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Visualization of small magnetic entities by nonmagnetic probes of atomic force microscope

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Abstract

We present an approach to magnetic imaging of single-domain magnetic entities in Fe(Co)-based composite media. The approach is based on atomic force microscopy (AFM) with nonmagnetic tips and an AC magnetic field applied in situ. The obtained images can be interpreted in terms of magnetostrictive deformations, which are detected by AFM.

Keywords: Fine particles; Magnetostriction; Magnetic susceptibility; Atomic force microscopy

1. Introduction

In scanning probe microscopy, for visualizing magnetic entities, as a rule, one uses the magnetic tips, which interact with sample's stray fields by their magnetic moments; so the pattern of magnetic poles and finally magnetic imaging of the entities can be obtained. However, the sample fields can cause random, partial remagnetization of the probe during scanning [1]. Another drawback is that in the lift mode, which is used for tip's scanning, the needed spatial resolution and sensitivity are often not achievable [2]. Our study deals with a possible alternative approach to magnetic imaging by an atomic force microscope (AFM) using nonmagnetic tips. The essence of the approach is detection of the magnetostrictive response at probe's scanning and applying an AC magnetic field in situ. Earlier this technique has successfully been applied to domain-wall imaging of submicron Co dots [3]. Here we use it for characterizing ferromagnetic nano-scale entities, which are formed in paramagnetic Fe–Cr layers at their irradiation by interfering laser beams [4,5]. The obtained data are compared to those of the MFM characterization of the ferromagnetic entities.

2. Experimental

The AFM contacting mode was used in this study to allow the instrument to detect the surface oscillations of magnetic samples on applying AC magnetic field in situ. We applied an external magnetic field by means of using a suitable coil near the sample to produce an AC magnetic field along the sample plane or normal to it. The amplitude of the applied AC field was not more than a few Oe's and its frequency, ω, was chosen so as to have 2ω (for magnetostriction) close to the resonance frequency of the cantilever ($\omega_c = 180-360$ kHz). The field-induced surface oscillations transferred to a cantilever. In the contact mode that corresponds to the regime of repulsive forces, the force acting on the cantilever is treated in accordance with the well-known models for intermolecular potentials.

3. Results

In Fig. 1 we show (a) topography (AFM image) of laser-patterned surface of a 15-nm thickness layer of $Fe_{70}Cr_{30}$ (Fe–Cr) and (b) its MFM image collected after the sample was magnetized by applying the magnetic field of about 1.0 kOe in the direction along the X-axis. The AFM image shows arrays of the crater-like regions

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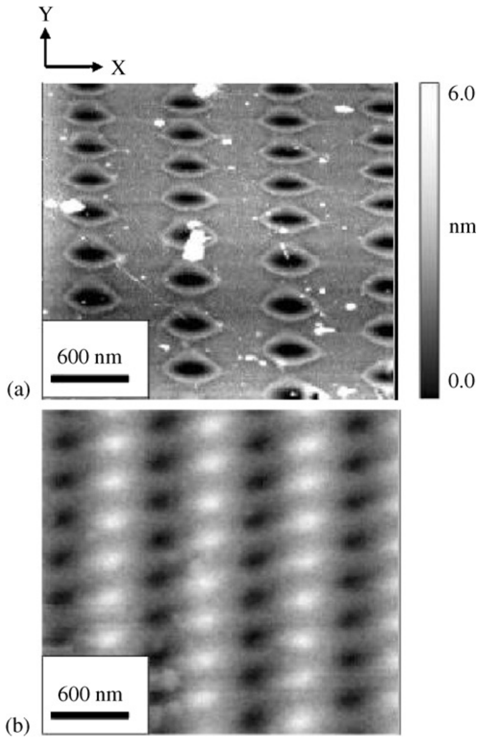

Fig. 1. AFM (a) and MFM (b) images of the patterned entities in a 15-nm thickness Fe–Cr film. The MFM image indicates the formation of single-domain ferromagnetic entities in the interference maxima. However, the magnetic features of the entities are not clear in detail.

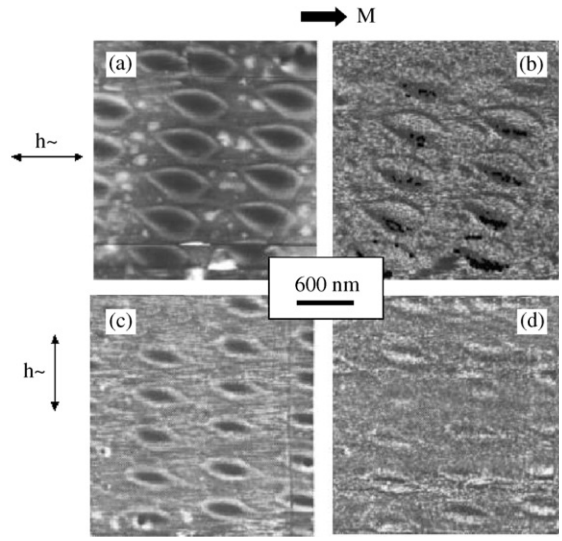

Fig. 2. AFM topography (a, c) and the corresponding images of the dynamic response (b, d). The dynamic images have been collected at different orientations of the AC field, $h_{\sim}$, with respect to the entities' magnetization, **M**: (b) $\mathbf{h}_{\sim} \| \mathbf{M}$, (d) $\mathbf{h}_{\sim} \perp \mathbf{M}$. Unlike MFM, these images indicate that the patterned ferromagnetic entities have a ring shape.

in which the width of the crater walls (light contrast around the craters) is of ≈ 50 nm, and their height is typically of ≈ 10 nm at laser fluences not more than 0.3 J/cm^2. The MFM image in Fig. 1(b) shows a periodic structure of dipoles: the dark and light contrast in the pattern indicate the poles of the ferromagnetic regions which are fully polarized in the same direction. This MFM image is the first and clear evidence for formation of ferromagnetic entities in patterned Fe–Cr layers.

Nevertheless, one can obtain some additional information on the patterned features by studying the AFM dynamic response. Fig. 2 depicts topographic images (a,c), obtained in the same mode as in Fig. 1(a) but in two different locations, versus the images of the amplitude of the induced probe's oscillations under the AC field applied in situ (b,d). The dynamic images in (b) and (d) were collected after prior magnetization of the sample up to saturation along the long axis of the craters; and the AC field was oriented both along the long axis (b) and the short axis (d) of the craters. It is remarkable that the crater's features observed in the conventional and dynamic modes are in direct relationship. This similarity may have a simple explanation, considering that the crater walls is the most distinctive topographic feature and that they also correspond to the maximum of the ferromagnetic matter which naturally can have the largest magnetic response. As seen from Fig. 2(b,d), the oscillation amplitude in the crater walls depends on the mutual orientation of the AC field and the static craters' magnetization, **M**. When $\mathbf{h}_{\sim}$ is applied parallel to **M**, the wall oscillations are even smaller than those of the surrounding medium [Fig. 2(b)]. However, some enhancement of the wall oscillations occurs when the AC field is applied in the film plane and perpendicular to the magnetization. In the latter case, the oscillations became larger than those of the surrounding medium [Fig. 2(d)].

The observed behavior of the local dynamic response and its dependence on the orientation of AC field can be interpreted in terms of the field-induced magnetostrictive response. This suggestion, firstly, is supported by our observations of vanishing of the dynamic response in a non-magnetic Fe–Cr layer with patterned craters. Moreover, such a response in the magnetic samples is observable at 2ω and within the narrow frequency range (~ 10 Hz) when 2ω is fitted to ω_c. As shown in Fig. 2, the magnetostrictive oscillations of the crater walls (rings) vanish when $\mathbf{h}_{\sim}$ is parallel to **M**, and these are enhanced at perpendicular orientation of $\mathbf{h}_{\sim}$ with respect to **M**. This change is explained by the absence of the precession of magnetic moments at parallel orientation of $\mathbf{h}_{\sim}$ with respect to $\mathbf{M}$.

Thus, the obtained AFM dynamic images of the ring-shaped ferromagnetic entities can be interpreted in terms of magnetostrictive deformations and a related quantity, the AC susceptibility. We can explain qualitatively the observed behavior of the dynamic response at different mutual orientation of the AC field and the entities' magnetization.

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