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1/f noise in magnetic $Ni_{80}Fe_{20}$ single layers and $Ni_{80}Fe_{20}$/Cu multilayers

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We have investigated the room temperature 1/f noise of microstructured soft magnetic $Ni_{80}Fe_{20}$ films, showing the anisotropic magnetoresistance effect, and of $Ni_{80}Fe_{20}$/Cu magnetic multilayers, showing the giant magnetoresistance effect. We find that the 1/f noise in magnetic multilayers is considerably enhanced with respect to the noise of the single domain layer, which sets a limit on the usability of giant magnetoresistance materials for low-frequency applications. © *1996 American Institute of Physics.* [S0021-8979(96)00216-2]

The discovery of the giant magnetoresistance (MR) effect in magnetic multilayers in 1988[1] has, since then, triggered a large research effort due to the important industrial application potential of the effect. Indeed, the magnetic field induced relative resistance change in some magnetic multilayer systems was demonstrated to be typically an order of magnitude larger than the so-called anisotropic magnetoresistance effect,[2] which is present in a single magnetic layer and which already has wide applications in the field of magnetic recording and sensing. An important question on the applicability of the giant MR effect is how the noise of these new multilayer systems depends on the frequency. Noise studies on Co/Cu magnetic multilayers[3] already showed that the noise at low frequencies has a 1/f character[4–6] and is a few orders of magnitudes larger, than the noise found in simple non-magnetic metallic thin films. This ''magnetic'' 1/f noise contribution has been described in terms of a fluctuation-dissipation relation for the magnetization, which couples to the (spin-dependent) conductance.[7] It was found that a maximum in noise is observed when the magnetoresistive derivative is maximum, showing that noise and spin-dependent scattering leading to giant MR are closely related.

In this letter, we report on a comparative noise study of microstructured soft magnetic $Ni_{80}Fe_{20}$ films and of $Ni_{80}Fe_{20}$/Cu magnetic multilayers. For both systems, we find that the noise spectral density has a 1/f behavior. For the single films, it is comparable to the noise measured on non-magnetic layers. On the other hand, the 1/f noise in the multilayers can be a few orders of magnitude larger. The huge difference in noise is related to the different magnetic domain state of the samples. Using the Bitter fluid technique, we find that the microstructured single layers have a monodomain state and that the multilayers have a very complex multi-domain pattern.

The samples are grown by high-vacuum magnetron sputtering. The base pressure of the system prior to the deposition is 4×10^{-7} Torr and the Ar presssure during sputtering is 7×10^{-3} Torr. The samples are deposited at a rate of 2–4 Å/s onto Si(100) substrates held at room temperature. Before sputtering, the substrates are *ex situ* cleaned by a HF dip and *in situ* by a 30 min glow-discharge treatment. For the multilayers (with a total thickness of a few thousand Å), we use a Cu buffer layer with a thickness of 200 Å to obtain epitaxial growth with the [001] direction of the face-centered cubic lattice perpendicular to the film.[8] The $Ni_{80}Fe_{20}$ single layers are a few hundred Å thick and are covered with a 50 Å Au layer for protection against corrosion.

The films are microstructured using conventional optical lithography and dry etching techniques (HCl plasma, 4 Pa, 2 W/cm^2). Hall bar structures with a width ranging between 2 μm and 10 μm and a length up to 100 μm are fabricated. The samples are mounted within a mu-metal cage and subjected to magnetic fields generated either by two orthogonal small Helmholtz coil sets or by permanent magnets. Six wire bond contacts are attached to the sample, two for the current supply and two pairs of voltage contacts which are connected to two battery fed ultra low-noise voltage preamplifiers (EG&G Brookdeal 5004). The outputs of the latter are connected to a HP3562A spectrum analyzer for measuring the noise spectrum of the sample using a cross-correlation technique.

We find for all our samples that the 1/f noise increases quadratically with the current through or voltage over the sample, characteristic for a fluctuating resistor. Such behavior was described more than 25 years ago by the following empirical expression:[9]

$$S_V=\alpha\frac{V^2}{fN} \tag{1}$$

with V the voltage over the sample, N the number of free electrons contributing to the conduction process in the homogeneous sample, and α a parameter characterizing the amplitude of the noise fluctuations. Curiously, for a lot of (non-magnetic) material systems it was shown that

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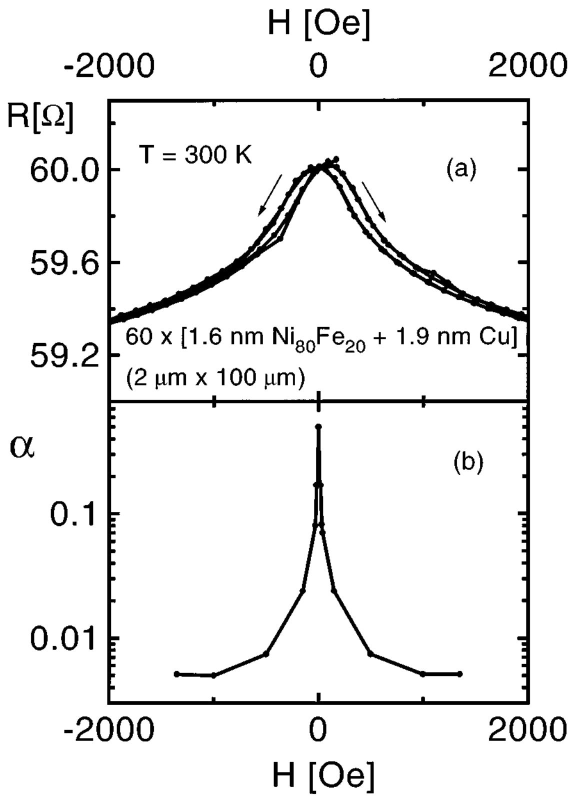

FIG. 1. (a) Room temperature magnetoresistance curve of a 2 $\mu m \times 100$ μm microstructured $60\times$ [1.6 nm $Ni_{80}Fe_{20}$ + 1.9 nm Cu] multilayer. (b) $1/f$ noise parameter α as a function of magnetic field for the same sample. The magnetic field is applied perpendicular to the long axis of the sample.

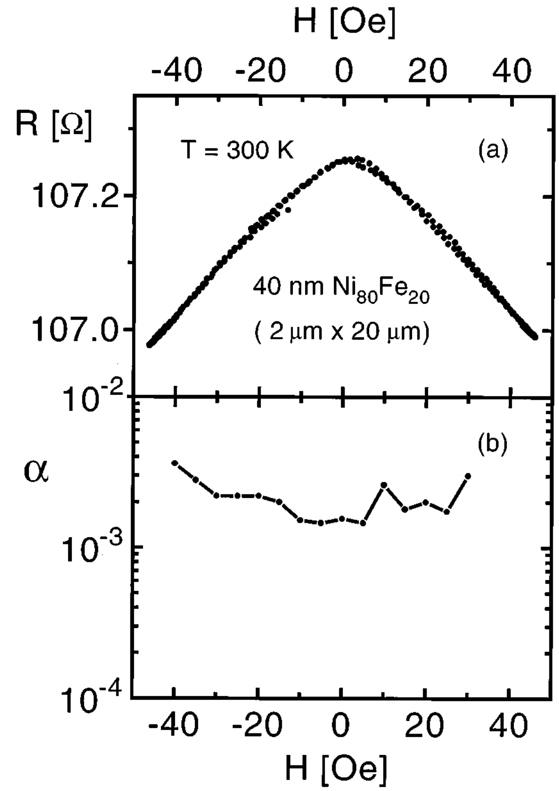

FIG. 2. (a) Room temperature magnetoresistance curve of a 2 $\mu m \times 20$ μm microstructured 40 nm $Ni_{80}Fe_{20}$ layer. (b) $1/f$ noise parameter α as a function of magnetic field for the same sample. A constant field of 20 Oe is applied along the long axis of the sample and the magnetic field perpendicular to that direction is varied.

$\alpha \sim 2\times 10^{-3}$.[4] We will use α in the following of this article as a phenomenological parameter characterizing the $1/f$ noise intensity. N is calculated by taking a ''free'' electron density of 17×10^{28} m^{-3} for $Ni_{80}Fe_{20}$ and 8.5×10^{28} m^{-3} for Cu.

The room temperature magnetoresistance curve for a 60 $\times$ [1.6 nm $Ni_{80}Fe_{20}$ + 1.9 nm Cu] multilayer is shown in Fig. 1(a). This behavior is typical for a $Ni_{80}Fe_{20}$/Cu multilayer in the second antiferromagnetic coupling peak with a partial antiparallel alignment of the magnetizations at zero field.[8] Indeed, magnetization measurements using a vibrating sample magnetometer show that about 1/3 of the volume fraction of the sample is coupled antiferrromagnetically. Figure 1(b) shows for this sample the $1/f$-noise parameter α as a function of magnetic field. The very strong peaked behavior at zero field is immediately clear. The magnitude for α is two order of magnitudes larger than the value found in non-magnetic thin films and is in agreement with noise experiments on Co/Cu multilayers.[3] However a difference is that we find only a single very sharp peak at zero field, nearly independent of the degree of antiferromagnetic coupling in the sample. This makes us believe that the origin for our huge noise peak is not directly related to the giant MR effect, but has to be sought in a very complex magnetic domain structure, as will be shown further on in this paper.

For purpose of comparison, we also have investigated the noise behavior of magnetic single films of $Ni_{80}Fe_{20}$, showing the anisotropic MR effect. A typical room temperature magnetoresistance curve is shown in Fig. 2(a). The magnetic field is applied perpendicular to the long axis of the sample. We should keep in mind that in these narrow samples demagnetization fields in this direction are larger than 100 Oe. At the same time, a biasing field of 20 Oe is applied along the sample axis to induce a magnetic monodomain state; this assures that the magnetoresistance effect shown in Fig. 2(a) is the result from magnetization rotation and not from domain wall motion. Figure 2(b) is the corresponding plot for α and shows a much flatter behavior than found for the multilayer sample. $\alpha \sim 2\times 10^{-3}$ in the field range studied, which corresponds well with the values found for non-magnetic systems.

We also investigated the magnetic domain structure of our samples using the Bitter figure technique.[10] Figure 3(a) shows that a single film of $Ni_{80}Fe_{20}$ has a magnetic monodomain structure with the magnetization lying along the long axis of the thin strip. On the other hand, the multilayer sample of Fig. 3(b) has a very complicated patch-like multidomain pattern, with a μm^2 domain size or smaller. This domain pattern reflects the large number of local magnetic energy minima in the film and seems to be correlated to the large value found for α at zero field. The question is whether this noise is due to domain wall motion or domain orientation fluctuations. As domain wall motions should persist over the entire hysteretic regime observed in the magntoresistance curve, unlike the field scale of the noise, the most probable

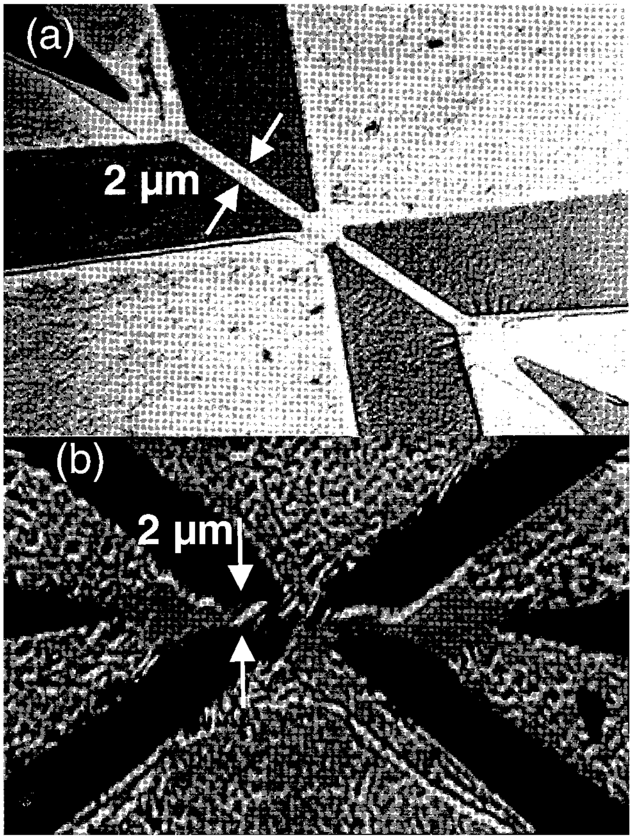

FIG. 3. (a) Bitter figure pattern of a 2 μm×20 μm and 40 nm thick $Ni_{80}Fe_{20}$ single layer, showing that the thin strip has a monodomain structure. (b) Bitter figure pattern of a 2 μm×10 μm 60× [1.6 nm $Ni_{80}Fe_{20}$ + 1.9 nm Cu] multilayer, showing the very complex multidomain structure.

process for the noise at very low fields is rotation of multilayer domains, as was already suggested in Ref. 7. At higher fields all magnetization vectors tend to be oriented along the field direction, a process which is accompanied by a strong noise reduction, reaching values found for non-magnetic thin films. We are not aware of domain size studies for the Co/Cu layers of Ref. 3, but a difference in magnetic anisotropy together with the large magnetoresistive anisotropy of $Ni_{80}Fe_{20}$ could offer an explanation for the differences between the two systems. When comparing the multilayer and single layer samples, it is clear that we have found a strong correlation between 1/*f*-noise and the magnetic domain state of the sample. Although the magnetoresistive output of multilayer samples may be larger than the output of single layers, it is clear that a discussion of the noise properties of these systems is very relevant for choosing the optimum structure for low-frequency sensing applications.

In conclusion, we have reported noise experiments on microstructured sputter deposited $Ni_{80}Fe_{20}$/Cu multilayers and $Ni_{80}Fe_{20}$ single layers. We find for the multilayers a large 1/*f*-noise and a complicated magnetic multidomain structure. For the monodomain single layers we find a reduced 1/*f*-noise, comparable to the noise of non-magnetic systems. We have found indications that a complicated magnetic domain structure in the multilayer samples is reflected by a large value of the 1/*f*-noise.

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