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Magnetic domain and domain-wall imaging of submicron Co dots by probing the magnetostrictive response using atomic force microscopy

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An approach to image the domains and domain walls of small ferromagnetic entities using atomic force microscopy (AFM), with a nonmagnetic AFM probe, has been developed. Exciting the sample in an external ac magnetic field, the distribution of magnetostrictive response at the surface is detected. By this technique, the domains and domain walls of submicron Co dots have been imaged with a 1 nm lateral resolution. In elliptical Co dots with a 350-nm-long axis on a triangular lattice array with 400 nm periodicity, we find evidence for two domains with opposite magnetization orientation across a wall. The domain-wall width in these dots is found to be about 35 nm. Furthermore, we observe a ferromagnetic alignment of the domains in the neighboring dots, which suggests a magnetostatic interaction among the dots. © *2000 American Institute of Physics.* [S0003-6951(00)02020-9]

Patterned media with submicron-to-nanosized magnetic entities are expected to play an important, competitive role as alternative media for magnetic information storage. In order to gain insight into the magnetic properties and the possible interactions between the recorded bits, a detailed understanding of the domain structures and their dependence on flux reversal are of utmost importance. Such a study would help in estimating the possible limits of high-density recording.

There are a variety of microscopic techniques with submicron resolution for detecting the magnetic structures of materials,[1] e.g., magnetic force microscopy (MFM),[2–5] Lorentz microscopy,[6,7] Foucault microscopy,[8] electron holography,[9,10] scanning electron microscopy with polarization analysis[11–13] and magneto-optic microscopy.[14] However, these techniques do not detect the dynamic features of the surface roughness caused by the external magnetic field.

Magnetostriction is a useful functional property with great potential for many applications, e.g., actuators and sensors. Moreover, when designing magnetic components, an understanding of the local magnetic response due to magnetostrictive effects is important. Recently, scanning probe techniques have been used to measure the magnetostrictive response of small bulk samples.[15–18] For example, Costa, Nogués, and Rao determined the magnetostrictive properties of 125 μm wires of length 10 mm or less, with positive as well as negative magnetostriction.[15] Also, Holden, Lord, and Grundy[19] studied deformations due to magnetostriction in samples of Terfenol-D.

In this letter, we describe a method to image domains and domain walls in small magnetic entities with a resolution of about 1 nm using atomic force microscopy (AFM) with *nonmagnetic tips*. The technique utilizes the magnetostrictive response of the magnetic entities when subjected to an ac magnetic field. We demonstrate how the local distribution of the magnetostrictive response can be used to image domains and domain walls.

Due to spin-orbit coupling, the formation of magnetic domains in ferromagnetic materials below the Curie temperature leads to spontaneous magnetostriction within the domains.[20] Within a domain, neglecting forced magnetostriction, the magnetization, and therefore the magnetostriction, is saturated. This gives rise to a domain-dependent deformation of the material which depends on the magnetization direction within the domain. The mechanism is illustrated in Fig. 1(a). Here, the magnetostrictive effect is illustrated by ellipsoidal volumes having their long axis in the direction of the magnetic moments. At the domain wall the magnetic moments, and thereby the direction of the long axis of the ellipsoids, changes direction, resulting in a domain-dependent deformation of the material.

The deformations due to local magnetostrictive effects are rather small in most materials. However, such effects

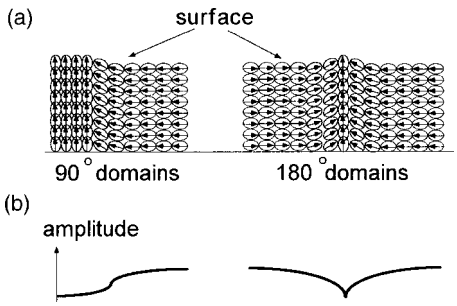

FIG. 1. (a) Domain-dependent deformation of a ferromagnetic material seen sideways. The magnetostrictive effect is illustrated using ellipsoidal volumes with the long axis parallel to the magnetic moment. Note that the deformation is highly exaggerated. (b) Expected amplitude variation of the magnetostrictive response of the domains shown in (a) in the direction of an ac magnetic field applied normal to the surface of the material.

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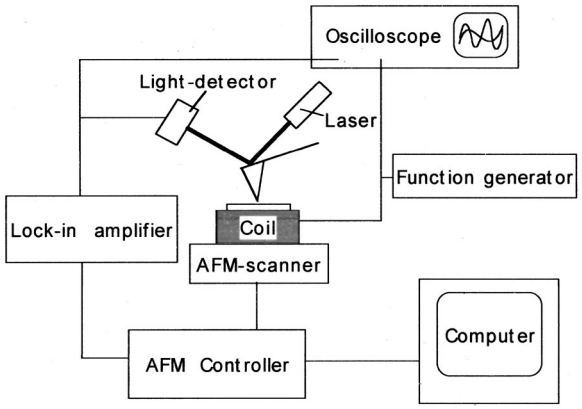

FIG. 2. Block diagram of the experimental setup.

have been reported recently using AFM on Terfenol-D,[19] which has an extremely large magnetostriction.

The application of a magnetic field to a ferromagnetic sample will try to align the magnetic moments with the external field, thereby also changing the magnetostrictive deformation of the sample. The amplitude of the field-induced deformation of a sample subjected to an ac magnetic field depends on the strength of the applied field, the magnetostrictive coefficient λ, and also on the angle between the direction of the magnetic moments and the applied field. Thus, if the direction of the magnetic moments in a part of the sample is parallel to the applied field, the field will not change the direction of the moments and the change in deformation will be minimal. However, if the direction of the magnetic moments is at an angle to the applied field the change in deformation will increase, because the torque due to the applied magnetic field on the magnetic moments in the material then increases. Therefore, the amplitude of the magnetostrictive response will depend on the local direction of the magnetic dipoles in the sample, i.e., on the domain configuration, as shown schematically in Fig. 1(b).

The experimental setup to measure the magnetostrictive response using an AFM is shown in Fig. 2. The crucial modification in our AFM involves the introduction of a suitable coil near the sample to produce a magnetic field normal to or along the sample surface. To image the distribution of the magnetostrictive response, an ac magnetic field having an amplitude of a few Oe at a frequency around $\omega = 30$ kHz was applied to the sample. If we consider only magnetostriction due to rotation of magnetic moments by the applied field, the magnetostrictive deformation is proportional to the square of the magnetization, and thus the sample surface oscillates at a frequency 2ω. In order to enhance the amplitude of the signal, the frequency ω was chosen as to have 2ω close to the resonance frequency of the cantilever–sample system. When operating the AFM in contact mode, the AFM tip follows the local oscillations at the sample surface. Since the frequency 2ω is well above the sampling frequency of the AFM, the topographic image (detecting the feedback signal) will show only the average deformation which is essentially the topography of the sample. Using a lock-in amplifier to detect the amplitude of the 2ω oscillations of the AFM tip, the local distribution of the magnetostrictive response, and thus the domain configuration, can be imaged *simultaneously* with the topography.

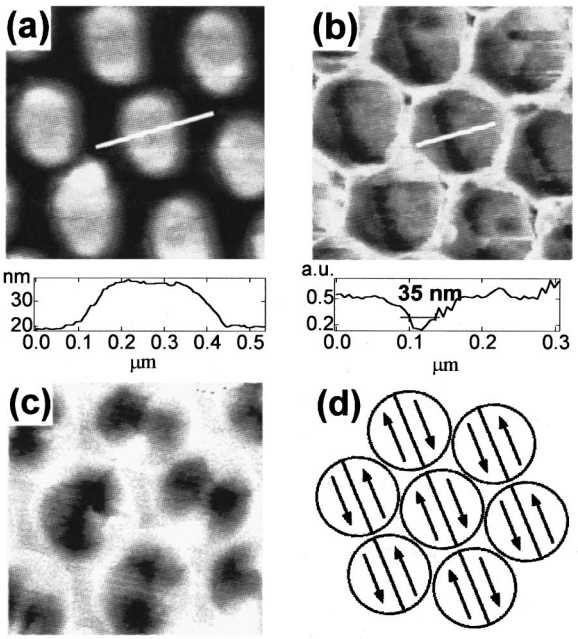

FIG. 3. (a) Topographic AFM image, (b) AFM image of the amplitude of the magnetostrictive response, (c) MFM image, and (d) schematic domain configuration of 20-nm-thick 350 nm×250 nm dots in a 400 nm triangular array. The insets show line profiles along the white lines in the figures. Note that all micrographs are over an area of $1\times1\ \mu m^2$.

The samples studied consist of 20-nm-thick elliptical Co dots with the long axis in the range of 100–350 nm grown on Si substrates. They were prepared by electron-beam lithography and a lift-off technique.[21] Shown in Fig. 3(a) is a topographic image of 350 nm×250 nm elliptical Co dots in a triangular array with a 400 nm lattice constant. The amplitude of the magnetostrictive response of the same dots is shown in Fig. 3(b). Domain walls can be observed in the image as dark lines parallel to the long axis of the dot. The line profile over the domain wall shows that the width of the domain wall at half maximum is about 35 nm. The domain-wall width w_L, given by Lilley,[22] $w_L = \pi\sqrt{A/K_u}$, where A is the exchange stiffness constant and K_u is the uniaxial anisotropy constant, is determined to be ~16 nm for a bulk Co crystal. However, for dots at the order of nanometer dimensions the domain-wall width may scale[23] with the exchange length of the stray field ($\Delta_d = \sqrt{A/K_d}$, where K_d is the stray-field energy constant[24]) rather than the exchange length of the anisotropy ($\Delta_u = \sqrt{A/K_u}$). Additionally, due to shape anisotropy as well as reduced crystal anisotropy due to the polycrystalline character of the dots, the domain-wall width could be expected to be quite different from that of a bulk Co crystal. Further investigations, including detailed micromagnetic calculations, could prove useful to clarify the discrepancy between the calculated and the experimentally determined values of the domain-wall width. Notice that the line profile shows that the lateral resolution with which the magnetostrictive response, and thus the magnetic structure, can be detected using our method, is about 1 nm.

Figure 3(c) shows a MFM image of dots in the same array. In this experiment, the MFM tip was magnetized perpendicularly to the sample surface. The image shows that each dot has two dark and two light spots. From the tip magnetization direction, we can infer that each dot has two north and two south poles. Moreover, neighboring dots are

found to always have adjacent poles of opposite polarity, i.e., the moments of the closest domains in neighboring dots are aligned ferromagnetically. This is in excellent agreement with the magnetostrictive response shown in Fig. 3(b), showing that the domain walls in the neighboring dots always are parallel to each other, suggesting a strong magnetostatic interaction between the dots. Thus, from the magnetostrictive response [Fig. 3(b)] and the MFM image [Fig. 3(c)], we conclude that each dot is composed of two oppositely magnetized domains, separated by a 180° domain wall, along the long axis of the elliptical dot, with neighboring dots having their closest domains aligned ferromagnetically, as shown schematically in Fig. 3(d). The ferromagnetic alignment of the closest domains of the neighboring dots can be understood considering the dipolar fields emanating from the dots, i.e., an arrangement of the domains that gives a north pole in one dot next to a south pole in the nearest-neighboring dot is energetically favorable. Thus, due to the triangular arrangement, the dipolar field emanating from one row of dots promotes the ferromagnetic alignment with the dots in the next row.

It is interesting to note that Grimsditch, Jaccard, and Schuller[25] found no magnetostatic interaction between elliptical Fe dots, with their long axes ranging from 90 to 150 nm, on a square lattice with a 400 nm period. On the other hand, Mathieu *et al.*[26] found evidence for magnetostatic interaction between circular permalloy ($Ni_{80}Fe_{20}$) dots with a diameter of 1 μm on a square lattice with a 1.1 μm period, while for the same type of dots with a 2 μm period they found no magnetostatic interaction. Such studies are of current interest, since the magnetostatic interaction seems to strongly depend on the detailed structure of the system (dot material, shape, thickness, or type of array and center-to-center or edge-to-edge distances).[27]

We have also investigated Pd/(Pt/Co/Pt) multilayer thin films, yttrium–iron–garnet thin films, and magnetic hard disks. Due to the small magnetostrictive coefficient of yttrium–iron–garnet thin films and hard disks, and the range of fields available, the magnetostrictive response was found to be too small for any reliable conclusions. However, the Pd/(Pt/Co/Pt) multilayer thin films, with a strong perpendicular anisotropy, yielded images that agreed well with the MFM images of the same material.

It is noteworthy that preliminary measurements of the magnetostrictive coefficient of the Co dots using AFM suggests that the magnetostrictive coefficient $\lambda = dl/l$ may be several orders of magnitude larger than that of bulk Co.[28] At this time we have no plausible explanation for the observed large magnitude of λ values. However, it is important to point out that for bulk materials, magnetostrictive coefficients measured using AFM were in good agreement with the literature values.

The described magnetostrictive response technique yields a higher resolution as compared to MFM. This is because in our technique the interaction between tip and sample will be dominated by the contact force acting at the very apex of the tip. However, in MFM, where the tip is usually more than 20 nm away from the sample, the magnetic force is integrated over all the magnetic material of the tip, resulting in an averaging of the magnetic states over an area of the sample.[29] Note that the ultimate resolution of the magnetostrictive response technique should, in principle, only be limited by the lateral AFM resolution.

Other imaging techniques based on the magnetostrictive response have been recently reported,[30] however, their lateral resolution is only about 100 nm.

In conclusion, we have shown that the distribution of the magnetostrictive response can be used to study domains and domain walls using atomic-force microscopy utilizing a nonmagnetic tip. We have used this technique to study the domain configuration and domain-wall width of submicron Co dots. The domain configuration of the arrays of elliptical Co dots appears to be controlled by magnetostatic interaction.

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