Progress in magnetic domain observation by advanced magneto-optical microscopy

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Received 9 February 2015, revised 14 April 2015
Accepted for publication 23 April 2015
Published 16 July 2015

Abstract
The observation of magnetic domains by magneto-optical microscopy, based on the Kerr and the Faraday effect, is one of the most prominent techniques for the visualization of distributions of magnetization within magnetic materials. The method has gained increased attention due to the possibility to visualize field and current induced phenomena in nanostructured magnetic materials on fast time-scales. Fundamental concepts and recent advances in methodology are discussed in order to provide guidance on the usage of wide-field magneto-optical microscopy in applied magnetism. Recent applications of magneto-optical microscopy in bulk and thin film materials are reviewed at the end.

Keywords: magnetism, magnetic domains, magneto-optical microscopy, magnetic materials, imaging

(Some figures may appear in colour only in the online journal)

1. Introduction
The knowledge of the magnetic domain behavior in ferro- and ferrimagnetic materials is of great importance in order to comprehend the magnetization reversal behavior in magnetic bulk and film structures from a fundamental as well as from an application point of view. Magnetic domain imaging provides the most direct access to the effective magnetic properties of materials from macro- down to the nanoscale, since the signature of the magnetic microstructure acts like a mirror for the material’s magnetic properties. Especially in conjunction with complementary integral measurement schemes, like magnetometry and simulations, the knowledge of the magnetic domain behavior with external stimuli gives unrivaled insight into the origin of magnetization reversal mechanisms.

Generally, the formation of magnetic domains and their separating domain walls is described as due to the minimization of its total magnetic energy [1, 2]. In this case the magneto-static energy is the primary driving force for magnetic domain formation. This energy is directly coupled to the dimension and shape of the magnetic material. Moreover, the exchange or stiffness energy, the magnetic anisotropy energy, being of different origin and possibly varying locally, and the existing magneto-elastic energies determine the shape and the size of the magnetic domains. Magnetic domain patterns in materials with hysteretic behavior also depend on the magnetic field history of the material of interest [2, 3]. Yet, the interaction of the energy terms can be very complicated and a prediction of the structure of domains in ferromagnetic materials is rather difficult to achieve. Therefore, in order to understand the material behavior of magnetic materials, the direct visualization of the domain structure is required.

Various techniques for obtaining spatially resolved magnetic images of magnetic materials are currently available, each with their individual advantages and disadvantages. Reviews on various magnetic domain observation techniques...
and recent developments are published in [2, 4–13]. Methods of domain observation differ, for instance, in terms of physical interaction with magnetization, contrast mechanism, information depth, and achievable spatial or temporal resolution. A more practical distinction can be made in terms of parallel vs. scanning techniques, which, for instance, define image acquisition time, and methods requiring special apparatus not available in a regular laboratory setting. The latter, for example, is true for x-ray based methods that are based on synchrotron radiation [14–16]. On the other hand, magneto-optical (MO) microscopy using wavelengths in or close to the visible spectra is an established laboratory technique for the investigation of magnetic domains. The quality of the obtained results depends strongly on the specimen’s surface quality and the correct adjustment of the MO contrast settings. Examples of early results of MO imaging are displayed in Figure 1.

A discussion on various MO imaging aspects, including a vast amount of MO images as well as a review on magnetic domain physics, is included in [2]. In this paper, we focus on recent advances in wide-field MO microscopy for the imaging of magnetic micro- and nanostructures. Quasi-static [20–22] and dynamic scanning MO microscopy [23–33] is not treated in this review.

The manuscript is organized as follows. Based on the fundamentals, MO imaging methods are introduced and the latest experimental developments in the technique are described in detail. Recent examples of application for different material systems are given and discussed towards the end.

2. Magneto-optical effects

Magneto-optical domain observations in reflection and transmission are mainly based on the magneto-optical Kerr effect [34, 35] and the magneto-optical Faraday effect [36]. The Kerr and Faraday effect are linear in magnetization. Yet, also the Voigt effect [37] or Cotton–Mouton effect [38] can be applied for the characterization of magnetic materials [39], the Voigt effect being quadratic in magnetization.

In general, the MO effects are based on small alterations of the polarization state of light in dependence of the state of magnetization, which is then detected and used for magnetic image formation. The origin of the MO effects lies in Zeeman exchange splitting together with spin–orbit interaction [40–42]. An introduction to this subject is given in [43]. Analogously, materials with a large Voigt effect are characteristic of a large spin–orbit coupling of second order.

Here, we focus only on the aspects of applied magneto-optics relevant for the investigation of magnetic materials. Introductions to basics of magneto-optics are provided in [44, 45]. Excellent summaries on early and recent aspects of MO material properties are given in [43, 46, 47]. Reviews of more general aspects of magneto-optics are found in [2, 43, 46, 48–50].

2.1. Phenomenology of magneto-optical effects

Magneto-optical phenomena are classified according to the orientation of the electromagnetic wave vector of light emission relative to the magnetic field [49, 51]. In general, two fundamental geometries can be distinguished. In the so-called Faraday longitudinal geometry the light propagates along the direction of the magnetic field or magnetization. The electromagnetic wave vector \( \mathbf{k} \) is parallel to the magnetization \( M \). The produced rotation and ellipticity is described by treating the propagation of light waves with circular right-hand and left-hand polarization. The Faraday effect is based on the magnetic circular birefringence and dichroism [52, 53]. The magnetic circular birefringence arises from the difference in refractive indices of circularly polarized components of light that lead to a rotation of plane of polarization of linearly polarized light. The magnetic circular dichroism arises due to different absorption coefficients of left- and right-handed circularly polarized light in the medium, leading accordingly to an ellipticity. The geometry includes the two most relevant and related MO phenomena: the magneto-optical Faraday and the magneto-optical Kerr effect. Whereas for the Faraday effect the plane of polarization of light beam is rotated during transmission through an at least partly transparent magnetized sample, the Kerr effect is based on the rotation of the plane of polarization of light during reflection from a magnetized and reflective sample. An important feature of these linear MO effects is their non-reciprocal character. Assuming the Kerr effect in reflection and that the right-handed circularly polarized light wave propagates with a refractive index \( n^+_{\text{mag}} \) of the magnetic medium, respectively the left-handed circularly polarized wave with a refractive index \( n^-_{\text{mag}} \), the individual light waves will be reflected from the surface with the complex reflection coefficients [49, 52, 54] (refractive index \( n_{\text{inc}} \approx 1 \) for air)

\[
\begin{align*}
    r^+ &= \frac{n_{\text{inc}} - n^+_{\text{mag}}}{n_{\text{inc}} + n^+_{\text{mag}}} \quad \text{and} \quad r^- = \frac{n_{\text{inc}} - n^-_{\text{mag}}}{n_{\text{inc}} + n^-_{\text{mag}}} \quad (1)
\end{align*}
\]

from which a rotated and elliptically polarized wave is obtained. In microscopic applications, the resulting elliptically polarized wave can be transformed into linearly polarized...
light by means of a retardation plate [54] integrated into the microscopic setup (see section 3, figures 8 and 9).

In the case of the transverse Voigt geometry, the light travels perpendicular to the direction of magnetization. The wave vector $k$ is perpendicular to the magnetization $M$. The resulting MO effect then arises from the differences in absorption between components that are parallel and perpendicularly polarized relative to the magnetization. The so-called Voigt effect is thereby based on the magnetic linear birefringence and dichroism. Linearly polarized light, where the polarization is aligned under an angle relative to the magnetization, becomes elliptically polarized due to the magnetic linear birefringence. Experimentally, it is observed as a phase shift of the two components of polarization. Accordingly, the magnetic linear dichroism due to the difference in absorption coefficients of the two linearly polarized waves leads to a rotation of polarization. An overview of the discussed magneto-optical phenomena is given in table 1.

In all cases, the quadratic or second order MO effects can contribute to the linear MO effects and strongly influence different aspects of the MO measurements [55–58], including MO microscopy. All MO effects are generally small in amplitude and it is fairly challenging to distinguish the MO effects from additional optical effects, which are resulting from other physical properties of the sample [53].

Phenomenologically, the magneto-optical effects can be described in terms of a refractive index tensor, replacing the ordinary index of refraction [48, 59]. For the linear MO effects the complex Voigt or magneto-optical parameter $Q$ is introduced, by which the gyration vector is coupled to the magnetization vector [54]. Furthermore, for the quadratic MO effect magneto-optical constants $B_1$ and $B_2$ are used [60]. The resulting electric displacement vector $D$ then depends on the electric field vector $E$ with

$$D = \hat{e}E$$

(2) for an isotropic or cubic symmetry material, where $\hat{e}$ is the effective dielectric permittivity tensor of an isotropic (or cubic) media. For the given gyrotropic law $\hat{e}$ is accordingly described by

$$\hat{e} = \epsilon \begin{pmatrix} 1 & -iQm_z & iQm_y \\ iQm_z & 1 & -iQm_x \\ -iQm_y & iQm_x & 1 \end{pmatrix}$$

$$+ \begin{pmatrix} B_1 m_z^2 & B_2 m_z m_y & B_2 m_z m_x \\ B_2 m_z m_y & B_1 m_y^2 & B_2 m_y m_x \\ B_2 m_z m_x & B_2 m_y m_x & B_1 m_x^2 \end{pmatrix}$$

(3)

with the directional cosines of the net magnetization $m_z$, $m_y$, and $m_x$ along the three directions in space [60, 61]. $m$ is the unit vector of magnetization ($|m|^2 = 1$). Hereby the sign convention of [2, 62, 63] for the description of the MO effects is adapted. The sign convention in equation (3) implies that for the Faraday and Kerr effect, rotation and ellipticity are positive for a clockwise rotation of the axes of the electric wave vector $E$ and correspondingly the polarization ellipse. The constants $B_1$ and $B_2$ become equal in the case of amorphous or isotropic materials. All constants display a spectral dependency [46, 64–68], which needs to be taken into account for MO imaging applications. In the following, the individual MO effects will be discussed from an application point of view with emphasis on MO microscopy.

2.2. The linear MO effects—the Faraday and Kerr effects

The two linear MO effects are the Faraday effect and the Kerr effect. Both effects are odd in magnetization. Depending on the orientation of the magnetization relative to the plane of incidence and the orientation of the polarization of light, three fundamentally different types of MO effects can be distinguished: the longitudinal or meridional MO effects, the polar MO effect, and the transverse or equatorial MO effect. The three basic geometries for the Kerr effect [46, 49, 51, 53, 54, 69] are depicted in figure 2.

In both, the longitudinal and the polar MO effect, the projection of the wave vector of the electromagnetic wave on the magnetization vector $m$ is non-zero. Experimentally, the MO sensitivity axis is defined by the plane of incidence of the light beam. For the polar effect and for the longitudinal effects the plane of incidence needs to be aligned parallel to a component of the magnetization vector. For the transverse or equatorial effect the plane of incidence is aligned perpendicular to the component of magnetization to be probed. The general symmetry of the effects is analogous to a Lorentz force acting on electrons [2, 43].

2.2.1. Longitudinal and polar MO effects. The most commonly used MO effects in microscopy are the polar and longitudinal Faraday and Kerr effects. A sketch of the corresponding geometry of the longitudinal Faraday and Kerr effect with oblique plane of incidence and s-polarization is displayed in figure 3. Perpendicular s-polarization (polarized perpendicular to the plane of incidence) and parallel

Table 1. Magneto-optical phenomena (adapted after [45]).

| Geometry | Physical phenomena | Dependence with $M$ |
|----------|--------------------|-------------------|
| $M \parallel k$ | Magnetic circular birefringence (Faraday and Kerr rotation) | Linear |
| $M \parallel k$ | Magnetic circular dichroism | Linear |
| $M \perp k$ | Magnetic linear birefringence (Voigt or Cotton–Mouton effect) | Quadratic |
| $M \perp k$ | Magnetic linear dichroism | Quadratic |

Figure 2. The three basic configurations of the (a) polar, (b) longitudinal, and (c) transverse magneto-optical Kerr effect. The unit vector of magnetization $m$ is lying along the corresponding sensitivity axes (as indicated).
Faraday rotation \( \theta \) is an angle of incidence and ellipticity \( \epsilon \) with oblique (partly out-of-plane) alignment of magnetic non-diagonal terms need to be considered. For the case of longitudinal configuration, only two symmetrical non-diagonal terms are possible for the longitudinal configuration.

If the direction of magnetization in the magnetic material coincides with one of the coordinate axes, only two symmetrical non-diagonal terms need to be considered. For the depicted longitudinal Kerr configuration shown in figure 3, with \( m_\parallel = \pm 1 \), \( m_\perp = 0 \) and \( m_z = 0 \), the dielectric permittivity tensor (equation (3)) is reduced to

\[
\hat{\varepsilon} = \begin{pmatrix}
1 & 0 & iQm_\perp \\
0 & 1 & 0 \\
-iQm_\perp & 0 & 1
\end{pmatrix}.
\]

It should be mentioned that with oblique plane of incidence and with oblique (partly out-of-plane) alignment of magnetization, \( m_z \neq 0 \) (compare equation (4) to (3)), a separation of pure longitudinal in-plane and polar out-of-plane MO signal is not trivial. Yet, for applied MO microscopy the effective magnitudes of the MO effects are important [2, 54]. From figure 3 it is seen that a discussion of the magnitude of the effective MO effects is based on the individual reflected (refl) or transmitted (trans) amplitudes. For instance, by illuminating the magnetic sample with an s-polarized wave, generally two orthogonal components exist in the reflected light. One is polarized along the identical s-direction and the p-component is aligned orthogonally [54]. As a result, a reflection coefficient \( r_{ss} \) that defines the s-polarized wave after reflection and a reflection coefficient \( r_{pp} \) for the orthogonal component polarized along the p-direction can be defined. \( r_{ss} \) and \( r_{pp} \) are the regular reflection coefficients. Transmission coefficients can likewise be defined [70, 71]. For the MO Kerr effect the reflected amplitudes corresponding to p- and s-polarization are coupled to the incident p- and s-amplitudes by the MO Fresnel coefficients. The Jones matrix for the reflection of light from the interface of a non-magnetic medium and a magnetic medium is then defined as [54, 70, 71]

\[
\begin{pmatrix}
E_p^{\text{refl}} \\
E_s^{\text{refl}}
\end{pmatrix} = \begin{pmatrix}
r_{pp} & r_{ps} \\
r_{sp} & r_{ss}
\end{pmatrix} \begin{pmatrix}
E_p^{\text{inc}} \\
E_s^{\text{inc}}
\end{pmatrix}
\]

(5)

Hereby, in equation (5) \( E_p^{\text{inc}} \) and \( E_p^{\text{refl}} \) are the vectors of the incident and reflected light beam, respectively, \( r_{pp} \) is then given by ratio \( E_p^{\text{refl}} / E_p^{\text{inc}} \). The complex Kerr angle \( \phi_k \) with the Kerr rotation \( \theta_k \) and Kerr ellipticity \( \epsilon_k \) for s- and p-polarized light [72] then follows as (see also figure 3)

\[
\phi_{k,s} = \theta_{k,s} + i\epsilon_{k,s} = \frac{r_{ps}}{r_{ss}} \quad \text{and} \quad \phi_{k,p} = \frac{r_{pp}}{r_{sp}},
\]

(6)

\( r_{pp} \) depends on \( Q \) only for the transverse MO effect. In the case of longitudinal or polar contrast adjustment, the reflectance coefficients \( r_{ss} \) and \( r_{pp} \) are independent of the Voigt parameter \( Q \) and only the coefficients \( r_{ps} \) and \( r_{sp} \) need to be considered for the change of the polarization state of the reflected light beam in relation to the incident electromagnetic wave. For the polar (pol), respectively the longitudinal (long) bulk MO Kerr effect the following dependencies as a function of the incidence of light \( \theta_{inc} \) are obtained [39, 54, 73–75]:

\[
r_{pp} = r_{ps}^\text{pol} = -iQn_{mag}n_{inc}^2 \cos \theta_{inc}^2 \\
\frac{(n_{mag} \cos \theta_{inc} + n_{inc}) (n_{inc} \cos \theta_{inc} + n_{mag})}{2(n_{inc} + n_{mag})} = \left. \frac{-iQn_{mag}n_{inc}}{2(n_{inc} + n_{mag})} \right|_{\theta_{inc} = 0, \theta_{mag} = 0},
\]

(7)

\[
r_{sp} = r_{ps}^\text{long} = -iQn_{mag}n_{inc}^2 \sin \theta_{mag} \cos \theta_{inc} - iQn_{mag}n_{inc} \cos \theta_{inc} + n_{mag} \cos \theta_{mag}) \cos \theta_{mag} \\
= \frac{(n_{mag} \cos \theta_{inc} + n_{inc}) (n_{inc} \cos \theta_{inc} + n_{mag} \cos \theta_{mag}) \cos \theta_{mag}}{2(n_{inc} + n_{mag})}.
\]

(8)

\( n_{inc} \) and \( n_{mag} \) are the complex refractive indices of the medium of the incident light, respectively the magnetic medium as depicted in figure 4, \( \theta_{mag} \) is the resulting angle of incidence inside the magnetic medium as directly following from Snell’s law (see, e.g. [52, 74, 76, 77]).

In the microscopic application, \( \theta_{inc} \) is one of the most important parameters for the adjustment of the MO Kerr effects, with \( \theta_{inc} \) depending on the numerical aperture NA of the microscope objective lens [76, 78], where

\[
NA = n_{inc} \sin \theta_{inc}
\]

(9)

is the characteristic variable by which the maximum possible angle of incidence \( \theta_{inc} \) for a given microscope objective is defined. \( n_{inc} \) is the index of refraction of the medium found between the objective lens and the magnetic specimen. The refractive index \( n_{inc} \) is 1.0 for air and 1.518 if an oil immersion objective is used. This is a fundamental difference to magnetometric applications, where \( n_{inc} \) is usually fixed to 1. Furthermore, in most cases of MO imaging the individual Kerr intensities are the relevant quantities [2, 79].
Consequently, for microscopy with the longitudinal or polar Kerr effect the reflective intensities $|r_{ps}|^2$ or $|r_{sp}|^2$ are the figures of merit [39, 49]. Exemplary, the dependencies of $|r_{sp}|^2$ for the polar and longitudinal MO Kerr effect are calculated for iron versus numerical aperture (NA) for the application of air and oil immersion objective lenses, the results of which are displayed in figure 5. Seen from figure 5(a), starting with small angles of incidence the polar Kerr intensity is high and almost not changing over a wide angular range. A significant drop of $|r_{ps}|^2$ occurs only for high values of NA. One important consequence of the presented dependencies is the substantial increase of the maximum Kerr intensity with the use of oil immersion objectives, increasing with $n_{inc}$ (equation (7), right for $\theta_{inc} = 0^\circ$). The same holds true for the longitudinal MO Kerr effect (figure 5(b)). The usage of oil immersion objectives thereby eases the MO imaging of magnetic domains in reflection. An additional important impact on MO microscopy is derived from figure 5. The imaging of magnetic materials with in-plane arrangement of magnetization is significantly more challenging than the imaging of out-of-plane magnetic arrangements. Comparing the maximum of polar and longitudinal Kerr intensities, the longitudinal effect is by more than one order of magnitude weaker than the polar Kerr effect. This holds true for most metallic magnetic materials, the reason of which is lying in the usually high refractive index and the resulting strong contribution to $\theta_{mag}$. An even small out-of-plane magnetization signal, leading to a polar Kerr signal, can easily conceal the longitudinal Kerr signal of an existing in-plane distribution of magnetization. For small NA objectives, commonly objective lenses with low magnification, the obtainable in-plane longitudinal contrast is very weak. Only for the highest magnification objective lenses it is possible to get near the maximum longitudinal Kerr contrast regime at $\theta_{inc} \approx 60^\circ$ to $70^\circ$. Small angles of incidence are only providing a small longitudinal Kerr effect and should be avoided in microscopic applications utilizing the longitudinal Kerr effect. Another advantage of high NA objective lenses, the obtainable improvement of spatial resolution with higher NA oil immersion objectives will be discussed in section 3.2.

2.2.2. MO depth sensitivity. For metallic thin film magnetic samples, especially for magnetic multilayers, the depth dependency of the Kerr effects needs to be considered. The penetration or skin depth for the reflection of visible light on metallic surfaces is around 50 nm [81], the irradiance dropping exponentially from its surface. The depth dependency of the MO Kerr effect has been analyzed in detail for various magnetometric applications [50, 70, 72]. For very small film thicknesses the MO effects are increasing roughly linearly with film thickness [82, 83], the effective MO signal also changing with the underlayer or substrate material. Various fundamental aspects of the MO effects for magnetic multilayers are set out in [51, 60, 62, 74, 84–86]. In principle, probing individual magnetic layers in multilayer stacks [87, 88] is achievable. In that case, for a structure varying with thickness (along the z-direction) the MO Voigt parameter $Q$ will not be invariable and the spatial variation of the optical parameters needs to be considered, a process being addressed in [51, 86, 89, 90]. For illustration, a calculated...
differential Kerr and resulting Kerr amplitude dependence with thickness [90] are displayed in figure 6.

The shown amplitudes in figure 6(a) correspond to the assumed differential contribution of thin magnetic layers. With homogeneous material properties and homogeneous magnetization in the specimen, the Kerr amplitude can be derived by integration of the differential dependency, the result of which is displayed in figure 6(b). In general, the information depth of the Kerr effect is approximately one half the penetration depth of the light [61]. Moreover, using a retardation plate in the optical pathway, the phase can be selected in order to adjust the MO sensitivity function [60, 86]. One calculated example is displayed in figure 6(b) for the differential curve of figure 6(a) and a phase shift of 0.36π. In this case, the top part of the layer is magneto-optically (nearly) invisible, as the amplitude passes through zero close to the surface.

The experimental determination of magnetization loops obtained by magneto-optics utilizes the fact that by varying the phase or the angle of incidence, the magnitude and even the sign of the MO signal from individual layers vary in a different way. In addition to the phase change, the information depth scales with the wavelength of the incident light, offering an additional opportunity for layer resolved MO microscopy. These facts are used to obtain layer resolved MO magnetization loops from magnetic sandwich structures [91, 92]. Despite the theoretical understanding, in practice the individual imaging of magnetization of two separate layers is rather demanding. It has been achieved with the knowledge of the magnetization distribution of individual layers with a well-defined magneto-crystalline anisotropy [93–95]. The methods for extraction of distinct layer’s magnetization response presented in [91, 92, 96] by a weighted superposition of magnetization loops measured under different MO sensitivity conditions offer more flexible opportunities. By finding suitable linear combinations of magnetization loops, for MO magnetometry, or images, in the case of domain imaging, it is possible to distinguish the magnetization signal of individual layers. For a magnetic bi-layer structure a linear equation with two unknown images needs to be solved. An example displaying the separation of individual layer magnetization by linear combination of magnetic domain images that were obtained with a different adjustment of phase is demonstrated in figure 7. The even more demanding extraction of the signal of three ferromagnetic layers in a magnetic multilayer stack by MO Kerr effect magnetometry was theoretically described and experimentally demonstrated in [96].

2.3. Transverse MO effect

The transverse MO effect, being an amplitude effect, is mostly used for MO magnetometry [97–102]. For the transverse MO configuration the magnetization is aligned perpendicular to the plane of incidence. Advantageous to the longitudinal MO effects is that in the transverse configuration the MO signal is purely resulting from the components of in-plane magnetization. No transverse MO Faraday effect exists. A superposition of contributions from in-plane and out-of-plane components of magnetization in the MO signal is excluded. Yet, the use of the transverse effect geometry in wide-field MO Kerr microscopy is not straightforward. The ability to sense the magnetization component perpendicular to the plane of incidence is possible by transferring the optical intensity effect into a rotational MO effect [103].

Aligning the polarization of the incident light in-between the p- and s-polarization case, at π/4 relative to the plane of incidence, the component of magnetization parallel to the plane of incidence can be detected [2]. Challenging is the compensation of the occurring phase shift during reflection from the magnetic surface under non-orthogonal polarization conditions, an effect that needs to be offset by a compensating phase shifting optical element, e.g. a rotatable retardation plate or by a magnetic mirror in the illumination path [104] (see section 3). In contrast to the ‘real’ transverse effect, in such a configuration an MO sensitivity to out-of-plane magnetization components still exists.

2.4. The quadratic MO effect—the Voigt effect

The quadratic MO effect is the Voigt effect, being even in magnetization. It is observed when the polarization axis of light is aligned normal to the orientation of magnetization. The effects are usually small and are best visualized in polar MO configuration with in-plane alignment of magnetization. By this, if the directions of magnetization in the magnetic material coincide with the coordinate axes being in the film plane, only the corresponding terms in equation (3) need to be considered. Thus, with m₁ ≠ 0, m₃ ≠ 0 and m₄ = 0 (m² + m²₃ = 1), the dielectric permittivity tensor is reduced to
layers become visible. By a linear combination of (a) and (b) an image (c) representing purely the magnetization of the Ni$_{81}$Fe$_{19}$ bottom layer is obtained (sample: D. Bürgler, FZ Jülich).

\[
\hat{e} = \begin{pmatrix}
B_1 m^2_x & B_2 m_x m_y & 0 \\
B_2 m_x m_y & B_1 m^2_y & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

(10)

In contrast to the linear reflective effect, where $r_{pp}$ ($r_{rp}$) (see equations (7) and (8)) is the figure of merit, for the quadratic effects the alteration of the reflective coefficient $r_{pp}$ ($r_{rp}$) with magnetization is relevant. As different contributions to different elements in the reflectivity matrix (equation (5)) are obtained, the Voigt effect can be separated experimentally from the linear MO effects. Maximum contrast between $m_x$ and $m_y$ is achieved when both components of magnetization are aligned under $\pi/4$ relative to the plane of polarization, by which, with the use of a phase shifting element, a rotational MO effect can be obtained.

Despite being rarely used for MO imaging, the Voigt effect contributes, to a certain degree, to all MO measurements. Especially, where a quantitative evaluation of the magnetization is needed, like in MO magnetometry and quantitative MO imaging, the influence of the even MO effect needs to be understood and to be considered. The Voigt effect, however, offers the only possibility to detect in-plane magnetic domain distributions with purely perpendicular illumination and therefore also with low NA objective lenses (see section 2.2.1).

2.5. The gradient effect—the Schäfer–Hubert effect

The MO gradient effect is exhibited at magnetic domain boundaries of in-plane magnetized films, best visible under imaging conditions where other MO effects are not contributing to the MO contrast [105–107]. It was discovered under perpendicular incidence of light in in-plane magnetized samples with well-defined magnetic anisotropy, confirmed and analyzed on different types of magnetic specimens [93, 108–110]. In contrast to the Kerr and Voigt MO effects, the anomalous MO gradient effect is not sensitive to homogeneously magnetized objects (magnetic domains), but originates from gradients of magnetization at micromagnetic objects. From the symmetry of the observed contrast across differently oriented domain walls a phenomenological 2D gyromagnetic equation for the description of the gradient effect was derived. For the case of perpendicular plane of incidence, the dielectric permittivity tensor is [105, 106, 108, 109]

\[
\hat{e} = P_{gr} \begin{pmatrix}
\frac{\partial m_x}{\partial y} - \frac{\partial m_y}{\partial x} & \frac{\partial m_x}{\partial x} - \frac{\partial m_y}{\partial y} & \frac{\partial m_z}{\partial x} + \frac{\partial m_z}{\partial x} \\
\frac{\partial m_x}{\partial y} - \frac{\partial m_y}{\partial x} & \frac{\partial m_x}{\partial x} - \frac{\partial m_y}{\partial y} & \frac{\partial m_z}{\partial x} + \frac{\partial m_z}{\partial x} \\
\frac{\partial m_x}{\partial y} - \frac{\partial m_y}{\partial x} & \frac{\partial m_x}{\partial x} - \frac{\partial m_y}{\partial y} & \frac{\partial m_z}{\partial x} + \frac{\partial m_z}{\partial x}
\end{pmatrix}
\]

(11)

with the gradients of magnetization $\partial m_x/\partial x$ and $\partial m_y/\partial y$ and the MO parameter $P_{gr}$, responsible for the gradient effect. The material constant $P_{gr}$ scales directly with the Voigt parameter $Q$, indicating the identical gyromagnetic cause as the MO Kerr effect. The cause of the effect was heavily disputed in the past [111], but seems to be clarified now, originating in microscopic MO currents due to the exhibited gradients of magnetization [112]. Once the exact distribution of magnetization is known, even a quantitative derivation of the Schäfer–Hubert effect by diffraction theory is possible [113, 114]. As for the Voigt effect, even for regular MO domain imaging based on the odd effects, influences of the gradient contrast at magnetic domain walls need to be deliberated.

3. Instrumentation—magneto-optical microscopes

The introduced MO effects can be used for the imaging of magnetic domains or domain boundaries by means of regular polarization optics. The use of these effects for magnetic domain observations has a long-lasting tradition. Early examples, also including a discussion of antireflection cover layers for the amplification of the low MO contrast, are found in [17, 115–121]. Aspects of the initial developments of the MO domain observation technique are summarized in [18]. A thorough discussion, including an enormous amount of magneto-optical images and discussions on magnetic domain behavior, is included in [2].

Two fundamentally different configurations of wide-field MO domain imaging setups are possible. An early comparison of the two principle methods is given in [122]. One arrangement makes use of a separated path of illumination and observation, most suitable for the MO imaging of large samples with an in-plane magnetic arrangement of the magnetic domains. The other kind of setup is based on a modified polarized light microscope, where a single objective lens is applied for the illumination of the magnetic specimen and the imaging of the lateral distribution of magnetization. This arrangement is suited for the observation of magnetic domains up to high
spatial resolution and with high magnification. Inherent to both systems, and in contrast to scanning probe microscopy methods, is the wide-field imaging scheme that allows the direct imaging of a magnetic sample independent of the used magnification or image size.

In general, all MOKE imaging schemes rely on the exact control of the illumination path and the states of polarization in the microscope, by which the individual magneto-optical contrast schemes are set precisely. Therefore, advanced MOKE imaging is only possible on the basis of a comprehensive knowledge of the principles of Köhler illumination and of the significance of the conjugate optical planes for the resulting images. In the following, we concentrate on the two basic designs applied to microscopic MO imaging of magnetic domains in reflection. Yet, most of the aspects will also apply to the imaging of magnetic domains in transmission by the MO Faraday effect.

3.1. Large view bright-field microscopes

The imaging of magnetic domains by the MO Kerr effect at low magnification with a viewing field of up to several centimeters is achieved by using a microscope setup consisting of an inclined microscope and a separate symmetrical illuminating system [123]. With this arrangement significant in-plane MO contrast is achieved as large angles of incidence under nearly optimal MO amplitude conditions can be obtained. Examples of the use of such a system [124] include the imaging of thin film samples with varying interlayer coupling [125–127]. A major drawback of the imaging scheme is that, because of the inclination, only a stripe of the sample is in focus [79, 104]. The width of the region in focus is defined by the depth of field of the optical system. This disadvantage can be partly overcome by tilting the objective lens away from the illumination axis in such a way that a focused image at the camera sensor is obtained [2, 121]. Yet, a strongly distorted image is formed, which can be corrected to the homogeneous magnification by digital image processing. Moreover, due to the requirement of having access to the focusing lens, the use of commercially available corrected microscope optics is often excluded.

One way to bypass the optical difficulties is a confocal slit arrangement [128] in which both, the focusing lens and a slit aperture, are scanned in a coordinated way. By this a magnetic image is obtained, only consisting of line elements of the sample being in focus. Thereby, a constant magnification image is achieved in the confocal MO imaging setup.

A modern MO system, demonstrating constant magnification imaging by direct wide-field imaging, is based on the use of telecentric lenses [129] together with a Scheimpflug arrangement [130]. Such an optical system avoids the disadvantage of magnification variations due to changes in focus. The telecentric system becomes invariant to defocus with the addition of a narrow aperture stop in the observation path [131, 132], by which all principal rays entering and exiting the lens are close to parallel. Moreover, other unwanted effects like image distortion and vignetting are strongly reduced as compared to regular imaging optics. Since only nearly parallel rays are contributing to the image formation, in comparison to a common low magnification system, the depth of field is likewise increased. The needed inclination of the sample relative to the optical axis is compensated by a Scheimpflug principle [133] camera mount. With the Scheimpflug adjustment mechanism a constant focus across the whole sample size is obtained. The major optical condition is that the extended image and camera plane, and the continuation of lens plane intersect in one line. Even for a strongly inclined axis of observation zero distortion images are acquired. All requirements that were put forward in [121] are fulfilled.

A principle sketch of a bi-telecentric MO imaging system is given in figure 8. The imaging paths for illumination
(figure 8(a)) and observation (figure 8(b)) are separated for better clarity. Resulting domain images are linearly compressed only along one axis, so that merely the aspect ratio needs to be fixed by a simple linear operation (figure 8(c)). The proportionality factor \( f_c \) for the procedure is directly given by the tilting angle of the microscope \( \theta_{\text{inc}} \) and the rotation angle of the camera system \( \theta_{\text{cam}} \) with \( f_c = \cos(\theta_{\text{inc}})/\cos(\theta_{\text{cam}}) \).

The system consists of a collimated high power light emitting diode (HP LED) illuminator. The LED illumination system offers higher stability of light intensity as compared to conventionally used high pressure arc lamps. Optical polarization elements like rotatable polarizer and analyzer as well as a retarder plate are integrated into the light path. Having the polarization optics in-between the imaging lenses eliminates the sensitivity to the MO Faraday effect in the imaging lenses with the application of high external magnetic fields. Polar and in-plane MO sensitivity relative to the plane of incidence can be obtained with proper adjustment of the optical polarization components. Imaging of in-plane magnetization distributions at or close to the optimum angle with the highest MO sensitivity is possible, independent of the magnification (compare to figure 5).

As discussed above, the key aspect of the optical system is the projection of the image plane onto the camera system without distortion by the use of bi-telecentric objective lenses in combination with a rotatable Scheimpflug mount. In most practical cases the effective spatial resolution of the large view imaging setup is determined by the camera system and not by the principal optical resolution of the imaging system (see section 3.2.4).

### 3.2. High resolution imaging bright-field microscopes

The visualization of magnetic domains with a single objective lens is possible with an adapted polarizing microscope [2, 79, 122, 134]. This setup allows for imaging down to the best possible spatial resolution. Imaging of in-plane domains is best with high NA objective lenses (see section 2.2.1). The principle ray diagram [135] of an advanced MO imaging setup is displayed in figure 9.

In order to obtain optimal and homogeneous MO contrast several aspects have to be considered: correct adjustment of illumination, polarization optics, and the characteristics of the digital camera.

#### 3.2.1. Illumination source

Conventionally, arc discharge lamps are used in MO imaging due to their high radiance output levels [2]. Yet, especially high pressure mercury arc lamps exhibit an inherent and significant arc instability, which is disadvantageous for MO imaging applications. The position of the arc is also varying with the application of magnetic fields, further introducing an unwanted source of intensity variation in magnetic imaging. The problems can partly be bypassed with metal halide lamps offering better stability along with similar radiance. By coupling the light source with an optical fiber into the MO microscope, a better separation of the light source and the magnetic field source is obtained, by which the interaction of the arc plasma with the magnetic field source can be reduced. Furthermore, physically detaching the light source and the microscope leads to a reduced input of heat into the microscope, thus improving the thermal stability of the microscope.
The use of alternative light sources, such as lasers, offers significant advantages. Lasers produce greater and steadier intensity than arc lamps. Yet, due to the exhibited laser coherence, image artifacts due to laser speckle are introduced in the low contrast MO images [136–138]. This problem was solved eventually by introducing a combination method, applying three diverse methods based on a fiber-optic laser illumination [139]. Using different modulation methods of reducing laser speckle, a spatially uniform, stable, and averaged over time incoherent illumination with extremely high irradiance was introduced and used for the magnetic characterization of magnetic recording heads pole-tips [139, 140]. Similar imaging schemes using continuous-wave lasers are reported in [141–144]. The technique is also successfully applied for wide-field time-resolved imaging using mode-locked picosecond lasers [145–150].

As a result of recent developments in LED technology [151, 152], LEDs have become an alternative for illumination in MO microscopy. For state-of-the-art high power LED illuminators the spectral irradiance is similar or superior to high pressure arc lamps. Several watts of collimated output power are achievable with current LED illuminators. Moreover, LEDs have high durability [153] and possess low noise [154]. This enables illumination sources with high efficiency and high brightness. DC and pulsed operation modes are available that allow an easy adaption of the imaging schemes for time-resolved microscopy applications (see section 3.3). Different wavelengths throughout the near-ultraviolet into the infrared spectrum with narrow bandwidth (spectral half width of approx. 15 nm) can be selected as an illumination source. Moreover, due to the non-coherence and in contrast to lasers, speckle patterns play no role for LED based illumination systems. High efficiency coupling into optical fibers is feasible, making high power LEDs a superior and flexible light source for MO microscopy [155]. Only for small objects, where higher zoom levels are needed, laser illumination schemes are still beneficial [140].

### 3.2.2. Illumination path

Essential for a homogeneously illuminated field of view and thus constant MO contrast across the whole viewing field is the exact adjustment of the so-called Köhler illumination [78, 156–158], by which the illuminating light source is fully defocused onto the specimen. Thereby an even illumination of the specimen is obtained. Important are the proper alignment of the axes, the foci of light, and the effective openings of apertures in the optical microscope setup as displayed in figure 9(a). The following elements lie in conjugate aperture planes (AP in figure 9): the light source, the aperture diaphragm or slit, and the back focal plane of the objective. Moreover, several conjugate image planes (IP in figure 9) exist, by which the Köhler illumination conditions are defined: the field diaphragm, the specimen, and the primary image plane. Spherical rays that are parallel in one of the conjugate planes are focused in the other optically reciprocal planes.

By limiting the size of the light source, the specimen is illuminated only by a slightly converging set of plane wave fronts. The resulting narrow angular spread of incidence gives rise to well-adjusted MO sensitivity conditions. By positioning the fiber output within the aperture plane, the desired MO contrast conditions can be adjusted. Multiple fiber outputs can be in principle focused into the back focal plane for the adjustment of MO sensitivity. Yet, with the use of holographic filters, a vast amount of different illumination patterns can be generated from one or a low number of fiber outputs. Exemplary positional settings of the light source in the aperture plane for the adjustment of different MO sensitivities are displayed in figure 10 (see also [139, 140, 159]).

By aligning the fiber output at different positions in the aperture plane, the corresponding plane of incidence is changed and the desired MO sensitivities are accomplished. Instead of or in addition to an optical fiber, a positionable iris diaphragm or rectangular aperture can be used. The application of a slit aperture for the adjustment of in-plane domain contrast [2], as it is essential for the imaging with arc lamps, often leads to a relatively wide angular range of incident light. Yet, contributions from small angle of incidence θinc only give a small MO signal and, thus, reduced efficiency of MO imaging (see figure 5). One advantage of a slit aperture, especially for the use of high NA objective lenses, is the better effective extinction coefficient κ. This fact is mostly relevant in regard of the MO contrast for the direct observation of magnetic domains. The coefficient κ depends only in first approximation on the extinction ratio of the polarization elements in the microscope (typically better than 10⁻³), κ decreases due to differential transmission and phase shift from s- and p-polarized components at curved optical interfaces [158, 160]. As a consequence, depolarization occurs more pronounced for higher NA objectives. The resulting background intensity decreases the signal-to-noise ratio (SNR) in MO imaging, as will be discussed in section 4.1. Due to the depolarization effects in the microscope, the extinction factor of the applied polarizers plays only a minor role: polarization prisms [2], high quality sheet polarizers [122], or wire-grid based polarizers can equally be applied for MO imaging applications.
The often varying position of the back focal plane (AP) for different objective lenses is problematical in practice. This flaw can best be compensated by altering the position of the illuminating fiber output along the imaging axis as indicated in figure 9. Alternatively, the condenser lens can be adjusted in a similar way to offset the mismatch of back focal positions.

### 3.2.3. Objective lens

The most important optical element of an MO microscope is the objective lens. The optical parameters of the objectives strongly define the overall performance of MO systems. Due to the diffraction limit, the numerical aperture NA of the objective lens sets the maximum achievable spatial resolution [78, 158]. Its resolution is a key figure of merit of the microscope system. The use of a Berek prism in the microscope ray path [2], mostly discussed as being superior for polarization microscopy and especially for high contrast MO microscopy, reduces the effective NA along one axis by a factor of two and should therefore be avoided for high resolution MO imaging. The optical limit of spatial resolution, however, is not solely determined by the NA of observation, but also by the ray characteristics of illumination. Oblique incidence of light, using high NA of illumination, is well suited for attaining good lateral resolution along the plane of incidence as the effective NA is thereby maximized (see e.g. [78]). Because of the restriction in illumination along the axis perpendicular to the plane of incidence, a small reduction of the optical resolution is common for all other orientations. The resolving power $R$ of a microscopic system is in accordance with the Rayleigh criterion [76, 78]

$$R = \frac{\lambda}{(\text{NA}_{\text{ill}} + \text{NA}_{\text{obs}})} = 0.61 \frac{\lambda}{\text{NA}},$$

with the wavelength of illumination $\lambda$ and the numerical aperture of illumination $\text{NA}_{\text{ill}}$ and observation $\text{NA}_{\text{obs}}$. Even slightly smaller values of $R$ are obtained with Sparrow’s criterion [78]

$$R = 0.47 \frac{\lambda}{\text{NA}_{\text{obj}}},$$

which is more applicable for imaging with digital image sensors [161]. It is defined as the distance in which the second derivative of a composite intensity distribution between two objects just vanishes. The accessible spatial resolutions for different numerical apertures and for different wavelengths of illumination according to equation 12(b) are shown in table 2 for typical objective lenses and two different wavelengths of illumination.

In general, with high NA microscope objective lenses lateral resolutions as low as 150 nm are possible, the exact value of which depends on the wavelength of illumination and NA. For instance, comparing the use of red ($\lambda = 640$ nm) and blue ($\lambda = 460$ nm) illumination sources, an according difference in lateral resolution by a factor of approximately 1.4 is obtained. The theoretically calculated resolution can also be obtained in practice. The magnification is irrelevant in this discussion, as only NA and the wavelength of the illumination determine the spatial resolution limit.

Examples of MO imaging at or close to the resolution limit can be found in [140, 162]. Exemplary results from the imaging of magnetic microstructures with characteristic length scales at the limit of the best achievable lateral resolution ($\lambda = 460$ nm, NA $= 1.3$) from unstructured soft and hard magnetic materials, structured out-of-plane anisotropy thin films, and a magnetic nanowire are shown in figure 11. Longitudinal and polar MO contrast configurations, in accordance with the exhibited magnetic properties, were used for imaging. The use of UV illumination with $\lambda = 360$ nm has been demonstrated [163] recently.

Orientations of magnetization of isolated linear structures with domain widths down to 400 nm, (c) a patterned PtCo(1.4 nm)/Cu(2 nm)/Co(1.4 nm)/Pt thin film with 340 nm feature size (Reprinted from [165], with permission from Elsevier [166]), and (d) 300 nm wide GMR nanowire (seed/PtMn/Co90Fe10(3 nm)/Ru(0.8 nm)/Co90Fe10(3 nm)/Cu(2 nm)/Co90Fe10(0.8 nm) Ni81Fe19(28 nm)-structure (sample courtesy R. Mattheis, IPHT Jena).

![Figure 11. Imaging of sub-micrometer magnetic feature sizes.](image)

### Table 2. Spatial resolution $R$ according to the Sparrow’s criterion.

| Magnification | NA  | $R_{460\text{nm}}$ | $R_{640\text{nm}}$ |
|---------------|-----|-------------------|-------------------|
| 5 ×           | 0.13| 1.66 µm           | 2.31 µm           |
| 10 ×          | 0.25| 0.86 µm           | 1.20 µm           |
| 20 ×          | 0.5 | 0.43 µm           | 0.60 µm           |
| 50 ×          | 0.8 | 0.27 µm           | 0.38 µm           |
| 100 ×         | 0.9 | 0.24 µm           | 0.33 µm           |
| 500 ×         | 1.0 | 0.22 µm           | 0.30 µm           |
| 1000 ×        | 1.3 | 0.17 µm           | 0.23 µm           |

*Data for oil immersion objectives.*
Moreover, the contrast of the resulting MO images is strongly dependent on the optical transmission properties, the scattering of light properties, and the polarization quality of the objectives. The transmission parameters of the objectives determine the effective overall accessible intensity. The scattering and the polarization quality affect the MO contrast, in particular the signal-to-noise ratio in MO imaging. Consequently, only high transmission low stray light objectives can be used for MO microscopic applications. Non or low magnetic objective lenses are also of great advantage for MO imaging applications.

3.2.4. Camera system. Almost as significant as the objective lens is the camera system for the performance of an MO microscope. It strongly contributes to the signal-to-noise ratio (SNR), but it also highly determines the achievable spatial resolution, especially in low magnification microscopy applications. High resolution high dynamic range monochrome digital cameras with a bit depth of 12 or 16 bit are best suited for MO imaging. They offer low noise characteristics and maximum quantum efficiency, typically above 70%. Low noise characteristics are obtained by Peltier and/or water cooling of the sensor chip. Due to the development in recent years, not only charge-coupled device (CCD) sensors are applicable for scientific imaging purposes, but also high sensitive complementary metal oxide semiconductor (CMOS) sensors with good imaging qualities are available. The available spectral response, however, varies for the different sensors. The achievable temporal resolution is determined by the minimum exposure time of the camera system. The CCD-based cameras, despite usually working with lower read-out speeds, allow for smaller exposure times as the CMOS sensors. CMOS-based sensors often use a so-called rolling shutter mode, in which the individual lines of the sensor array are exposed at different times. Exact imaging of dynamic processes is then only achievable by means of external gating, e.g. through a pulsed illumination source or an additional fast shutter. In contrast, in CCD sensors a global shutter mode is used, where each pixel in the sensor is exposed simultaneously.

Binning of camera pixels, the combining of adjacent pixels, offers advantages in terms of faster read-out speeds, but, and this is more relevant for MO applications, results also in an improvement in SNR. Binning also increases the dynamic range of the device, though at the expense of decreased spatial (camera) resolution.

For the camera resolution the effective cell size of the camera is the figure of merit. The eventual resolution of the imaging sensor is determined by the dimensions of the individual photo-sensitive elements relative to the image projected onto the imaging array in the microscope system. In order to match or exceed the optical resolution of the objective lens and to preserve the spatial resolution of the objective lens in the resulting MO image, the sampling interval of the camera sensor array has to be at least twice the maximum spatial frequency of the sample. This relation is given by the Nyquist criterion [169, 170]. The camera sensor must be able to sample at intervals equal or less than half the resolution of the microscope. A comparison of the change of resolution for a captured image depending on the camera’s cell size is given in figure 12. Corresponding data on the achievable spatial resolution from typical objective lenses is given.

For low magnification images and for the chosen properties of camera and objective lens, the best achievable resolution is limited by the camera, and not the NA of the objective lens. Without binning and below a threshold of about 50 times in magnification, the actual image resolution is determined by the camera property and not by the objective lens. For instance, with binning the spatial resolution is diffraction limited only for the case of 100 × magnification objectives independent of the wavelength of illumination.

3.3. Temperature dependent imaging

Adapting the microscope setups for temperature dependent imaging is straightforward. Cryostats, for low temperature imaging, and heating stages, for the imaging at higher temperatures, can be integrated into the setups. Low temperature applications include the imaging of flux penetration into type-II superconductors with ferrimagnetic MO indicator films [171–181] (see also section 8), the imaging of domains in magnetic semiconductors [182–190], and exchange coupling phenomena in magnetic multilayers [191–195]. Also magnetic phase transitions at low temperature [196–198] and around room temperature [199] are of relevance. High temperature observations deal with crystallization processes in soft magnetic nanocrystalline materials [200, 201], again with exchange bias phenomena [202], and the change of magnetic properties with temperature in hard-magnets [203]. Other applications include for instance rock magnetism [204] for elevated temperatures, and the investigations of structural phase transitions [205, 206] for low temperatures.
One obstacle for the use of heating stages and cryostats is related to the use of viewports to optically access the samples. Two in principle different approaches are used. In one case, the imaging is performed through an optical window between the magnetic object and the objective lens. With that approach (figure 13(a)), the use of long-distance objective lenses with an optical correction for the viewing window thickness is required (at least for high NA objectives). By this, highest spatial resolution is not possible to achieve. In another approach (figure 13(b)), the objective lens is integrated into the cryostat or heater and the viewing window is between the objective lens and the microscope. Regular high NA objective lenses can be used. Yet, the application of oil immersion lenses is excluded. For both principle variants the viewing window must be stress-free in order to not alter the polarization state of light. A complete integration of electromagnet and focusable objective lens inside a vacuum chamber for temperature dependent measurements has been used in [207].

Vibrational influences need to be reduced by mechanically decoupling or damping of the connected vacuum systems. Internal vibration isolation and a low thermal-expansion support structure help to reduce vibrations and drifts of the sample position. For the applications of external magnetic fields heaters and cryostats are equipped with an extended sample mount, permitting for the high magnetic field applications by allowing a close integration of magnetic pole-tips at the magnetic sample.

3.4. Imaging magnetization dynamics

One of the utmost advantages of MO imaging over the majority of other imaging methods is the ability to visualize fast dynamic magnetization processes. However, different definitions of magnetization dynamics exist, ranging from femtosecond processes for ultrafast spin-dynamics, Landau–Lifschitz dynamics on the nanosecond time-scale to eddy-current dominated magnetization dynamics in the micro- to millisecond range for thick samples. Yet, creeping phenomena on the time-scales of seconds or more can be part of it. The whole range of time-scales can be covered by MO microscopy. Depending on the requirements of the experiment, different methods are applied to obtain the needed temporal resolution. A discrimination has to be made between single shot imaging and stroboscopic imaging techniques, the latter used for imaging of fast dynamic magnetization processes.

3.4.1. Slow dynamics. Dynamics on time-scales of several seconds or even longer can be imaged directly and in real-time by MO microscopy. Of particular interest for long-term dynamic studies are magnetization relaxation processes as they occur in ultrathin magnetic films. An overview on certain aspects of magnetization reversal studies by MO methods, including MO imaging of thermally activated processes, is given in [208] and [209]. Examples of snapshot domain images from the reversal of magnetic single and multi-layers with perpendicular and in-plane magnetic anisotropy that display thermally activated effects are depicted in figure 14. Creeping effects related to antiferromagnetic layer contributions in epitaxial CoO/Pt/Co/Pt/Al2O3 were studied in [214]. Other magnetization processes of interest are related to non-repeatable domain wall motion in electrical steel and amorphous ribbon samples with 1 Hz to 50 Hz field excitation frequency [215].

3.4.2. Milliseconds to microseconds. Magnetization dynamics at the kHz range can be imaged by means of stroboscopic
imaging using gated image intensifiers as demonstrated firstly for the observation of garnet domains using the Faraday effect [216]. This method has been revived for the imaging of eddy-current limited magnetization dynamics in magnetic core materials [217–219]. From stroboscopic MO Kerr effect microscopy observations, the dynamic magnetization process on nanocrystalline tape wound cores is clarified. Of particular interest in these studies were magnetic excess losses, the related eddy-current driven magnetic domain wall refinement, and the repeatability of the magnetization processes. An exemplary image of such a measurement, displaying patch-like domain behavior, is displayed in figure 15(a). High and variable repetition rates and continuously adjustable time resolutions are possible with such imaging systems. The coarse hexagonal capillary structure of the microchannel plate (MCP) image intensifier results in an effective reduction of spatial resolution. Moreover, the use of MCPs has drawbacks due to the strong drop of SNR resulting from the signal amplification. The use of a two-stage or three-stage MCP image intensifier can partly reduce that circumstance.

At least partial repeatability of the magnetization processes is required for stroboscopic imaging. Single shot imaging of magnetization relaxation in exchange-biased perpendicular anisotropy thin films was realized by imaging with an arc flash lamp [220]. The flash lamp was used to measure single shot remagnetization events with a time resolution of approximately 10 μs. Yet, the typical dependence of light intensity with time for the imaging with such schemes is strongly influenced by the long exponential decay of intensity of the illuminating light pulse. Maximum flash rates are typically about 10 Hz. An exemplary single shot image from an asymmetric magnetization reversal in an exchange-biased thin film with out-of-plane anisotropy is displayed in figure 15(b). A similar illumination scheme was used for the imaging of magnetic field induced transformations in magnetic shape memory alloys [207, 221].

Single shot imaging of the magnetization reversal in a grain oriented electrical steel sheet, however, is also possible with a large field MO microscope (see section 3.1) due to the excellent MO contrast conditions. Some microsecond resolution is achievable by direct imaging at low exposure times with regular CCD-based cameras without the need of image intensifiers (figure 15(c)).

3.4.3. Nanosecond dynamics. Wide-field imaging on the nanosecond time-scale [222] has been realized by similar ways as discussed in the previous section. Also here, time resolution is achieved by imaging with a gated image intensifier. The principal use of such a camera system for the imaging of magnetization dynamics in recording head writers in the nanosecond time range was demonstrated [223]. Stroboscopic imaging of magnetization processes of thin film samples with time resolution down to 250 ps is shown by this method. In an alternative (pioneering) approach [224–227], using pulsed Q-switched ruby and gas lasers and in combination with gated illumination, a temporal resolution down to some nanoseconds is achieved.

3.4.4. Picosecond dynamics. Stroboscopic wide-field imaging with mode-locked picosecond lasers has been used for investigations of magnetization dynamics of thin film elements on the micrometer length scale. Different techniques were applied, all relying on pulsed magnetic field applications with sub-nanosecond rise-times [145–149]. In a time-resolved pump-probe microscopy experiment, the mechanism of all-optical magnetization reversal by a singular circularly polarized 100 fs laser pulse was studied [228, 229]. All-optical recording and optical read-out of local magnetic information within 30 ps is proved by that technique. In the laser-based stroboscopic imaging schemes, time resolution is defined from the laser pulses. A continuous DC recording of the camera signal is applied.

Nearly jitter-free time-resolved wide-field MO Kerr effect microscopy with picosecond time resolution and with phase-locked harmonic excitation is demonstrated in [150]. Such a system allows for the direct imaging under a continuous microwave field excitation. By this the direct imaging of fundamental dynamic modes of magnetic domain and domain wall states in soft magnetic thick film elements becomes possible. Domain wall oscillations can be imaged directly and domain wall velocities can be extracted. The basic imaging setup is displayed in figure 16.
High temporal resolution is achieved by using a mode-locked diode-pumped and frequency doubled Nd:YVO₄ laser with a pulse width of 6 ps and a fixed repetition rate of 50 MHz. A magnetic rf-field is applied through a coplanar wave-guide. A phase-locked loop is used to synchronize the repetition rate of the passively mode-locked laser system to the reference clock signal, by constantly adjusting the laser cavity length, controlling its frequency and phase. With the clock synchronizer feedback system, a timing jitter of less than 0.5 ps is obtained. The direct observation of magnetization processes up to several GHz excitation frequencies is possible with such a microscope system.

In general, picosecond time-resolved MO imaging is performed in a stroboscopic differential imaging mode with varying the phase between the rf field excitation and the imaging laser pulse. Two individual differential images are formed from the difference of two magnetization states at different time delays. By imaging in this manner, only alterations of magnetization become visible in the domain response images. Exemplary data demonstrating the imaging of precessional magnetization response, the direct observations of nanosecond domain wall displacements and spin-wave generation from magnetic thin films samples are displayed in figure 17.

Despite the application of in-plane microwave field excitations, out-of-plane contributions of magnetization precession including dynamic magneto-static coupling between individual magnetic domains are imaged (figures 17(a) and (b)). Precessional domain wall motion with out-of-plane magnetization components is seen in figure 17(c) [150]. The domain wall precession acts as a source for spin-waves within the central magnetic domains as seen in figure 17(d). The spin-waves propagate with 0.65 km s⁻¹. Moreover, the direct imaging of standing spin-waves at field excitations up to several GHz is possible by the technique, an example of which is displayed in figure 17(e).

Figure 16. Stroboscopic time-resolved imaging setup consisting of a mode-locked laser as an illumination source, a standard MO microscope, and a GHz magnetic field excitation source. The mode-locked Nd:YVO₄ laser runs from the same clock as the rf signal generator, providing low jitter imaging conditions [150]. The shown amplifier and the oscilloscope are optional.

Figure 17. Dynamic domain response images for a magnetic element with a Landau domain pattern at magnetic resonance of 2 GHz (a) displaying only out-of-plane and (b) combined out-of-plane and in-plane sensitivity. (Reprinted with permission from [150]. Copyright 2014 by the American Physical Society.) (c) Domain wall motion at wall resonance and (d) domain wall induced spin-wave propagation with time with a 100 MHz field excitation [sample: (Fe₉₀Co₁₀)₂₀Si₃₂B₃₀(160 nm)]. (e) Imaging of standing spin-wave modes in a Co₄₀Fe₄₀B₂₀/Ru/Co₄₀Fe₄₀B₂₀ anti-dot array at 2 GHz.
3.4.5. Femtosecond dynamics. Stroboscopic Faraday imaging of sub-picosecond processes using femtosecond lasers is demonstrated in [230]. Time-resolved MO imaging with an angular resolution of light polarization of a few millidegrees, 100fs temporal resolution, and micrometer spatial resolution is obtained from a rotating analyzer method. No (saturated) background image (see also section 4.2) is needed for the imaging by that technique. A pump-and-probe all-optical switching experiment is applied to a ferrimagnetic GdFeCo thin film sample. Exemplary data of the evolution of magnetization during the all-optical switching event is displayed in figure 18.

4. MO contrast considerations and enhancement

A general challenge of MO Kerr or Faraday imaging is the obtained low magnetic domain contrast as a result of the weak nature of the MO effects. In practice, the realizable magnetic domain image quality is determined by the achievable signal-to-noise ratio. For a given plane of incidence and a given magnetic material, the SNR is mainly influenced by two additional experimental parameters. Firstly, for the set MO sensitivity the overall MO contrast needs to be optimized by proper setting of the polarization optics. This is in first approximation done by correct setting of the analyzer angle in order to obtain the optimum SNR. Secondly, the MO or domain contrast is amplified and image noise is reduced by digital image processing, by which clear and low-noise domain images are produced.

4.1. MO contrast—signal-to-noise ratio

For a given setting of illumination, the MO contrast is mostly determined by the analyzer settings, meaning the angle of analyzer rotation from maximum extinction in the optical microscope path. For digital imaging applications, the figure of merit is the SNR of the captured domain image with a variation of magnetization along the sensitivity direction. It represents the ratio of the measured light signal to the combined noise of different origin. A large SNR is essential for the acquisition of high-quality MO domain images. Unwanted image signal components originate from the used electronics and from variations of the incident photon flux. Common sources of noise in a digital imaging system are therefore photon noise, dark noise, and read noise [158]. Dark noise and read noise are directly determined by the digital camera system. The overall SNR for a digital imaging system can be approximated by

\[
\text{SNR} = \frac{B \cdot P \cdot QE \cdot t}{\sqrt{B \cdot P \cdot OE \cdot t + B \cdot D \cdot t + N_r^2}},
\]

with the incident photon flux \(P\), the image sensor’s quantum efficiency \(QE\), and the total integration time \(t\). \(D\) is the dark current value and \(N_r\) denotes the read noise [231, 232]. \(B\) is the number of binned camera pixels. Subsequently, we will focus on the regime, where photon noise is dominating and other noise sources are not relevant, thereby neglecting very short exposure and integration times. With the intensities of the individual magnetic domains \(I_r\) and \(I_c\) aligned along the sensitivity direction, the SNR is given by

\[
\text{SNR} = \frac{B \cdot QE \cdot t}{E \cdot (I_r - I_c)} = \sqrt{\frac{B \cdot QE \cdot t}{E}} \cdot \frac{(1 - \kappa)(\sin^2(\beta + \theta_{MO}^+) - \sin^2(\beta + \theta_{MO}^-))}{(1 - \kappa)(\sin^2(\beta + \theta_{MO}^+) + \sin^2(\beta + \theta_{MO}^-)) + 2\kappa},
\]

with the individual MO angles \(\theta_{MO}^+\) and \(\theta_{MO}^-\) and the analyzer angle \(\beta\) relative to a crossed analyzer-polarizer setting. In most cases \(\theta_{MO}^+ = -\theta_{MO}^-\) will be valid. The effective extinction ratio \(\kappa\) is set by the quality of the polarizers in the microscope, but to an even greater extent by the characteristics of the microscope (see section 3.2.2). The first term in the equation is defined by the used illumination and camera settings. The SNR can be increased by integrating or averaging over time, using a high quantum efficiency digital camera and binning. The variation of the overall photon energy \(E = (h \cdot c / \lambda)\) has a small contribution. The second term is determined by the analyzer setting and the strength of the MO effect. By optimization of the analyzer’s uncrossing angle, maximum SNR is obtained. The variation of SNR with \(\beta\) for typical MO rotation angles for an MO Kerr effect with \(\theta_k = \pm 0.15^\circ\) as obtained from metallic materials and an MO Faraday effect with \(\theta_t = \pm 5^\circ\) as typically achieved from micrometer thick garnet layers that are optimized for MO applications, is depicted in figure 19.

Two main conclusions become obvious from the shown modelling results. Firstly, the optimal analyzer-polarizer uncrossing angle \(\beta\) is higher than \(\theta_k\) and \(\theta_t\). With increase of background intensity (increase of \(\kappa\), the optimum angle \(\beta\) is increasing. Yet, good SNR is achieved over a relatively wide range of \(\beta\). With an increase of the effective value of \(\kappa\), being a measure of background intensity, the SNR reduces. However, the reduction of SNR is relatively low. The relevance of such calculations for applied MO microscopy should be treated with care. Yet, the shown general dependencies are in agreement with results from experiments.
Fast image processing provides the basis of state-of-the-art MO imaging. By digital image processing techniques such as digital (Fourier) filtering [233, 234], (real-time) background subtraction, and averaging of MO signals improved quality magnetic domain images became practical. Digital image processing in real-time was firstly applied for low-contrast imaging in medical [235] and biological [236–238] imaging applications and was later adapted for the use in magnetic domain imaging. Many different schemes for the improvement of MO signals are conceivable. The main objective is obtaining a high contrast magnetic signal, in which non-magnetic contrast contributions are eliminated. Most of the applied routines for contrast enhancement are based on differential imaging of magnetic states. With alterations of optical polarization or of the magnetic settings purely magnetic high contrast (response) images are acquired. SNR is improved by averaging multiple image frames. Naturally, gain and offset to the digital camera sensor can be applied in order to achieve a maximum camera contrast [239].

Imaging by alteration of the optical polarization conditions relies on a modulation of polarization [240–242] or on differential imaging of the same magnetic state imaged with two different analyzer or polarizer settings in the microscope. In the most simple case, the MO image $MO(x,y)$ is constructed by the difference of two imaging states $I_+$ and $I_-$.

$$MO(x,y) = I_+(x,y) + I_-(x,y) = ΔI(x,y).$$ (15)

Practically, better imaging quality is obtained by changing the state of polarization of the illumination settings, as compared to the analyzer settings. For this kind of differential imaging, no alteration of the magnetization state is needed. This makes it most applicable, where an alteration of magnetization is not feasible. For instance, it is applied for domain observations of permanent magnet materials [243–247] or where a modification of the magnetic state of interest is unwanted [22]. An alternative method relies on the fitting of the local sensitivity function from multiple MO images [230] (see figure 18).

An exemplary set of two raw magnetic images taken from an extended soft magnetic metal film using two different polarization conditions is displayed in figures 20(a) and (b).

Obtaining both images under different conditions of polarization, an inversion of the MO contrast is achieved. After subtracting the images, the weak magnetic domain contrast can be amplified and a clear high contrast magnetization domain map is achieved (figure 20(c)).

In the standard approach, a background image that displays no (or an averaged out) magnetic signal or a homogeneous magnetic information (figure 20(d)) is acquired, which is then subtracted from the magnetic domain pattern of interest [248–250] (figure 20(e)). The resulting MO domain image is displayed in figure 20(f). Most of the images shown in this article
are acquired by this technique. Real-time and high contrast domain imaging is achievable by this method.

In an alternative approach neither of the MO images is acquired in a homogenous state of magnetization. Differential images are obtained from variations of magnetization with a small magnetic stimulus [27, 148, 251, 252]. The method of differentiating of slightly altered domain states has gained renewed attention for the imaging of small nanostructures, especially for the investigation of magnetic field- and current-induced domain wall motion in magnetic nanowires [253–257]. Likewise, the same approach is used for time-resolved stroboscopic imaging schemes that rely on repeatable magnetic events [145–150, 222]. Variations of the imaging scheme, including more complicated imaging sequences are discussed in [258]. In imaging techniques relying on magneto-optical indicator films, a differential image in the indicator film is acquired by removal of the magnetic sample of investigation, keeping the indicator film in place [259].

For samples with locally varying reflectivity, however, the total MO intensity difference between images for positive and negative magnetization saturation can be uneven. Examples are samples with surface topography, different or locally changing roughness, and optically anisotropic polycrystalline (large grain) materials. The local effective MO sensitivity variation is then superimposed on the magnetic domain image, by which an interpretation of the magnetization distribution is hampered. Related to quantitative domain imaging, the procedure applies only to MO images obtained for a single sensitivity direction. A signature of such an imaging error would be a lateral inhomogeneity in MO intensity, the difference between images for positive and negative magnetic saturation along the sensitivity axis. The thus effective non-uniformity of the MO sensitivity will be superimposed on the magnetic domain image. Various examples together with improved MO images are given in [260]. By normalization of the obtained differential image (Δ, figure 20(g)) with a saturation differential image (±M, figure 20(h)) an image displaying the component of magnetization along the sensitivity direction is obtained (figure 20(i)) [260]. The normalized MO image MOnormalized(x, y) is constructed from a regular differential MO image normalized by the difference of two saturated imaging states Ix,sat and Iy,sat with

\[ MO_{\text{normalized}}(x, y) = \frac{2\Delta I(x, y)}{I_{x,sat}(x, y) - I_{y,sat}(x, y)} = \frac{\Delta M}{M_{x,sat}} = m_{x,y}. \]  

Surprisingly, the technique is not used routinely so far. Special care has to be taken on the correct treatment of non-magnetic sample elements with zero MO contrast (Mx,sat ≈ 0) and image noise. The method can also be applied for correction of uneven illumination in not properly set MO microscopes.

Instabilities in the optical illumination source and mechanical instabilities reduce the quality of the results. Magnetic sample or microscope movements of only a few nanometers lead to a degradation of the MO image. Hence, a very steady intensity illumination source and a mechanically stable microscope are a prerequisite for all differential imaging schemes. Mechanical instabilities can be (partly) compensated by digital image cross-correlation, by which an improved alignment of the background and the domain state image is achieved. With sub-pixel digital image alignment, image drifts with accuracy below one nanometer can be compensated, an example of which is shown in figure 21. In the depicted example, the influence of the defects in the differential image is nearly eliminated by digital sub-pixel alignment that corresponds to a spatial variation of Δx = 1.28 nm and Δy = 0.44 nm. The technique can be applied after imaging, but also in situ and in real-time.

5. Advanced MO imaging techniques

5.1. Quantitative domain imaging

Despite its advantages for the understanding of magnetization patterns of complicated magnetic domain structures, quantitative magnetic MO microscopy is a technique that is hardly applied for magnetic materials investigations. It is based on the use of a complicated calibration scheme involving multiple calibration images, by which the angular MO sensitivity function in the MO microscope is determined [261–263] experimentally. Similar vectorial mapping of magnetization can be obtained by other domain imaging techniques like spin-polarized scanning electron microscopy [264–267] and by differential phase contrast imaging (DPC) with Lorentz microscopy [268, 269]. Restrictions of the MO microscopy approach lie in the presumed sinusoidal MO sensitivity function. Existing errors can partly be eliminated by including a quadratic Voigt term in the fitting of the sensitivity functions [270]. Examples of applied quantitative MO domain imaging include low magnetic anisotropy ribbons [271] and mixed
anisotropy hybrid magnetic property thin films [272], where an easy domain interpretation is not feasible. Magnetization maps from thin films with orthogonally laterally distributed magnetic anisotropy axes are displayed in figure 22 (see also [273] and section 7.6). Real-time imaging with vector information of the magnetic domains is not possible with this imaging technique.

### 5.2. Multi-component imaging—dual-wavelength imaging

Multiple wavelength imaging schemes are used routinely in life science microscopy investigations [274–276]. An MO imaging approach for the simultaneous imaging of multiple magnetization components based upon a dual-wavelength approach is demonstrated in [155]. In this imaging scheme two imaging paths are merged in the microscope. For the demonstrated implementation of the technique two fiber-coupled high power LEDs with different optical wavelengths are applied concurrently for illumination. An individual independent positioning of illumination settings for both light sources, like oblique and orthogonally aligned planes of incidence, is possible by this. Accordingly, illumination conditions for simultaneous s- and p-mode longitudinal MO sensitivity can be obtained. The imaging beams are coupled into the illumination light path through a wavelength sensitive dichroic mirror (figure 23(a), compare to figure 9). Other arrangements are possible. Most important, in the reported scheme, the reflected light is yet again divided into two separate light paths that are directed onto two synchronized high sensitivity microscope cameras, by which two domain images under different MO conditions are ultimately obtained. In an alternative arrangement an image splitter is used, which enables recording of MO images simultaneously with one camera system (figure 23(b)). Alternatively, by sequentially imaging and synchronizing the individual LEDs with the exposure of a regular camera system, similar results can be obtained, but with only nearly simultaneous imaging.

In general, the use of a divided optical illumination and observation path allows for the direct extraction of different complementary magnetic information. The multi-channel image approach permits complicated imaging schemes, like combination images involving multiple applied MO sensitivity conditions, including mixed Kerr and Voigt imaging and quantitative evaluation from one magnetic pattern. So far imaging with only one pair of images was possible [2]. An illustrative example of an advanced measurement involving four complementary MO images of a single unaltered domain structure from an epitaxial iron film is displayed in figure 24.

From such an analysis, the magnetization distribution of samples with complicated magnetization behavior can be derived and magnetic domain features remaining hidden with standard single sensitivity domain imaging techniques are directly exposed. In particular, the biggest advantage of the multicomponent measuring scheme is the possibility of real-time imaging of multiple components, by which, among other potentialities, the quantitative imaging of magnetic domain in motion becomes realizable. The application of real-time magnetic vector imaging to complicated domain processes in stressed magnetostrictive films for magnetoelectric sensor application is first demonstrated and used for the understanding of the noise mechanism in magnetoelectric composite sensors [155] (figure 25). The applied field interval for the two magnetization patterns is $\Delta H = 0.1$ Oe.

Yet, dual beam—dual sensitivity imaging is not limited to quantitative evaluation of magnetization. Other embodiments of imaging include the separation of in-plane and out-of-plane magnetic contrast in oblique plane of incidence MO microscopy and layer selective magnetic domain imaging. The separation of in- and out-of-plane magnetization components in an oblique magnetic anisotropy Pt/Co/Pt-multilayer structure is demonstrated in figure 26. By local ion irradiation regions with locally varying magnetic properties are obtained (similar to [277]). Shown is a generated square element with oblique plane of anisotropy, displaying a mixed longitudinal and polar
MO contrast (figures 26(a) and (b)), surrounded by a matrix with pure in-plane anisotropy. By addition and subtraction of MO images obtained with opposite oblique incidence, pure polar (figure 26(c)) and pure longitudinal in-plane sensitivity (figure 26(d)) images are obtained. The latter is not possible by other means in MO microscopy (see also section 2.2.2).

Moreover, the dual imaging scheme can be applied to the simultaneous imaging of individual layer magnetization in multilayer stacks. The feasibility of the concept of simultaneous depth selective microscopy is demonstrated in the imaging of individual layer magnetization in a CoFe/Ta/ Ni81Fe19 bi-layer structure. Displayed in figure 27 are two domain images from the same structure, which are recorded simultaneously in a dual image arrangement. Only one single digital camera image with two domain images is shown. Clearly, two dissimilar domain patterns corresponding mainly to the top and bottom layer magnetization, respectively, are distinguished.

Figure 24. (a), (b) Concurrently obtained Kerr images of a single crystal iron film with orthogonal sensitivity directions, and (c) obtained quantitative domain image. Concurrently obtained (d) diagonally aligned Kerr and (e) Voigt image after change of the fiber output alignment. (f) Vector representation of magnetic domain pattern. The corresponding illumination arrangements in the back focal plane of the objective are indicated. (Imaging: R. Malik, Kiel University; sample: D. Bürgler, FZ Jülich; GaAs/Fe(1 nm)/Ag (150 nm)/Fe(50 nm)/ZnS).

Figure 25. Magnetization reversal in an amorphous magnetostrictive FeCoSiB layer. (a), (b) Simultaneously recorded complementary magnetic domain images with orthogonal sensitivity directions including quantitative domain evaluations. The orientation of the applied magnetic field is horizontal. The exposure time of the individual domain image is 5/100 s. The edge of the sample is located on the bottom (Si/SiO2/Ta(10 nm)/(Fe90Co10)78Si12B10 (2000 nm)/Ta(5 nm)) (Reprinted with permission from [155]. Copyright 2014, AIP Publishing LLC.).
In conclusion, using two imaging paths, domain images with different sensitivities are recorded simultaneously. Quantitative domain imaging, layer selective magnetic domain imaging in multi-layered thin film structures, as well as the separation of in-plane and out-of-plane magnetization components in film structures with out-of-plane and in-plane magnetization components are now possible. An extension to time-resolved imaging techniques is straightforward.

5.3. MO dark-field imaging

Even being a standard method in optical microscopy, dark field imaging is almost never used for MO microscopy applications [279, 280]. Yet, dark-field MO imaging based on the Faraday effect is demonstrated for the investigations of Bloch lines and conically shaped bubble domains in transparent epitaxial ferrimagnetic garnet films [281–284]. With an inclined plane of incidence using a high aperture condenser lens together with a low aperture objective lens, diffractive MO contrast images of the magnetic domain boundaries and internal domain wall features are obtained from diffraction. While the directly transmitted light is omitted, the MO image is produced purely from the diffracted light. Despite recent advances in diffractive MO magnetometry on periodic magnetic nanostructures [285–290], dark field MO imaging in reflection remains untested.

6. Image data representation

In general, imaging of a complete magnetization loop with varying magnetic field \( H_{\text{ext}} \) by MO microscopy provides a large amount of microscopic information, which is usually viewed as a series of sequentially obtained magnetization maps \( M(x, y, H_{\text{ext}}) \). From this data a regular magnetization loop can be derived, by which the data is reduced to its most essential core. However, valuable information is lost thereby. Only a few attempts have been made to bridge that gap. In [291] a method of representation of multiple images is introduced that allows for compact representation of magnetization reversal information. Analyzing and plotting the information obtained from histograms of individual reversal maps, the information of fractions of different kinds of domains and magnetization components is gained. In another attempt [292] the reversal of magnetization in single quasi 1D magnetic stripes with \( H_{\text{ext}} \) is analyzed and the data is presented in a 3D map of the magnetic reversal process (See also figure 17(d) for a similar approach for time-resolved imaging data of spin-wave propagation from a single domain).

Exemplary domain images of the magnetic reversal of the magnetostrictive phase of a magnetoelectric composite are displayed in figure 28(a). A map of the complete reversal extracted from line-plots for the individual field steps of the overall reversal process is shown in figure 28(b). Decreasing the magnetic field from saturation, first narrow domains develop which coarsen with decreasing field. At a certain threshold field, a reorganization process takes place and wide domains instantaneously nucleate. In the reversed field, narrow domains penetrate from the edges and a continuous domain refinement [293] takes place. All this can be followed from the presentation displayed in figure 28(b). Plotting the histogram in a similar way as in [291, 294] (figure 28(c)), the development of multiple domains, magnetic domain coarsening, and the continuous domain refinement can be understood in a similar way. As the MO sensitivity direction is chosen perpendicular to the applied magnetic field, a hysteresis loop cannot be extracted. However, the evolution of the transverse components of magnetization in the individual domains with field can be tracked.

The shown example demonstrates only some of the possibilities of presenting large datasets of domain imaging data. Fourier components or the application to continuous quantitative imaging are other possible ways for data analysis.
7. Applications of magneto-optical Kerr effect microscopy

As set out, MO microscopy offers a great variety of ways for the investigation of magnetic materials. MO microscopy is one of the most versatile techniques to image magnetic domains and magnetization processes. The ability to observe the magnetic domain structure is especially important for the understanding of the origin of magnetic properties. Also, the performance of magnetic devices correlates with the spatial distribution and time evolution of the magnetization. Significant results in fundamental science, applied physics, and engineering have been obtained by MO microscopy. An (incomplete) overview of data obtained from various material systems on different length scales is shown in figure 29.

Shown are examples from grain-oriented electrical steel (figures 29(a) and (b), see also section 7.2), patterned soft magnetic elements like Ni$_8$Fe$_{19}$ [295, 296] in figure 29(c), higher magnetic anisotropy amorphous CoFeSiB elements with a modified closure domain structure (figure 29(d)), and reduced anisotropy CoFeSiB elements [297] that again display a regular closure domain structure (figure 29(e)). Stress relaxation, occurring at the edges can lead to an avoidance of closure domain structure [298], closure domains are repelled from the edges in positive magnetostrictive tensile stressed Ni$_{45}$Fe$_{55}$ films (figure 29(f)). An alternative way of patterning by local ion irradiation leads to domain formation without the need of magneto-static energy contributions (figures 29(g)–(i)) as will be discussed in section 7.6. Low magnetic anisotropy leads to complicated domain structures in soft magnetic CoFe-based films [234, 300] as seen in figures 29(j) and (k). Soft magnetic thin films with out-of-plane anisotropy display different types of magnetic stripe domains [234, 301] (figures 29(l) and (m)), the characteristics of which can be studied by MO microscopy (see also figure 11(a)). Magnetic domain formation due to nucleation and incomplete annihilation strongly influences the magnetization processes in perpendicular anisotropy thin films [302] (figure 29(n)). Domain observations on antiferromagnetically coupled multilayers as part of synthetic spin valve sensors [303], asymmetric magnetization reversal in exchange bias systems [304], and magnetization reversal in exchange spring systems [194] as shown in figures 29(o)–(q), provide insights in symmetry breaking coupling phenomena. Working magnetic devices like the writing process at the air bearing surface of a recording head [139, 140] can be analyzed (figure 29(r)). In addition to metallic materials, domain observations in non-metallic materials are achievable (see section 7.3), LSMO (figure 29(s)), GaMnAs (figure 29(t)), CoFe$_2$O$_4$ (figure 29(u)), and BiLu$_3$Fe$_5$GaO$_{12}$ garnets are exemplary shown (figure 29(v)). Domain observations on soft magnetic nanowires based on Ni$_{45}$Fe$_{55}$ (figure 29(w)), Co$_{30}$Fe$_{50}$ (figure 29(x)), and Fe (figure 29(y)) [306] with dimensions well below one micrometer are feasible [307]. Examples from out-of-plane anisotropy thin film wires

Figure 28. (a) Selected domain images from the magnetization reversal of the magnetic phase of a magnetoelectric composite [293]. (b) Change of domain spacing with applied magnetic field for the backward loop. (c) Change of magnetization components $m_x$ with $H_{ext}$. The magnetic field $H_{ext}$ axis is displayed on the right.
are discussed in section 7.8. In the following paragraphs some recent applications of MO microscopy are described.

7.1. Permanent magnetic bulk materials

For the investigation of hard magnetic materials MO microscopy offers many possibilities. Despite the surface sensitivity of the MO effect, for bulk materials useful information for the understanding of magnetic reversal mechanism and temperature dependent effects can be extracted from MO domain images [163, 244–246, 308–322]. Applications vary from high throughput MO screening of novel magnetic materials [203] by qualitative and quantitative analysis to fundamental studies [316] by Kerr and Faraday based MO microscopy.
The interpretation of the obtained magnetic surface structure is in many cases not straightforward. Micromagnetism and complementary high resolution techniques need to be applied to relate the magnetic surface to the bulk domain structure [2, 316, 323]. Additional applications include magnetic domain observations by the MO Kerr effect on magnetocaloric materials [198, 205, 206].

7.2. Soft magnetic bulk materials

The control of the magnetic reversal in soft magnetic bulk materials is essential for improving their energy efficiency. For grain-oriented electrical steels the reduction in core losses in recent years is due to three major technological advances [324]. One is the development of better gauge materials. The other two, improved texture control and, especially, the establishment of domain refining technique, are directly related to the control of the magnetic domain structure [324–326]. It was shown that eddy-current losses reduce with decreasing 180° domain wall spacing and increase with increasing fraction of 90° domains. Providing favorable local mechanical stresses to refine the magnetic domains is the key for the optimization of soft magnetic iron-silicon alloys. Magnetic domain observations by MO techniques deliver the scientific fundamentals to understand the important issues of nucleation and annihilation of surface closure domains and pinning processes in the movement of 180° domain walls and their interaction with defects [327].

Various aspects of magnetic domain formations in transformer steel sheets based on MO investigations are discussed in [108, 325, 326, 328–331]. An extensive review of various scientific aspects of magnetic domain formations in electrical steels as derived by MO observations is found in [2]. The influence of applied stress, grain size, and texture on the performance and magnetic domain behavior is a current field of interest [332–337]. Highly debated is the question what amount of stress is required to improve the magnetic properties of grain-oriented electrical steel, as the magnetic domains are formed from a complex interplay of crystallographic grain orientation, grain size, and the applied stress (compare figures 29(a) and (b)). Combined large view (figure 30) and high resolution MO microscopy form the basis for imaging magnetization behavior at operational frequencies.

Another class of soft magnetic materials where the observation of magnetic domain structure is of high interest are amorphous and nanocrystalline ribbons. Observations from dc to high ac frequencies have been performed. Thicknesses are usually on the order of some 10 μm. Complex magnetic anisotropy effects lead to domain behavior that depends strongly on thermal treatment and stress inside the ribbons. Also structural and surface effects give rise to complicated magnetic behavior. MO microscopy for the investigation of magnetic domain wall aspects [338, 339], random anisotropy effects [201], but also for magnetoimpedance sensor applications [340–343] have been a focus of research. Complex MO analysis has made it possible to distinguish magnetic surface from bulk effects [343–345]. Recent related research on magnetic

Figure 30. Ad-operando domain observation at the operation frequency of 50 Hz from an electric steel disc. Single shot images are displayed (for the experimental setup see figure 8). The individual phase relative to the magnetic field excitation is indicated. (Sample courtesy R. Schäfer, IFW Dresden).

microwires by MO microscopy is possible [346–350]. Some of the challenging aspects of MO observation on cylindrically shaped non-flat microwires have been mastered [159] by advanced MO microscopy.

7.3. Non-metallic materials—oxides, semiconductors, and half-metals

Domain observations in non-metallic materials are performed regularly. Especially the observations of magnetic behavior in garnet materials (see figure 29(v)) based on the MO Faraday effect have a long tradition [233, 281, 351–357]. Due to the optical transparent material, valuable insights of magnetic domain distributions inside the material can be obtained [358]. MO imaging is in most cases easy to perform, even allowing for second harmonic MO effect imaging and MO dark field imaging [281] as discussed in section 5.3. Recent research includes the MO analysis of intrinsic and extrinsic defects in garnet crystals by means of stochastic imaging reconstruction [359] and studies of thermally driven domain wall motion in a temperature gradient [360]. Magnetoelectric domain wall motion is directly observed by MO microscopy [361–363] in a ferrite garnet layer. Garnet layers are also used for MO imaging as an MO indicator layer (see section 8). The MO observation of ferrites [364] is not often performed. The use of MO microscopy for the investigation of single and poly-crystalline MnZn ferrite based recording heads is demonstrated [365–367]. A correlation of the magnetic domain behavior and the stress states of the recording heads is found.

Diluted ferromagnetic semiconductor materials like magnetic (Ga1-xMnx)As (figure 29(i)) and half-metallic lanthanum strontium manganite (La1−xSrMnO3, LSMO, figure 29(s))
have been in the center of recent research for spintronic applications. MO imaging is used for the direct observation of the spin Hall effect in magnetic semiconductors by direct imaging of the spin density [368–370]. Domain observations have proved to be also essential for the characterization of the complex and temperature dependent magnetic anisotropies exhibited in such diluted ferrimagnets, and for determining of exchange energy data from domain wall analysis [186, 188, 371–377]. Spin-polarized current induced domain wall switching is observed at low temperatures [378, 379]. LSMO films have been studied by MO microscopy in order to get a clearer understanding of the magneto-resistive behavior that is influenced by grain boundaries [380], by microcracks [381, 382], and by step-induced uniaxial magnetic anisotropy effects [189]. The connection between MR response and noise in patterned devices with the magnetization processes dominated by domain wall nucleation and propagation is investigated by longitudinal MO Kerr effect observations [383, 384].

7.4. Soft magnetic metallic thick films

Investigations of magnetic domain structures in magnetic thin film in the above 100 nm or micrometer thickness range are mostly driven by technical applications, focusing on subjects related to magnetic recording heads, micro-inductors, and sensor applications. Early domain investigations are on general and dynamic aspects of domain formation in magnetic model structures and inductive recording heads, including laminated multi-layer structures with magnetic edge closure structures and varying domain wall structures [252, 385–388]. A later investigation dealt with cross-sectional analysis of the magnetic domain state in a bisected inductive recording head [389].

The micromagnetics of the magnetic shields of merged recording heads [301, 390–392] are studied by MO microscopy with the goal to control the domain patterns and thereby to achieve low noise in the adjacent magneto-resistive sensor of the recording head. The influence of local magneto-elastic effects is clarified in [298].

Overall, MO microscopy offers the possibility of the investigation of full workable devices and the observation of magnetic domain behavior through micrometer thick transparent Al₂O₃ and photore sist layers. Further investigation focused on write-head material properties [298, 393, 394]. Various kind of domain wall structures are observed in the laminated multi-layer stacks (figure 31 [393]), the magnetic microstructure of which strongly determines the effective magnetic properties.

For the performance of magnetic microinductors [395, 396] and stress sensors the magnetic domain structure is of similar relevance [297, 397, 398]. For the inductors, a special focus is on the correlation between domain structure and the exhibited magnetization dynamics. Only complementary inductive and MO magnetic domain analysis gives insight in the interaction between magneto-dynamic response and magnetic domain features [148, 150, 399–401].

Magnetic stripe domains in thick soft-magnetic films with weak out-of-plane magnetic anisotropy are usually probed by magnetic force microscopy. Observations by MO microscopy are relatively rare and mostly limited to the micrometer thick films [2]. Yet, the imaging of low MO contrast and weak stripe domain patterns with a stripe width of about 200 nm can be achieved with advanced MO microscopy (see figures 11(a) and 29(k), (m)). The MO imaging of coexisting weak and strong stripe domains is possible [301].

7.5. Soft magnetic thin films

Magnetic thin film studies are a domain of MO microscopy. Due to the MO surface sensitivity, nearly bulk MO contrast can be obtained for many thin film magnetic specimens. In contrast to bulk samples, in soft magnetic thin films the obtained domain images usually mirror the complete domain behavior of the sample. Recent studies on extended single layer soft magnetic structures include studies on magnetic anisotropy dispersion [294], domain wall nucleation and creeping [402] in amorphous thin films [403]. Of interest for the investigation of thin film structures of various thicknesses are domain wall transformations [2].

Fundamental research is performed on magnetic multi-layer films. Magnetically exchange coupled structures display significant different magnetic domain behavior compared to single layer films. From an application point of view magnetic domain studies on giant magneto-resistance sensor (GMR) [126, 404–407] and exchange coupled multi-layers are of scientific interest [93, 94, 125, 408–410]. The discovery of bi-quadratic interlayer exchange coupling [93] is one of the great

Figure 31. Domain wall zoo. Magnetic configurations for (a) single layer (50 nm), (b), (c) sandwiched FeN(50 nm)/Al₂O₃(1.2 nm)/FeN(50 nm), and (d) FeN(50 nm)/Al₂O₃(2.5 nm)/FeN(50 nm) high magnetic moment films. (a) and (b) show a cross-tie and compensated Néel wall configuration obtained after magnetization by an external field along the easy axis of magnetization. Mixed twin and compensated wall structures shown in (c) and (d) are obtained after magnetization along the hard axis of magnetization. (a)–(c) Reprinted with permission from [393]. Copyright 2000, AIP Publishing LLC.)
magnetic anisotropy. The reversal asymmetry between the forward and recoil branch of the magnetization loop of the ferromagnetic film is found to be related to a non-static antiferromagnetic spin structure, varying with the reversal. Through studies on exchange-biased antiferromagnetically coupled hard/soft bi-layer films, reversal mechanisms related to planar magnetic domain walls [194] (see figure 29(q)) and training effects are directly visualized [192]. Exchange bias training is due to the relaxation of the hard layer, where a partial interfacial magnetic reorientation of magnetization occurs during the first reversal of magnetization of the soft layer.

7.6. Thin films patterned by local ion irradiation

Magnetic reversal in locally ion irradiated thin films has been the focus of recent research [419, 420]. The purely magnetic patterning of out-of-plane anisotropy films offers the possibility for high density media [421]. By local ion irradiation the magnetic properties of multilayers are patterned with only minor changes in topography and roughness. By controlling magnetic moment and anisotropy of the films, a magnetically patterned medium is formed. The investigations of the patterning effects in such materials are generally performed by MO microscopy applying the polar Kerr effect [165, 166, 422–428]. Magnetic features of a size below 100 nm are fabricated by focused ion beam techniques and investigated by MO microscopy at the limit of lateral optical resolution (see figure 11(c)).

Patterning of soft-magnetic layers by ion irradiation [420, 429] has mostly focused on exchange-biased ferromagnetic/antiferromagnetic thin film systems (see figure 29(i)) with special static and dynamic magnetic properties [212, 299, 430–433]. The magnetic patterns consisting of high-density domain walls are also probed by MO microscopy. A strong focus of the MO investigations is on magnetic effects of overlapping magnetic domain wall structures. Striped structures with head-to-head and tail-to-tail domain walls are furthermore used for verifying of the contrast symmetry of the MO gradient effect [110]. Complex magnetoresistive response behavior of zig-zag aligned magnetization configuration [434] is explained from high resolution MO Kerr effect microscopy investigations. Lateral exchange spring behavior in saturation magnetization patterned films [273] and exchange-coupled sandwich structures [435] are probed and comprehended by MO microscopy investigations. Quantitative MO microscopy is applied to understand complex magnetic patterns in induced magnetic anisotropy patterned amorphous thin films [272, 436, 437] (see figures 22 and 29(g), (h)).

7.7. Multiferroics—magnetoelectric composites

Multiferroic materials which exhibit simultaneously ferroelectric and (ferro/ferrimagnetic) magnetic order are of great interest for the development of potential future spintronic devices. Yet, materials exhibiting two order parameters are not very common. Therefore, multiferroic composites that combine ferromagnetic (or ferrimagnetic) and piezoelectric (or ferroelectric) materials have drawn much attention in recent research [438–440]. They are investigated in particular for magnetoelastic (ME) field sensing applications. The ferromagnetic and electric properties of the material systems are coupled indirectly via piezoelectric or ferroelastic strain transfer. By this, they can give rise to a direct or inverse ME effect. For the direct ME effect, applying an electrical field to a piezoelectric phase through magnetoelastic interaction, the magnetic anisotropy of a magnetostrictive ferromagnetic phase is altered. For the inverse ME effect, changing the magnetization of the magnetic phase by an external magnetic field, an electric field is introduced in the piezoelectric phase. From a magnetic domain point of view, two facts are of relevance. On one hand, through magnetoelastic interaction a transfer of strain from a modulated ferroelectric domain structure might result in a modulated magnetic anisotropy and domain structure that also changes with the application of an electric field to the ferroelectric phase. On the other hand, for magnetic sensor applications, magnetic domain formation in the magnetic phase generates an altered piezoelectric response. Both effects are investigated by MO microscopy.

Magnetic domain imprinting has been realized with ferromagnetic/ferroelectric, BiFeO3/Ni81Fe19, BaTiO3/Ni81Fe19, BaTiO3/Fe and BaTiO3/CoFeB structures [441–450]. The exhibited alignment of magnetization is given by the ferroelectric domains of the BaTiO3 crystal. Key point is the introduction of a well-defined domain pattern in the ferroelectric crystal, by which an ordered magnetic domain arrangement is induced into the ferromagnetic phase. Examples of different magnetic domain configurations with magnetoelectrically imprinted magnetic domains are displayed in figure 32. The exhibited domain patterns are very similar to the ones in multiferroic magnetic shape memory alloys (compare figures 32(a)–35(c)). Magnetic flux closure structures (figure 32(b)) and charged head-to-head (tail-to-tail) magnetic configurations (figure 32(c)) are realized in such materials.

Domain formation in ultrasensitive magnetic field sensors based on 2–2 magnetoelectric (ME) piezoelectric composites has a strong influence on the resulting ME signal of the sensor. For such sensors the detection limit of magnetic field is as low as 3 pT/Hz” [451]. As the sensor sensitivity is connected directly to the local susceptibility of the piezomagnetic phase, a strong interrelation between the magnetic microstructure of the magnetoelectric phase and the ME response is found [155, 293, 452]. In situ MO imaging reveals a direct correlation between the magnetic domain structures and a drop of ME response of up to 50% in maximum ME amplitude. Dissimilar magnetic domain structures at the same magnetic bias field are displayed in figure 33. A hysteretic ME response originating from interlocking magnetic domain processes is found [293]. Blocked domain states lead to a strong reduction and asymmetries in the ME signal response. Only by combining large-field together with high resolution MO microscopy and with in-operando ME
measurements a complete picture of the electrical response characteristics is obtained.

7.8. Current induced domain wall motion

Devices based on the controlled propagation of magnetic domain walls by spin-polarized currents are envisioned for magnetic storage and logic applications. The magnetic domain wall displacements are, however, often not reproducible. Current-induced motion of domain walls in magnetic nanowires is a topic of recent research, where advanced MO microscopy provides a lot of opportunities to clarify details of interaction between applied current and domain wall characteristics. Recently, out-of-plane magnetic anisotropy films have become the center of attention for current induced domain wall motion [253], where structural asymmetries [254, 255] (figure 34(a)) and local modification of structural properties, for instance by local ion irradiation [453, 454] (see also section 7.6), play a crucial role for the controlling of domain wall propagation induced by spin polarized currents. Also the control of domain wall pinning by local variation of magnetic anisotropy with the application of an electrical field [455] is investigated by MO microscopy. Domain wall velocities of several hundred meters/sec are extracted from MO data. Furthermore, effects like tilting of the domain wall angle are observed, pointing to a contribution from an interfacial Dzyaloshinskii–Moriya interaction or a chiral spin torque arising from proximity-induced magnetization [456, 457]. Exemplary MO images displaying different directions of domain wall motion in dependence of an underlayer material in underlayer/Co/Ni/Co stacks are displayed in figure 34(b). The domain wall moves in the direction (for Ir underlayers) or opposite to the direction (for Au underlayers) of the electron flow. Domain wall motion introduced by the spin-Hall effect [256, 458] offers an additional degree of freedom for current induced domain wall motion.

Related studies on perpendicular anisotropy films by MO microscopy are dealing with domain wall nucleation...
mechanisms in Pt/Co/Al₂O₃ [460] in relation to an existing Dzyaloshinskii–Moriya interaction, with the effects of Ruderman–Kittel–Kasuya–Yosida coupling in Pt/CoSiB multilayers [461] and domain wall propagation in (Pt/Co)/Pt(spacer)/(Co/Pt)x/patterned films with spatially varying domain wall pinning potentials [462].

8. Indirect imaging methods—imaging by MO indicator films

The imaging of magnetic stray fields by means of MO imaging can be achieved by ferrite garnet single-crystalline films or other magnetic films with either in-plane or out-of-plane magnetic anisotropy as a detection layer. Magnetic stray field imaging with ferrite garnet MO indicator films (MOIFs) is applied for the investigation of flux-penetration in type-II superconductor materials [171, 175, 463–467]. The method is based on the MO Faraday effect. An early review of the topic is found in [468]. An extensive state-of-the-art discussion on further developments and the usage of MOIF imaging for the visualization of stray fields and domains of magnetic samples is provided in [469].

For magnetic material structures with a very weak or vanishing MO contrast, which can be due to non-transparent covering layers or in the case of certain magnetic shape memory alloys [470], MOIF imaging is the only option for attaining information on the magnetic domain structure by magneto-optics. Yet, the magnetic domain structures are imaged indirectly. Magnetic domain generated magnetic stray fields, for instance at, but not limited to, magnetic domain walls, form the resulting magnetic image. The principal method of MOIF imaging is displayed in figure 35.

The magnetization in the MOIF film is altered in correspondence with local stray fields generated from the magnetic sample of interest. The alteration of magnetization in the MOIF is imaged in reflection in a regular MO microscope setup with the help of a thin film reflective mirror at the bottom of the upside-down turned MOIF structure. In most applications the MO sensing layer is an iron garnet (IG) based ferrite film grown epitaxial on transparent gadolinium gallium garnet (GGG) substrates. The achievable spatial resolution is limited by the sample distance and the thickness of the active MO layer [469]. It is thereby reduced relative to the high resolution direct MO imaging. The demonstrated spatial resolution is one micrometer at best.

Magnetic stray field and domain imaging of magnetic samples from in-plane anisotropy magnetic films is demonstrated by different groups. An early overview is given in [471]. Magnetic imaging and quantification of lateral stray field distributions is achieved for several structures [472–481]. The method is of particular interest for the investigation of magneto-static interactions between magnetic elements of hard magnetic thin films [482, 483].

For the investigations of magnetic domain structure of soft magnetic thin films, the MOIF technique has proved to be a powerful tool [484–489]. It is especially useful for the
investigation of asymmetric reversal processes in exchange coupled thin films [490–494]. The sensitivity to magnetic stray fields makes it most suitable for the investigation of magnetization processes in exchange spring systems. Using a patterned MOIF the direction of magnetization in magnetic thin films can be directly probed [495], an example of which is displayed in figure 36(a). Similar studies of exchange spring reversal behavior by regular MO Kerr effect microscopy are demanding [192, 194].

A particular plus of the MOIF technique over regular Kerr effect MO microscopy is that usually no differential imaging technique, which would involve the application of magnetic fields, needs to be applied. This advantage is used for the imaging of purely stress induced magnetization reversal processes in highly magnetostrictive thin films [500], processes that are demanding to visualize by regular MO microscopy [397]. Also studying the process of thermomagnetic reversal of an otherwise not influenced domain structure at the compensation point is achieved with the MOIF technique [496] (figure 36(b)).

For Ni$_2$MnGa-based and similar ferromagnetic shape memory alloys the visualization of the surface domain structure was used for the investigation of twin boundary motion in bulk crystals [207, 221, 497–499, 501, 502]. The micromagnetic process of magnetic field induced twin boundary motion in the multiferroic crystals is clarified by MOIF microscopy [497] (figure 36(c)). It was found that no magnetic domain wall motion within the individual twins is needed for the structural reorientation by twin boundary movement. From imaging of different surfaces of the twinned crystals a direct correlation between surface and bulk magnetic domains is made [499]. It was verified that magnetic domains are mirrored across the structural twin boundaries inside the material. Such observations have been only achieved so far by the MOIF technique. A composite MOIF image, displaying the domain of a millimeter-sized Ni$_2$MnGa crystal [498], is shown in figure 36(d).

Figure 36. (a) MO image of a region of an exchange spring sample, containing a circular opening with an in-plane anisotropy MOIF film. (Reprinted from [495]. Copyright 2002, with permission from Elsevier.) (b) Temperature-induced inversion of magnetization of a GdCo$_3$Cu$_4$ single crystal imaged with an out-of-plane MOIF film below and above the compensation temperature. (Reprinted with permission from [496]. Copyright 2006, AIP Publishing LLC.) (c) Magnetic domain structure from an off-stoichiometric Ni$_2$MnGa crystal across a twin boundary (TB). (Reprinted with permission from [497]. Copyright 2007, AIP Publishing LLC.) (d) Structure of magnetic (macro)domains obtained from a millimeter sized Ni$_2$MnGa crystal. (Reprinted with permission from [498]. Copyright Advanced Study Center Co. See also [499].)
The use of MOIF layers for the investigation of magnetic recording heads is demonstrated in [144, 503]. In an alternative approach a thin soft magnetic layer was used as a transducer [305] for mapping of the write field distribution of recording heads.

9. Conclusions

Magneto-optical microscopy is one of the most flexible available techniques for the investigation of magnetic domain and magnetic domain wall behavior. Wide-field MO microscopy allows for the imaging with a field of view from centimeters down to a few micrometers. Correspondingly, magnetic domain features on length scales from centimeters to submicrometers can be visualized directly. MO microscopy using the MO Kerr effect, the MO Faraday effect, and the MO Voigt effect offers numerous options for the imaging of magnetic microstructures. Direct imaging modes and indicator film techniques are available for the investigation of magnetization behavior of magnetic materials. Despite a minimum spatial resolution of about 200 nm, alteration of magnetization features of much smaller sizes can be recorded. Digital imaging routines are used for MO contrast enhancement and post processing. Using gated image intensifiers, pulsed light emitting diodes, or pulsed laser illumination sources, imaging with adjustable temporal resolution down to picoseconds and below is feasible in a laboratory environment. Magnetic field induced, electric field induced, and stress induced magnetization reversal can be visualized directly. Due to the use of polarized light, complementary qualitative information on crystallographic phases can be obtained.

With recent developments like multi-component dual-wavelength imaging, advanced magneto-optical microscopy will continue to be one of the most important techniques for the investigation of magnetic domain behavior. Thus, it will continue to exert great input for the development of magnetic materials and the optimization of magnetic devices. The potential of applications of MO microscopy is still without limit.

Acknowledgments

My first thanks go to the late A Hubert for introducing me to and teaching me the basics of magnetic domains, for giving me the chance to build my first MO Kerr effect microscope many years ago, as well as for continuously supporting me on many levels.

I am also grateful for support that was given to me over several years at IBM Storage Division (San Jose), the Leibniz Institute for Solid State and Materials Research IFW Dresden, the Helmholtz-Zentrum Dresden-Rossendorf, and now at Kiel University. Data obtained at all of these places is included in this review. J Heidmann, B Argyle, R Schäfer, L Schultz, S Mangin, J Fassbender, and E Quandt helped me during these years. I am extremely thankful to R Matthias for preparing almost every sample I asked him to deposit. Own data included in this review is achieved from fruitful cooperations with A Berger, D Bürgler, A Ehresmann, J Fassbender, M Freudenberger, R Grechishkin, O Gutleisch, O Hellwig, M Kläui, R Knöchel, M Kustov, S Mangin, R Mattheis, P Mazalski, A Mazieiewski, D Meyners, E Quandt, R Schäfer, K Seemann, K Theis-Bröhl, and J Westwood. Many thanks go to the students who contributed to MO imaging experiments in the last years: D Chumakov, S Flohrer, C Hamann, C Hengst, M Klug, R Malik, N Martin, B Mozoony, A Neudert, U Queitsch, S Reddy, T Strache, J Trützschler, and N O Urs was of great help.

Additional thanks go to the German Science Foundation (DFG) for continuous support through the grants Mc9/7-1, Mc9/7-2, Mc9/8-1, Mc9/8-2, Mc9/8-3, Mc9/10-1, and through the Collaborative Research Centre SFB 855 ‘Magnetoelectric Composite Materials-Biomagnetic Interfaces of the Future’. Finally, funding and support through the Heisenberg Programme of the DFG is greatly acknowledged (grants Mc9/9-1 and 9-2).

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