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Magnetization processes in micron-scale (CoFe/Pt)$_n$ multilayers with perpendicular anisotropy: First-order reversal curves measured by extraordinary Hall effect

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First-order reversal curves (FORCs) were recorded using the extraordinary Hall effect in micron-sized crosses of [Co$_{90}$Fe$_{10}$ (0.5 nm)/Pt (1.0 nm)]$_n$ multilayers with $n = 10$, 20, and 50, which exhibit perpendicular magnetic anisotropy. Both the major hysteresis loop and the FORCs are compared to previous results, where the magnetization was measured directly on unpatterned stacks using alternating gradient force magnetometry. The FORC diagrams are dominated by two "hysteron" peaks, and their separation increases when n becomes larger. A frustrated domain growth process is suggested in our $n = 20$ and 50 samples. © *2012 American Institute of Physics*. [doi:10.1063/1.3679143]

Thin films with perpendicular magnetic anisotropy (PMA) have been under intensive investigation in the last few decades, thanks mainly to their applications in magnetic storage and magneto-electronic devices.[1–3] Strong PMA in magnetic multilayers arises from interface symmetry breaking and a magneto-elastic anisotropy term due to interface strain.[4] Magnetization switching in PMA films is often more complicated compared to conventional magnetic films with in-plane anisotropy. The existence of perpendicular anisotropy creates a delicate balance among different energy terms, namely the demagnetizing energy, the interlayer exchange energy, and the anisotropy energy.

The magnetization process is commonly characterized by the major hysteresis loop. The magnetization of a sample is first saturated, then decreased slowly until saturated in the opposite direction, and then increased again. This measurement may be stopped at any point and the applied field switched to the opposite direction, driving the sample back to saturation. This is called a first-order reversal curve (FORC).[5] The magnetic field at the turning point is the reversal field H_R. We denote the magnetization on the FORC with a reversal field H_R as $M(H_R, H)$, where H is the applied magnetic field. The FORC distribution parameter $\rho(H_R, H)$ is then defined by a mixed second-order derivative,[6]

$$\rho(H_R, H) = -\frac{\partial^2 M(H_R, H)}{\partial H_R \partial H}.$$

By definition, $\rho(H_R, H)$ eliminates the purely reversible part of the magnetization.[7] $\rho(H_R, H)$ is conventionally plotted on the Preisach plane by changing the coordinates from $\{H_R, H\}$ to $\{H_c, H_u\}$, with the local coercive field $H_c = (H - H_R)/2$ and the interaction field $H_u = (H + H_R)/2$.[8,9] This plot is called a FORC diagram.

Previously, FORCs measured by an alternating gradient force magnetometer have been used to characterize magnetization switching in macroscale PMA (Co/Pt)$_n$ thin film stacks.[10–12] The authors identified three different regions during the magnetization switching and observed characteristic domain patterns corresponding to each region by transmission x ray microscopy.

In contrast to previous work, here, we report on FORCs of micrometer-scale (Co$_{90}$Fe$_{10}$/Pt)$_n$ (numbers in atomic percentage) multilayers measured by the extraordinary Hall effect (EHE). This allows us to characterize the magnetization switching processes in a tiny sample area of less than 10 μm^2, in which only $\sim$400 domains ($\sim$150 domains for the $n = 10$ sample) exist in the demagnetized state. Similar measurements are very difficult to perform using conventional inductive magnetometers, because of the rather small coil fill-factors. Our (CoFe/Pt)$_n$ stacks with $n = 10$, 20, and 50 were deposited by DC magnetron sputtering on SiO$_2$/Si substrates. Layer thicknesses were 0.5 nm and 1.0 nm for CoFe and Pt, respectively. We used a seed layer and a capping layer of Pt, both 2 nm thick. The stacks were then patterned into Hall bars, with an active area of 3μm $\times 3 \mu$m, using photolithography. Cu or Au contacts were fabricated by a second lithography step to reduce the series resistance of the low repetition samples. The EHE measurement was carried out using a GMW water-cooled electromagnet, field-controlled by a Bouhnik linear power supply in a control loop with a purpose-built Hall probe. Both the sample mount and the twisted-pair wiring were completely electrically shielded. A Keithley 2400 sourcemeter was used for the measurement of the DC Hall voltage, which was completely dominated by the anomalous component within the field region studied. A typical bias current of 1 mA was chosen so as to exclude any significant self-heating. FORC diagrams were calculated from a group of FORCs following Ref. 8 with a local two-dimensional second order polynomial regression. The smoothing factor for all the FORC diagrams is set at 5% of the full-field scale.

Figure 1 show the measured first order reversal curves for $n = 10$, 20, and 50 samples, respectively. The major hysteresis curves for all three samples follow the process described in Ref. 11. When the magnetic field decreases from positive

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saturation, reversed domain nuclei form in the sample. These spot-like bubble domains then suddenly grow into labyrinth stripe domains at the sharp switch in the major hysteresis loop. When n increases from 10 to 50 this switching field also increases from about −10 mT to 100 mT. The $n = 10$ sample has a remanent magnetization close to its saturation magnetization, while both $n = 20$ and 50 samples are nearly fully demagnetized in their remanent state. This corresponds to a loss of perpendicular anisotropy, while the layer repetition n increases. We have previously identified the "quality factor" Q, defined as the ratio of the perpendicular anisotropy energy to the demagnetizing energy $\frac{2K_u}{\mu_0 M_s^2}$ (where K_u is the perpendicular uni-axial anisotropy constant and M_s is the spontaneous magnetization) of our multilayers.[13] While the $n = 10$ sample clearly has a $Q > 1$, both $n = 20$ and 50 samples have Q < 1. The perpendicular anisotropy of domains in the latter case can be stable in
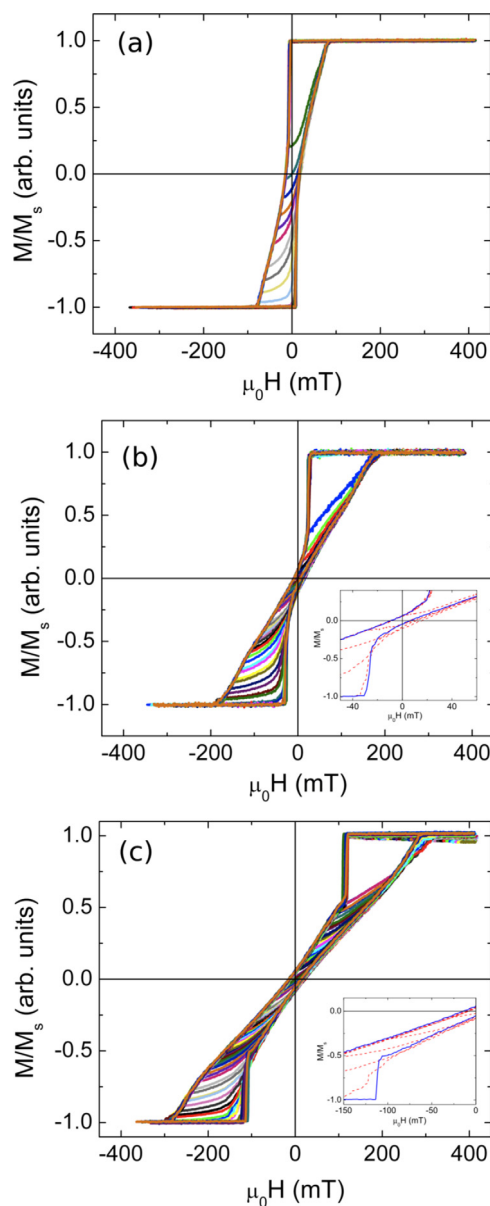
remanence, because domain formation reduces the demagnetizing energy below $\frac{1}{2}\mu_0 M_s^2$. When the applied magnetic field increases further, stripe domains annihilate at the annihilation field which also becomes more negative when n increases.

It is interesting to compare the measured hysteresis loops with those obtained by modeling the magnetic media as a quasi-two-dimensional system with perpendicular z-axis anisotropy.[14] According to the phase diagram, all our samples belong to the region where finite magnetization jumps occur upon magnetic field sweeping, but the jumps do not completely reverse the sample magnetization. This happens when the disorder in the system is below a critical amount and the exchange interaction is not extremely high.

FORC diagrams $\rho\,(H_c, H_u)$ are plotted in Fig. 2. Some key observations are as follows: There are two clearly distinguishable peaks ($\rho\,(H_c, H_u) > 0$) in all the diagrams, one of which has a positive interaction field $\mu_0 H_u$, and the other has a negative $\mu_0 H_u$. The former is associated with the stripe domain avalanching process, while the latter is associated with domain annihilations. The local coercive field $\mu_0 H_c$ for both peaks increases with the number of repetition n from 10 to 50, while $\mu_0 H_c$ for the annihilation peak is always larger. The peaks become broader in $\mu_0 H_c$ with increasing n, from about 25 mT for $n = 10$ to almost 100 mT for $n = 50$. This seems to be in direct relation with the change in quality factor. When n increases from 10 to 50, the distance between the two peaks also becomes larger. The area between the two peaks is quiet, with a diminished $\rho\,(H_c, H_u)$. This corresponds to the domain growth process between avalanche and annihilation, where reversible magnetization processes dominate (Fig. 1). A slightly larger $\rho\,(H_c, H_u)$ in this region is observed for the $n = 50$ sample than that for the $n = 10$ and 20 samples.

Besides the two peaks identified above, there exists a small bump with a local coercive field $\mu_0 H_c \approx 20$ mT for the $n = 50$ sample. This bump also has a positive $\mu_0 H_u \approx 160$ mT and is connected to the main peak with positive $\mu_0 H_u$ by an area having significant $\rho\,(H_c, H_u)$.

By plotting the FORC diagrams, we are able to relate our results to features described in the classical Preisach model.[15] The two distinct peaks may be associated with two different sets of "hysterons" with their respective local coercive field H_c and interaction field H_u. The distance between these two peaks shows how different the two sets of "hysterons" are. When n goes from 10 to 50, the two sets of "hysterons" become more different, judging by an enlarged distance. In each set of "hysterons," there is a distribution of its H_c and H_u. The spread of each peak indicates how similar the "hysterons" are. It can be readily observed that the similarity among "hysterons" also decreases as n increases.

Compared to previous work on a macro-scale [Co (0.4 nm)/Pt (0.7 nm)]$_{50}$ sample,[11] the lateral confinement in a $\sim 10\,\mu m^2$ area hardly alters either the major hysteresis loop or the FORC diagram. This may be due to the fact that the current sample size is still too large for any lateral confinement effect to dominate. The avalanche and annihilation fields observed on our (CoFe/Pt)$_{50}$ sample are both extremely close to those reported in Ref. 11. However, our data clearly show how the two main peaks in the FORC diagrams evolve with increasing n. The avalanche peak and the
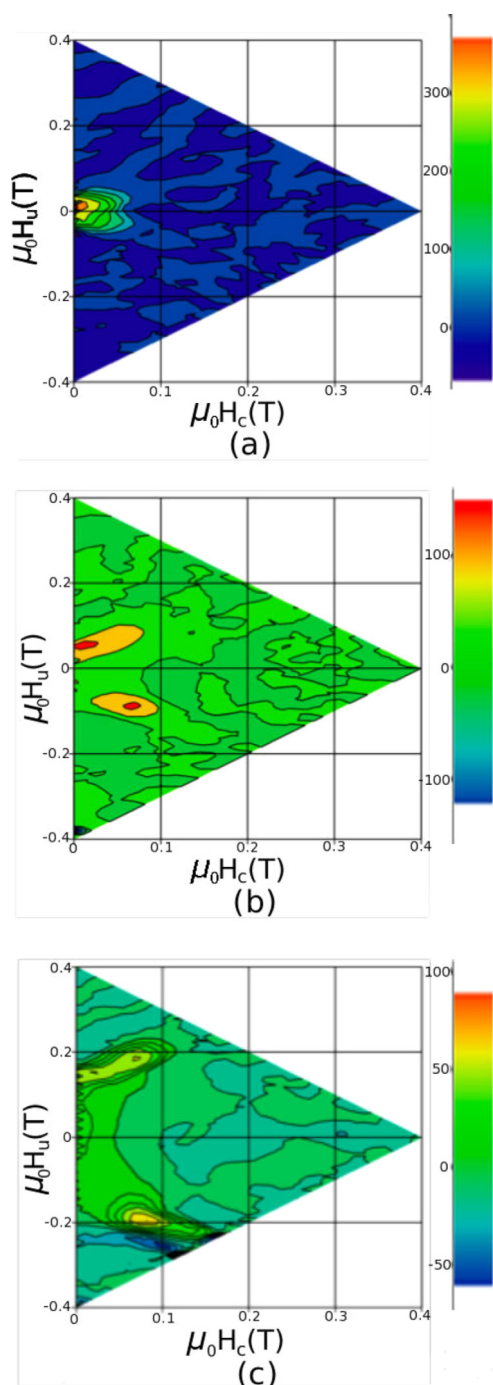
FIG. 1. (Color online) First-order reversal curves measured on (CoFe/Pt)$_n$ multilayers with $n = 10$ (a), 20 (b), and 50 (c). Insets to (b) and (c) are close-up views of selected FORCs protruding outside the major hysteresis loops for the $n = 20$ and 50 samples.

FIG. 2. (Color online) First-order reversal curve diagrams on $(CoFe/Pt)_n$ multilayers with $n = 10$ (a), 20 (b), and 50 (c).

Figs. 1(b) and 1(c)), but this is hardly identifiable when $n = 10$. This occurs because the rate of field change was the same for both the "major loops" and the FORCs. However, there are irreversible processes occurring on a time-scale exceeding 20 min at room temperature, which is probably why the magnetization extends to areas outside the "major loop" during the prolonged measurement period necessary to acquire all the FORCs. The lateral confinement of the domains may also play a role here, as the number of frustrated moments during the labyrinth domain growth is reduced, and the time needed to approach equilibrium is therefore shortened. However, this is unlikely to be the dominant effect, as the current sample size is still large compared to the domain size. Further studies are required in order to verify the influence of lateral confinement on frustrated domain growth.

In conclusion, extraordinary Hall effect has been shown to be a convenient method for measuring FORCs in patterned perpendicular anisotropy media. The accuracy and speed of the measurement are both comparable to conventional methods using alternating gradient force magnetometry, while measurement background is not limited by the substrate and total sample volume can be made orders of magnitude smaller. Further reducing the lateral dimension of the active area may lead to novel effects induced by lateral confinement of the magnetic media and make possible the studies of systems exhibiting a very small number of well-resolved Barkhausen jumps.

annihilation peak are attached to each other in the $n = 10$ sample, and their separation increases with n. The positive-negative pair on the FORC diagram is only associated with the $n = 50$ sample.

It was previously reported that samples with n between 10 and 50 undergo a frustrated domain growth process during magnetization switching.[12] This frustrated domain growth reveals itself by having some of the FORCs protruding outside the major hysteresis loop.[12] In our case, similar observations were also made in samples with $n = 20$ and 50 (insets to

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