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Magnetic hysteresis and Barkhausen noise in thin Fe films at 10 K

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Abstract
The role of temperature during magnetization reversal in a thin Fe film grown on MgO has been investigated. At a microscopic level the process takes place through jumps whose amplitude ΔM follows a power-law probability distribution: $P(\Delta M) = \Delta M^{-\alpha}$, with $\alpha = 1$ at 300 K and 1.8 at 10 K. During each avalanche, thermal activation does not play a relevant role in the initial overcoming of the potential barrier and therefore the temperature-dependent amplitude probability is related to cooperative effects taking place during the avalanche itself.

The magnetization process in ferromagnets has been extensively investigated. At a macroscopic level the hysteresis loop describes how the overall magnetization of the sample changes under the effect of an external field. This process is normally smooth and reproducible. At a microscopic level, however, the process is discontinuous and random [1, 2] and takes place through a series of jumps which drive the system between different metastable states. This effect has been discovered a long time ago and is called Barkhausen noise (BN) [3]. The physical reason of this random behaviour is the presence of defects, impurities, local stress, and so on, which act as pinning sites for the domain walls. Since its discovery, BN has been extensively investigated with the major aim of interpreting its statistical properties and to create a bridge between the macroscopic and the microscopic picture of the magnetization process. In recent years the interest for BN extended well beyond the field of magnetism since it is a relevant example of complex systems (see [4] for an extended review on complexity and the role of BN in this field). One of the most striking features of BN, shared with many complex systems in the so-called 'critical' state, is that the amplitude ΔM of the magnetization jumps has a probability distribution $P(\Delta M)$ which follows a power-law behaviour over several decades. In other words, the distribution is linear in a log–log plot and can be interpolated with a simple exponential law: $P(\Delta M) = \Delta M^{-\alpha}$. In order to explain the value of the critical exponent α observed in BN experiments different models, based on different approaches, have been developed. A comparison between their predictions and the experimental observations can be found in [4].

All the models for BN presented until now refer to zero temperature whereas all the experimental data on BN have been obtained at room temperature. More generally, in the field of complex systems we are aware only of two works in which the role of temperature is discussed within the framework of self-organized criticality [5]. The models described in these two works bring two contradicting results [6, 7]. The need for experimental data on BN at low temperature, i.e. in a situation closer to the available theoretical predictions, is therefore strong.

In the present paper we present experimental data on the statistical properties of BN in a thin Fe film at different temperatures. It will be shown that the effect of temperature is strong and the observed values of the critical exponent α change from $\alpha = 1$ at room temperature to 1.8 at 10 K. Let us first summarize the available knowledge on the role of temperature in magnets when they are observed at a macroscopic scale. In this situation it is well established that the coercive force H_c is strongly affected by temperature. A model which explains this effect in terms of wall motion in a disordered medium has been proposed [8]. In this model the wall is pinned by a potential well from which it can escape due to thermal motion. The model predicts that H_c depends on T according to the following law: $H_c^{1/2} = H_{co}^{1/2}(1 - CT^{2/3})$, where C is a constant depending on the size and shape of the potential well and H_{co} is the coercive force at zero temperature [8].

Our experiment consisted in a measurement of BN in a thin Fe film grown on MgO. The recently introduced experimental technique is based on the magneto-optical Kerr effect [9] and has been already used for room temperature investigations of BN in thin films [10] and magnetic microstructures [11]. The measurements have been conducted with a magneto-optical Kerr ellipsometer whose sensitivity allows us to perform the acquisition of a hysteresis loop in 1 s or less with a noise level of the order of 10^{-3} times the overall width of the loop [9]. The sample has been mounted on a cryostat in order to change its temperature from 10 to 300 K. In our experiment a stream of 5000 loops has been measured at each temperature. Each loop has been taken by sweeping the field with a triangular wave at a frequency of 0.1 Hz. During the acquisition of each stream the laser beam has been kept in a fixed position on the sample surface and also the size of the laser spot has been fixed to a particular value. Different streams have been collected with a spot size ranging between 20 and 500 μm[1].

The sample [12] is an epitaxial Fe film 900 Å thick. 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. Fe has been evaporated in a vacuum chamber with a base pressure of 5×10^{-11} Torr at a rate of 10 Å min^{-1}. The film's thickness has been measured with a quartz microbalance and purity has been checked with XPS and Auger spectroscopy. Magnetization is in the plane of the film and the loops have been measured with the external field parallel to the sample surface.

The macroscopic behaviour of our sample versus temperature is summarized in figure 1. The filled dots in the upper part show the average loop at 300 K, simply obtained by adding all the data of a stream taken with a spot diameter of 100 μm. The empty dots of figure 1 show the average loop measured on the same sample region at 10 K. Clearly, the coercive force increases as expected. The relationship between H_c and T is shown in the lower part of figure 1 where the square root of H_c is plotted versus $T^{2/3}$. This linear trend confirms that, on a macroscopic scale, the coercive force depends on temperature according to the model described in [8]. This is consistent with the microscopic picture of the magnetization process in our sample where the domain walls jump between randomly distributed pinning sites [10].

[1] The Gaussian laser beam impinges onto the sample surface at an angle of 45° off-normal. Therefore the actual shape of the spot is elliptical and the value of 100 μm refers to the minor axis.

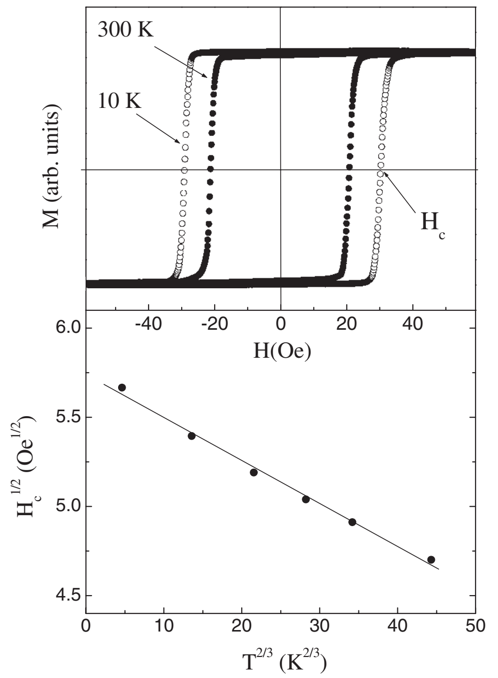

Figure 1. Upper panel: average hysteresis loops at 300 K (filled dots) and 10 K (empty dots). Lower panel: temperature dependence of the coercive force. The linearity in this plot indicates a functional dependence as predicted by [4].

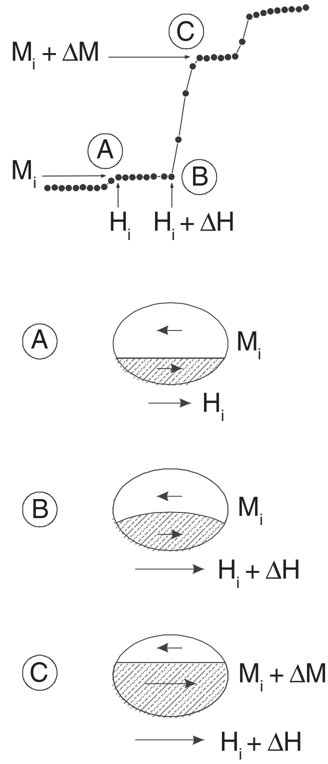

Figure 2. Example of a loop showing magnetization jumps. It illustrates the evolution of the systems between three states A, B and C (see the text for a detailed discussion).

As already stated, at variance with the average loop, each individual loop of the series presents fluctuations, as shown by the experimental points in the upper part of figure 2 [10] which illustrate the upper branch of a typical loop measured at room temperature with a spot diameter of 100 μm. Under the effect of the applied field, magnetization evolves through a series of jumps separated by flat regions. These steps are not deterministic and randomly change by repeating the loop measurement. At 10 K fluctuations are still observed, but the amplitude of the steps appears to be, on average, smaller with respect to the highest temperature situation.

A statistical analysis of these magnetization fluctuations can be performed by considering the relevant parameters of the steps. In this work our attention is focused on two of these parameters, ΔH and ΔM, both illustrated in figure 2. The physical meaning of these two quantities can be better understood by considering the evolution of magnetization at an increasing field. Let us start from a system configuration such as the one represented in figure 2 by point A. This point corresponds to a metastable equilibrium position reached by the system during its jumpy evolution and is pictorially represented in the lower part of figure 2. The ellipses represent the area sampled with the laser beam. Within this area a fraction of the sample magnetization is already aligned with the external field whereas the other fraction is still opposing the field. The metastability of this state is determined by the presence of pinning sites that determine a local minimum in the energy landscape. By increasing the value of the applied field the system remains in this state and the only effect produced is a bowing of

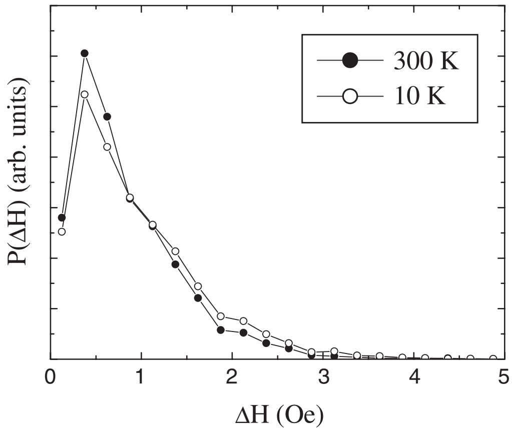

Figure 3. Probability distributions of ΔH (see figure 2 and the text for details).

the domain wall. This situation lasts until a particular value of the applied field is reached, as indicated by point B of figure 2. At this stage the energy of the system is sufficient to overcome the potential barrier and a jump occurs which brings the system into a new metastable state labelled by C in the figure. The extra field necessary to produce the wall depinning is ΔH. The amplitude of the avalanche which brings the system from point B to point C is ΔM.

The statistical distributions of ΔH and ΔM are shown, respectively, in figures 3 and 4. Figure 3 shows $P(\Delta H)$, the probability distribution of ΔH at two different temperatures, 300 K (filled dots) and 10 K (empty dots). The probability distribution of ΔM at two different temperatures is shown in figure 4. The experimental procedure adopted for obtaining the curve of figure 4 is described in detail in [10]. Here we note that this procedure allows us to obtain reliable experimental data spanning over several decades of ΔM. In both cases the experimental curve is nearly linear in a log–log plot and therefore can be fitted with a power law: $P(\Delta M) = \Delta M^{-\alpha}$. The critical exponent has a value $\alpha = 1$ at 300 K and 1.8 at 10 K. In other words, at both temperatures the statistics is still described by a power law, but the different values of the critical exponent indicates that, on average, the size of the jumps increases with temperature. More precisely, the occurrence of large jumps is favoured at higher temperatures. In this connection we observe that the upper distribution shown in figure 4 is obtained by convoluting different curves, each having a well defined cut-off. This cut-off is due to the finite size of the region defined by the laser spot on the sample surface. In the lowest distribution this cut-off is not present and this is another indication that large jumps, i.e. whose size is comparable to or larger with respect to the spot size, are much less favoured at lower temperatures.

As already stated, the accepted view of the magnetization process is schematically represented in figure 2 where the system evolves through a series of jumps between different metastable states. Each of these states has a relative stability and, in order to escape to make a jump to another metastable state, the system must overcome an energy barrier. In BN experiments the escape from the initial state is determined by the increasing applied field ΔH. A simple model has been presented [13] which explains the shape of $P(\Delta H)$. In this model a magnetic dipole mimics the complex magnetic system initially trapped in a potential well such as case A of figure 2. This dipole senses a local field H_{loc} which, in turn, is the sum of three different magnetic fields. The first is the field experimentally generated, ΔH, which will be assumed to be positive. Since the dipole is in a metastable configuration, a pinning field

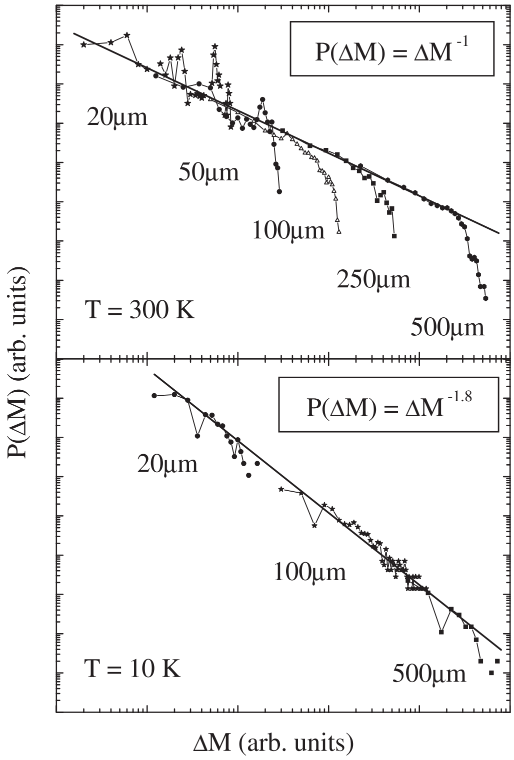

Figure 4. Probability distributions of ΔM (see figure 2 and the text for details).

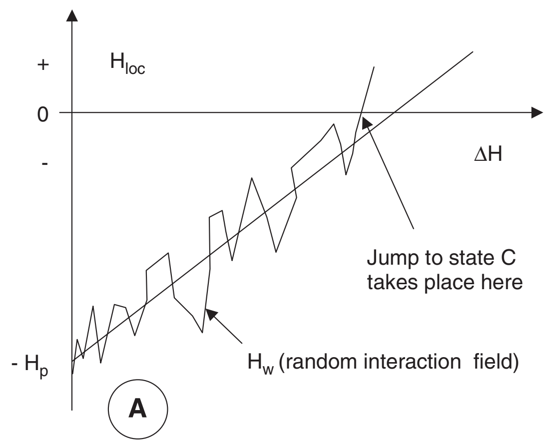

Figure 5. Pictorial representation of the stochastic process which brings the system from one metastable state (such as A in figure 2) to another (such as C).

H_p is also acting. The value of this field is negative (in opposition to the external field ΔH). Finally, the dipole interacts with the rest of the sample via an interaction field H_w. Since this field depends on the configuration of the whole sample, i.e. on the orientation of all the other dipoles, it is a random field which suddenly changes any time a Barkhausen jump takes place within the sample. In summary:

$$H_{loc} = \Delta H + H_w - H_p.$$

A pictorial representation of the escape from the potential well is shown in figure 5. The initial value of the local field is $-H_p$ and the system will leave the well when the field increases above zero. With no interaction field ($H_w = 0$) the process is deterministic and a single value of ΔH would be observed, the one corresponding to the intersection between the horizontal axis and the straight line which represents the experimental ramp in ΔH. The presence of a random interaction field is responsible for the spread in the observed values of ΔH. The distribution $P(\Delta H)$ therefore depends both on H_p and on H_w, i.e. on the parameters which characterize the escape process.

The data in figure 3 show that $P(\Delta H)$ does not depend on temperature and this observation can be interpreted by saying that the escape of the system from the potential is weakly influenced by temperature. After the system has overcome the energy barrier a complex chain of events eventually brings the system to a new metastable state. It is hard to model this avalanche but our data indicate that it is at this stage of the process that the thermodynamic temperature plays its role by determining the statistical properties of the avalanche size. Trying to interpret the details of this behaviour in terms of the available theories is beyond our scope. Much work has to be done in this field and our hope is that the present paper will stimulate interest in this argument of the statistical physics community. As a final remark we point out that the observed variation of the critical exponent when temperature changes from 10 K to room temperature is close to the spread of the available theoretical predictions and the experimental data on BN (see, for instance, figure 9 of [4]). This is a strong reason for doing more work on the role of temperature on BN and, more generally, on complex systems.

References

[1] Hubert A and Schafer R 1998 *Magnetic Domains* (Berlin: Springer)
[2] Bertotti G 1998 *Hysteresis in Magnetism* (San Diego, CA: Academic)
[3] Barkhausen H 1919 *Z. Phys.* **20** 401
[4] Sethna J P, Dahmen K A and Myers C R 2001 *Nature* **410** 242
[5] Bak P, Tang S and Wiesenfeld K 1987 *Phys. Rev. Lett.* **59** 381
[6] Vergeles M 1995 *Phys. Rev. Lett.* **75** 1969
[7] Caldarelli G 1998 *Physica* A **252** 295
[8] Gaunt P 1976 *Phil. Mag.* B **48** 261
[9] Puppin E, Vavassori P and Callegaro L 2000 *Rev. Sci. Instrum.* **71** 1752
[10] Puppin E 2000 *Phys. Rev. Lett.* **84** 5415
[11] Callegaro L, Puppin E and Ricci S 2000 *Appl. Phys. Lett.* **76** 2418
[12] Bertacco R, De Rossi S and Ciccacci F 1998 *J. Vac. Sci. Technol.* A **16** 2277
[13] Callegaro L, Puppin E and Zani M 2003 *J. Phys. D: Appl. Phys.* **36** 2036