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Magnetization reversal in out-of-plane magnetized Ni/Cu(1 0 0) films

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Abstract

Field-induced magnetization reversal in Ni/Cu(1 0 0) films with perpendicular anisotropy is studied in situ by magneto-optical Kerr effect (MOKE) and Kerr-microscopy. We discuss the time dependence of the reversal process and determine the Barkhausen volume. Surface defects are found to generate metastable 360° domain walls that strongly influence the magnetization reversal process. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetization reversal; Magnetic domains; Thin magnetic films

1. Introduction

Recently, much attention has been paid to magnetization-reversal processes in ultrathin magnetic films induced by external magnetic fields [1,2]. For the magnetic field parallel to the easy axis of magnetization, the reversal process generally takes place by domain nucleation and subsequent domain growth by domain-wall motion. Both processes are thermally activated and depend on the strength of the external magnetic field. Variations of the domain-wall energy due to surface defects and film morphology (locally varying film thickness) represent barriers for domain-wall motion and may slow down the magnetization reversal process by several orders of magnitude. For the same reason, domain-wall motion occurs in discontinuous steps, and the average volume that is magnetically reversed in one step is the so-called "Barkhausen volume", V_B.

In the present work, we have studied the dynamics of magnetization reversal in out-of-plane magnetized 15-monolayers (ML) thick Ni/Cu(1 0 0) films. Ni/Cu(1 0 0) is known for its anomalous thickness dependence of the magnetic anisotropy. In contrast to most thin-film systems, Ni/Cu(1 0 0) shows a spin-reorientation transition from in-plane (below ≈ 7 ML) to out-of-plane magnetization (> 7 ML) [3]. From dynamical magnetization measurements, we can determine V_B and the activation energy for a Barkhausen step, E_a. Furthermore, macroscopic surface defects are found to pin the domain walls: The walls wind around these defects and form metastable 360° domain walls behind them.

2. Experimental details

The experiments were performed in a UHV system equipped with low-energy electron diffraction (LEED), scanning tunneling microscopy (STM), MOKE, and Kerr-microscopy [4,5]. The ex situ electro-polished Cu(1 0 0) single-crystal surface was cleaned in situ by several sputter-anneal cycles [4,5]. The Ni films were deposited at room temperature by e-beam evaporation of a Ni wire, and the film thickness was measured with a quartz balance.

In situ polar MOKE and Kerr-microscopy were carried out at room temperature. Domain images were recorded with a CCD camera by first taking a background image of the magnetically saturated film that was

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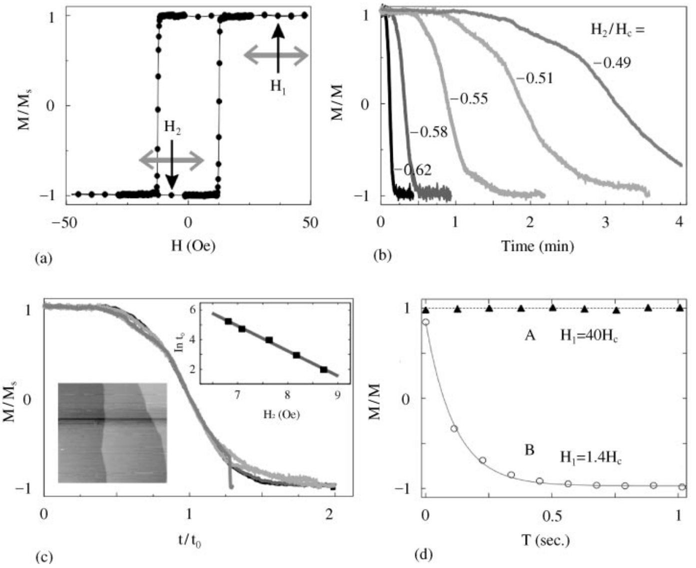

Fig. 1. (a) Polar MOKE hysteresis loop for 15 ML Ni/Cu(1 0 0) with coercive field of ≈ 12.5 Oe ($=: H_C$). (b) Relative magnetization M/M_S as a function of time for various external magnetic fields H_2. Prior to magnetization reversal, the film was magnetized with $H_1 = 40\,H_C$. (c) Same curves as in (b) but scaled with $t/t_0(H_2)$. The linear dependence of $\ln(t_0)$ on H is shown in the inset. Lower left inset: (400 nm)^2 STM image of a clean Cu(1 0 0) surface. (d) Magnetization curves for $H_2 = -0.6\,H_C$ for two different initial magnetization fields H_1. Curve B is fitted with an exponential function.

subsequently subtracted in real time from the images taken during magnetization reversal. The lateral resolution of the Kerr-microscope is ≈ 3 μm.

3. Results and discussion

In Fig. 1(a), the rectangular-shaped polar MOKE hysteresis loop of a 15-ML-thick Ni/Cu(100) film is shown. It was recorded with a field sweep rate of about 10 Oe/s, resulting in a coercive field of ≈ 12.5 Oe ($=: H_C$). For higher (lower) sweep rates, the coercive field increases (decreases) since the magnetization-switching time depends exponentially on the external magnetic field H. In Fig. 1(b), the time dependence of the magnetization reversal is plotted for several field values. The shapes of the plotted curves are nearly identical, which is seen by plotting the curves with different time scales $t/t_0(H_2)$ (see Fig. 1(c)); here, t_0 is defined by $M(t_0) = 0$. As is seen in the inset of Fig. 1(c), t_0 depends exponentially on the external magnetic field as is expected for thermally activated domain-wall motion: $t_0 \propto \exp[(E_a - \mu_0 M_S H V_B)/k_B T]$. M_S is the saturation magnetization within the domains. With $T = 300$ K and $\mu_0 M_S = 0.45$ T [6], V_B is determined from the slope of $\ln t_0(H_2)$ as $V_B = 1.9 \times 10^5$ nm^3. It corresponds to a Barkhausen area (V_B divided by the film thickness) of 0.073 μm^2, which is of the same order as the average size of a terrace on the Cu(1 0 0) surface (see STM image in the inset of Fig. 1(c)). Obviously, surface or interface steps represent obstacles for the domain-wall motion, which is also found for other thin-film systems [7].

A series of domain images, taken in the process of magnetization reversal at room temperature at the same 15-ML-thick Ni/Cu(1 0 0) film, is shown in Fig. 2(a) (images 1–5). Basically, one domain front with reversed magnetization (dark area) moves across the field of view. By changing the magnetic field, the speed of the domain wall can be adjusted to any desired value. Since the easy axes of magnetization within the Ni-film plane are the $\{1\,1\,0\}$ directions [3], the Bloch-type domain walls are preferably oriented along these directions. At several points on the surface the domain walls are pinned, wind around the defects, and finally merge behind them. If the magnetic field is again reversed after magnetic saturation was obtained (image 5), domain nucleation takes place along a line network that corresponds to the lines along which the domain walls merged in the first reversal process. Even though it cannot directly be resolved with the Kerr microscope, the present data imply that behind the defects the merging domain walls do not annihilate but form 360° walls. The reason for the formation of metastable 360° domain walls is that the sense of rotation of the magnetization within the two merging Bloch-like 180°-domain walls is identical, which is sketched in Fig. 2(b).

It is interesting to note that the speed of domain-wall motion is strongly enhanced if magnetization reversal

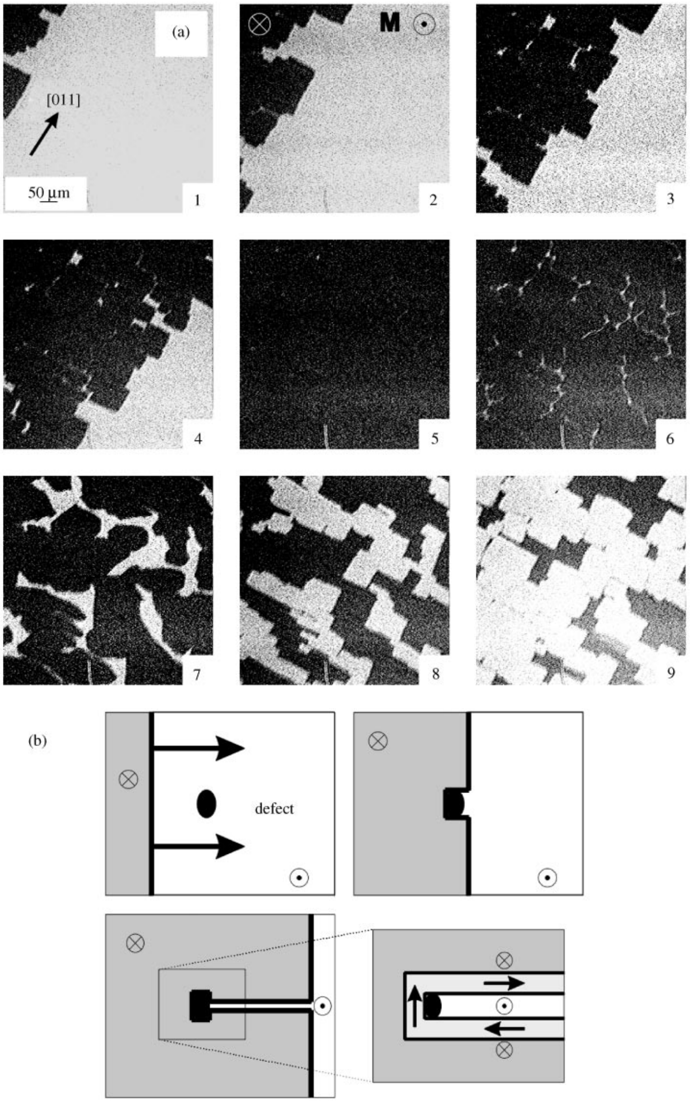

Fig. 2. (a) Magnetic-domain images taken in the process of magnetization reversal on a 15-ML Ni/Cu(1 0 0) film (images 1–5). After an apparent one-domain state was obtained in a magnetic field close to H_C (image 5), the external magnetic field was reversed (images 6–9). Images 6–9 were recorded in magnetic fields significantly smaller than H_C. (b) Schematic drawing of the formation of a 360° wall. The arrows in the domain wall indicate the sense of rotation of the magnetization vector within the Bloch-like wall.

starts from a 360° domain wall network (images 6–9 in Fig. 2(a)). It needs up to a factor 2 higher magnetic fields to observe the same propagation speed if no 360° domain walls are present (images 1–5). This Kerr-microscopy result is also reflected by dynamical MOKE measurements. In Fig. 1(d), two magnetization curves are shown that were recorded for the same external magnetic field $H_2 = -0.6H_C$. Prior to recording of curve A, the film was magnetized in a magnetic field $H_1 = 40\,H_C$ that was sufficient to destroy the metastable 360° domain walls. For curve B, on the other hand, the film was magnetized in $H_1 = 1.4\,H_C$, which obviously did not affect the 360°-wall network. While the magnetization is almost unchanged within the first few seconds in curve A, it switches within <1 s in curve B. This effect can be explained in the following way: Formation of 360° domain-walls costs energy and slows down the magnetization-reversal process; the effective activation energy E_a is enhanced. On the other hand, if the 360° domain walls have already formed, the magnetization-reversal process is basically the time-reversed process of the 360° domain-wall formation: The walls open up with an area of reversed magnetization in between two 180° walls. In this case, E_a is reduced since pinning by defects does not occur.

A detailed description of the magnetization curves in Fig. 1(b) and (d) will be published elsewhere [8]: As a result, it turns out that the exponential time dependence observed in the presence of 360° domain walls (curve B in Fig. 1(d)) can be described with a model based on Fatuzzo's theory [9]. With this model, the intrinsic activation barrier height for a Barkhausen step can be determined as $E_a \cong 0.7$ eV, which is attributed to variations of the domain-wall energy in the vicinity of Cu(1 0 0)-surface steps.

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