Statistical Properties of Barkhausen Noise in Thin Fe Films

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The statistical properties of Barkhausen noise in an epitaxial Fe film grown on MgO have been characterized with magneto-optical Kerr effect measurements. The data reveal that magnetization reversal takes place via sudden jumps between a discrete number of randomly distributed magnetic configurations. The smallest jumps occur on a scale length of 10 μm and their amplitude distribution can be fitted with a power law: $P(\Delta M) = \Delta M^{-\alpha}$ with $\alpha = 1.1$ and ΔM spanning over several decades.

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Magnetization reversal in ferromagnetic solids takes place via discrete jumps. If, during this process, a pickup coil is placed near the sample a characteristic noise is induced in the coil by the random changes of the magnetic flux. This noise is called Barkhausen noise (BN) from the name of the scientist who made its first observation [1], whereas the individual jumps are known as Barkhausen jumps (BJ). Generally speaking, a magnetic solid under the action of an external field belongs to a larger class of physical systems whose common feature is a strongly nonlinear and dissipative behavior in the presence of a structural disorder. Among the numerous examples, it is worth mentioning flux lines in type-II superconductors [2], microfractures [3], earthquakes [4], and liquid crystals in porous media [5]. Even though a unifying theory for this class of physical systems is far from being formulated, a distinctive feature is always observed: the presence of scaling behavior for certain measurable quantities. In the case of BN, scaling is shown by the probability amplitude of the jumps that appear to be linear in a log-log plot over several decades. The presence of scaling in BN attracted the interest of statistical physicists, and several models have been proposed with different underlying physical assumptions and varying fortune in explaining the experimental observations [6–10] (for a more complete review, see Ref. [6] and references quoted therein).

The experimental technique normally adopted in BN measurements is based on the same principle of the original work of Barkhausen, i.e., magnetic flux variations connected with BJ are detected with an inductive pickup coil wound around the sample. The voltage signal across the coil consists of a series of peaks having random amplitude and duration. Modern electronics and computer driven data acquisition allowed the collection of a larger amount of high quality data, thereby making possible a systematic investigation of the statistical properties of this phenomenon. A drawback to the inductive technique is that it is intrinsically unable to assign a precise spatial location to each pulse. Another limitation is the relatively low sensitivity of the inductive technique, which prevented its systematic application to thin films and magnetic microstructures with only a few exceptions [11].

In this paper, data collected with a recently developed experimental technique will be presented. This technique overcomes the major limitations of the standard pickup coil since it is space resolved an sufficiently sensitive for thin films. The basic layout of the apparatus is shown in Fig. 1. Briefly, a conventional ellipsometer for magneto-optical Kerr effect measurements (MOKE) has been modified by introducing a focusing optics which allows one to vary the size of the laser beam onto the sample from 10 μm to several mm [12]. The high noise rejection of the system allows the measurement of individual hysteresis loops in 1 s or less with a good signal-to-noise ratio. A typical data acquisition consists of a series of 1000 loops measured one after the other at a frequency of 1 Hz. The sample [13] is an epitaxial Fe film having a thickness of 900 Å. The substrate is a single crystal of MgO (001) heat treated in vacuum in order to observe a sharp (1×1) LEED pattern characteristic of the bulk-terminated lattice. The Fe evaporation has been performed in a vacuum chamber with a base pressure of 5×10^{-11} Torr at a rate of 10 Å/min. The films' thickness has been measured with a quartz microbalance, and purity has been checked with x-ray photoelectron spectroscopy and Auger spectroscopy. Magnetization is in the

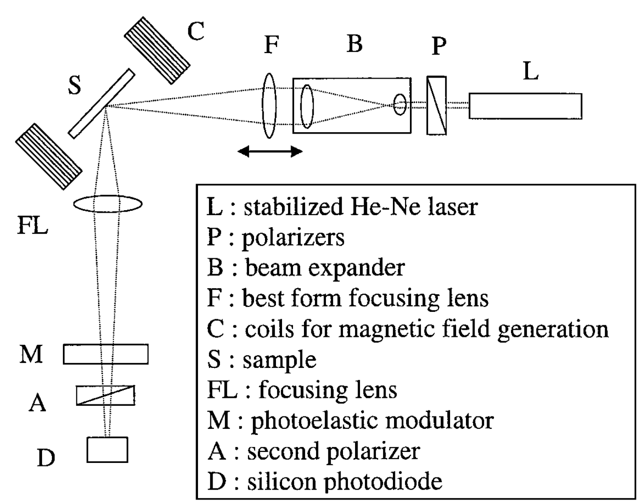

FIG. 1. Optical setup. The field generated with two coils in air is measured with a Hall probe (not shown).

plane of the film, and the loops have been measured with the external field parallel to the sample surface. A selection of four loops, measured one after the other with a spot size of 100 μm, is shown in Fig. 2. The values of magnetization at saturation have been arbitrarily set equal to -50 and 50 (arbitrary units) and therefore the overall magnetization reversal in a single loop is, by definition, equal to 100. The most visible characteristic of these loops is the presence of steps whose amplitude and field position randomly fluctuate by repeating the cycle measurement: It is obvious to relate these jumps to the usual Barkhausen jumps. The presence of sudden magnetization reversals has already been pointed out in magneto-optical experiments. In one of these works, BJ during domain wall motion in thin films with perpendicular anisotropy are described [14] and information is extracted on the spatial distribution of the wall pinning sites and their corresponding pinning times. In another paper [15] the wall dynamics and the pinning mechanisms in thin Fe films with in-plane magnetization have been investigated. In particular, Ref. [15] describes sudden magnetization reversals observed in the Kerr signal during magnetic relaxation.

From a series of 1000 loops, such as those shown in Fig. 2, it is possible to extract the probability distribution that a jump with a certain amplitude will occur. The amplitude (ΔM) of a single jump is simply defined, as shown in Fig. 2. In a series of 1000 loops several thousand jumps are observed and the histogram of their amplitudes can be drawn. This process has been repeated for different values of the spot size, and the corresponding distributions are shown in Fig. 3. The vertical axis of each curve is simply

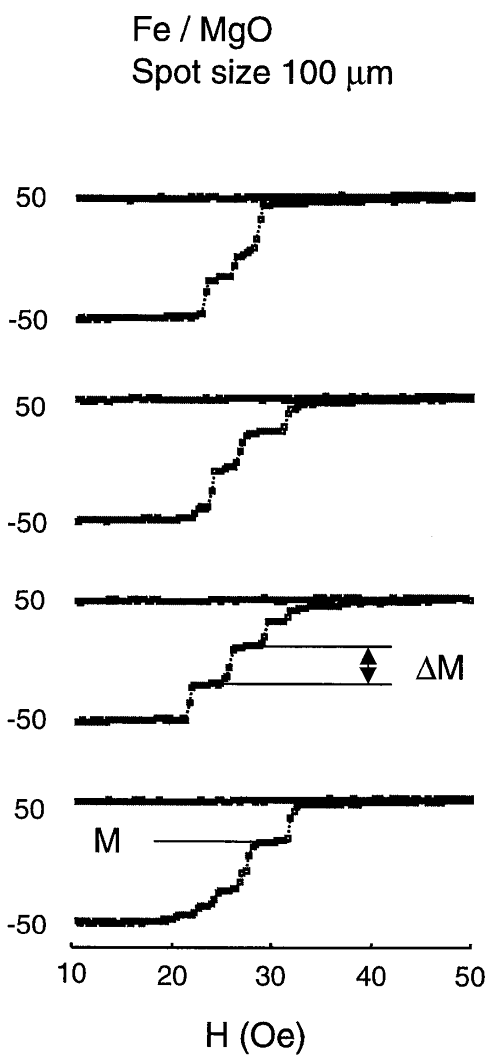

FIG. 2. A series of 4 loops taken in close succession at a frequency of 1 Hz.

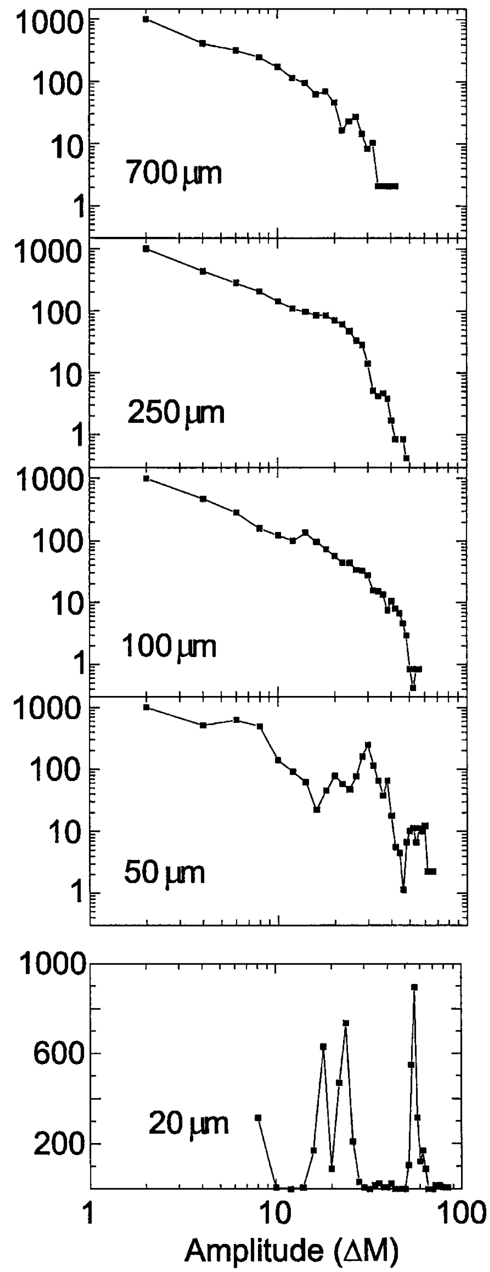

FIG. 3. Statistical distributions of the jump amplitudes for different values of the spot size.

the histogram of the experimental data without any normalization. By reducing the spot size, and therefore the sampled area on the sample surface, the distribution ceases to be a smooth curve and sharp peaks appear. It is important to note that the statistical weight of the various distributions in Fig. 3 is always the same and therefore the structures observed cannot be considered as a noise destined to be wiped out by increasing the number of loops in the series. These structures represent a true physical effect and this is more clearly observed in the lower part of Fig. 3, where the distribution for a spot size of 20 μm is shown. In this case the peaks are well separated and the distribution is truly equal to zero in between. For this reason the distribution has been drawn in a linear-log plot instead of the log-log plot of the other curves in Fig. 3.

In order to explain the presence of sharp peaks in the amplitude distribution another related distribution must be taken into account, i.e., the probability distribution of the values assumed by magnetization in the flat portions of the loops and indicated by M in Fig. 2. When magnetization takes one of these values it remains nearly constant by changing the external field H until a new jump occurs. In other words, these particular values can be regarded as "stable" configurations of the systems, being stability defined as a relatively low sensibility to variations of the external field. By considering the possible values taken by M in a series of 1000 loops with a spot size of 20 μm, the distribution shown in the upper part of Fig. 4 is observed. Also in this case sharp peaks are observed and this indicates that only a discrete number of magnetization values are allowed during magnetization reversal within the area sampled by the laser beam. This experimental observation indicates that BJ are taking place between a discrete set of possible states characterized by a particular value of M. The physical origin of these states has to be found in the random distribution of magnetic pinning sites. This interpretation is confirmed by repeating the same set of measurements with a spot diameter of 20 μm in a different location of the sample surface: The distribution is always peaked but the number, position, and relative intensity of the peaks randomly changes. In this energy landscape the system can only be found, during its magnetization reversal, in a numerable set of metastable states, and each individual jump corresponds to a transition between two of these states. Within this picture jumps will occur only between M values corresponding to the peaks in $P(M)$. The correspondence between allowed M values and jump amplitude is better understood by considering the lower part of Fig. 4, where $P(\Delta M)$ is shown (this is the same curve as in the lower part of Fig. 3). The various peaks are labeled with letters and their ΔM value is indicated. The transitions from which these peaks are generated are shown in the upper part of Fig. 4 and labeled with the same letters used for the peaks. Clearly, all of the peaks in the amplitude distribution have a counterpart in the magnetization distribution and each of them can be associated with a

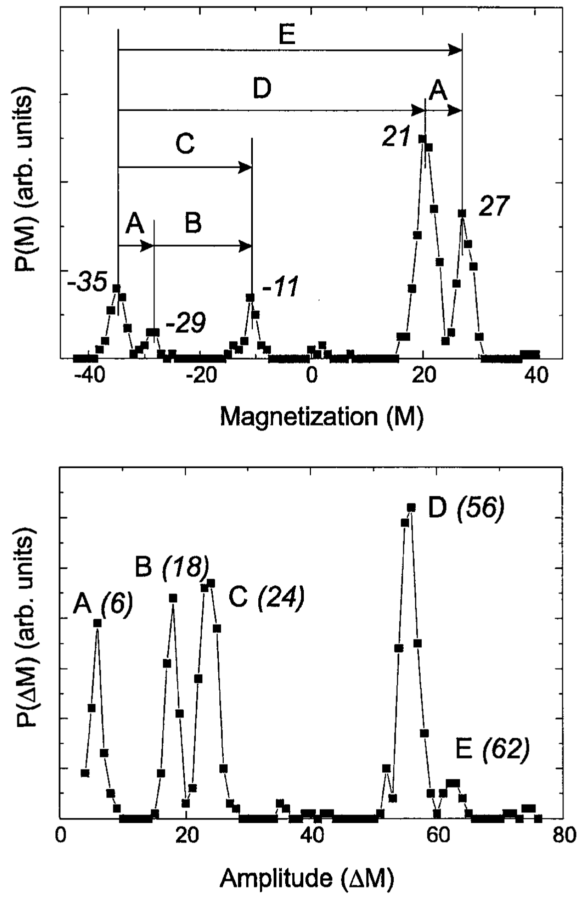

FIG. 4. Lower panel: probability distribution for a spot size of 20 μm. Upper panel: probability distribution of M extracted from the same set of data.

transition between two states, each identified by a particular value of M. This correspondence will be investigated in more detail in successive papers [16].

Returning to the distributions of Fig. 3, it will now be considered how they can be assembled in a unique plot by rescaling the horizontal and the vertical axis in a simple way by taking into account only the spot size. In this way a distribution is obtained which spans over several decades such as those already published in literature and obtained with the inductive technique [17]. Let us first consider the horizontal axis in two arbitrary distributions taken with two different spot sizes, $D_1 < D_2$. A jump ΔM_1 in the first distribution represents the percentage variation of magnetization within an area proportional to D_1^2. The same percentage variation observed in the second distribution, where the sampled area is proportional to D_1^2, will correspond to a real magnetization variation larger by a factor $R = D_2^2/D_1^2$. This correction factor, simply representing the ratio of the sampled area, must be applied to the various distributions. More precisely, the horizontal coordinates must be multiplied times R. On the other hand, let us consider the vertical axis. The number of jumps occurring within a certain area of the sample is

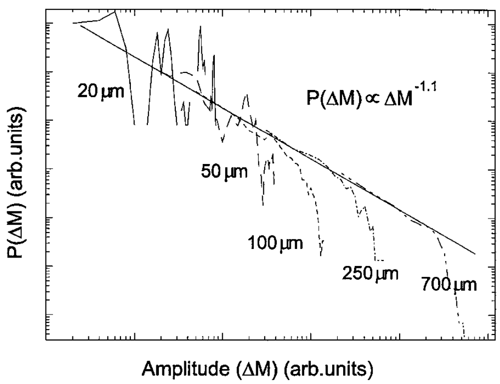

FIG. 5. Overall distribution of the jump amplitudes. This curve is obtained from the data of Fig. 3 by rescaling both the horizontal and the vertical axis (see text).

proportional to the area itself. This trivial observation necessitates that one must correct the probability distribution, actually extracted from the experimental data by making a frequency count, by the same ratio used for the horizontal axis. In this case, R must divide the vertical coordinates of each distribution.

The final result of this rescaling is shown in Fig. 5. Here The different distributions of Fig. 3 are now plotted in a single diagram. The normalization according to the above discussion has been performed by arbitrarily assuming $D_1 = 1$ for the distribution measured with a spot size of 20 μm. The resulting distribution is equivalent to the other already published, where the peak amplitude is defined as the integral over time of the pulse shape measured with the inductive pickup coil. The normalization operation, based only on the spot size without any attempt to fit the various data, brings a series of curves whose envelope, in the log-log plot, defines a rather well-defined straight line whose linearity spans over several decades. The associated power law $P(\Delta M) = \Delta M^{-\alpha}$ is best fitted with $\alpha = 1.1 \pm 0.05$. Data taken with the inductive technique from ribbon shaped samples with a thickness of more than 10 μm indicate a value of the coefficient ranging from 1.3 [6,8] to 1.77 [7]. The only available thin film data [11] indicate that NiFe with a thickness comparable to our sample follows a power law with α around 1.6. In the future it will be interesting to verify if the existing models, successfully applied to bulk samples, can be modified for two-dimensional systems in order to explain the experimental data described here.

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[12] The laser beam is Gaussian and the spot size is defined as the FWHM of the intensity profile. Since the beam impinges on the sample at 45° as shown in Fig. 1, the spot on the beam is nearly elliptical with a major axis larger, with respect to the beam size, by a 1.414 factor.
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[16] Also the saturation region of the loop is flat but this cannot be regarded as a metastable state of the system in the sense used here. For this reason the data shown in Fig. 4 have been filtered in order to eliminate all of those jumps starting or ending in a saturated state. This point must be stressed, otherwise some paradox will emerge from Fig. 4. For instance, the magnetization state corresponding to $M = -11$ would trap the system indefinitely since no jumps are starting from there. In reality, from this state, jumps reaching $M = 50$ (saturation) are observed.
[17] Since the laser spot has a Gaussian profile, a magnetic reversal having a real value ΔM_r (in magnetic units) will produce a measured value ΔM dependent on the location of this reversal on the sample surface. This effect will produce a distortion in the probability distribution $P(\Delta M)$. For this reason the shape of each individual distribution of Fig. 3 is not discussed in detail in this paper. Here the discussion is based on the overall distribution obtained by considering the envelope of the various curves of Fig. 3 and shown in Fig. 5. This approach allows one to neglect the distortion effect related to the Gaussian profile of the beam.