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Vectorial Kerr magnetometer for simultaneous and quantitative measurements of the in-plane magnetization components

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A vectorial magneto-optic Kerr effect (v-MOKE) setup with simultaneous and quantitative determination of the two in-plane magnetization components is described. The setup provides both polarization rotations and reflectivity changes at the same time for a given sample orientation with respect to a variable external magnetic field, as well as allowing full angular studies. A classical description based on the Jones formalism is used to calculate the setup’s properties. The use of different incoming light polarizations and/or MOKE geometries, as well as the errors due to misalignment and solutions are discussed. To illustrate the capabilities of the setup a detailed study of a model four-fold anisotropy system is presented. Among others, the setup allows to study the angular dependence of the hysteresis phenomena, remanences, critical fields, and magnetization reversal processes, as well as the accurate determination of the easy and hard magnetization directions, domain wall orientations, and magnetic anisotropies. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4871098]

I. INTRODUCTION

Magneto-optic Kerr effect (MOKE) is widely applied in Nanomagnetism research because of its high sensitivity (down to nanometer thickness), vanishing substrate effects (limited penetration depth), immunity to external fields (photon-in/photon-out approach), and relatively simple experimental implementation. The experimental observations are carried out utilizing the rotation of polarization and/or the change in the intensity of a linearly polarized light beam upon reflecting from magnetic material subjected to a variable magnetic field.1 As described below, both effects result from the off-diagonal components of the dielectric tensor, and are widely used to probe low dimensional magnetism.2–6

For instance, magnetic properties such as hysteresis and magnetic anisotropies,3 critical temperatures,3 magnetic domains,5 and magnetization reversal processes6 can be determined by MOKE.

Particular attention has been given to vectorial MOKE (v-MOKE) magnetometry. Traditionally, different Kerr geometries have been used to determine the magnetization of a given material, as schematically depicted in Fig. 1. In practice, MOKE effects depend on the orientation of the magnetization vector \( \mathbf{M} = (m_x, m_y, m_z) \) with respect to the reflection (xz) and sample (xy) planes. Polarization rotations arise from magnetization components within the reflection plane (longitudinal and polar Kerr signals which are proportional to \( m_z \) and \( m_y \), respectively), whereas reflectivity changes originate from the component perpendicular to the reflection plane (transversal Kerr signal, proportional to \( m_x \)). Usually, the polar Kerr signal is one order of magnitude greater than the longitudinal signal,4 but in thin films the magnetization generally lies into the surface plane, i.e., \( m_z = 0 \). It should be pointed out that the magnetization is not strictly fixed to the field direction during reversal. In such a situation, the Kerr signal is a mixture of different Kerr effects. Several other groups have shown different procedures to obtain the in-plane magnetization components by measuring several loops in different conditions.7–15 In this case, either the optical components have to be changed,7,9,10,12 the direction of the external magnetic field has to be varied,8,11,13,14 or a combination of both procedures have to be employed.15 Furthermore, the system has to be calibrated after any changes are made.

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FIG. 1. Standard MOKE geometries: (a) Longitudinal: The applied field vector is parallel to both the surface and the reflection plane. (b) Transversal: The field vector is parallel to the surface but perpendicular to the reflection plane. (c) Polar: The field vector is perpendicular to the surface and parallel to the reflection plane. The polarizations of the incident (s and p) and reflected (s′ and p′) electric fields are also depicted, to illustrate that longitudinal and polar geometries exploit polarization rotations while the transversal geometry uses the reflectivity changes (only for p).

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The proof of concept for simultaneous acquisition of the two in-plane components for a given field direction has been provided with our study of orthogonally coupled ferromagnetic films, which we extended to include an automated v-MOKE setup to perform whole angular studies.6, 17–22 Other groups have recently implemented similar setups.23 Our studies have been focused on ferromagnetic (FM) and antiferromagnetic (AFM) materials with different magnetic anisotropy strengths and configurations. These include randomly oriented magnetic nanostructures,17 single FM thin films with well-defined uniaxial anisotropy,18, 22 and competitive anisotropies.19, 24 Exchange-biased FM/AFM systems with collinear20 and non-collinear21, 25 anisotropy configurations and exchange-biased spin valve structures26 have also been investigated systematically with the setup. Our aim was to disentangle their angular-dependent magnetic behaviors in order to understand the influences of reduced dimensionality and magnetic symmetry on the magnetic properties.

In this paper we provide a detailed experimental and theoretical description of our automated angular-dependent v-MOKE setup, which can provide simultaneous and quantitative information of the in-plane magnetization reversal phenomena for both sample and field angle conditions. To illustrate the capabilities of the setup, we present a full-angular study performed in a model four-fold magnetic anisotropy system.

The paper is organized as follows. The experimental details of the setup are described in Sec. II. The theoretical description is given in Sec. III, including the discussion on errors due to misalignments and solutions. A detailed description of the model is further reported in the Appendix. Section IV introduces the measurement and analysis procedures to obtain simultaneous and quantitative information. The full angular study performed in a Fe(100) thin film epitaxially grown on MgO(100) is given in Sec. V. The angular dependence of the hysteresis phenomena, remanences, critical fields, domain wall orientations, and the magnetic anisotropy. The summary is presented in Sec. VI, concluding that the magnetic symmetry of the system controls its main features, and suggesting that similar studies have to be performed in order to obtain a basic understanding of low dimensional magnetic systems.

II. THE EXPERIMENTAL SETUP

Our home-made v-MOKE system combines simultaneous acquisition of rotations of polarization and changes of reflectivity for a given sample orientation with respect to a variable external magnetic field, and allows full angular studies. The system is sketched in Fig. 2. The setup is placed on an optical bench and can be explained in three parts, the optical path, the mechanical sample stage, and the control unit.

The optical path is attached to the optical bench by using two rails, referred to as incident and reflected branches, forming a v-shape with the sample position in the vertex. The incident branch is provided with an intensity stabilizing randomly polarized 5 mW HeNe laser (λ = 632 nm), a Glan-Taylor prism polarizer with extinction coefficient 5 × 10⁻⁵, and a focusing lens. The latter defines the size of the laser spot on the sample, i.e., the measured area. The polarizer is mounted on a rotatable head that sets the polarization of the incoming beam. As shown below, simultaneous acquisition of polarization rotations and reflectivity changes requires incoming p-polarized incident light, whereas s-polarized incident light provides only polarization rotations. Therefore, for simultaneous determination of the two in-plane magnetization components, i.e., \( m_s(H) \) and \( m_p(H) \), the polarization of the laser is set to p. In turn, s-polarized light is used for cross checking and to evaluate out-of-plane magnetization components, i.e., \( m_s(H) \), after the combination of two hysteresis loops with reversed optical geometry.11

The reflected branch is equipped with a lens, a half-wave plate (\( \lambda/2 \)), a Wollaston prism with extinction coefficient 10⁻⁵, and the home-made Twin Photodetector (TP) device. The \( \lambda/2 \) retarder, set to 22.5° of the optical axes, intermixes the outgoing s’- and p’-waves (see discussion, Sec. III). Finally, the s’- and p’-waves are split into two separate beams using the Wollaston prism. The intensity of the beams is measured by the photodiodes of the TP device, which is at the very heart of our setup. The TP device provides three outputs: the sum of the signals coming from both photodiodes (\( I^{DC}_{\Sigma} \)), the AC component of the sum (\( I^{AC}_{\Sigma} \)), and the difference (\( I_{\Delta} \)). As described below, \( I^{AC}_{\Sigma} \) accounts for reflectivity variations, whereas \( I_{\Delta} \) accounts for polarization rotations. \( I^{DC}_{\Sigma} \) is related to the total reflectivity and is used to normalize the other two signals, in order to correct photon flux variations of the laser during the acquisition of a whole angular series.

The mechanical part of the setup consists of an xyz-sample stage, a rotatable eucentric goniometer, and a rotatable electromagnet. The positioning stage in combination with the focused beam and a microscope allows the selection of specific areas of microstructured samples. Spot sizes from...
2 mm down to 30 μm can be used. The sample is placed on the
eucentric goniometer head to ensure a fixed plane of reflection
upon sample rotation. In magneto-optical measurements this
is important to be able to compare the values of the magneti-
zation components measured at different angles and between
different samples. The whole head can be rotated by a step-
ning motor in steps of 0.9°. The magnetic field is provided by
a home-made air-gap electromagnet. We have developed and
calibrated several electromagnets with different gaps and/or
coil turns, depending on the frequency and maximum field
required. Magnetic fields up to ±100 mT driven at frequen-
cies up to 1 kHz can be obtained. This enables performing
dynamic studies over 10 orders of magnitude of applied field
sweep rates, from 10⁻⁴ mT/s to 10⁺⁶ mT/s. In the present
study, we have used a 10 mm air-gap electromagnet mounted
on a rotatory stage, allowing a controlled way to change from
longitudinal to a transversal MOKE geometry. Polar geometry
can also be set.

The control unit consists of a computer, an arbitrary func-
tion generator driving a bipolar current source, and a four
channels digital oscilloscope. Via a home-made measurement
software, the computer controls the stepper motor of the go-
niometer as well as the applied magnetic field ramp. The latter
is driven by the bipolar current source programmed with the
arbitrary function generator. Additionally, the software reads
out the hysteresis data, i.e., the signals from the digital oscillo-
scope triggered by the trigger output of the arbitrary function
generator. The signals are

1. The applied voltage to the coil: applied field ramp.
2. $I_D$: the difference of intensities on the diodes.
3. $I_{DC}^r$: the AC component of the sum of intensities.
4. $I_{DC}^p$: the AC component of the added intensities.

The software allows adjustment of the parameters to perform
specific measurement procedures in order to carry out vector-
ial resolved magnetization reversal studies in the whole an-
terior range. These may include major and minor loops, and/or
first order magnetization curves as well as quasi-static and dy-
namical studies.

III. THEORETICAL DETAILS OF THE SETUP

All Kerr measurements are based on the fact that the mag-
netization alters the dielectric tensor such as making an other-
wise isotropic material optically anisotropic. Proper consid-
erations of the boundary conditions of Maxwell’s equations
enable the calculation of the corresponding reflection matrix
of a magnetic material. Typically the symmetry breaking
due to the magnetization results only in small modifications
of the reflection matrix such that the optical anisotropy can
be handled as a first order perturbation. The components of
the reflection matrix for a thin magnetic film are given in the
Appendix. It is found that in the first order the matrix is of the
form

$$
\mathbf{r} = \begin{pmatrix}
  r_{ss} & r_{sp} \\
  r_{sp} & r_{pp}
\end{pmatrix} \approx \begin{pmatrix}
  a & b_1 m_x + b_2 m_z \\
  -b_1 m_x + b_2 m_z & c + d m_y
\end{pmatrix},
$$

(1)

For the sake of simplicity we use the frame of reference
shown in Fig. 1. The $x$ and $y$ directions are lying within the
film plane, the surface normal is the $z$ direction, and the in-
cident angle $\theta_i$ is contained in the $xz$ reflection plane. All
calculations presented here are performed using the Jones
formalism. It is important to note that $r_{ss}$ is independent of
magnetization. The components $r_{sp}$ and $r_{pp}$ are proportional
while $r_{pp}$ contains an additional constant term. Upon reflect-
on on the surface of the magnetic sample the electric field
vector $\vec{E}$ of the incident light is reflected and results in $\vec{E}'$ as

$$
\vec{E}' = r \vec{E}.
$$

(2)

Naturally, the final measurement procedure consists of meas-
uring the intensity, i.e., $I = \vec{E}' \cdot (\vec{E}')^*$ where the asterisk
denotes the complex conjugate. It is easily seen that the intensity
of the reflected s’-polarized light due to incoming p-polarized
light (or vise versa) results in a signal that is quadratic in $m$.
Consequently, such a measurement does not give proper in-
formation on the magnetic state of the sample. However, the
measurement of the reflected p'-polarization of incoming p-
polarized light gives

$$
I_p = E_p^r(E_p')^* = c^* + 2 \text{Re}[c^* m_y + d^* m_z] \\
\approx c^* + 2 \text{Re}[c^* m_y + O(m_z^2)],
$$

(3)

assuming the typical case where $\text{Re}[c^*] \gg d^*$. Hence, the
constant term in $r_{pp}$ allows for easy measurement of $m_y$ in
a transverse Kerr setup.

The presented setup is based on the idea of introducing
an additional constant term in the $E_x$ component, therefore
generating a linear term in the corresponding intensity. This
is achieved by introducing a $\lambda/2$-retarder $\mathbf{L}_2$, rotated by $\pi/8$
off the optical axes, and by reading the two orthogonal com-
ponents of the reflected light. In general, the reflected signal
has the form

$$
\begin{pmatrix}
  E''_x \\
  E''_p
\end{pmatrix} = \mathbf{L}_2 \mathbf{r} \begin{pmatrix}
  E_x \\
  E_p
\end{pmatrix}
$$

$$
= \frac{i}{\sqrt{2}} \begin{pmatrix}
  1 & 1 \\
  1 & -1
\end{pmatrix} \begin{pmatrix}
  r_{ss} & r_{sp} \\
  r_{sp} & r_{pp}
\end{pmatrix} \begin{pmatrix}
  E_x \\
  E_p
\end{pmatrix}.
$$

(4)

For simplification let us assume only in-plane magnetization,
i.e., $m_z = 0$, and incoming pure $p$-polarized light. The electric
field vector after passing the retarder then has the form

$$
\begin{pmatrix}
  E''_x \\
  E''_p
\end{pmatrix} = E_p \begin{pmatrix}
  b_1 m_x + c + dm_y \\
  b_1 m_x - c - dm_y
\end{pmatrix},
$$

(5)

and the intensities read

$$
I_s = \frac{I_0}{2} \left[ |c|^2 + |b_1|^2 m_x^2 + |d|^2 m_y^2 + 2 \text{Re}[b_1 d^*] m_x m_y \\
+ 2 \text{Re}[b_1 c^*] m_x + 2 \text{Re}[d c^*] m_y \right],
$$

(6)

$$
I_p = \frac{I_0}{2} \left[ |c|^2 + |b_1|^2 m_x^2 + |d|^2 m_y^2 - 2 \text{Re}[b_1 d^*] m_x m_y \\
- 2 \text{Re}[b_1 c^*] m_x + 2 \text{Re}[d c^*] m_y \right],
$$

I_0 = |E_p|^2.
where \( I_0 \) is the intensity of the incident beam. Adding and subtracting the two intensities gives

\[
I_\Delta = I_s - I_p = 2I_0\{\text{Re}[b_1c^*]m_x + \text{Re}[b_1d^*]m_y\}
\approx 2I_0\text{Re}[b_1c^*]m_x + \mathcal{O}(m_x m_y),
\]

\[
I_\Sigma = I_s + I_p = I_0\{c^2 + |b_1|^2m_x^2 + |d|^2m_y^2
\]
\[
+ 2\text{Re}[b_1d^*]m_x m_y + 2\text{Re}[dc^*]m_y\}
\approx I_0\{c^2 + 2\text{Re}[dc^*]m_y\}
\]
\[
+ \mathcal{O}(m_x^2, m_y^2, m_x m_y).
\]

As a result the difference signal is proportional to \( m_x \), whereas the sum is linear in \( m_y \), but has an additional DC-component, i.e., \( I_\Sigma^{DC} = |c|^2 = |r_{pp}^{DC}|^2 \). Note that due to this DC component one finally gets

\[
\frac{I_\Delta}{I_\Sigma^{DC}} = \frac{2\text{Re}[r_{sp}^{DC}(r_{pp}^{DC})^{*}]}{|r_{pp}^{DC}|^2} = \frac{2\text{Re}[r_{sp}^{DC}r_{pp}^{DC}(r_{pp}^{DC})^{*}]}{|r_{pp}^{DC}|^2}
\]
\[
= 2\text{Re}\left[\frac{r_{sp}}{r_{pp}^{DC}}\right] \approx 2\theta_K^{p} \propto m_x,
\]

\[
\frac{I_\Sigma}{I_0} = \frac{I_\Sigma^{DC}}{I_0} = R_{ss},
\]

which are the Kerr rotation and reflectivity change, which are proportional to the two in-plane components of the magnetization \( m_x \) and \( m_y \), respectively.

Similarly for incoming s-polarized light one obtains for the difference and the sum terms

\[
\frac{I_\Delta}{I_\Sigma} = 2\text{Re}\left[\frac{r_{ps}}{r_{pp}^{DC}}\right] \approx 2\theta_K^{c} \propto m_x,
\]

\[
\frac{I_\Sigma}{I_0} = \frac{I_\Sigma^{DC}}{I_0} = R_{ss},
\]

the Kerr angle and a constant term, respectively. In this case, the sum, \( I_\Sigma \), does not contain useful information other than \( R_{ss} = |r_{ss}|^2 \), as \( I_\Sigma \propto R_{ss} + \mathcal{O}(m_y^2) \). Consequently, there is no \( I_\Sigma^{DC} \) in the first order.

Therefore, the combination of p-polarized light and the detection of the two orthogonal components of the reflected light at the same time allows the determination of both in-plane magnetization components simultaneously. Notice that this is accomplished independently of the MOKE geometry. In this sense, we define the in-plane magnetization components parallel \( M_\parallel \) and perpendicular \( M_\perp \) with respect to the external magnetic field direction. In correspondence with Fig. 1, for longitudinal MOKE geometry, i.e., \( B_z \), the in-plane magnetization components can be derived from

\[
M_\parallel = m_x \propto 2\theta_K^{p} \approx \frac{I_\Delta}{I_\Sigma^{DC}},
\]

\[
M_\perp = m_y \propto \frac{I_\Sigma^{DC}}{I_\Sigma},
\]

whereas for transversal MOKE geometry, i.e., \( B_z \),

\[
M_\parallel = m_y \propto \frac{I_{\Sigma AC}}{I_\Sigma^{DC}},
\]

\[
M_\perp = m_x \propto 2\theta_K^{c} \approx \frac{I_\Delta}{I_\Sigma^{DC}}.
\]

Notice that each in-plane magnetization component can be derived independently from Kerr rotations or reflectivity changes, depending on the MOKE geometry. This will be used to determine experimentally the scale factor between both Kerr effects to obtain quantitative information of the in-plane resolved hysteresis loops. This is further discussed in Sec IV.

### A. Errors due to misaligned optical components

In the previous paragraph the ideal case has been discussed. In experiment, however, one must assume small angular errors in the optical components, i.e., polarizer, \( \lambda/2 \)-retarder, and analyzer. Let us assume that these components have angular errors of \( \alpha_1, \alpha_2 \), and \( \alpha_3 \). In the following errors of the order \( \alpha_i \alpha_j \) (\( i, j = 1, 2, 3 \)) as well as \( \alpha_i m_x, m_y \) (\( \xi, \zeta = x, y, z \)) are neglected. In this approximation the final intensities including errors have the form

\[
I_\Delta \propto I_\Delta^{(1)} + 2\text{Re}[b_1d^*]m_x m_y + 2\text{Re}[b_2d^*]m_x m_y
\]
\[
+ 2\alpha_1(\text{Re}[a^*c^*] + \text{Re}[a^*d^*]m_y)
\]
\[
+ 2(2\alpha_2 - \alpha_3)I_\Sigma^{(1)},
\]

and

\[
I_\Sigma \propto I_\Sigma^{(1)} + |d|^2m_x^2 + |b_1|^2m_y^2 + |b_2|^2m_z^2
\]
\[
+ 2\text{Re}[b_1b_2]m_x m_z
\]
\[
+ 2\alpha_1(\text{Re}[a^*b_1 - b_1c^*]m_x + \text{Re}[a^*b_2 + b_2c^*]m_z)
\]
\[
- \alpha_3I_\Sigma^{(1)},
\]

where \( I_\Delta^{(1)} \) and \( I_\Sigma^{(1)} \) are the error free first order approximations of the signals. Furthermore, the summation and subtraction, resulting in \( I_\Sigma \) and \( I_\Delta \), are assumed to be without error. Note that \( \alpha_2 \) does not effect \( I_\Sigma \) as its effect cancels out in the sum, but mixes \( I_\Sigma \) into \( I_\Delta \). Moreover, \( \alpha_3 \) intermixes \( I_\Delta \) and \( I_\Sigma \); however, due to the adding and subtracting of the signals, \( I_\Delta \) is doubly affected. Furthermore, one must keep in mind that the measured intensities, at both diodes, are dominated by the retarder plate and introduces a non-magnetic reflecting material, i.e., without off-diagonal elements. Assuming that one wishes incoming s-polarized light, the according intensity is at the lowest order approximation of the form

\[
I_p \propto (r_{pp}\alpha_1 - r_{ss}\alpha_3)^2.
\]
This equation, however, has infinite solutions. Therefore, the optimizing process consists in three steps. First one of the polarizers is repeatedly rotated by 180°, such that the beam is entering from the opposite site. This operation transforms the according angle into its negative and the intensity will remain unchanged only if the angle is 0. In the second step the intensity in the p-channel must be minimized for the second polarizer. As the minimum is quadratic, a precise adjustment can be difficult. This can be avoided by finding two opposite angles with identical intensity, such that the minimum will be at the average of these two angles. This procedure is applied when incoming p-polarized light is required. Finally the retarder is reintroduced. The retarder position is then optimized by making the intensities in the I_e and I_p channel identical, thereby minimizing I_Δ.

B. Optional λ/4-retarder

In Sec. III, the theoretical description of the setup has shown that the detection of the two orthogonal light reflected components using incoming p-polarized light can provide, at first order, the simultaneous determination of the Kerr rotation angle and reflectivity variation, which are related to the two in-plane magnetization components. For instance, for longitudinal MOKE geometry, m_σ is provided by the Kerr angle, whereas the change of reflectivity gives m_σ.

In principle, the polarization rotation of a linearly polarized light when reflected by a magnetic material can be quantified by the Kerr rotation angle θ_K, as shown above, and by the Kerr ellipticity ε. In order to deal with the latter, an additional quarter wave-plate (λ/4-retarder) before the Wollaston prism can be introduced in the setup, since it produces a π/2 phase difference between the p'- and s'-reflected components and interchanges Kerr angle and ellipticity. Within the Jones formalism, the additional λ/4-retarder has the form

$$\begin{pmatrix} i \sqrt{2} & 1 + i 0 \\ 0 & 1 - i \end{pmatrix}.$$  \hspace{1cm} (19)

It is easy to find that the sum is not affected by the λ/4-retarder, such that the result is identical to Eq. (9) and Eq. (11) for incoming p and s polarized light, respectively. For the difference, one finally gets

$$\Delta I = \frac{2 \Delta \epsilon_p}{\Delta \epsilon_p} \approx 2 \alpha_K \propto m_\sigma,$$  \hspace{1cm} (20)

for incoming p and s polarized light, respectively. In both cases the difference is proportional to the Kerr ellipticity.

IV. EXPERIMENT

The capabilities of our v-MOKE setup are shown by presenting detailed angular measurements of a 20 nm thick Fe film epitaxially grown on a MgO(100) single crystal substrate in ultra-high-vacuum conditions. The substrate was first cleaned by repeated cycles of sputtering with 0.5 kV Ar⁺ ions and annealing up to 800 K. Fe deposition was performed at 400 K with a home-made electron-beam evaporator at a rate of about 0.4 nm/min. After deposition, the samples were annealed to about 750 K, in order to reduce possible defects formed during the epitaxial growth, and characterized by low energy electron diffraction (LEED). The Fe film grows according to the well-known Fe(001)[110][MgO(001)[100] epitaxial relation, as indicated by diffraction LEED patterns (not shown). The film was then capped at room temperature with a 3 nm thick Cu film, to prevent oxidation. The four-fold crystal symmetry of the Fe(100) film promotes a pure biaxial magnetic anisotropy in the film, as shown below.

A. The measurement procedure

A simple measurement procedure starts with a field calibration. Next, the ecentric goniometer is aligned to have a fixed reflection plane upon sample rotation. This allows that the absolute values of the magnetization determined in different measurements can be compared. In addition, a fixed reflection plane allows for the compensation of diamagnetic or paramagnetic contributions, by subtracting the same linear function for the whole angular study. In order to improve the signal-to-noise ratio, the λ/2 retarder must be tuned to get comparable signals in both photodiodes by centering I_Δ around zero voltage on the oscilloscope screen. The main error source comes from mechanical vibrations. This random noise is avoidable by using the built-in averaging features of the oscilloscope and/or multiple acquisitions with additional averaging processes via software. The measurement parameters such as, applied field, frequency, number of taken hysteresis loop per angle, are set within the control program. From this point a full series of measurements can be performed completely automatically as the sample is rotated by the stepping motor. α_H is the in-plane angle of the sample with respect to the (fixed) external field. For each angle α_H, hysteresis loops with the given field parameters are recorded.

The v-MOKE measurements were performed at room temperature with a 10 Hz triangular-shaped magnetic field ramp. For each angular condition the signals were averaged during 1 min (i.e., over 600 loops). Our setup provides a sensitivity better than 1 μrad and 10⁻⁶ for Kerr rotation angles and reflectivity changes, respectively. For the present study, the accuracy of both in-plane magnetization components normalized to the saturation magnetization value was better than 10⁻³. It is worth mentioning that the experimental data presented here is the raw data without any linear compensation, indicating negligible diamagnetic contributions from both MgO substrate and Cu capping layer.

B. The analysis procedure

A typical experimental data set for one angular condition is shown in Fig. 3. In this case, longitudinal geometry, incoming p-polarized light, and α_H = 18° were used. α_H = 0° is
FIG. 3. Top: Time evolution of the different channels recorded simultaneously with the digital oscilloscope: (a) The field is represented with filled symbols (left y-axis), whereas the open symbols are the total reflectivity $I_{\text{DC}}/\Sigma_1$ (right y-axis). (b) The difference $I/\Delta_1$ (circle symbols, left y-axis) and the reflectivity changes $I_{\text{AC}}/\Sigma_1$ (square symbols, right y-axis, red online). Bottom: (c) Corresponding in-plane vectorial-resolved magnetization hysteresis loops. The in-plane magnetization components parallel $M_\parallel$ (black) and transversal $M_\perp$ (gray) to the field direction are derived from $I/\Delta_1$ and $I_{\text{AC}}/\Sigma_1$, respectively, as discussed in the text. Solid and open symbols correspond to descending and ascending field branches, respectively.

The time evolution of the applied magnetic field, driven by the current into the coil, and the $I_{\text{DC}}$, i.e., sum of intensities measured at both photodiodes which is proportional to the total reflectivity. $I_{\text{DC}}$ is approximately constant during a single acquisition and is used to normalized the other two intensities, to correct possible photon flux changes during a complete acquisition series.

The time evolution of $I_\Delta/I_{\text{DC}}$ and $I_{\text{AC}}^M/I_{\text{DC}}$ are displayed in Fig. 3(b). Notice that different y-axis scales have been used, originating from different Kerr effects, namely, Kerr rotation and reflectivity change. Quantitative information is reached by using a scale factor between both, as described below. Finally, the vectorial-resolved in-plane hysteresis loops are derived from the time evolutions by plotting the processed signals, scaled and normalized, as function of corresponding magnetic field values, as Fig. 3(c) shows. The in-plane resolved hysteresis loops are referred to the surface magnetization components of the film with respect to the applied magnetic field direction, i.e., parallel $M_\parallel$ and perpendicular $M_\perp$ to $\mu_0 H$.

FIG. 4. $M_\parallel(H)$ curves acquired at the easy axis in longitudinal (left y-axis) and transversal (right y-axis) MOKE geometries, as depicted schematically on top. Notice that the hysteresis curves are obtained from different Kerr effects, i.e., polarization rotation and reflectivity change, respectively. The scale factor is 0.4.

C. Scale factor between Kerr effects

The procedure to determine experimentally the factor between the Kerr effects is schematically shown in Fig. 4. In brief, the scale factor is calculated by comparing in-plane resolved hysteresis curves acquired in both longitudinal and transversal MOKE geometries, for the same relative orientation of sample and field. According to Eqs. (12) and (14) (Eqs. (13) and (15)), the parallel (transversal) component of the magnetization can be derived from polarization rotation (reflectivity change) and reflectivity change (polarization rotation) for longitudinal (transversal) geometry. For instance, the graph of Fig. 4 compares $M_\parallel(H)$ curves acquired at the magnetization easy-axis, i.e., $\alpha_H = 0^\circ$, with both geometries. The curves are qualitatively similar and the proportionality factor gives the scale factor between both Kerr effects. Since the optical plane is kept fixed, the scale factor can be applied for any other $\alpha_H$ condition, for the whole angular study. The quantitative information between magnetization components is crucial in order to study the magnetization reversal processes and, in particular, to determine the direction of magnetization and the domain wall orientation during hysteresis loop. This is discussed in Sec V.

D. $s$ vs. $p$ incoming polarized light

The capability of the setup to determine simultaneously the two in-plane magnetization components required incoming $p$-polarized light, independently from the Kerr geometry used. Fig. 5 compares measurements performed with incoming $s$ and $p$ polarization. Two different $\alpha_H$ angle conditions are shown. At the easy axis, i.e., $\alpha_H = 0^\circ$, where the magnetization vector lies always aligned along
field direction, the magnetic information obtained with both polarization conditions seems alike. However, this is clearly not true at $\alpha_H = 27^\circ$. In this case, similar Kerr rotation effects are found for both incoming polarization conditions. By contrast, the reflectivity changes are just found for incoming $p$-polarized light while a negligible signal is found for incoming $s$-polarized light, as shown in Eq. (11). This indicates that by using $s$-polarized incoming light it is not possible to determine both magnetization components simultaneously, as $s$-polarized light is only sensitive to Kerr rotation effects. While this property is clear from the basic principles of the transverse Kerr effect, it has additionally been confirmed by experiment.

V. ANGULAR-DEPENDENT PROPERTIES

The angular-dependent study has been performed as a function of the in-plane angular rotation $\alpha_H$ angle, by using incoming $p$-polarized light and keeping fixed the external magnetic field direction, i.e., fixed MOKE geometry. $\alpha_H = 0^\circ$ was referred to the in-plane [100] crystal direction of the Fe(100) film aligned parallel to the field direction. The measurements have been performed at room temperature. The hysteresis loops of the in-plane magnetization components, parallel $M_\parallel$ and perpendicular $M_\perp$ to the field direction, were determined simultaneously for a given $\alpha_H$, as described above. The whole angular range was probed every $0.9^\circ$, with $0.5^\circ$ angular resolution.

A detailed discussion on the effects of the magnetic symmetry on magnetic properties will be reported elsewhere. Here, we will show relevant experimental data in order to illustrate the capabilities of the setup.

A. Hysteresis and magnetization reversal processes

Representative in-plane resolved hysteresis loops measured with our v-MOKE setup at different $\alpha_H$ angles are shown in Fig. 6. The angles have been selected to show the rich variety of hysteresis and magnetization reversal processes that a single Fe(100) thin film presents. Two different representations, standard $M-H$ (top graphs) and polar $M_\perp-M_\parallel$ (bottom graphs) curves, have been used in order to identify relevant magnetic properties. Remarkably, a simple inspection of the in-plane resolved hysteresis loops provides direct information about the magnetization easy-axis (e.a.) and hard-axis (h.a.) directions, critical fields, domain wall angles and magnetization reversal processes. At first glance, the in-plane resolved hysteresis loops display different magnetization reversal pathways, which strongly depend on $\alpha_H$, highlighting the importance of the simultaneous determination provided by our setup. Interestingly, this is more obvious for the $M_\perp(H)$ loop. The directional dependence originates from the symmetry breaking introduced by the magnetic anisotropy of the film. Here, the e.a. behavior is found for $\alpha_H = 0^\circ$, where the in-plane [100] crystal direction of the Fe film is aligned parallel to the field direction. At this angle, the perfect squared shape of the $M_\perp(H)$ loop, just showing one irreversible sharp transition, and $M_\parallel(H)$ $\approx 0$ are signatures of an e.a. direction. A more complex reversal pathway is found for $\alpha_H \neq 0^\circ$. In general, $M-H$ loops show one or two irreversible (sharp) and fully reversible (smooth) transitions for both $M_\parallel$ and $M_\perp$ components. The irreversible transitions are more relevant close to the e.a. direction, whereas reversible transitions become increasingly important away from it. Similar features are found every $90^\circ$, due to the four-fold crystal symmetry of the Fe(100) film.

There is a range of angles near the e.a. directions in which only one irreversible transition is observed (see $M-H$ loops for $\alpha_H = 0^\circ$ and $10^\circ$ in Fig. 6). Out of this range, around the h.a. directions, two consecutive irreversible transitions are found (see $M-H$ loops for $\alpha_H = 33^\circ$ in Fig. 6). The critical angle with respect to the e.a., defined as the angle where only one transition takes place, is $\alpha_c = 12^\circ$. Remarkably, for a given field sweep direction the perpendicular component behaves against and like the field direction during the first and the second irreversible transitions, respectively. This opposite behavior arises from the sensitivity of the perpendicular component to the anisotropy direction, as is shown in the polar representation of the hysteresis loop.

The quantitative information obtained from our v-MOKE setup allows the visualization of the in-plane trajectory of the magnetization vector during reversal (see bottom graphs of Fig. 6). In this polar-plot representation, the data lying on the circle of radius unity, depicted with a solid line, represent rotation processes. Every time the data is off this circle, magnetic domains are present. In this way, the specific mechanisms of the magnetization reversal are easily elucidated. In all the cases, except for e.a., as the field is decreased from the maximum field (A), the magnetization vector rotates reversibly along the circle of radius unity. The rotation continues beyond zero field with the opposite field sense until an irreversible process is initiated, as indicated by the departure of the magnetization vector from that circle (B). Notice that both departure and return points are closed to e.a. directions, which accounts for irreversible process due to nucleation of magnetic domains oriented along the e.a. directions and further domain wall propagation. The return point C is found ca.
180° or 90° away from B, depending on \( \alpha_H \). The crossover between both behaviors is found at \( \alpha_C \). For the first case, e.g., for \( \alpha_H = 10^\circ \), after the first irreversible transition the magnetization vector rotates along the circle until the maximum field is reached (D). In turn, e.g., for \( \alpha_H = 33^\circ \), a second irreversible transition takes place (D), with the return point near to the closest e.a. direction (E), which is ca. orthogonal to D. Thereafter, rotation of magnetization continues until the maximum field is reached (F). Note that the magnetization vector is far to be saturated along the field direction even for the largest field used, except for \( \alpha_H = 0^\circ \).

Therefore, in a pure fold-fold magnetic symmetry system, the reversal proceeds by reversible magnetization rotation processes, in order to get the closest e.a. direction, with one (two) irreversible transition, related to nucleation of antiparallel (orthogonal) magnetic domains and further propagation of 180° (90°) domain walls, when the applied field direction is close to one of the two easy- (hard-) axis magnetization directions. In addition, the magnetic domains are not oriented necessarily parallel to the field direction but rather to the e.a. directions.

For a more quantitative analysis, magnetic parameters, such as remanence magnetization, coercivity, and domain wall angle, can be readily obtained as a function of \( \alpha_H \) from the hysteresis loops, as indicated in Fig. 6.

**B. Remanence and magnetic symmetry**

The simplest information that can be extracted from the angular evolution is the anisotropy determined by the magnetic symmetry of the system. This can be done easily by plotting the normalized remanence values of the two in-plane magnetization components as a function of \( \alpha_H \) (see Fig. 7(a)). Both magnetization components display a pronounced oscillation with periodicity of 90°. The parallel component follows a \(|\cos 2\alpha_H|\) law dependence, the perpendicular component changes the sign when a characteristic e.a. or h.a. direction is crossed, and both components are complementary, i.e., \( M_{R,S} = (M_{R,\parallel} + M_{R,\perp}) M_{R,S} \parallel \) (Fig. 7(b)) and \( M_{R,S} \perp \) (Fig. 7(c)) display characteristic “four-leaves clover” and “four-wings windmill” shapes, respectively. This originates from the four-fold magnetic symmetry, due to the cubic crystal symmetry of the Fe(100) film. All these features confirm a pure biaxial magnetic anisotropy behavior of the film, where the anisotropy axes are aligned parallel to the in-plane [001] crystallographic directions of the film.

It is worth mentioning that, in the present case for a pure biaxial anisotropy system, the information on the magnetic symmetry does not require the measurement of \( M_{R,\perp} \) (\( H \)). However in a magnetic system with competing anisotropies, the second magnetization component allows for a more
For the data shown in the present study, $M_{R,\perp}(\alpha_H)$ vanishes progressively when approaching an e.a. direction from negative angles changing its sign for positive ones, whereas it suddenly changes around a h.a. direction, as shown Fig. 7. This dissimilar zero-crossing evolution is therefore exploited in order to distinguish between easy or hard magnetization directions and to evaluate different anisotropy contributions.\textsuperscript{10,22}

D. Irreversible transitions and critical fields

Critical fields, i.e., coercive fields, are related with the effective anisotropy of the system and determine, for example, the field needed to control the orientation of stable magnetization directions in spintronic devices. From the quantitative analysis of the $M_\parallel - M_\perp$ loops described above, the smooth reversible transitions are related to rotation of the magnetization, while sharp transitions correspond to nucleation of magnetic domains oriented along a preferential direction of magnetization and a further domain wall propagation. The position of sharp irreversible transitions can easily be detected by looking at the $M-H$ curves.

An irreversible transition results in an abrupt change in the $M-H$ loop, i.e., in a large peak in the derivative. For hysteresis loop with just one irreversible transition, the critical field is the applied field where the magnetization crosses zero (see Figs. 6(a) and 6(b)). In a more general case, where two or more irreversible transitions take place, e.g., for biaxial (Fig. 6(c)) or a more complicated anisotropy symmetry,\textsuperscript{9,14,19} the critical fields are taken at the middle point of the corresponding two stable magnetization states, or more accurately at the maximum value of the corresponding numerical derivative curve. On other hand, the hysteresis jumps found in both components, and their corresponding derivative curves, are not necessarily of the same height. For instance, when looking only at the $M_\parallel$ in the top graphs of Fig. 6(c), the second transition is significantly smaller than the first. The difference is even more pronounced when approaching to a h.a. direction. In this case, the corresponding jump in $M_\perp$ is increasing, allowing a more precise determination of the angular evolution of critical fields. Obviously, at a given angle condition, similar critical field values are derived by looking at $M_\perp(H)$ or $M_\parallel(H)$ curves measured simultaneously, as shows by the dashed lines depicted in the top graphs of Fig. 6. Note that, the latter could not be the case from non-simultaneous v-MOKE measurements for some specific range of angles with strong angular dependence, due to experimental inaccuracies.

Fig. 8 displays the angular dependence of the critical fields extracted from $M-H$ loops, as the ones shown in Fig. 6. $H_{C,1}$ and $H_{C,2}$ are the critical field values of the first and second irreversible transitions, respectively. In general, both angular evolutions display fourfold symmetry, i.e., a behavior repeated every $90^\circ$. $H_{C,1}$ presents the maximum value at the e.a. directions, it is roughly constant around them, and it decreases slowly until it reaches its minimum value at the h.a. direction. By contrast, $H_{C,2}$ presents a larger rising evolution as approaching to the h.a. direction, in the angular range

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7}
\caption{(a) Angular dependence of the normalized remanent magnetization components of the four-fold crystal symmetry Fe(100) film. Corresponding polar-plot representation of the parallel (b) and perpendicular (c) component. The values of $M_{R,\perp}$ (open circle symbols) and $M_{R,\parallel}$ (filled square symbols) have been extracted from the in-plane resolved hysteresis loops, as the ones shown in Fig. 6. Both the ranges of angles where two irreversible transitions take place during the reversal are marked by shadowed areas.}
\end{figure}

precise determination of the symmetry, by locating precisely the characteristic axes, as we have pointed out in precedent studies.\textsuperscript{6,19–22}

C. Characteristic axis

The identification of the characteristic anisotropy axes is crucial for spintronics applications, since both magnetic and transport properties depend on it.\textsuperscript{26} This is sometimes not a simple task in standard non-vectorial experimental studies, where only $M_\perp(H)$ is measured. By contrast, our v-MOKE setup provides a great accuracy in determining both e.a. and h.a. directions. In fact, we can precisely locate them by looking for the change of sign of the $M_\perp(H)$ loops when a characteristic direction is crossed.\textsuperscript{6}

In general, for most systems the magnetization reversal at the e.a. direction is completely governed by nucleation of opposite magnetic domains oriented along the field direction and further propagation of domain walls. As expected in thin films, a negligible $M_\perp(H)$ signal is expected when the relative areas of magnetic domains and domain walls are compared. Close to a hard axis direction, instead, one can expect large $M_\perp$ signals. This component, moreover, changes sign when crossing a h.a. direction. Due to experimental uncertainties, both signs contribute near the h.a. and the averaging process of the measurement procedure results in a net zero signal. As a consequence, a zero $M_\perp$ signal is a simple indicator for a characteristic axis (hard and easy).\textsuperscript{6,19–22} Furthermore, if magnetic anisotropies of different symmetry are present, and result in non-orthogonal characteristic axis or non-collinear configurations, the precise knowledge of the angular position of the characteristic axes allows for the determination of the relative strength of the contributing anisotropies.\textsuperscript{19–21}
value, i.e., single transition by a domain wall of approximately 180° component (see text). Notice that near the easy axes the results coincide in a single two transitions are observed around the hard axes (emphasized by the light Fe(100) film, and how they are strongly related to each other. For accuracy reasons, the values of critical field values of the first and second irreversible transition, respectively. Component, while the values 

FIG. 8. Angular dependence of the critical fields of the four-fold crystal symmetry Fe(100) film. $H_{C,1}$ (solid symbols) and $H_{C,2}$ (open symbols) are the critical field values of the first and second irreversible transition, respectively. For accuracy reasons, the values of $H_{C,1}$ are determined from the parallel component, while the values $H_{C,2}$ are extracted from the perpendicular component (see text). Notice that near the easy axes the results coincide in a single value, i.e., single transition by a domain wall of approximately 180°, while two transitions are observed around the hard axes (emphasized by the light gray background).

where the reversal takes place via two consecutive irreversible transitions.

Finally, it is worth highlighting the strong influence of the magnetic symmetry on the magnetic properties of the Fe(100) film, and how they are strongly related to each other. This can be generalized for other systems with more complex magnetic symmetries.\cite{6,17,22,25,26} In this case, the biaxial magnetic anisotropy is promoted by the four-fold crystal symmetry of the Fe film and determines hysteretic phenomena, remanences, critical fields, domain wall angles, and magnetization reversal processes.

VI. CONCLUSION

We have presented a detailed description of our automated v-MOKE setup which provides simultaneously and quantitatively the two in-plane magnetization components during the hysteresis loop for a given orientation, allowing full angular studies. The in-plane resolved components are obtained by using incoming $p$-polarized light through the acquisition of polarization rotations and reflectivity changes, at the same time. This is achieved independently of the MOKE geometry. This is done by neither moving optical parts nor the electromagnet, i.e., the setup is completely static.

The capabilities of the v-MOKE are shown with a four-fold magnetic symmetry system. From the hysteresis loop the reversal magnetization processes can be deduced. The simultaneous measurement of two in-plane magnetization components in combination with the full angular study provides a precise characterization of the angular-dependent magnetic reversal processes and allows the determination of the characteristic anisotropy axes with great accuracy. The technique allows the study of the symmetry of the magnetic anisotropy that strongly influences the magnetic properties including reversal fields, remanence, magnetic stability, magnetization reversal processes, domain wall angles, and magnetization reversal processes. This suggests that similar studies have to be performed in order to better develop a basic understanding of magnetic nanostructures.

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APPENDIX: REFLECTION COEFFICIENTS

To justify the form of the reflection matrix given in Eq. (1) we calculated the matrix according to the boundary matrix method of Qiu and Bader.\cite{4} Within this framework one multiplies the medium boundary ($A_i$) and medium propagation matrices ($D_j$) to obtain the matrix $M$ defined by

$$\begin{align*}
M &= A_i^{-1} \prod_{m=1}^{N} (A_m D_m A_m^{-1}) A_f = \begin{pmatrix} G & H \\ I & J \end{pmatrix},
\end{align*}$$

(A1)

where the Fresnel reflection and transmission coefficients are defined as

$$\begin{align*}
G^{-1} &= \begin{pmatrix} t_{sx} & t_{sp} \\ t_{px} & t_{pp} \end{pmatrix}; \quad IG^{-1} = \begin{pmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{pmatrix}.
\end{align*}$$

(A2)

In case of a thin magnetic film of thickness $d$ (the thickness small compared to the wavelength $\lambda$) on top of a semi-infinite medium ($\lambda_\infty$) on top of a semi-infinite medium ($\lambda_\infty$)

$$\begin{align*}
r_{ss} &= \frac{1}{(n_i \cos \theta_i + n_t \cos \theta_t)} \left[ n_i^2 \cos^2 \theta_i - n_t^2 \cos^2 \theta_t ight. \\
&+ 4\pi \frac{d}{\lambda} n_i \cos \theta_i \left( n_m^2 \cos^2 \theta_m - n_t^2 \cos^2 \theta_t \right) \bigg].
\end{align*}$$

(A3)

$$\begin{align*}
r_{sp} &= -4\pi \frac{d}{\lambda} n_t^2 \sin \theta_t m_z + n_m^2 \cos \theta_m z \\
&\quad \times n_i \cos \theta_i Q,
\end{align*}$$

$$\begin{align*}
r_{ps} &= +4\pi \frac{d}{\lambda} n_t^2 \sin \theta_t m_z - n_m^2 \cos \theta_m z \\
&\quad \times n_i \cos \theta_i Q,
\end{align*}$$

$$\begin{align*}
r_{pp} &= \frac{1}{(n_i \cos \theta_i + n_t \cos \theta_t)} \left[ n_i^2 \cos^2 \theta_i - n_t^2 \cos^2 \theta_t ight. \\
&- 4\pi \frac{d}{\lambda} \left( n_m^2 \cos^2 \theta_t - n_t^2 \cos^2 \theta_t \right) \\
&\quad + n_t^2 \sin 2\theta_t m_z Q \bigg] n_i \cos \theta_i \bigg],
\end{align*}$$

(A3)
where \( n_i, n_f, \) and \( n_m \) indices of refraction of the initial, the final, and the magnetic medium. The incident angle is \( \theta_i \), while \( \theta_m \) and \( \theta_f \) are the (complex) angles of propagation in the magnetic layer and the substrate, respectively. The magneto-optic effect also depends on the material constant \( Q \)—the Voigt constant—that accounts for the off diagonal elements in the dielectric tensor.