Low-Frequency Noise in NiFe/Cu Spin-Valves

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***Abstract*—We report one of the first observations of low-frequency noise of NiFe/Cu spin-valves. Although the observed noise is very low in comparison to multilayer systems, it is typically concentrated in the linear response region where such devices are expected to operate. Increased noise is also associated with Barkhausen jumps in the magnetoresistance trace. In devices one micrometer high, structures start to appear in the noise spectra as a perturbation to the simple 1/*f*-like noise observed in larger devices.**

INTRODUCTION

Although the large magnetoresistance of spin-valves make them attractive as magnetic read heads, this same sensitivity could also make them susceptible to thermally activated noise. Due to processing effects, edge effects, and nonuniformities in the layer structure, there may be regions in a spin-valve that are weakly coupled to the main part of the device which could give rise to 1/*f* noise. These regions may be thought of as consisting of domains which are distinct from and in addition to the "single domain" of an ideal spin-valve. Additionally, due to strong magnetostatics, microdomains may also show 1/*f* noise which is correlated with Barkhausen noise. In particular, as linear response is sought in sub-micrometer devices, either of two scenarios could result in increased noise. Domain sizes may be expected to decrease with a possible corresponding increase in their sensitivity to thermally driven noise. Alternatively, if domain sizes remain constant, unstable domains could come to dominate small device behavior.

We have pursued observations of 1/*f*-type noise in NiFe/Cu spin valves. The noise we observe is typically concentrated near the low-field linear response region. The noise does not scale in an obvious manner with device height. We also find peaks in the noise near Barkhausen jumps in the magnetoresistance (MR) curve. These peaks may arise from thermally driven fluctuations of the large domain responsible for the Barkhausen resistance jump.

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EXPERIMENT

Our spin-valves are fabricated from $Ni_{80}Fe_{20}$ (7.5 nm)/Cu (3.0 nm)/$Ni_{80}Fe_{20}$ (7.5 nm) films grown on $Si/Al_2O_3/Ta$ substrates using sputter deposition and are pinned with FeMn (10 nm) and capped with 5 nm of Ta. Growth specifics are described in detail in [1]. Most data presented in this paper were taken on 11:1 aspect ratio stripes of 16 μm to 0.5 μm stripe heights. The devices have active areas of lengths 0.5 to 2 times the stripe height and are connected in a two-terminal geometry. A few devices were measured which were patterned in a four-terminal geometry with an active area length 10 times the stripe height. Magnetoresistance curves were taken with applied DC bias currents ranging from 0 to 5 mA supplied by a very quiet battery driven current supply. An AC excitation current of 1 μA at 1 kHz was used to measure device resistance. A maximum magnetic field of 32 kA/m (~400 Oe) in the plane of the films and perpendicular to the device strip and bias currents was used. Devices were stabilized at a set temperature, typically 312 K, and bias current for 20 to 30 minutes before MR curves were obtained. Voltage fluctuations across the devices were amplified with a low-noise amplifier and measured with a low-frequency spectrum analyzer.

RESULTS AND DISCUSSION

Fig. 1 (a) shows the MR response and its derivative of a 4 μm × 4 μm device with a bias current of 1.90 mA, approximately 5×10^6 A/cm^2. Below, in Fig. 1 (b), is shown the 10 Hz noise amplitude and the 1/*f* slope. The noise is above the level of Johnson noise of the spin-valve (4×10^{-17} V^2/Hz) and is typically 1/*f*-like. Occasionally a larger domain produces a Barkhausen jump in the MR response, which is often correlated with a peak in the noise spectra. We purposefully measured noise at low DC bias currents to avoid any interference of bias current generated self-fields or possible current induced noise with the spin-valve response. The magnitude of the noise in V^2/Hz increased as the square of the DC bias current, indicating that the noise is due to resistance fluctuations in the spin-valve.

We are interested in the origin of the device noise. One possibility is that the device acts as a sensor in the presence of some noisy field and merely shows the noise of that field:

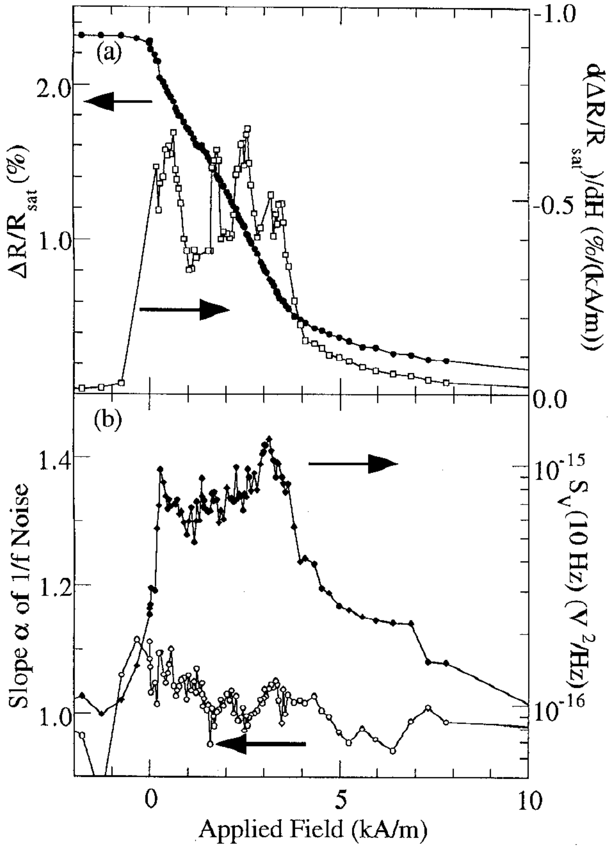

Fig. 1. (a) Magnetoresistance curve (●) from a 4 μm × 4 μm spin valve and its derivative (□). (b) Voltage noise at 10 Hz (◆) and the $1/f$ slope (O) with an applied bias current of 1.90 mA.

$$S_V = I^2\left(\frac{\partial R}{\partial H}\right)^2 S_H = I^2 R_{sat}^2\left(\frac{\partial}{\partial H}\frac{\Delta R}{R_{sat}}\right)^2 S_H. \quad (1)$$

If true, the noise should correlate with the derivative of the MR response. In Fig. 1 (a) the noise response increased markedly in the region where the device exhibited its linear response and also shows good correlation to the derivative of the MR response. However from 4 kA/m to 7 kA/m the MR response's slope has almost flattened, whereas the noise is still appreciable. This indicates that the noise is intrinsic to the devices, not due to the surrounding field environment. The noise also increased near -14 kA/m, the pinned layer switching field, where the pinned layer rotates. The observed noise is similar to that found in the standard operating low-field region, consistent with the hypothesis that the observed noise is due to fluctuations in the orientations of internal magnetic moments. This noise is below that typically found in GMR multilayer systems [2],[3], although acquired at comparable current densities.

Fig. 2 (a) shows the MR response and its derivative with respect to applied field for a 1 μm × 1 μm device with a bias current of 1.00 mA, approximately 1×10^7 A/cm^2. Fig. 2 (b) shows the 10 Hz noise amplitude and the slope of the $1/f$ noise. Although the response has broadened considerably, again an increase in noise is observed under the region of greatest MR response. The increased noise in Fig. 2 (b) does not correlate with the derivative of the magnetoresistance response illustrated in Fig. 2 (a), indicating that the observed noise in this device is not a measure of a magnetically noisy environment.

The correlations between the variations in the $1/f$ slope and the changes in the noise amplitude may be related theoretically by following the treatment given by Dutta and Horn [4]. We may treat the noise of a spin-valve as an ensemble of bistable magnetic domains with a distribution of switching rates. As few as three or four bistable fluctuators yield an ensemble noise which has a $1/f$ appearance. If we assume that the switching rates are thermally activated, this translates into a field dependence for the single fluctuating domain's Lorentzian knee frequency (the -3 dB point in a Lorentzian noise source, above which the noise amplitude decreases as $1/f^2$),

$$f_{knee} = f_0 e^{-mH_{applied}/k_B T}, \quad (2)$$

where m is the magnetic moment of the fluctuating domain. We assume that the domain noise adds to yield a net $1/f$-like noise of the form:

$$S_V(f) = \frac{S_0}{f^\alpha}. \quad (3)$$

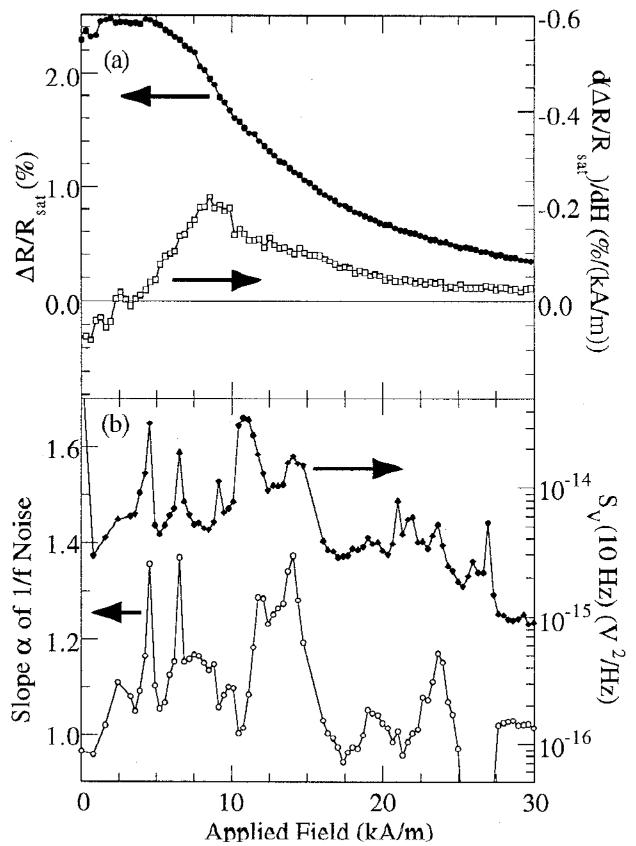

Fig. 2. (a) Magnetoresistance curve (●) from a 1 μm × 1 μm spin valve and its derivative (□). (b) Voltage noise at 10 Hz (◆) and the $1/f$ slope (O) with an applied bias current of 1.00 mA.

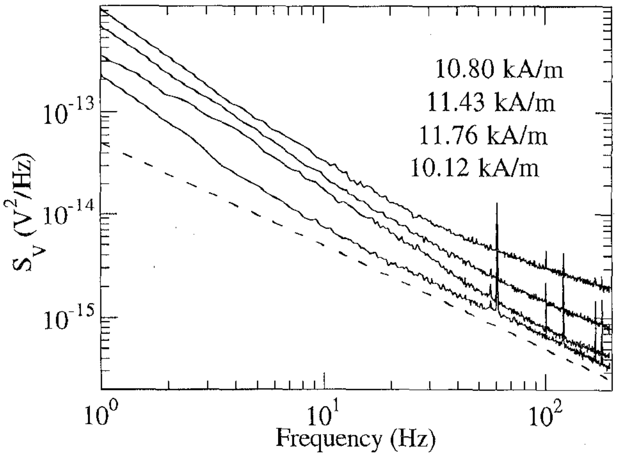

Fig. 3. Several noise spectra of the 1 μm height device shown in Fig. 2. The applied field for each spectrum is stacked in the same order as the spectra. The dotted line indicates a simple *1/f* dependence. A small perturbation to a simple linear *1/f* dependence may be seen.

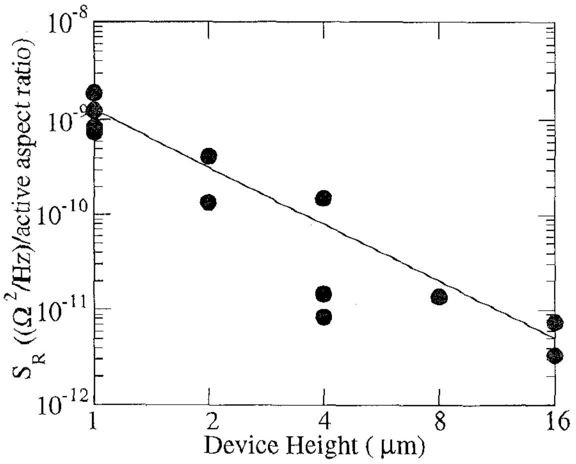

Fig. 4. The 10 Hz noise amplitude per square of material plotted versus device height. The noise points are resistance noise values normalized by the number of squares in each device. An increase in noise with decreasing device height is evident.; the line illustrates a linear decrease with device area.

We may derive a relationship between the slope α of the *1/f* noise spectrum and the amplitude normalized derivative of the noise amplitude with respect to magnetic field at a fixed frequency *f*:

$$\alpha = 1 - \frac{k_B T}{m} \frac{1}{S_v(f)} \frac{dS_V(f)}{dH} \quad (4)$$

Such a treatment of the data in Fig. 1 yields an average domain moment of 2×10^4 Bohr magnetons. We emphasize that this is not the net moment of the spin-valve but is an estimated moment for small fluctuating areas of the device. This treatment is not strictly accurate since the amplitude of each fluctuator's noise also changes with magnetic field, but does yield a good order-of-magnitude estimate.

Fig. 3 shows several typical noise spectra from a 1 μm device height at different magnetic fields. The noise is *1/f*-like, but some smooth structure is apparent. Noise signatures of this type appear with different 1 μm devices and change with applied magnetic field, indicative of a single domain or group of domains fluctuating coherently. We have as yet been unable to separate out the individual contributions, but anticipate that their behavior with applied magnetic field should yield an independent estimated domain size for these fluctuators.

Fig. 4 is a plot of 10 Hz noise magnitude divided by the active area aspect ratio (0.5 to 10) versus device height for 12 different devices. These amplitudes were taken from the high-field region where the spin-valve's response has flattened out. This precludes these amplitudes being skewed by the presence of the noise peaks associated with possible Barkhausen events. The noise magnitudes are normalized by the bias currents to yield resistance noise magnitudes and show obvious decrease in noise with device height. This decrease scales approximately as the inverse of the device area.

Conclusion

NiFe/Cu spin valves larger than 1 μm show average low-frequency noise consistent with their use as magnetic read heads. We have observed significant (100 nV/√Hz) *1/f* noise in several micrometer size devices and find that the noise increases as the reciprocal of the area of the spin-valve. The observed noise is 1 to 2 orders of magnitude less than what we previously observed in discontinuous NiFe/Ag multilayer devices [3] at comparable current densities. We have not measured a statistically large ensemble of devices and cannot characterize whether spin-valve noise is consistent in very small devices or the result of regions of poor NiFe microstructure on a wafer, which would imply that *1/f* noise is a sensitive diagnostic of nanoscale behavior in spin-valves. A number of sub-micrometer size devices should have their noise examined to see if the presence of *1/f* and Barkhausen single-domain type switching noise is a consistent or common feature of such small structures.

References

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