF domains are located around the edge of FM dots, they become more and more significant as the dot size decreases. Therefore, smaller dots could be driven into positive EB at lower H_{FC}, as observed experimentally. For dots much smaller than the AF domain size, the H_{FC} for positive EB onset is only dependent on the coverage of the AF by FM dots and a smaller coverage leads to smaller H_{FC} for positive EB. As we will demonstrate next, this corresponds to the nanodots in the second group with fixed periodicity $D=300$ nm and varying dot sizes.

Based on the above model, a quantitative evaluation can be made to estimate the domain size of untwinned FeF_2. There are two competing energies. The Zeeman energy of AF uncompensated moments is proportional to the AF area (a_{AF}) and the external field $E_Z=a_{AF}\varepsilon_{AF}H_{FC}$, while the interfacial coupling energy is proportional to the FM area (a_{FM})

in contact with the AF layer $E_I = a_{FM}\varepsilon_I$. For the unpatterned bilayer, the characteristic cooling field is $H_{FC0}^{film} = 35$ kOe. In this case, both energies become equal for $a_{AF} = a_{FM}$, which leads to a ratio between proportionality constants, $\varepsilon_I/\varepsilon_{AF} = H_{FC0}^{film}$. Assuming the domain size x to be smaller than half of the periodicity $D/2$ so that on average an AF domain is covered by only one FM dot for simplicity, the interfacial coupling energy is proportional to the area of a FM dot $E_I = \varepsilon_I \pi d^2/4$, while the effective Zeeman energy is proportional to an area with its diameter increased by $2x$; thus $E_Z = \varepsilon_{AF}\pi(d+2x)^2 H_{FC}^{dot}/4$ (Fig. 3). Therefore, for a nanodot with H_{FC0}^{dot}, it should satisfy $H_{FC0}^{film}/H_{FC0}^{dot} \times d^2 = (d+2x)^2$. Thus, the AF domain size is $x = d(\sqrt{H_{FC0}^{film}/H_{FC0}^{dot}} - 1)/2$. For dots with $d = 700$ nm, $H_{FC0}^{dot} = 6.0 \pm 0.5$ kOe, so $x = 500 \pm 40$ nm. For smaller dots, the above assumption that $x < D/2$ becomes invalid. However, if applying the above calculation to 400 nm dots, one will get $x = 390 \pm 40$ nm, larger than half of the periodicity and consistent with the above estimate. This estimate of AF domain size $x \approx 500$ nm is also consistent with the previous prediction that double hysteresis loops occur when the AF domain size is much larger than the FM domain wall width,[6] which is about 80 nm for Ni.[16] For dots with $D = 300$ nm, multiple dots are covering a single AF domain; thus the H_{FC} dependence can be explained with the coverage of the AF surface by the FM dots. In the case of dots with $d = 110$ nm, the FM coverage of the AF is $(\pi d^2/4)/D^2 = 0.10$. Therefore, the corresponding H_{FC0}^{dot} is expected to be 3.5 kOe, close to 3 kOe found experimentally (Fig. 2).

In summary, we have observed a strong cooling field dependence of EB in submicron circular dots. With decreasing dot sizes, the FM becomes more strongly influenced by the cooling field. In the case of the untwinned $FeFe_2$ sample, positive EB is found with cooling fields one order of magnitude smaller than what is necessary for the unpatterned sample. This unexpected behavior is attributed to the relevance of lateral length scales between the FM dots and the AF domain size from which the AF domain size is estimated to be around 500 nm in untwinned FeF_2.

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