Dynamic hysteresis in Finemet thin films

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Abstract—We performed a series of dynamic hysteresis measurements on three series of Finemet films with composition Fe$_{73.5}$Cu$_1$Nb$_3$Si$_3$B$_9$, using both the longitudinal magneto-optical Kerr effect (MOKE) and the inductive fluxmetric method. The MOKE dynamic hysteresis loops show a more marked variability with the frequency than the inductive ones, while both measurements show a similar dependence on the square root of frequency. We analyze these results in the frame of a simple domain wall depinning model, which accounts for the general behavior of the data.

I. INTRODUCTION

The physics of thin and ultrathin magnetic films has been extensively studied in the recent past, because of its great importance in several applications, ranging from multilayers to high frequency devices. For this reason, many recent papers have been devoted to measure the magnetization reversal dynamics in two dimensional structures, revealing the existence of universal features and scale-invariant properties of the hysteresis loops [1]–[4]. Despite these efforts, a general description of these features is still an open problem, as most experimental results are still to be interpreted in the framework of the existing models [5]–[8]. In particular, the dynamic hysteresis loop area $A$ is often assumed to scale as $A / H_0^2 T$, where $H_0$ is the amplitude of sinusoidal external field of frequency $!$, $T$ is the temperature, and $\ldots$ three are scaling exponents. As a matter of fact, experimental evaluation of the exponents and in the low dynamic regime spans a quite large range from 0 to 0.8, with a general higher value for thinner films [8], [10] (see also Tab. 1 of [9]). The proposed theoretical models roughly span the same range, so that a clear identification of the fundamental properties of magnetization dynamics seems far to be reached. In order to investigate this complicated problem offering a new perspective, we present a series of dynamic hysteresis measurements on Finemet thin films by using the magneto-optical Kerr effect (MOKE), as employed in all the studies presented in the literature, and the fluxmetric inductive method, using a pick-up coil wound around the sample. This enables us to investigate the hysteresis properties not only considering the magnetization changes of the surface within the laser spot area, but also those of the total volume of the sample; this is particularly important in order to check the dependence of the loop area on the film thickness, and to understand the true nature of the magnetization dynamics. Quite unexpectedly, MOKE hysteresis loops show a remarkable variability with the frequency, about one order of magnitude higher than the inductive ones; on the other hand, both methods give a similar dependence on the frequency. We try to interpret these results with a simple domain wall depinning model which can be solved analytically, giving reason of the general behavior of the data.

II. MATERIALS AND MEASUREMENT METHODS

Films having nominal composition Fe$_{73.5}$Cu$_1$Nb$_3$Si$_3$B$_9$ have been deposited on glass substrates by rf magnetron sputtering under a 5 mTorr Ar atmosphere at room temperature. The sample thickness, ranging from about 21 nm to 5 m, is measured by angle X-ray diffractometry, which also confirms the amorphous state of the samples. The hysteresis loops of the in-plane magnetization are measured in the as-prepared materials as a function of the applied field (up to a few kA/m) at 100 Hz, and as a function of the frequency. The longitudinal MOKE measurements are performed with an optical bench equipped with an He-Ne laser light source, covering a sample surface of about 1 mm$^2$, and a photodiode having a frequency cutoff above 150kHz. Samples are cut to a maximum size of about 2 x 2 mm and inserted in a Helmholtz coil setup giving a maximum field of about 15 kA/m. In this configuration, we could perform measurements up to 300 Hz.

The fluxmetric measurements of hysteresis loops are performed on larger samples, usually cut within an homogeneous region of 3 by 1.5 cm. For these samples, we prepared a 10 cm long solenoid with 720 coils and a N/L value of 13200. The sinusoidal applied field is measured detecting the voltage over a calibrated 1 resistance. The induced flux is detected with two sets of 50 coils wound around the sample and covering an area of about 1 cm; the two sets are wired in order to cancel out the air flux and directly detect the film magnetization changes. As the film cross section is much smaller than the area of the coils, a perfect cancellation of the air flux is often difficult, requiring a continuous adjustment of area of one of the sets. This problem further increases at high frequencies, due to the different coupling between the wires, making it hard to perform the measurement. We thus get the full cancellation by numerically subtracting a sinusoidal wave with proper amplitude and phase from the induced signal. This procedure has a certain degree of arbitrariness, as small changes of the sinusoidal amplitude and phase give slightly different loop shapes. In all cases, the loop area and the coercive field are not substantially affected.

III. EXPERIMENTAL RESULTS

The first fundamental result of both kind of measurements is the existence of a well defined static hysteresis, as usually
found in magnetic materials (see for instance [11]). Therefore, the loop area $A$ is better described by

$$A = A_0 + H_0 \times T$$

(1)

where the static loop area $A_0$ is estimated using data at the lowest frequencies. Clearly, the choice of $A_0$ completely changes the experimental estimation of critical exponents. We believe that this simple observation could explain the so called dynamic transition, a sharp change in the value of the exponent at intermediate frequencies. Due to the usual large value of $A_0$ with respect to variation of the data with the frequency, log-log plots can mimic a dynamic transition when data actually follow a simple power law as assumed in (1). Our results and the theoretical analysis should help to clarify this important point.

The MOKE hysteresis loop area for different sample thickness show large variations with the frequency, as shown in Fig. 1 for the thickest (5 μm - open dots) and thinnest (21 nm) samples. Visual inspection of this Figure would suggest a dynamic transition around a few Hz. A plot of the area after subtraction of the static value $A_0$ (bottom) shows instead a linear dependence with the square root of frequency ($\sqrt{f}$) in (4).

As a matter of fact, the data show a much simpler behavior: the loop area

$$A' = A_0 + k \times \sqrt{f}$$

follows a simple law of the type $A' = A_0 + k \times f^{0.5}$, where $A_0$ is estimated using low frequency data.

Surprisingly, hysteresis loops obtained with the fluxometric setup do not show the same frequency variability. As reported in Figs. 2 for the 21 nm film, the loop area changes only about 10% with respect to the static value $A_0$. On the other hand, when plotted as a function of the square root of frequency, these data follow reasonably well a linear behavior. This suggests a common mechanism responsible for the magnetization change, which we try to interpret considering the domain wall depinning models, as discussed below.

Inductive measurements of the hysteresis loops at 100 Hz as a function of the applied field amplitude do not show any scaling behavior as given by (1) or similar. Simple squared loops as the ones shown in Fig. 2 are observed only for the thinner films, while more complicated shapes appear for thicker samples, showing a clear evidence of multi-domains magnetization processes. We postpone the discussion of these rich but complex features to a further longer publication.

IV. Model

To understand the frequency dependence of our experimental data, we employ the domain wall depinning model described in Ref. [1]. Under the assumption that hysteresis is mainly due to domain wall motion, we consider a phenomenological law for the wall velocity given by

$$v(\theta) = (\dot{\theta} \times \mathbf{H}_p) \times (\mathbf{H} \times \mathbf{H}_p);$$

(2)

where $\mathbf{H}_p$ is the depinning field, is the step function, and the applied field is $\mathbf{H} = H_0 \sin(\theta)$. Following [6], we solve (2) and compute the coercive field and the loop area, which at low frequency are given by

$$H_c(\theta) = \frac{q}{L} \left[ H_0^{2} + H_p^{2} \right]^{1/2}$$

(3)

where $L$ is the sample size, in the case of a single domain wall, or the typical distance between domain walls in a more general case. The lower branch of the hysteretic loop is then given by

$$M(\theta) = \begin{cases} 0 & H < H_p \\ M_s \left[ \left( \frac{H}{H_0} \right)^2 + \left( \frac{H_p}{H_0} \right)^2 \right] & H < H_p \end{cases}$$

(4)

where $M_s$ is the saturation magnetization and $H_p$ is the coercive field.
changes of the entire sample, as long as we consider the dimension so, in principle, it should detect the magnetization.

MOKE measurement uses a laser spot area close to the sample in the change of the loop area. It is worth noting that the thickest samples, for instance in the case of a few microns. It this is expected in thin films, it is not necessarily valid for the general behavior of the data obtained with complementary measurement techniques.

magnetization dynamics. That means that the MOKE measurements on the surface are related to those of the volume, given by the inductive method. While this is expected in thin films, it is not necessarily valid for the thickest samples, for instance in the case of a few microns. It is not clear anyway what can account for the large differences in the change of the loop area. It is worth noting that the MOKE measurement uses a laser spot area close to the sample dimension so, in principle, it should detect the magnetization changes of the entire sample, as long as we consider the thinnest films. Therefore, we should observe similar variations using the two methods. On the other hand, one can suggest that samples with the same thickness but different later dimensions could not have the same magnetization dynamics, because of the different role of the demagnetizing fields, or of the number of domain walls. This possibility has been ruled out by performing fluxometric measurements on the same sample used in MOKE, having thickness 5 m. In this case the fluxometric measurements show the same behavior described in Fig. Unfortunately, measurements at lower thickness are not possible due to the very low intensity of the induced signal, given the reduce cross section available. However, we feel confident that this result proves that the sample lateral dimensions are not relevant, also considering that the data reported in literature refer to dependences only on the sample thickness and not, more generally, to the other two dimensions.

In summary, we have shown in this paper that the dynamic hysteresis of Fe$_{23}$Cu$_{1}$Nb$_{5}$Si$_{3}$ films exhibit different behavior as a function of sample thickness and magnetizing field frequency, and that the domain wall depinning model accounts for the general behavior of the data.

\[ \frac{\partial M}{\partial t} = M - M_s \]

where the second equation is valid as long as $M < M_s$. Fig. displays the loop shapes for different values of frequency. The loop area is thus easily computed and, for low frequencies, is given by

\[ A' = A_0 + M_s \frac{8}{3} \frac{2 \Omega}{H_0^2 + H_0^2 \Omega^2} \]

where $A_0 = 4M_s H_p$ is the area of the loop in the quasistatic limit.

\[ V. \text{ DISCUSSION AND CONCLUSION} \]

The simple model shown above gives a simple $\mathcal{PT}$ dependence of the loop area, which we believe can account for some experimental data found in the literature and interpreted assuming the presence of a dynamic transition. The value $= 0.5$ is a strict consequence of the linear form of the model in a more general case, shown in detail in [6], one gets $0.5$. It is worth noting that the model above describes the magnetization dynamics of a single domain wall having a well defined depinning field $H_p$. The model does not include the effects of any random disorder, the multiplicity of the domains, or the field-dependent nucleation of domain walls. As a consequence, it cannot describe minor hysteresis loops or other features, such as more complicated shapes of the loops. Despite these limitations, we believe it can account for the general behavior of the dynamic hysteresis, and could be successfully applied to describe thin films showing simple magnetization dynamics.

Using the results of the model, we found that our experimental data obtained with complementary measurement techniques are the consequence of the same magnetization dynamics. That means that the MOKE measurements on the surface are related to those of the volume, given by the inductive method. While this is expected in thin films, it is not necessarily valid for the thickest samples, for instance in the case of a few microns. It is not clear anyway what can account for the large differences in the change of the loop area. It is worth noting that the MOKE measurement uses a laser spot area close to the sample dimension so, in principle, it should detect the magnetization changes of the entire sample, as long as we consider the thinnest films. Therefore, we should observe similar variations using the two methods. On the other hand, one can suggest that samples with the same thickness but different later dimensions could not have the same magnetization dynamics, because of the different role of the demagnetizing fields, or of the number of domain walls. This possibility has been ruled out by performing fluxometric measurements on the same sample used in MOKE, having thickness 5 m. In this case the fluxometric measurements show the same behavior described in Fig. Unfortunately, measurements at lower thickness are not possible due to the very low intensity of the induced signal, given the reduce cross section available. However, we feel confident that this result proves that the sample lateral dimensions are not relevant, also considering that the data reported in literature refer to dependences only on the sample thickness and not, more generally, to the other two dimensions.

In summary, we have shown in this paper that the dynamic hysteresis of Fe$_{23}$Cu$_{1}$Nb$_{5}$Si$_{3}$ films exhibit different behavior as a function of sample thickness and magnetizing field frequency, and that the domain wall depinning model accounts for the general behavior of the data.

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