Nonreciprocal differential detection method for scanning Kerr-effect microscopy

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We describe an optical detection scheme for scanning Kerr-effect microscopy (SKEM) which does not require modification of the magnetic state of a sample for domain observation. The scheme exploits the nonreciprocal nature of the magneto-optic Kerr effect (MOKE) to distinguish polarization rotation due to sample magnetization from other spurious sources, such as sample roughness and birefringence of the microscope optics. We present SKEM images of domain structures in lithographically patterned $Ni_{81}Fe_{19}$ elements which demonstrate the imaging capabilities of the new detection scheme for materials with typical MOKE magnitudes.
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I. INTRODUCTION

Numerous methods which use the magneto-optic Kerr effect (MOKE) for the observation of microscopic magnetic domains have been developed over the past four decades.[1–4] In the case of samples with in-plane magnetization, it is necessary to employ some kind of image enhancement or ac detection in order to discriminate the MOKE contrast from nonmagnetic contrast mechanisms, such as variations in the reflectivity across the sample surface. Such image enhancement is particularly important in the case of MOKE microscopy since the polarization change in the reflected light is so small, typically on the order of 0.1° or less.

All previously developed longitudinal MOKE microscopy methods perturb the magnetic structure of the sample with an applied magnetic field. In the case of wide-field MOKE microscopy, a reference image of the sample in an original magnetic state (often, the saturated state) is subtracted from a second image of the sample in a perturbed magnetic state.[1,2] Alternatively, in a scanning Kerr effect microscope (SKEM), the sample is excited with an ac magnetic field while the MOKE signal is extracted from the optical detector with phase-sensitive (lock-in) detection.[3,4]

We describe a new method for MOKE microscopy with which it is not necessary to apply an external magnetic field for the extraction of the magnetic-contrast image. By exploiting the nonreciprocal nature of longitudinal MOKE in a SKEM geometry, we demonstrate the ability to image static magnetic domains in $Ni_{81}Fe_{19}$ (Permalloy) films. Applications for this technique include feature finding for magnetic force microscopy (MFM) and defect analysis in magnetic hard disks.

II. TECHNIQUE

MOKE results in slight alterations in the polarization state of light when reflected from a magnetic medium.[5] In the case of longitudinal MOKE, where there is a nonzero component of the magnetization vector in the optical plane of incidence, both the angle and ellipticity of the incident light are changed. The effect finds its origins in the spin-orbit splitting of the electronic energy levels in the magnetic medium.[6]

Owing to the time-reversal symmetry-breaking nature of electron spin, longitudinal MOKE exhibits nonreciprocity: The polarization alterations which occur when light is incident upon a magnetic medium in one direction are not inverted when the direction of incidence is reversed.[7] An illustration of the nonreciprocal properties of MOKE may be found in Fig. 1: If an observer measures a counterclockwise polarization rotation resulting from the reflection of light from a medium magnetized parallel to the direction of incidence when viewed from the right, then a measurement of polarization rotation *from the opposite direction* (such that the medium magnetization is now anti-parallel to the direction of incidence) will find the polarization rotation direction to now be clockwise. If the sample is illuminated by a microscope objective lens for reflection-mode microscopy, then the polarization rotation of the reflected light is antisymmetrically distributed along the axis parallel to the direction of sample magnetization. The nonreciprocal nature of the Faraday effect (the analog to MOKE in the case of transmission) has been used for many years in Faraday optical isolators.

A schematic for the differential SKEM design is shown in Fig. 2. In the conventional SKEM design, asymmetrical Koehler illumination is used in order to ensure detection of the MOKE signal from a single optical detector.[3,4] If the rear focal plane of the objective is uniformly illuminated, then the superposition of the clockwise and counterclockwise polarization rotations will cancel each other out. In order to ex-

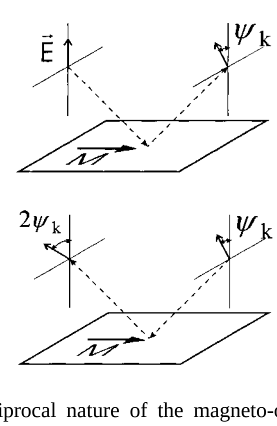

FIG. 1. The nonreciprocal nature of the magneto-optic Kerr effect. The sense of polarization rotation is independent of the direction of incidence.

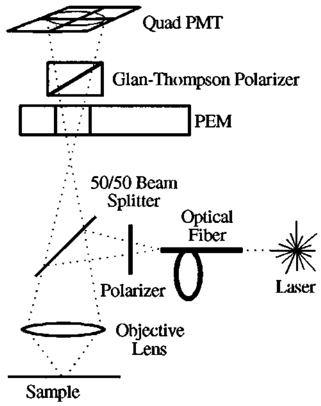

FIG. 2. Diagram of differential SKEM design.

ploit the non-reciprocity of longitudinal MOKE, uniform illumination and a segmented optical detector are required. A simple split detector suffices for the extraction of the nonreciprocal MOKE signal. By differentially detecting the optical signal from the two halves of the split detector, we can now sense magnetization perpendicular to the line separating the detector halves.

The microscope we have constructed uses a quadrant-segmented photomultiplier tube (PMT). The output signals from the four quadrants are summed with user-selected gains of either $+1$ or -1 for the individual quadrant channels, thereby making it possible to change the orientation of the effective split detector. Figure 3 shows the layout of the four quadrants, labeled A through D on the PMT faceplate. The resulting photo-induced voltages from the individual quadrants is represented by $V_A,\ldots,V_D$. To be sensitive to magnetization in the y-axis direction, the individual voltages are combined as $V_A+V_B-V_C-V_D$. If the polarization of the incident light is in the y-axis direction, then this would be sensitive to p-incidence MOKE contrast. To observe the orthogonal magnetization component in the x-axis direction with s-incidence contrast, the voltages are summed as $V_A-V_B+V_C-V_D$.

In addition, a photoelastic modulator (PEM) is used to measure the polarization state of the detected light.[8] The PEM is placed in the optical path following reflection of the linearly polarized light from the magnetic medium. The resulting ac electrical signal is then measured with a phase-sensitive detection amplifier. By using ac detection, we avoid the $1/f$ noise inherent in the laser light source and are able to measure the polarization rotation independent of intensity fluctuations in the reflected light.

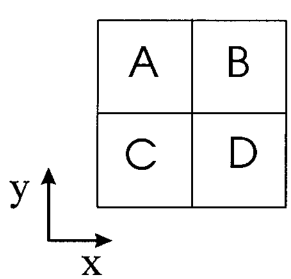

FIG. 3. Layout of quadrants for segmented PMT.

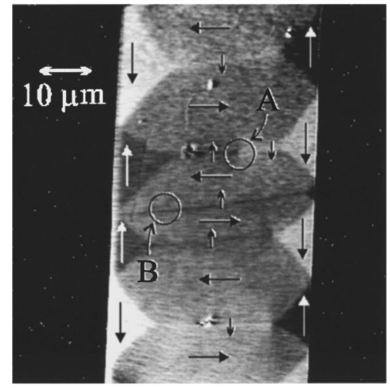

FIG. 4. SKEM image of static magnetic domains in thin film Permalloy.

An argon ion laser is used for sample illumination, using the 457.9 nm line of the laser. The light is focused through the oil-immersion objective lens (1.0 N.A.) to a diffraction-limited spot on the sample surface. The sample is scanned past the fixed illumination spot with a piezoelectrically driven flexure stage with a 200 μm scan range. The quadrant detector is mounted far beyond the conjugate image plane of the objective lens in order to spatially separate the angular distribution of the reflected light.

III. RESULTS

In Fig. 4 we present an image of magnetic domain structure in a lithographically patterned, 50 μm stripe of Permalloy film. The dark regions to the sides of the Permalloy stripe are the bare silicon substrate. The detector is configured for observation of magnetization oriented parallel to the Permalloy stripe direction. The incident light polarization is also oriented parallel to the stripe direction for p-polarized longitudinal MOKE detection. The image is composed of 400 $\times$400 pixels. The scanning rate for this image was 6 s/line and the time constant on the lock-in amplifier set to 30 ms, resulting in an image acquisition time of 80 min.

The long acquisition time was necessitated by the relatively poor broadband noise characteristics of the laser employed (about 5% rms from 10 Hz to 10 kHz). While the differential detection method removes most of the common-mode noise, difficulties in aligning the optics of the microscope allowed for only a 40 dB common-mode rejection ratio. Use of a low-noise laser source could improve the image acquisition time by two orders of magnitude.

The magnetic domain structure in Fig. 4 is produced by ac demagnetizing the sample, producing a classical Landau-like domain structure: Triangular closure domains form at the sides of the stripe with their magnetization parallel to the stripe direction. Long arrows in the figure indicate the direction of magnetization in the domains. This film is less than 30 nm thick, so there are Néel walls between the domains. It is possible to clearly distinguish the orientation of the oppositely polarized 180° domain walls between the central domains. The polarity of the domain walls in indicated with short arrows in the figure. The light-colored domain walls are polarized parallel to the magnetization direction in the white triangular closure domains, whereas the dark colored domain walls are polarized oppositely. The second 180° domain wall from the top of the image is dark on the left side and light on the right side, with a discontinuity where the two polarities meet, labeled A. The discontinuity is similar to the Bloch line feature observed in 180° Bloch walls for thick Permalloy films.[1] It is even possible to discern a vortex-like magnetization distribution surrounding the discontinuity.

The third domain wall from the top of the image, labeled B, does not have a closure domain on the left side, where we would expect a white-colored domain. A small black closure domain is just barely resolvable on the right side of the wall. This is also a 180° domain wall which still satisfies the flux-closure requirements of the Landau domain pattern; however, it does so at the expense of addition domain wall energy. We conclude that this domain wall results from a defect in the film surface which has pinned the wall to that particular location.

The MOKE signal obtained for *s*-polarized light is far weaker than for *p*-polarized light. It is not yet clear why this is the case.

IV. CONCLUSIONS

We have demonstrated the ability to image microscopic magnetic domains in a thin film of Permalloy without the need to perturb the magnetic domains with an applied magnetic field. Such a capability may find great use in conjunction with MFM. MFM has excellent utility for imaging static magnetic structures at resolution approaching tens of nanometers.[9] For example, MFM has the potential to become an important tool for magnetic recording studies in the magnetic disk industry.[10] Unfortunately, the use of MFM for recording investigations is often hampered by the difficulty of locating a recorded feature of interest. Bitter fluid decoration (the treatment of a magnetic surface with a colloidal suspension of microscopic magnetic particles) has been used successfully to this end but results in the inability to record on the disk again due to surface contamination. The technique described here could be used in conjunction with MFM for the nondestructive low resolution (approximately 1 μm) imaging of magnetic disk surfaces in order to find magnetic features for subsequent high resolution study.

Note added in proof: It has since come to the attention of the authors that Ursula Ebels, Cavendish Laboratory, Cambridge University, U.K. has independently developed a similar form of SKEM which has been used successfully to image magnetic domains in epitaxially grown Fe/GaAs films.[11] A similar microscope was described by Clegg and Heyes, University of Manchester.[12,13] While two-dimensional images of perpendicularly magnetized materials were obtained, only one-dimensional line scans of the magnetization distribution in Permalloy films were presented.

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