Magnetic Noise in Structured Hard Magnets

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The anomalous Hall effect of wires patterned from $(Co_{90}Fe_{10}/Pt)_n$ multilayers, with $10 \leq n \leq 50$, is used to determine the magnetization process in a small volume of maze domains. Time-independent $1/f$ noise appears in samples with a quality factor $Q < 1$ at points on the hysteresis loop where the magnetization reverses continuously. The magnetic noise is associated with reversible excursions of segments of a domain wall ~100 nm long. Barkhausen jumps are observed close to either the switching field or the saturation field where the noise power spectrum varies as $1/f^{1.7}$, and its magnitude decays with time.

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Hysteresis is the defining property of a ferromagnet. The irreversible, nonlinear, and time-dependent response of the magnetization to an external magnetic field is traced as a time- or frequency-dependent open loop, which represents the sequence of metastable states occupied by the magnet as it adapts its domain configuration to the external field. Magnetic noise associated with the loop was first heard by Barkhausen in 1919, when he detected irreversible domain wall movement in nickel wires via the emf generated in a pickup coil by the flux jumps [1,2]. Barkhausen noise provides the basis for a method of nondestructive testing of steel parts under ac excitation [3]. It has been used to study correlations in magnetization reversal cascades by recording the jumps with a magneto-optical microscope [4].

Single-domain particles of hard magnets may exhibit coherent magnetization reversal—the classical Stoner-Wohlfarth behavior [5]—when they are about 10 nm in size, or less [6]. Uniformly magnetized films of similar thickness having spontaneous magnetization M and perpendicular anisotropy K_u exhibit perpendicular magnetization when the quality factor $Q = 2K_u/\mu_0 M^2$ is greater than 1. The hysteresis may then be a simple square loop like that of a Stoner-Wohlfarth particle, with an abrupt switch from magnetization $+M$ to $-M$ at the coercive field H_c, when the applied field is along the easy axis. Perpendicular magnetization remains possible when $Q < 1$, but in a multidomain state, which is stabilized by the stray field created by a maze of stripe domains. The magnetization switches from a uniformly magnetized state in a positive applied field to a maze domain state, which is then progressively demagnetized by domain wall motion. The reverse stripes broaden and the normal stripes narrow before breaking up into segments and bubbles, and eventually disappear as the sample reaches saturation in the reverse direction [7,8]. Thin film multilayers of Fe or Co and Pt or Pd with perpendicular magnetization are of great interest for magnetoelectronics, magnetic recording and studies of the physics of magnetic interactions at the nanoscale level. In this Letter, we show how the magnetic noise due to fluctuations in the magnetization of a small sample volume changes as we go around the hysteresis loop. The fluctuations are measured using the anomalous Hall effect.

Our samples were deposited by dc sputtering in a Shamrock tool on Si/SiO_2 substrates. Layer thicknesses were 0.5 and 1.0 nm for the $Co_{90}Fe_{10}$ and Pt, respectively, with a 2 nm cap and seed layer. The number of repeats, n, were 10, 20, and 50. The stacks were patterned into Hall bars ($w = 3$ μm) by optical lithography. The Hall resis-

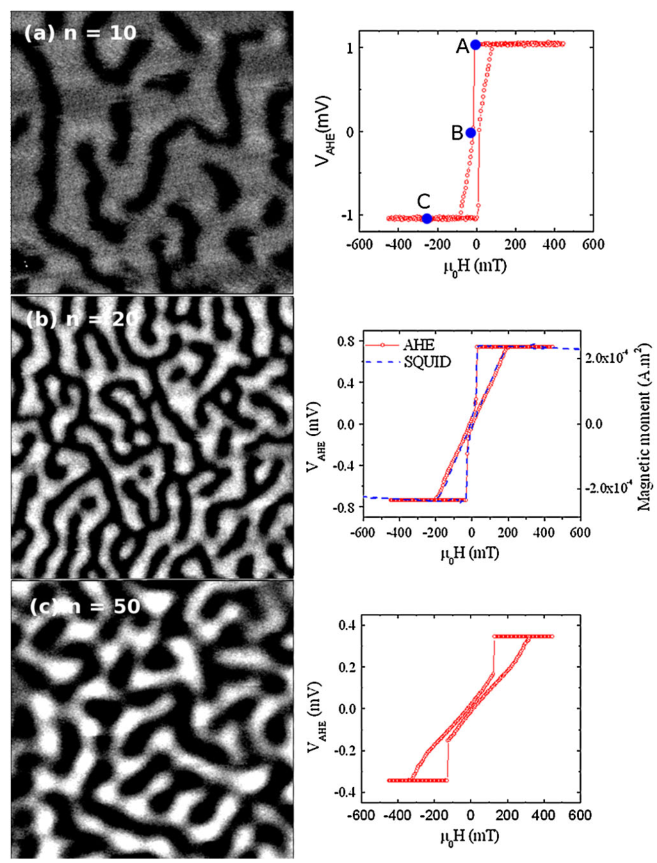

FIG. 1 (color online). Magnetic hysteresis loops of three $(Co_{90}Fe_{10}/Pt)_n$ multilayer stacks. MFM images (2.5 μm × 2.5 μm) are for the center of the Hall cross in the remanent state of each sample.

tance $R_H = V_z/I_x$ is

$$R_H = R_0 B + R_s \mu_0 M. \quad (1)$$

Here R_0 is the normal Hall coefficient, which is small in metals. The second term, the anomalous Hall effect R_s, is dominant in ferromagnets [9]. It is proportional to the perpendicular magnetization M averaged over the active volume Ω in the Hall bar, which is approximately $w^2 t$. When cobalt is prepared in thin film form and interleaved with layers of Pt or Pd, the interfacial anisotropy and the reduced magnetization of the stack ensure that $Q \sim 1$.

The magnetization of the unpatterned stacks was determined as $M = 500$ kA m^{-1} using a SQUID magnetometer. The magnetic moment in the active volume of the Hall bar is only of order 10^{-13} Am^2, or about 10^{10} Bohr magnetons. This is far beyond the sensitivity of the SQUID. Greater sensitivity to magnetic fluctuations may be achieved by measuring the stray field of a tiny magnet placed *on* a microsquid [10], or by passing an electron beam through the specimen, in Lorentz microscopy [11]. However, the anomalous Hall resistance provides a signal proportional to the magnetization in a submicron volume, and its temporal fluctuations over a range of temperatures.

The hysteresis loops in Fig. 1 were deduced from the anomalous Hall voltage with a bias current $I = 1$–3 mA at a field scan rate of 1–2 mT s^{-1}. On the left, are illustrations of the domain structure in the remanent state, determined by magnetic force microscopy. The domain structures for the $n = 20$ and $n = 50$ stacks in zero field, after saturation, resemble those in the virgin state. The domain width of 100–150 nm, can be well described by the Kooy-Enz model [12]. A comparison with the magnetization loop measured on an unpatterned film ($n = 20$) using the SQUID magnetometer is shown by the dotted line in Fig. 1(b). Evidently, the magnetization averaged over the small active Hall volume is representative of the magnetization of the whole film. Comparisons with loops calculated by Clarke *et al*. [13] are used to associate values of Q of 1.06, 0.94, and 0.69, respectively, with the three samples.

Hall noise measurements involved sweeping the magnetic field in small increments, recording the transverse voltage fluctuations across the sample a few seconds after reaching the field set point, and averaging 50–100 power spectra. The resulting spectra were binned into 7 consecutive octaves. Figure 2 shows a half hysteresis loop with the Hall noise in an octave centered at 4.8 Hz as a function of field. Similar noise-field profiles are observed for the lowest three octaves (extending up to ~50 Hz) on all the stacks measured. Profiles of the higher octaves show progressively higher field-independent background levels. This is due to the thermal noise of the lead resistance, R_L, in series with the Hall element which dominates at high frequencies; R_L is about 500 Ω, much larger than $R_s \sim 1\ \Omega$.

To summarize the behavior in Fig. 2, when the magnetic field is at positive saturation (450 mT), no low-frequency noise above the thermal background is observed. Spikes in the low-frequency noise power, more than an order of magnitude above the background level, are observed when the field is swept back to the domain nucleation value, where a sudden switch in Hall voltage occurs. The Hall voltage then crosses over into a linear regime, which is characteristic of the widening of reversed stripe domains. Concurrently, the magnetic noise is considerably lower, but remains well above the background. At a more negative field (-150 mT), close to reverse saturation, huge noise spikes reappear together with changes in the slope of Hall voltage ($dV_H/d\mu_0 H$). The noise spikes persist over a field range of about 50 mT, and disappear when the magnetic layer reaches negative saturation.

In order to better understand how the noise is related to the magnetization switching process, we recorded spectra at several representative magnetic fields (Fig. 3). The acquisition time at each field set point was about 5 min for an averaged spectrum.

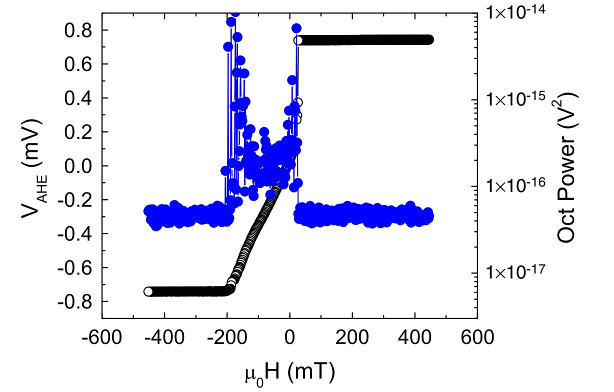

FIG. 2 (color online). Anomalous Hall voltage and octave noise power (centered at 4.8 Hz) against magnetic field for an $n = 20$ sample. The bias current is 1.2 mA.

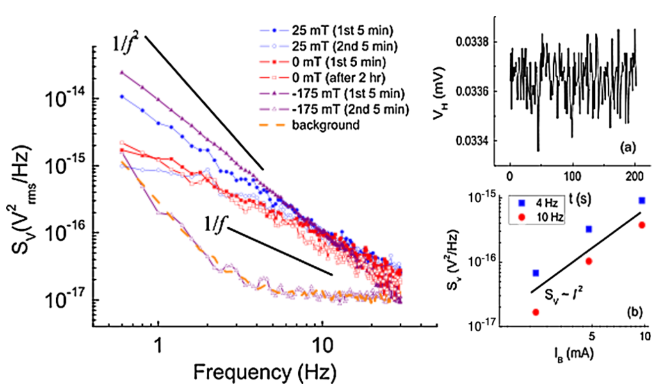

FIG. 3 (color online). Noise spectra at three different magnetic fields for the sample of Fig. 2. The background has been subtracted from the spectra except for the one taken in the second 5 min at -175 mT. The dashed line is the background, consisting of the amplifier noise and the thermal noise of the sample. Inset (a) a time sequence of voltage fluctuation at 0 mT; inset (b) power spectrum density at 4 and 10 Hz in zero field against current bias.

The two noise spectra in Fig. 3 having the highest slopes (denoted by the solid symbols • and ▲) were obtained at 25 mT (just before the magnetization switch) and at −175 mT (just before negative saturation). Their low-frequency variation is fitted by a power-law form, $S_V = 1/f^{\beta}$, with $\beta \sim 1.7$.

It was shown by Koch [14] that a $1/f^{\beta}$ spectrum with $\beta = 2$ can be attributed to a continuous or steplike drift of resistance during electromigration. In our case, the large noise spikes that occur around the magnetization switching and just before negative saturation are due to steplike magnetic relaxation events. A superposition of both $1/f^2$ and ordinary $1/f$ noise [15] is likely; hence, β values between 1 and 2 are evident. Relaxation processes giving rise to nonstationary noise spectra are illustrated by two other spectra in Fig. 3, taken 5 min after the set point fields were reached. The spectrum denoted by open circles was measured after reaching a 25 mT set point. It closely resembles the $1/f$ spectra measured at a 0 mT set point (■ and □), because after the magnetization switch is complete, the sample is in a maze domain state. The open triangles denote the spectrum taken after 5 min at −175 mT. It is just the amplifier plus thermal resistance noise (dashed line) because the relaxation process has already driven the system to negative saturation. On the other hand, magnetic noise spectra obtained at a set point field of 0 mT were stationary, and of $1/f$ character. There was little or no change of these spectra in a time frame of hours (□ in Fig. 3), or even days.

In the inset (b) of Fig. 3, we plot the noise power density at 4 Hz and 10 Hz in zero field against current bias I. From Eq. (1), the Hall resistance is proportional to the magnetization in the active area. Hence, the observed quadratic dependence, $S_V \sim I^2$, indicates that the current is probing the magnetization fluctuations in the sample.

Two explanations of the magnetic noise are (i) Spontaneous reversals of an activation volume (nucleus), which are not followed by growth of the reverse domain. The activation volume in a hard magnet is approximately δ_B^3, where δ_B is the Bloch wall width $\pi(A/K_u)^{1/2}$, where A is the exchange stiffness. Using values of $A = 10$ pJ m^{-1} and $K_u = 1.5 \times 10^5$ J m^{-3} for our $n = 20$ sample, we estimate that δ_B is 25 nm and δ_B^3 is 15×10^3 nm^3. (ii) Fluctuations of the position of the domain walls. Walls are expected to be strongly pinned at defect sites. If the average distance between these is d, the fluctuating reversed volume will be approximately $0.1d^2t$. The value of $d(\sim 300$ nm) corresponds to the length of the straight segments of domain wall shown in Fig. 1(b). The reversal volume is then $\approx 270 \times 10^3$ nm^3. These domain wall reconfigurations can be modeled as a fluctuating two-level system, characterized by an activation barrier between two, nearly equivalent energy levels. It is well known that a superposition of a large number two-level systems with a broad distribution of activation energies gives a $1/f$ spectrum [16,17].

The amplitude of the fluctuations shown in the time record in the inset (a) of Fig. 3 indicates that the fluctuating magnetic volumes are of order 300×10^3 nm^3. This volume is similar to the reversal volume due to a moving domain wall, but significantly greater than the activation volume. Furthermore, an area of new wall ($\approx \pi\delta_B t$) has to be created to form the activation volume. The energy cost is expensive—$\gamma_w = 4\sqrt{AK} = 5$ mJ m^{-2} for a Bloch wall, or $\approx 3300 k_B T$ per nucleus in the $n = 20$ sample. Even if the wall is partly or entirely of Néel character [18], the prefactor will not be reduced by 2 orders of magnitude, necessary to observe stationary nucleation at room temperature. By contrast, there is no need to create new wall area to accommodate the reversal in the second model because the walls themselves are not straight. Therefore, we conclude that the magnetic fluctuations that give rise to stationary $1/f$ noise are related to domain wall movements, rather than spontaneous nucleation.

Next, we examine whether the magnetization fluctuations responsible for the stationary $1/f$ noise can be characterized as reversible domain reconfigurations in thermal equilibrium. The fluctuation-dissipation theorem (FDT) relates the magnetization fluctuations and the susceptibility [19,20]. For a sample in thermal equilibrium which exhibits a linear response, the power spectrum of the magnetic moment $S_m(f)$ is given by [21,22]

$$S_m(f) = \frac{2k_B T}{\pi \mu_0 f} \chi_m''(f), \tag{2}$$

where μ_0 is the permeability of free space, k_B is Boltzmann's constant, and $\chi_m''(f)$ is the out-of-phase susceptibility. The Kramers-Kronig relation gives [23]

$$\chi_m'(f = 0) = \frac{2}{\pi} \int_0^{+\infty} \frac{\chi_m''(f)}{f} df. \tag{3}$$

In our samples, we have

$$S_V(f) = \left(\frac{\partial V_H}{\partial m}\right)^2 S_m(f) = (1/\Omega)^2 \left(\frac{\partial V_H}{\partial M}\right)^2 S_m(f), \tag{4}$$

where $(\partial V_H/\partial M)$ can be worked out from Eq. (1). Using Eqs. (2)–(4), we arrive at the fluctuation-dissipation relation for the anomalous Hall effect

$$\frac{\partial V_H}{\partial(\mu_0 H)} = \frac{\Omega}{\mu_0 I R_s k_B T} \int_0^{+\infty} S_V(f) df. \tag{5}$$

The left-hand side of Eq. (5) comes from Fig. 2, which leads to a dc Hall voltage susceptibility of 3.5×10^{-3} V T^{-1}. This value is close to that obtained from the right-hand side of Eq. (5), by integrating the $S_V(f)$ curve at zero field in Fig. 3 across our measurement window, which is 2.5×10^{-3} V T^{-1}. The upper limit of integration is finite because the magnetic noise power falls below the thermal background above 100 Hz, and it can no longer be distinguished. Assuming the magnetic $1/f$ noise extends out to 1 GHz then the predicted Hall voltage susceptibility is still only 3–4 times larger than the measured one. Given this

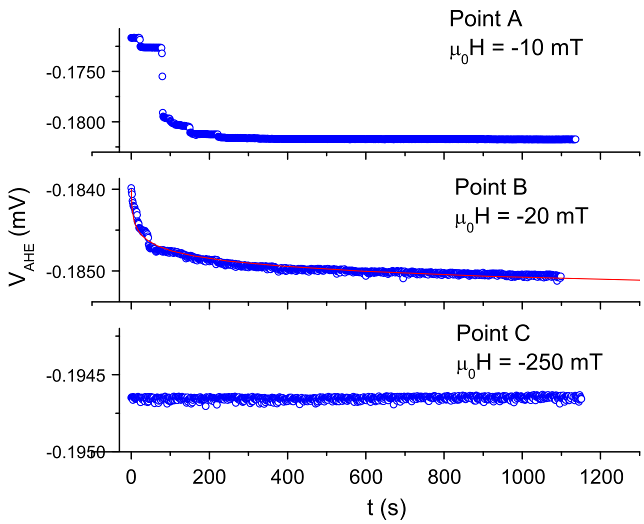

FIG. 4 (color online). Time sequence measured on a $n = 10$ sample with different set point fields. Points A, B and C refer to those labeled in Fig. 1(a). The bias current is 1.2 mA.

uncertainty, the two sides of Eq. (5) are in fair agreement and this is reasonable evidence that in an applied magnetic field between 0 mT and -150 mT, the sample is in a quasiequilibrium condition.

The time evolution of the magnetization can be used to categorize the magnetic noise spectra. Figure 4 shows three time records of the Hall voltage starting ~1 s after reaching the set point field, following a field sweep down from saturation. Substantial magnetic relaxation is observed at short times for set points near the switching field [Fig. 4(a)] and there is also some relaxation in the quasilinear V_H vs $\mu_0 H$ region [Fig. 4(b)]. No relaxation is observed when the sample is driven to negative saturation [Fig. 4(c)]. For set point fields just before magnetization switching, the relaxation is characterized by a series of Barkhausen jumps such as those shown in Fig. 4(a). In the quasilinear V_H vs $\mu_0 H$ region, the relaxation is continuous and is related to the magnetic after effect. This is the sluggish time response of the magnetization after a change in applied field. At times which are neither very short, nor very long, the change varies as

$$\Delta M = S \ln(t/t_0), \quad (6)$$

where S is the magnetic viscosity [24]. The relaxation of the magnetization of the $n = 10$ sample at -20 mT can be fitted to Eq. (6), with $S \approx -50\ \mathrm{A \cdot m^{-1}}$ and $t_0 \approx 1$ s.

In conclusion, we show that both the magnetization, and its fluctuations can be conveniently measured in patterned Hall bars with micron-scale dimensions by means of the anomalous Hall effect. The patterned samples have relatively few walls in their active volume Ω. Magnetic noise, which is observed only in the unsaturated sections of the hysteresis loop, provides a direct view of the magnetic fluctuations in the sample. $A \sim 1/f^{1.7}$ spectrum in regions where domains are created or annihilated, is due to irreversible Barkhausen jumps and magnetization drift. After a time, the magnetization in the center of the loop reaches a steady state, with a stationary $1/f$ frequency spectrum, associated with reversible excursions of roughly hundred-nanometer segments of domain wall. It should be possible to extend the method to the nanoscale, by patterning smaller Hall bars and using low-resistance leads.

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