History dependent domain structures in giant-magnetoresistive multilayers

H. T. Hardner and M. B. Weissman
Department of Physics, University of Illinois at Urbana–Champaign, Urbana, Illinois 61801-3080

S. S. P. Parkin
IBM Almaden Research Center, San Jose, California 95120-6099

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Resistance noise measurements of several types reveal the field history dependence of domain structure in sputtered Co/Cu multilayers. We find many smaller domains as the field is decreased from saturation towards zero, but as the field changes sign and is increased in the opposite direction we observe a smaller number of larger domains. Cycling the field without changing its sign preserves the smaller domains, strongly reducing the Barkhausen noise. Discrete fluctuations in resistance due to individual domains yield domain size estimates. © *1995 American Institute of Physics.*

Transition-metal-nonmagnetic multilayers exhibiting giant magnetoresistance (GMR) are currently of great interest for various magnetic field sensor applications including magnetic recording.[1] The domain structure in these multilayers is important to a complete theoretical description of the GMR[2] and is crucial to understanding the GMR kinetics. Several techniques have been used to look at domains and domain walls in magnetic multilayers and sandwiches including scanning electron microscopy,[3] Kerr microscopy,[4] and a recently developed magneto-optical indicator film technique.[5] However, determining the domain structure in multilayers is very difficult, in part because most techniques are surface sensitive. Domain images produced by transmission electron microscopy (TEM) (which requires extensive sample preparation) have shown hysteretic domain structures in Co/Cu multilayers.[6]

In this letter, we describe using resistance noise measurements to estimate domain sizes in GMR materials and to study the field history dependence of the domain structure. The noise method can be used directly on GMR devices, allowing study of a large number of samples relatively quickly. The technique does not produce spatial images, but does reveal domain dynamics, and provides spatial information by comparison of samples with different geometries.

We studied sputtered Co/Cu multilayers (with various numbers of bilayers) from two batches representing the first and second peaks in antiferromagnetic coupling between Co layers. (Somewhat different results on uncoupled samples, including Co/Ag, will be presented in a future article.) Table I gives further details on the samples.

Each sample is photolithographically patterned into a bridge of four parallel legs in one of two different sizes: 3 μm by 30 μm legs or 3 μm by 256 μm legs. A constant dc current is applied to the sample and the resulting voltage noise across the bridge is amplified with commercial low-noise amplifiers, anti-alias filtered, and digitally sampled. The resulting digital signal is either Fourier transformed and squared to give the noise power spectrum (more fully described in Ref. 7), or is simply recorded for display and inspection.

When an (in-plane) magnetic field H was applied, measurements could be made either at fixed H (quasiequilibrium) or while H was being ramped (Barkhausen). We have previously reported both Barkhausen noise[8] and an increase in equilibrium noise in regimes with large $|dR/dH|$.[7] Every domain in the sample which participates in the GMR and which changes its magnetization in large enough steps will be observed at some H in the Barkhausen measurement. In contrast, large domains with fixed or very slowly fluctuating magnetization are not seen in the equilibrium noise.

Figure 1 shows a typical plot of equilibrium noise power parameter α(20 Hz) and resistivity versus H, with $\alpha(f) \equiv f S_R(f) N/R^2$,[9] where $S_R(f)$is the power spectral density of fluctuations in R, and N is the total number of atoms in the sample. The spectral slope $[1-d\ \ln(\alpha)/d\ln(f)]$ ranged from 1.04 to 1.19. Two large peaks in $\alpha(H)$ occur for large $|dR/dH|$, with the larger peak always found when $|H|$ has been *reduced* from saturation.

Figure 2(a) shows time series corresponding to the top of the large peak in α in Fig. 1 while Fig. 2(b) corresponds to the top of the smaller α peak. Discernible discrete steps are often apparent in the equilibrium time series around the smaller α peak, but were not found in some 20 min of data from the larger peak.

Figure 3 shows typical Barkhausen noise, which was always largest as $|H|$ was *increasing*. For H near the larger peak in $\alpha(H)$ (as $|H|$ was *reduced*), only a small Barkhausen peak appeared in the large samples, and none were evident in

TABLE I. Sample specifications and estimates of the largest domain area from Barkhausen data. Area is calculated making the assumption that a domain is one magnetic layer thick.

Sample No.	Description	Pattern area (μm^2)	Largest domain area (μm^2)
1	Co/Cu 39×(10 Å/10 Å)	90	0.25
2	Co/Cu 39×(10 Å/21 Å)	90	4.8
3	Co/Cu 39×(10 Å/23 Å)	768	60
4	Co/Cu 39×(10 Å/23 Å)	90	33
5	Co/Cu 2×(10 Å/21 Å)	90	20
6	Co/Cu 3×(10 Å/10 Å)	768	73
7	Co/Cu 10×(10 Å/21 Å)	768	10
8	Co/Cu 30×(10 Å/21 Å)	768	2
9	Co/Cu 40×(10 Å/21 Å)	768	15

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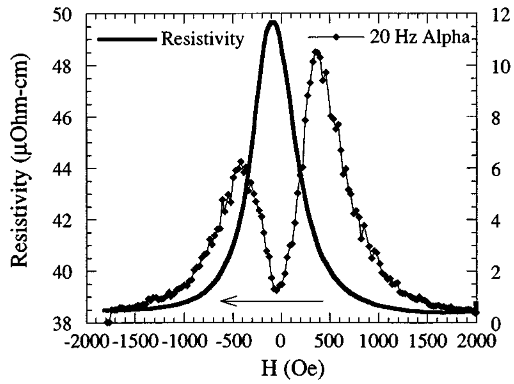

FIG. 1. The dimensionless noise parameter α(20 Hz) and resistivity as a function of field for sample 2 (Co/Cu 10 Å/21 Å×39 layers).

the small samples. Individual steps such as those shown are most often visible in the smaller samples and are presumably due to discrete reorientations of individual domains. The largest Barkhausen steps are nearly four times larger than the largest equilibrium steps seen in Fig. 2(b) from the same sample.

The resistance step sizes seen in both equilibrium time series and Barkhausen noise can be used to get a simple estimate of domain volumes (V_D)

$$V_D \geqslant V_S \delta R / \Delta R, \tag{1}$$

where V_S is the sample volume, δR is the step in R, and ΔR is the total GMR change in R. This estimate yields a minimum V_D because the δR step ordinarily comes from a region making less than a full GMR change in its resistivity. Table I shows such V_D estimates, reported in the form of the domain areas which would correspond to domains one magnetic layer thick for the largest individual step observed in each sample. V_D shows little or no dependence on the number of bilayers, from 2 to 40 bilayers, indicating that the large relative domain reorientations do not occur coherently over many layer boundaries. This is in agreement with the observation of stacks only 2–4 layers thick in a 14-layer sample.[6] Given the large areas, the domain sizes must be partly limited by the 3 μm pattern width.

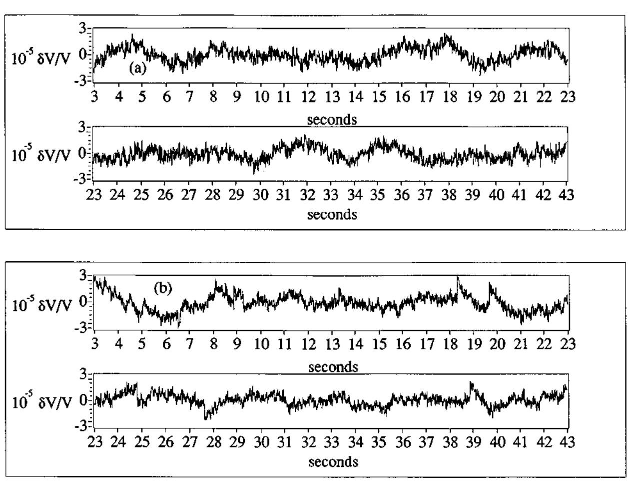

FIG. 2. Equilibrium time series ($\delta V/V$ vs t) for sample 2 taken at (a) 686 Oe (corresponding to the top of the large peak in Fig. 1 and (b) -774 Oe (corresponding to the top of the smaller peak in Fig. 1).

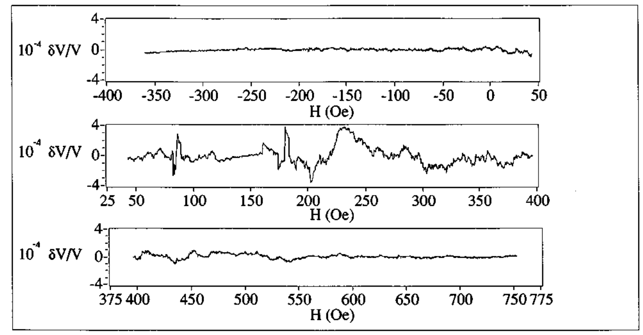

FIG. 3. Barkhausen noise, $\delta V/V$ as a function of a constantly swept field, in sample 4 (Co/Cu 10 Å/23 Å×39 layers).

The data shown so far involve cycling H from saturation through zero and out toward the opposite saturation. Figure 4(a) shows α versus H when cycling between zero and saturation without changing the sign of H. The increasing-H peak is larger than when sweeping from the opposite sign. The Barkhausen noise is nearly eliminated, as shown in comparing Fig. 4(b) with Fig. 3, taken with a full cycle on the same sample. The single-sign sweep produces noise more like that found on reduction from saturation than like that found on sweeping through $H = 0$.

The field history dependence of the Barkhausen noise in these antiferromagnetically coupled multilayers indicates the

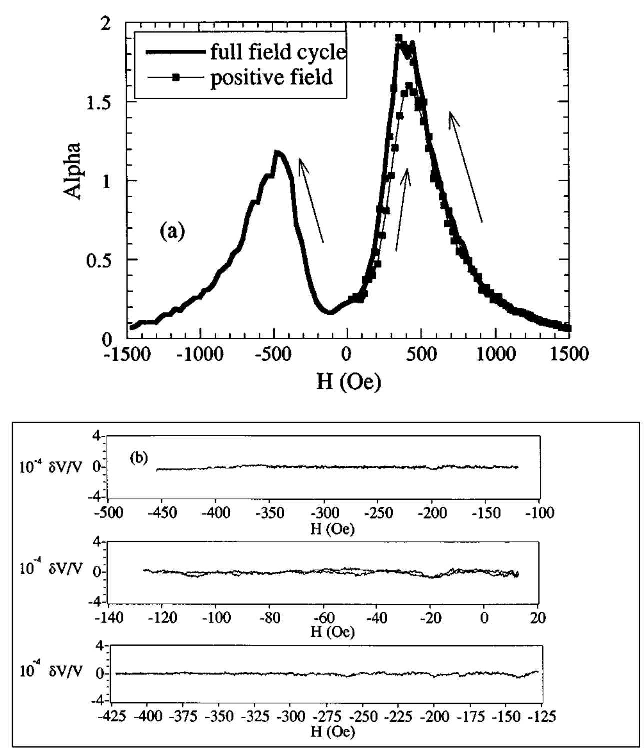

FIG. 4. (a) α as a function of H for sample 7 (Co/Cu 10 Å/21 Å×10 layers). The solid line is data taken starting from about 1500 Oe and stepping all the way to -1500 Oe while the solid squares are data points taken starting at 1500 Oe going down to zero and then going back up to 1500 Oe. (b) Barkhausen data identical to Fig. 3 (same sample, 4) except the H sweep is reversed near zero.

field history dependence of the domain structure. Larger domain rearrangements produce more Barkhausen noise than smaller ones. Therefore, the consistent strong asymmetry of the Barkhausen effect shows that there are more large domain motions when H has passed through zero than when a single sign of H has been maintained after saturation.

A change of the distribution of domain sizes will also affect the equilibrium noise. The spectral slope >1 indicates that there are more domains a bit too slow, i.e., too large, than there are ones a bit fast (i.e., too small) to show up in the equilibrium noise near 20 Hz. A shift of the size distribution toward larger (slower) domains would then reduce the number within our frequency window. Thus, we would expect that after H sweeps through zero, α(20 Hz) would be reduced and it would be easier to pick out discrete steps (which are obscured when the number of fluctuators increases). The reduction of α was observed in all samples, and the increased detectability of steps was found in the one small sample for which it was checked.

Thus both the Barkhausen noise, which probes the larger domains, and the equilibrium noise, which probes an intermediate range of domain sizes, show that the domain size distribution in all the tested antiferromagnetically coupled samples is shifted toward larger sizes after H sweeps through zero. A similar result has been obtained via TEM images.[6] An explanation of this history dependence of the domain size distribution may lie in the predicted production of metastable parallel layered Neel domain wall configurations on reducing H from saturation.[10]

In conclusion, we have studied the hysteresis of the domain structure in Co/Cu multilayers using a simple technique suitable for any small magnetoresistive element. The substantial Barkhausen noise allows us to observe individual domains and estimate their (rather large) sizes. Comparison of different sample geometries shows that the lateral coherence extends over microns, while there is little coherence in GMR changes between layers. The Barkhausen noise can be nearly eliminated by cycling with only one sign of H.

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