Magneto-Optic Kerr Effect Microscopy

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Magnetic domains are introduced as an interesting topic arising in solid state physics with a variety of technological applications. The Magneto-Optic Kerr Effect (MOKE) is briefly discussed as a microscopy technique for observing domain patterns and dynamics in thin ferromagnetic films. A recent paper from Phys Rev B is exhibited, in which MOKE imaging lead to insight into an unexpected magnetic hysteresis phenomenon.

INTRODUCTION

Although it was not covered during our course in Solid State Physics, ferromagnetic ordering is an interesting and important topic arising in the study of condensed matter. Many atoms exhibit magnetic polarization due to the presence of unpaired electrons in their atomic orbitals, which possess a magnetic moment due to their spin. In most solids, thermal fluctuations tend to orient the moments of the constituent atoms randomly, so that no net magnetization is observed in the bulk (paramagnetism). However, for a few materials such as iron, nickel, cobalt, and certain alloys, a quantum mechanical effect called the exchange interaction can cause the moments to spontaneously align in the absence of a magnetic field.

In 1906, even before the exchange interaction was properly understood, Pierre-Ernest Weiss had correctly postulated that ferromagnetic materials have a tendency to break up into small regions of uniform magnetization called domains [1]. These domains would in general not share a common direction of magnetization, and could cancel out the average magnetization of the material. The concept of domains explains, for example, the observation that macroscopic object containing iron, such as a wrench, is not magnetized even though it is composed of a ferromagnetic material.

Over the past few decades, micromagnetic structure has been a rich area of scientific research, driven in large part by useful applications. Ferromagnetic materials now pervade our electronic world. They are used as high permeability materials in our RF devices and transformers, and as permanent magnets in our generators, motors, etc. They store the majority of the world's digital information in hard drives, and form the basis for magnetic sensors as used in recording and elsewhere.

Today, magnetic materials are studied to optimize their properties for existing applications, and are continuing to be investigated for future memory storage applications and for use in the emerging field of spintronics. Studying the formation and dynamics of magnetic domains is highly relevant for such technological applications, and it is now possible to study them through direct observation.

MAGNETIC DOMAINS

To understand why magnetic domains are formed, one need only consider the energetics involved in a micromagnetic system. Already mentioned is the exchange interaction energy, which tends to align nearby moments. Considering a finite set of discrete moments $\boldsymbol{M}_i$, the exchange energy is given by

$$E_{ex} = -\sum_{i,j} J_{ij}(\boldsymbol{M}_i \cdot \boldsymbol{M}_j),$$

where J_{ij} is the so-called exchange constant between the ith and jth moments, which falls off rapidly as the distance between moments increases. Thus, any misalignment in neighboring magnetization vectors costs exchange energy. An

energy is also imposed by any external magnetic field, $\boldsymbol{H}$, called the Zeeman energy

$$E_{zee} = -\sum_i \boldsymbol{M_i} \cdot \boldsymbol{H},$$

where $\boldsymbol{M}$ is the magnetization vector. The Zeeman energy tends to align all the $\boldsymbol{M}_i$ with $\boldsymbol{H}$. There is also the anisotropy energy, which establishes a preferred orientation for M. Anisotropy can be imposed by the crystal (magnetocrystalline anisotropy), or by magnetostatic fields due to the sample geometry (shape anisotropy). Anisotropy energy can exist in many different forms, but for simplicity consider a simple uniaxial first-order anisotropy

$$E_a = \sum_i K \sin^2 \theta_i$$

where K is the anisotropy energy, and θ_i is the angle between $\boldsymbol{M}_i$ and the anisotropy axis. To complete our simplified picture, we finally have the stray field energy, generated by the divergence of the magnetization,

$$E_s = \frac{1}{2}\mu_0 \int_{\text{all space}} \boldsymbol{H}_d^2 dV,$$

where $\boldsymbol{H}_d$ is the stray field.

With reference to Fig. 1, we can now conceptually see how it may be energetically favorable to form domains. The single domain case in Fig. 1.a has a low exchange energy, but a high stray field energy. The stray field energy may be reduced somewhat by forming the domain in Fig. 1.b, at no cost to the anisotropy energy, but by increasing the exchange energy by forming a domain wall. Finally, the stray field may be eliminated as in the configuration of Fig. 1.c, at a price of both anisotropy and exchange energy. The domain formed will depend to a large degree on the system parameters such as shape and anisotropy, and on the conditions such as applied fields, stress, and temperature.

Magnetic domains tend to appear in systems which are smaller than a critical size in at least one dimension. Ferromagnetic thin films show a bewildering variety of domain patterns (see Fig. 2). By imaging domains, we can gain understanding about their formation and dynamics which is key for scientific and technological progress in magnetic materials.

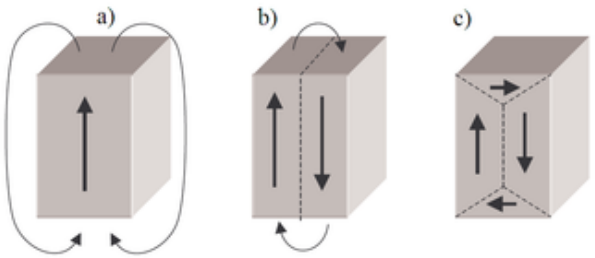

FIG. 1. Cartoon showing three possible domain configurations for a magnetic shape. Stolen from [2]

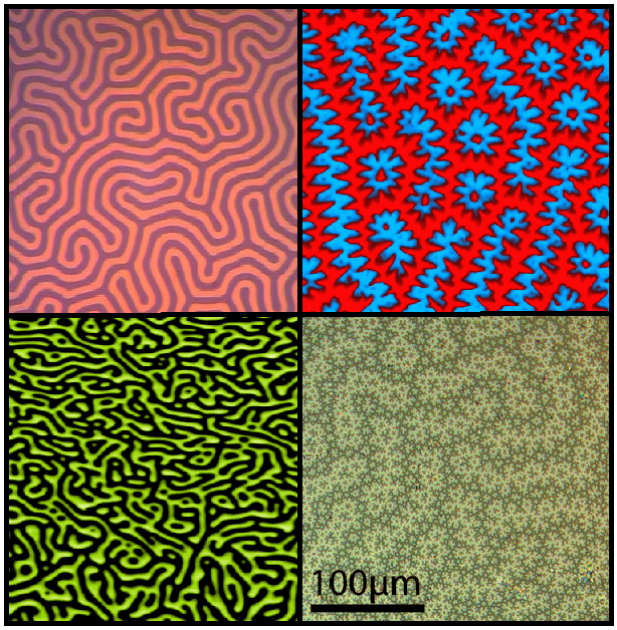

FIG. 2. Some of the fancier examples of magnetic domains found online. The first, a Faraday rotation image of 3μm stripe domains, found in BiFeG [2]. Second and third are MFM images of YIG and TbGdFeCo films [3]. The fourth is a MOKE image of a fractal domain pattern in a NdFeB film [4].

MAGNETO-OPTIC KERR EFFECT

The Magneto-Optic Kerr Effect (MOKE) is similar conceptually to the phenomenon of Faraday rotation, in which linearly polarized light experiences a rotation of its polarization direction upon transmission through a dielectric material with a magnetic field applied parallel to the direction of light propagation. This effect can be understood intuitively by considering that the linearly polarized light will induce charge oscillations in the dielectric that will interact with

the internal magnetic field via the Lorentz force. The result is a perpendicular contribution to the electric field, leading to a polarization rotation proportional to the magnetic field.

More commonly, the effect is understood as arising from a difference in the index of refraction for circularly polarized light of opposite handedness (Circular Birefringence). A beam of linearly polarized light may be decomposed into two circularly polarized beams of left and right handedness. The medium will then introduce a phase shift between the circular beams, and when combined they will form a linearly polarized beam with the polarization direction rotated through some angle.

The Faraday effect used as an experimental technique to probe magnetic fields requires that a sample be transparent at the light frequency used. However, for magnetic materials this is rarely the case. Metals in general have a penetration depth for light that is approximately 20 nm [5]. Materials that are thicker than the penetration depth may be investigated in the reflection geometry, and when this is done the effect is referred to as MOKE. The effect in reflection is very small ($< 0.1°$), due to the small distance traveled in the magnetic medium, and requires sensitive optical and electronic elements to detect.

Measurements by MOKE can be made in several geometries distinguished by the direction of the sample magnetization with respect to the sample plane and the plane of incidence of the light. When the magnetization is perpendicular to the sample plane, the effect is called Polar MOKE (see Fig.3). When the magnetization is in the sample plane, the effect is called Longitudinal MOKE or Transverse MOKE, with the former referring to the magnetization lying in the plane of incidence, and the latter perpendicular to the plane of incidence. A strong advantage of MOKE is that it can be made sensitive directly to the sample magnetization in any one or multiple directions. This allows an experimenter to observe the magnetization vector directly, without ambiguity.

A polarized laser is commonly employed as the light source for MOKE due to the achievable high intensity, which aids in the detection

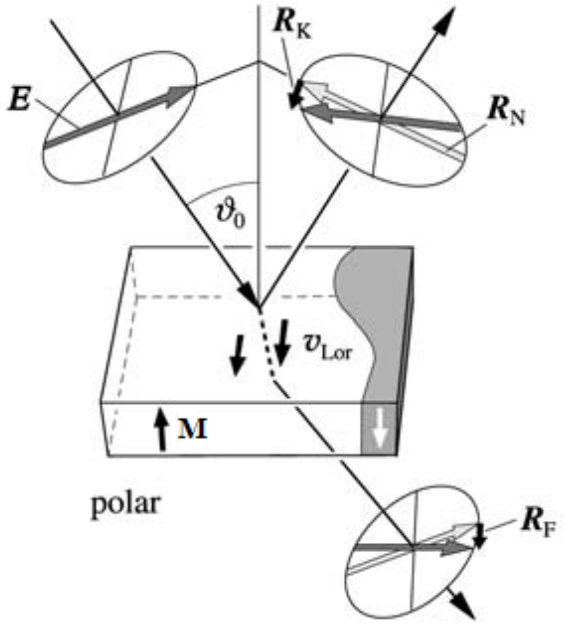

FIG. 3. MOKE in the polar orientation. Lorentz forces induced in the sample give rise to a transvese component of light polarization, detected as a rotation of the plane of polarization. [6]

of small kerr rotations. Most of these setups use a stationary laser to measure local or average magnetization, and are used extensively for conveniently characterizing magnetic properties, for example through hysteresis measurements. The simplest setup would consist of a polarizer and analyzer placed in the path of the incident and reflected laser beam, respectively. The intensity of the transmitted light would be measured by a sensitive photodiode, and Kerr rotations would be detected as modulations in the intensity.

MOKE MICROSCOPY

MOKE can also be used as a microscopy technique, whereby a focused laser is raster scanned across a surface and the kerr rotation is plotted as a function of position to produce an image. This method is rather slow in practice, and MOKE microscopy is more often performed in standard or modified polarization microscopes, using video cameras for detectors. The light source is most commonly a high pressure mercury lamp, with suitable filters. In addition to the polarizer and analyzer of the previously men-

tioned setup, there is an objective lens placed between them. Digital subtraction of non-magnetic background effects and post-processing is often used to enhance images [7]. The resolution is of course limited by the optical wavelength and numerical aperture, and has been demonstrated to reach 300 nm [8].

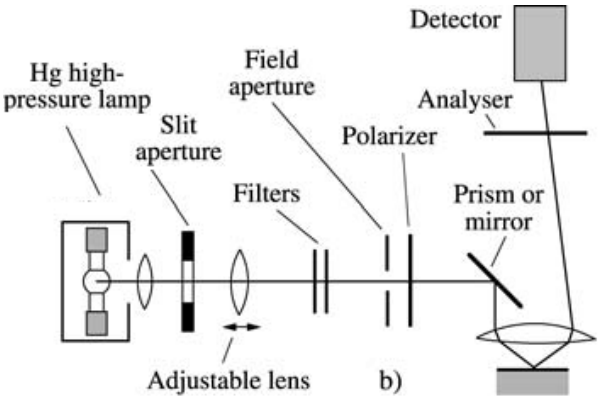

FIG. 4. A common configuration of a polarizing microscope used for MOKE microscopy. Light from an Hg high-pressure lamp passes through apertures and polarizers before it is focused on the sample, and viewed through an analyser using a camera. [6]

An important advantage of MOKE microscopy is that it is convenient to use and quite versatile. Samples of nearly arbitrary shape can be used, provided only that they are reasonably flat and smooth. The technique is non-destructive, and does not in most cases affect the magnetization which is being measured. Crucially, the sample can be manipulated during imaging and viewed in real-time. External fields may easily be applied, temperature can be controlled, stress can be applied, etc. Stroboscopic techniques using a pulsed light source can yield fast time-resolved images that are useful for studying high-speed magnetization processes with frame rates that can exceed 1 GHz [9]. Magnetic characterization, for example hysteresis loops, can be performed at many sample points simultaneously.

REFERENCE FROM RECENT LITERATURE

Ferromagnetic thin films with anisotropy perpendicular to the plane have many technological applications, as in magnetic recording media and sensors. These materials are commonly characterized and selected for an application by their macroscopic hysteresis behavior, that is, the response of the sample magnetization, M, to an applied field, H. In general this magnetization curve will not only depend on the applied field but also the history of the magnetic state. Above a critical field called the closure field, $H*$, the magnetization is said to have been saturated, in a well defined uniformly magnetized state for which the H vs M curve is single-valued.

A hysteresis loops measured by sweeping the applied field from $H > H*$ to $H < -H*$ is called a major loop, where many material parameters such as the saturation moment, M_s, coercivity, H_c, among others may be extracted. Loops starting or reversing from $|H| < H*$ are called minor loops, which are the basis for a variety of techniques used to characterize magnetic reversal mechanisms [10]. It is assumed that major and minor hysteresis loops are repeatable on the macroscopic scale under the same external conditions, except for the small effects of reptation in minor loops [11]. Many of the techniques of characterization rely on this assumption.

It came as a surprise when a recent paper in Physical Review B, by A. Berger, S. Mangin, J. McCord, O. Hellwig, and E. Fullerton [12], prompted us to rethink our assumption about minor loop repeatability. In this paper, the researchers discovered massive growth in the minor loop reversal under repeated field sweeps along the easy axis of perpendicularly anisotropic Co/Pt and Co/Pd multilayers (see Fig. 5). As the cyclic sweeps brought the magnetization up to within 1% of its saturation value, the minor reversal increased from about 25% to 90% after 19 repetitions. This was a noteworthy result as no effect anywhere near this size had been measured previously.

Without an imaging technique to quickly investigate the domain structure over a large area during the application of the cyclic fields, the

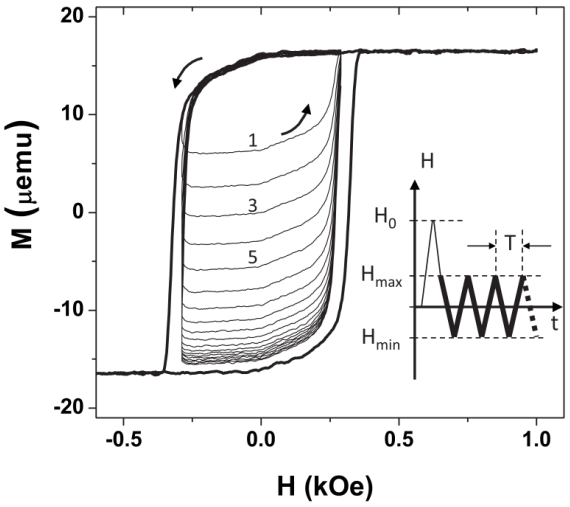

FIG. 5. Massive cumulative minor loop growth occurs in perpendicular Co/Pt multilayers through application of a cyclic magnetic field. [12]

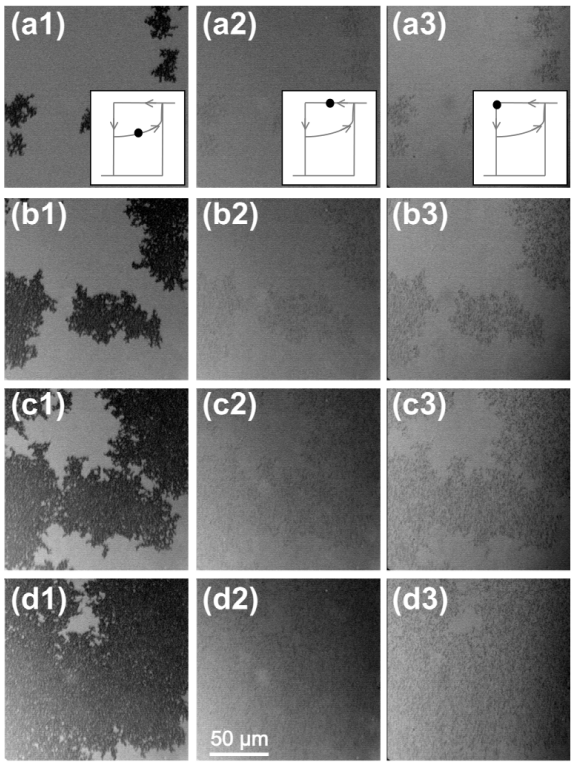

FIG. 6. MOKE images reveal the nature of the cumulative reversal mechanism. The columns show the domain pattern at the point of the minor loop indicated by the inset loop, and the rows depict subsequent repetitions of the field sweeps. [12]

cause of the cumulative minor loop growth may well have remained a mystery. However, a MOKE microscopy investigation of the reversal domain pattern was quite revealing. Figure 6 shows the domain pattern at each stage of the repeated minor loops. It was found that small domains which were nucleated in the first minor reversal retained some contrast after the sample was resaturated. Subsequent minor loops then, instead of stochastically nucleating new domains as would be expected, reversed in the same pattern and expanded upon what was previously reversed. This ability of the film to memorize its previous configuration even after being nearly completely reversed was a quite unexpected and remarkable phenomenon uncovered by MOKE microscopy.

CONCLUSIONS

We have seen how the energetics of ferromagnetic solids give rise to the formation of magnetic domains, which fuel scientific investigation due to their technological relevance. MOKE microscopy was introduced as a means to directly image domain structure, and an example of its use from the literature was discussed. No doubt, MOKE microscopy will continue to help lead to ongoing scientific discovery in coming years, and to provide topics for countless graduate students to write papers about that no one will ever read.

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[1] P. Weiss, J. de Phys. Rad. **6**, 661 (1907).
[2] T. F. E. Wikipedia, *Magnetic domain* (2014), URL `http://en.wikipedia.org/wiki/Magnetic_domain`.
[3] NT-MDT, *Magnetic domains of tbgdfeco film, yttrium iron garnet* (2014), URL `www.ntmdt.com/scan-gallery`.
[4] A. Kreyssig, R. Prozorov, C. Dewhurst, P. C. Canfield, R. W. McCallum, and A. Goldman, Phys. Rev. Lett. **102**, 047204 (2009).
[5] G. Traeger, L. Wenzel, and A. Hubert, Phys. Status Solidi A **131**, 201 (1992).
[6] A. Hubert and R. Schäfer, *Magnetic Domains: The Analysis of Magnetic Microstruc-*

tures (Springer, 1998), ISBN 9783540641087.

[7] R. Schäfer, *Investigation of Domains and Dynamics of Domain Walls by the Magneto-optical Kerr-effect* (John Wiley & Sons, Ltd, 2007), chap. 3.5, pp. 1464–1564, ISBN 9780470022184.

[8] F. Schmidt and A. Hubert, J. Magn. Magn. Mat. **61**, 307 (1986).

[9] M. Kryder, P. Koeppe, and F. Liu, IEEE Trans. Magn. **26**, 2995 (1990).

[10] C. Leighton, Physics **3**, 79 (2010).

[11] V. G. Lewis, P. I. Mayo, and K. OŠGrady, Journal of Applied Physics **73**, 6656 (1993).

[12] A. Berger, S. Mangin, J. McCord, O. Hellwig, and E. Fullerton, Phys. Rev. B **82**, 104423 (2010), URL `http://link.aps.org/doi/10.1103/PhysRevB.82.104423`.