Nonlinear AC Response and Noise of a Giant Magnetoresistive Sensor

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***Abstract*—We compare bridge voltage response measurements to ac magnetic fields from a giant magnetoresistive sensor with noise measurements on the same sensor. The small-signal response (for applied ac magnetic fields between 0.1 mOe rms and 30 mOe) is much less than is the slope of a dc voltage versus field curve, because of hysteretic effects. Noise statistics are used to estimate the size and number of the sites at which domain realignments occur near the response peak. Similar estimates are made by using fine-structure on the ac response curve. For ac fields of about 0.3 mOe rms, sharp spikes appear in the field-dependent response, giving rise to large harmonic distortion, varying in an irregular way with the ac amplitude. Domain sizes are estimated for the regions, giving these nonlinear response spikes, and for the domains, giving the magnetic noise, and a comparison based on a fluctuation–dissipation relation of the noise, and the response shows the importance of hysteresis.**

I. INTRODUCTION

THE POSSIBILITY of using giant magnetoresistive (GMR) materials in device applications [1]–[3] is often limited by the transport noise of the GMR materials, which typically originates in the fluctuations of magnetic domains [4]–[9]. Thermal fluctuations in the magnetic domain structure give rise to $1/f$ noise in the resistance R, which is largest at fields for which the magnitude of dR/dH is large [4]–[9]. When the applied magnetic field changes over time, Barkhausen noise from the uneven growth of domains aligned with the field often becomes the dominant noise mechanism [4]. Practical application of GMR devices as low-field sensors requires maximizing their linear response to small fields, while minimizing their noise.

Both the quasi-equilibrium thermal noise and the Barkhausen noise provide information about the size of the magnetic domains and the processes by which they align [4]–[7]. In this paper, we combine measurements of fine structure in the ac response of a particular GMR sensor with measurements of noise spectra and non-Gaussian statistics to obtain such information on a particular sensor. Our purpose is less to elucidate the properties of that particular sensor than to show the utility of some new characterization techniques, which can be used without destructive testing or microscopic examination.

We measured $\chi_v(H)$ the normalized response of the device voltage to small ac magnetic fields at dc field H. We define $\chi_v(H)$ to be the rms voltage response of the device (at a fixed current bias) divided by the rms ac field applied, with $\chi_v'(H)$ giving the in-phase response and $\chi_v''(H)$ the out-of-phase. The first question to be addressed is whether the response comes from a fairly homogeneous magnetization rotation (as is often assumed in simplified theories) or whether the response is the sum of responses from many domain walls, each responding over a narrow range of H. We shall present a fairly unsurprising result—that the response is an inhomogeneous sum of many distinct responses, each limited to a narrow field range. The questions then become how narrow is the range over which these individual responses occur, how many domains or domain wall segments are active in any range of H, and to what extent are the individual responses linear in small applied ac fields.

If the response function $\chi_v(H)$ developed from either a single smoothly rotating domain or a very large number of independent domains or domain wall segments, it would be expected to be a smooth function of H. (We henceforth use "domain" to refer to a region in the material whose magnetization responds coherently to the applied ac field, although this region may only include a small area around the border between two big domains.) If $\chi_v(H)$ developed from a small number of sites at any particular H, it would be expected to be a rough function of H, because of the statistical variation in the number of sites contributing at each H. The variance in $\chi_v(H)$ then can be used to estimate the number of domains responding to a given ac field, which combined with the net response, allows an estimate of the size of the individual domain realignments [10], [11].

In some cases, spikes in $\chi_v(H)$ are big enough to measure individually, allowing direct determination of the size of those domain realignments. The width of the spikes in $\chi_v(H)$ also directly depends on the range of dc fields over which those domains are active.

In general, the response at any given ac field will consist of two parts: a genuinely linear response, which therefore obeys a fluctuation–dissipation relation and a microhysteretic response, which will give Barkhausen noise but which will not be accompanied by any quasi-equilibrium noise in the absence of a time-varying field. It has been shown that for GMR devices with sufficiently homogeneous sensitivity of R to the magnetization, the $1/f$ noise can be predicted from the out-of-phase response of R to H_{ac} [4]. For the true linear response, the deviation of the noise statistics from the Gaussian statistics expected for the sum of a large number of independently fluctuating units also allows an estimate of the number of fluctuating domains and, hence, of the size of each such domain fluctuation [10], [11].

Further information on the fraction of the sample contributing to the nonhysteretic response can be obtained from a comparison of the magnitude of the in-phase response to small ac mag-

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netic fields with the slope of the response obtained from a sweep of H. It is, of course, only the small-signal response, not the slope of $V(H)$, the voltage versus field in a hysteresis loop, which is important for most applications of a field sensor.

II. Experimental Techniques

Measurements were performed on a Ta(30 Å)/NiFeCo(40 Å)/CoFe(15 Å)/Cu(40 Å)/CoFe(15 Å)/NiFeCo(40 Å)/Ta(200 Å) sample prepared by R. Beech at Non-Volatile Electronics. The sample consists of a Wheatstone bridge containing four 14-legged (each leg 2 μm wide by 30 μm long) serpentine GMR resistors, with approximately square pads some 20 μm on a side connecting each of the 14 narrow legs. The films were deposited to make the in-plane easy magnetization axis orthogonal to the current in the legs, reducing hysteretic effects for fields applied along the current direction (as were all the fields in these experiments). Thus, the magnetization changes within the arms occur primarily via rotation, whereas domain wall motion can occur in the connecting pads [12].

Two flux concentrators, 14-μm thick NiFe ribbons, were located over a portion of the sample, providing on two opposite bridge arms a local increase in H of about a factor of 20 over the externally measured values, while screening the other two arms from the applied (in-plane) field. (This approximate field enhancement was measured by disassembling the device after the other measurements were made and measuring a magnetoresistance curve on one arm to determine by what factor the saturation field changed.) The change of the bridge imbalance in response to a small applied field thus involves the realignment of the magnetic layers in two of the four arms. The volume of magnetic material in the narrow legs of two arms is 2×10^{-11} cm^3, but the total volume in those arms is an order of magnitude larger, if the pads connecting the legs are included. (Although in these sandwich materials the GMR effect develops primarily at the interfaces, the volume is relevant to those calculations in which total magnetic moment enters. Fluctuator volumes may be converted to areas by dividing by the 55 Å thickness of magnetic material on either side of the nonmagnetic Cu layer.) See Fig. 1 for a schematic of the sample and the placement of the flux concentrators.

A constant current of 0.1 mA was passed through the terminals I^+ and I^-, whereas the bridge voltage was measured across terminals V^+ and V^- (see Fig. 1). The bridge voltage was first amplified with a low-noise SR-552 preamplifier and then passed through a PAR-113 amplifier. Noise measurements, including both spectra and other statistical information, were taken on a PC using data from an analog-to-digital converter preceded by an anti-alias filter [5], [6].

The magnetic fields were created with a 50-cm solenoid powered by an amplifier capable of combining an ac ripple with a dc offset. An SR-530 lock-in amplifier, with a sine-wave mixer, was used to perform the ac response measurements. The reference phase for these measurements was set using a small series resistor to measure the solenoid current, and using the same amplifier chain on it as used on the bridge, to avoid spurious phase-shifts.

Because the measurements to be reported were all made at the same constant current, on a bridge for which the average measured voltage was close to zero, it is most convenient to describe the bridge voltage response function $\chi_v(H)$ rather than the resistance response function. We define $\chi_v(H)$ to be the ac voltage response of the bridge divided by the rms external applied ac field, with the in-phase response giving $\chi_v'(H)$ and the out-of-phase response giving $\chi_v''(H)$. This informal definition allows the value of $\chi_v(H)$ to depend on the magnitude of the ac field, if the response is nonlinear. Each point in the $\chi_v(H)$ data represents the average of 1008 analog-to-digital voltage measurements.

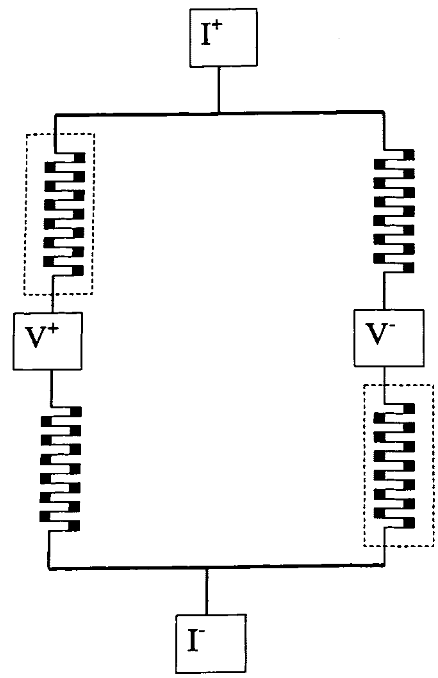

Fig. 1. A simplified schematic of the GMR sensor. There are four GMR resistors, two of which are in-between the flux concentrators (enclosed by the dotted lines). An increase in the dc magnetic field drives the bridge out of balance.

III. Results

Fig. 2 shows the bridge voltage $V(H)$ as a function of dc field, as H is swept through a range sufficient to align the two GMR elements within the flux-concentrators, but not sufficient to have much effect on the other two. Fig. 3 shows the in-phase response of the bridge $\chi_V'(H)$ measured with external ac fields of 27, 0.3, and 0.1 mOe. The in-phase response is obviously nonlinear, although weakly so, with the normalized response increasing about a factor of 2.5 for an increase of a factor of 270 in H_{ac}. The broad peaks of $\chi_V'(H)$ occur at the same fields for which the magnitude of the derivative of $V(H)$ is the largest. The maximum $|dV/dH|$ of this sensor is approximately 16 mV/Oe. Measured at the dc field for which $|dV/dH|$ is maximal and with $H_{\text{ac}} = 0.1$ mOe, $\chi_V'(H) \approx 4$ mV/Oe, approximately one-fourth of the slope of $V(H)$ in the hysteresis loop. Hysteresis, thus, significantly reduces the small-signal ac response.

For small ac fields, $\chi_V'(H)$ contains a series of small spikes, evident near the peaks, with the same sign as the peak. The magnitude of each of these spikes corresponds to a response of about 8×10^{-5} of the total GMR ΔV of the bridge. The volume of the magnetic region whose realignment gives a typical spike is

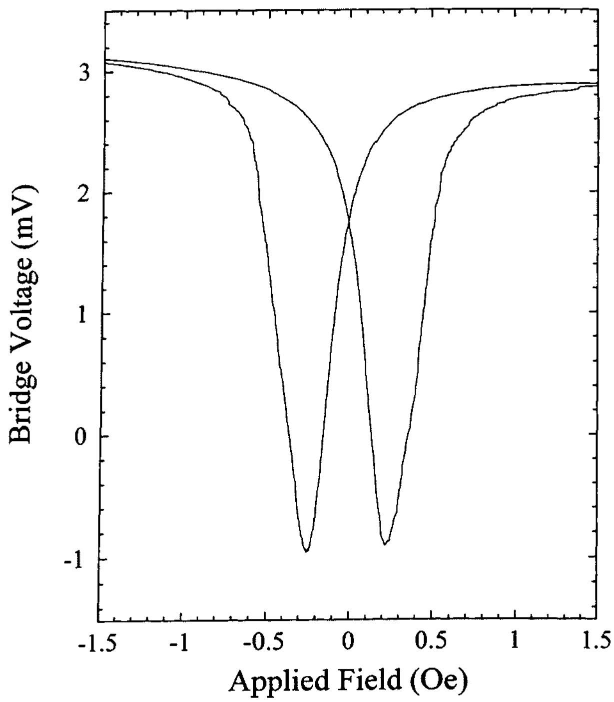

Fig. 2. The bridge voltage, $V(H)$, as a function of dc field for the bridge sensor. $|dV/dH| \approx 16$ mV/Oe near $H_{\rm dc} = -0.1$ Oe.

thus at least about 1.6×10^{-15} cm^3, assuming the region is contained in a leg. At the larger ac field, the response becomes much smoother.

Fig. 4 shows the out-of-phase response $\chi''_V(H)$. For $H_{\rm ac} = 0.3$ mOe, there is very evident fine structure in $\chi''_V(H)$ near the peaks, qualitatively similar to the peaks that are easier to see in $\chi'_V(H)$. (The "fine structure" away from the response peaks is simply measurement noise, which becomes smaller at higher $H_{\rm ac}$ simply because of the normalization of the response by $H_{\rm ac}$.) At larger ac fields, this fine structure becomes roughly symmetrical around the smoothed curve, the very sharp peaks are lost, and the maximum deviation from the smoothed response becomes is reduced slightly, from about 0.2 to about 0.1 mV/Oe.

It is difficult to determine from simple inspection if there is any additional variance near the peaks of $\chi''_V(H)$ above the background noise of the low-field susceptibility data ($H_{\rm ac} = 0.1$ mOe). We proceed by fitting the response to a smooth curve, presumed to represent the ensemble average response. If the peak in $\chi''_V(H)$ is fit with a seventh-order polynomial, the residual variance from the fit is 1.25×10^{-3} (mV/Oe)^2. (This result is not significantly changed by using an eighth-order fit.) The same analysis using a linear fit near 1.4 Oe gives a background variance simply because of measurement noise of 0.69×10^{-3} (mV/Oe)^2, with that value also insensitive to the order of the fit. Thus, the extra variance around the smooth fit near the peak in $\chi''_V(H)$ is 5.6×10^{-4} (mV/Oe)^2. Normalizing by the square of the response gives a fractional variance about the mean of 3×10^{-3} at an ac field of 0.1 mOe rms.

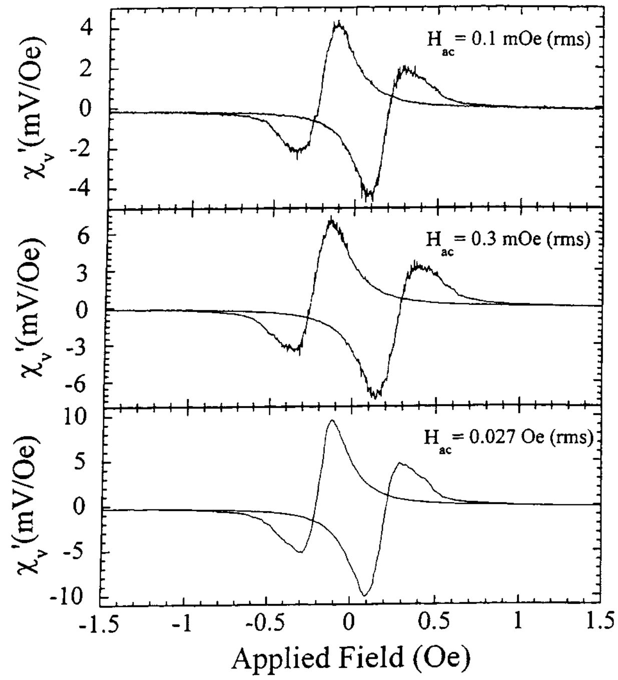

Fig. 3. $\chi'_V(H)$ for ac fields of 0.1 mOe, 0.3 mOe, and 0.37 Oe (rms).

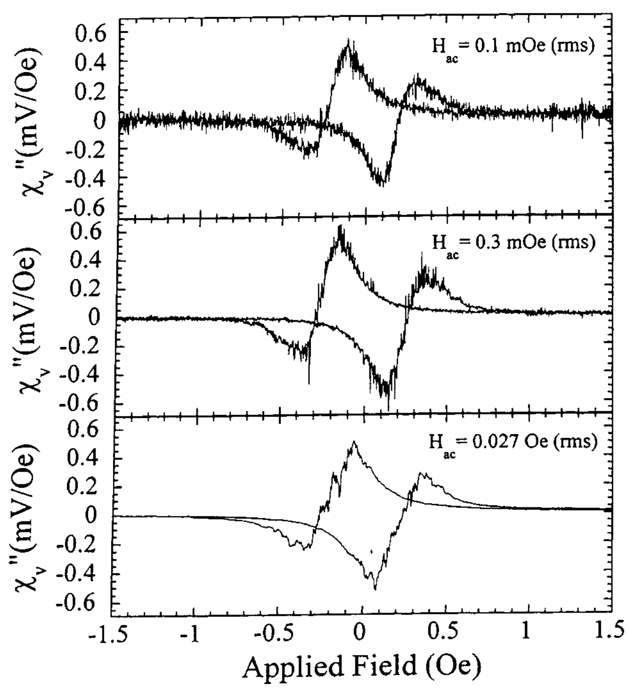

Fig. 4. $\chi''_V(H)$ for ac fields of 0.1 mOe, 0.3 mOe, and 0.37 Oe (rms).

Inspection of the overall magnitude of $\chi''_v(H)$ shows only very weak nonlinearities. However, both the dependence of the fine structure of $\chi''_v(H)$ on $H_{\rm ac}$ and the weak, but unmistakable, nonlinearity in $\chi''_v(H)$ suggest that the true linear response might differ from the response measured at 0.1 mOe. Therefore, it is useful to probe the linear response via noise.

Fig. 5 shows the power spectra of the fluctuations in the bridge voltage collected at dc fields of 1.5 and 0.06 Oe. The

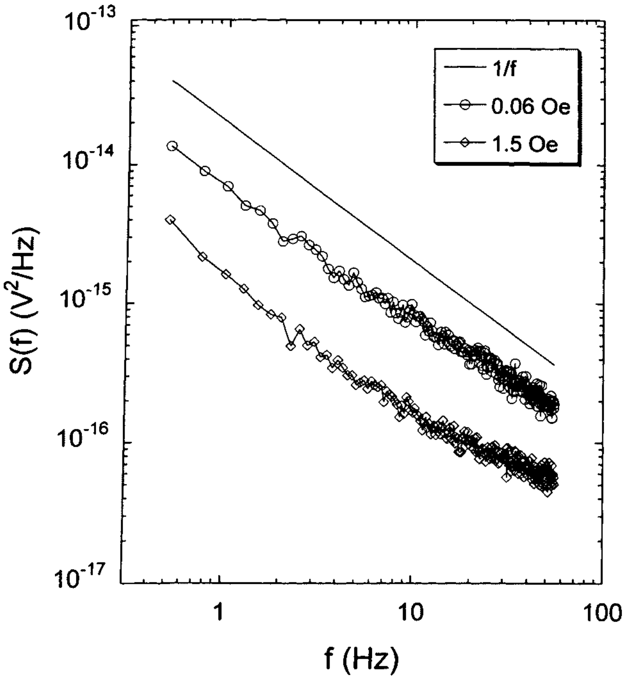

Fig. 5. Power spectra of the fluctuations in the bridge voltage collected at dc fields of 0.06 Oe and 1.5 Oe. The solid line indicates $S(f) \propto 1/f$. The Johnson noise for this device is approximately 4.0×10^{-17} V^2/Hz.

TABLE I
THE FRACTIONAL NON-GAUSSIAN TEMPORAL VARIANCES AND COVARIANCES OF THE NOISE POWER IN FOUR OCTAVES (WITH THE CENTER FREQUENCY OF THE HIGHEST OCTAVE AT 35 Hz)

	OCT 2	OCT 3	OCT 4	OCT 5	OCT 6
OCT 2	0.041				
OCT 3	0.060	0.050			
OCT 4	0.036	0.048	0.044		
OCT 5	0.027	0.029	0.034	0.033	
OCT 6	-0.002	0.029	0.037	0.038	0.065

Johnson noise spectral density for this device is 4.0×10^{-17} V^2/Hz, and this background has not been subtracted from the spectra presented. The excess noise spectra fall off nearly as $1/f$. The magnitude is larger for $H_{\mathrm{dc}} = 0.06$ Oe, where dV/dH is large, as in several prior works [4]–[6], [8], [9] indicating that the noise primarily develops from the same magnetic degrees of freedom responsible for the GMR response. Because half the sample lies outside the flux concentrators, its magnetic noise is not fully suppressed at the 1.5-Oe applied field.

Table I shows the fractional variances and covariances of the noise power in five octaves, with the Gaussian variance subtracted out [11]. There is statistically significant variance above the Gaussian value (which ranges from 0.08 to less than 0.01 in the octaves chosen), with the average excess fractional variance being approximately 0.04. That indicates that the noise is coming from a small number of sites.

Fig. 6 shows the power of bridge voltage fluctuations at harmonics of a 4-Hz driving frequency as a function of ac field. The magnitudes of the harmonic content at different harmonics change unpredictably for small changes in the ac field, an indication of the practical drawbacks of a sensor that has a highly uneven response as a function of field.

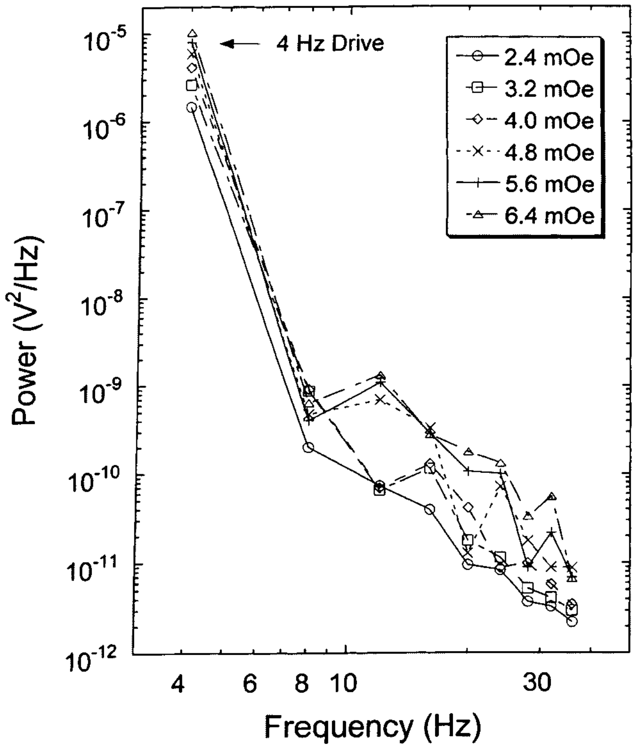

Fig. 6. Noise power at harmonics of the 4 Hz ac magnetic field frequency for several ac field magnitudes.

IV. ANALYSIS AND DISCUSSION

The noise statistics allow an approximate calculation of the number and typical size of the domain realignments contributing to the linear response at a given field. If n is the density, per factor of e in characteristic frequency and per k_BT in free-energy asymmetry (where k_B is Boltzmann's constant and T is temperature), of the two-state systems contributing to the $1/f$ noise, the excess fractional variance is approximately $0.02/n$ [11] with an uncertainty of about a factor of two depending on details of the model. Thus, we obtain, near the response peak, $n \approx 0.5$. Using the relation $fS_V(f) = n\langle(\delta V)^2\rangle$ [11], where δV is the bridge voltage change for an individual realignment, we obtain an rms value: $\delta V \approx 1.4 \times 10^{-7}$ V, involving realignment of 3×10^{-5} of the material in the legs of the sample, including about 6×10^{-16} cm^3 of magnetic material. The magnetic moment change in each realignment would then be about 1×10^{-12} emu, if the fluctuating region only consisted of material in the legs. A local field between the flux concentrators of 40 mOe, or an external field of 2 mOe, is sufficient to change the free-energy asymmetry between the two magnetic states of such a metastable region by k_BT so that each such region would be expected to contribute to the ac response only over a range of about 8 mOe (full-width at half-maximum) in H. This 8 mOe would also give the minimum field range over which the response would be nearly linear.

The 8-mOe field scale calculated above assumes that the domains are in the sample legs within the concentrators, and that the remainder of the sample does not significantly affect the field change seen by the domain when the external field is changed. Of course, realignment of domains within the pads at the ends of the legs also serves to increase the effective field changes within the leg, decreasing the characteristic applied-field scale. In effect, inclusion of pad magnetism increases the magnetic size of the fluctuators, without increasing their transport effects correspondingly.

The spikes observed in the response correspond to somewhat larger domains, at least 1.6×10^{-15} cm^3, assuming that the response comes from domains within the legs, not the wide pads (with lower current density) connecting the legs. The magnetic moment change associated with one spike would then be approximately 2×10^{-12} emu. The width of these spikes is less than or equal to the resolution of the measurements, 1.5 mOe, also implying that the spikes are from domains nearly an order of magnitude larger than the typical ones contributing to the noise and linear response, independent of the location of the domains. Thus, there are definite effects of nonlinear slightly hysteretic response even at external fields as low as 0.3 mOe. However, the product of the internal field and the minimum inferred domain moment would then only be approximately 10^{-14} ergs, well under the thermal energy k_BT and, thus, insufficient to give hysteretic response. Thus, it appears that the response spikes at least are from domains significantly larger than would be expected if they are located in the high-current-density legs. If these same responses were to arise in the larger pads, where the current density is about an order of magnitude smaller than in the legs, they would involve magnetic regions some two orders of magnitude larger, and could easily be hysteretic at the ac fields used.

Somewhat more subtle arguments must be used to extract information about the domains for which individual response spikes are not evident. The variance from the ensemble average determined for the out-of-phase response at 0.1 mOe can be used to estimate a density of domains contributing to the response in the range for which no spikes are evident, if we assume that the nonlinear response is approximately the superposition of a number of independent few-state contributors. We obtain about $n \approx 5$, which is smaller than is the corresponding density determined from noise statistics, suggesting that the response may include effects of some larger domains that do not contribute to the noise and to the true linear response. However, both estimates involve assumptions about how much of the variance appears in a time-averaged measurement $(\chi_v''(H))$ versus how much variance appears in successive measurements over time at fixed field (the noise statistics) [11], so that this discrepancy cannot be taken as conclusive evidence that the response at 0.1 mOe has sources other than those of the noise.

The noise spectrum may be related to the linear out-of-phase response by the fluctuation–dissipation theorem, if we make the simplifying (and not completely accurate) assumption that the resistance is a unique function of the magnetization, independent of which particular domains have which alignment [4]. Deviations from that assumption lead to noise bigger than that predicted by the fluctuation–dissipation argument [4]. Without repeating the derivation and calculation [4], we find here that the measured noise is smaller than that predicted by a factor of about 20, if the effective sample volume is assumed to be the volume of the narrow legs that contribute most of the resistance. That assumption would be appropriate if the susceptibility were uniform and linear throughout the material, and the fluctuations in different regions independent on a length scale of a few microns. If the sample volume is instead assumed to include the pads between the narrow legs (as would be appropriate if the magnetization changes in the connecting pads were highly correlated with the changes in the legs), the effective magnetic moments entering into the calculated response would be increased an order of magnitude, but the noise would scarcely change, because of the low current density in the pads. The resulting noise expected from the fluctuation–dissipation calculation would still exceed the observed noise by about a factor of two. Thus, there is good indication to believe that even at the smallest applied fields used, the response had not yet reached the linear limit corresponding to the noise. The most likely reason why the noise is lower than would be expected from a fluctuation–dissipation relation is that the measured out-of-phase response includes some nonlinear, weakly hysteretic response from the pads, even at the lowest ac fields used.

In conclusion, we have shown that by combining equilibrium noise measurements, including determination of non-Gaussian statistics, with detailed response measurements at low excitation fields, we may distinguish the response from slightly hysteretic domains from the true linear response and characterize the size of the magnetic regions involved in each of the different types of response. The small-signal ac response of these sensors is strongly dependent on the geometry of the resistors, with distinct contributions from narrow legs and square pads. If a smooth, linear, not very hysteretic response is desired, elimination of the pads (i.e., replacement with nonmagnetic metals, as in newer versions of this type of bridge sensor [12]) would be beneficial.

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