A mirror based polar magneto-optical Kerr effect spectroscopy arrangement

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An arrangement is described for performing magneto-optical Kerr effect (MOKE) spectroscopy in polar geometry with a conventional C-frame or H-frame type electromagnet. It uses an additional mirror which eliminates the need for an electromagnet pole piece with an axial hole and allows for easy switching between polar MOKE geometry and longitudinal or transverse MOKE geometries. A theoretical analysis of the photo-elastic modulation based detection scheme shows that the mirror causes a strong mixing of signals corresponding to Kerr rotation and ellipticity. The influence of the mirror is experimentally demonstrated and a procedure is given to correct for it. MOKE spectrum of nickel films obtained using this arrangement is shown to match with reports in the literature.

I. INTRODUCTION

Magneto-optical Kerr effect (MOKE) spectroscopy is a powerful tool for studying spin polarized electronic structure of solids.1,2 In MOKE, one studies the change in the polarization state of light after it undergoes reflection from a magnetized solid and is analogous to the Faraday effect in transmission state of light after it undergoes reflection from a magnetized solid and is analogous to the Faraday effect in transmission. The effect arises because the complex refractive indices of solids.1, 2 In MOKE, one studies the change in the polarization state of light after it undergoes reflection from a magnetized solid and is analogous to the Faraday effect in transmission. The effect arises because the complex refractive indices of solids.1, 2 In MOKE, one studies the change in the polarization state of light after it undergoes reflection from a magnetized solid and is analogous to the Faraday effect in transmission.

Depending upon the relative orientation of the magnetic field $B$ and the plane of incidence of the probe light, MOKE is studied in three configurations: longitudinal, transverse, and polar as shown in Fig. 1. In the longitudinal (transverse) geometry, the magnetic field is applied in the plane of the sample and is parallel (perpendicular) to the plane of incidence of light. In the polar geometry, the magnetic field is applied perpendicular to the plane of the sample. The polar geometry has the advantage in that results in relatively large $\phi_k$ and $\eta_k$ values for normal or small angles of incidence.3 This geometry is also useful for studying spin polarized transport in semiconductors.4

The conventional way of performing polar MOKE measurement involves the use of an electromagnet where one of the pole pieces has a long narrow axial hole.5 The sample is mounted in between the electromagnet pole pieces with its surface parallel to the face of pole pieces so that $B$ is normal to the sample surface. Light is made incident on the sample through the pole piece which has the hole and is reflected back through it. The reflected beam is separated later using a beam splitter arrangement. In this conventional arrangement, the hole in the pole piece has to be kept narrow (typically a few mm in diameter) in order not to distort the magnetic field on the sample. Typically, therefore, one uses a laser light source which can be transported back and forth through this narrow hole. However, for MOKE spectroscopy measurements, one needs a wavelength tunable light source with very wide tunability. Typically, such a source is obtained by the combination of a broadband lamp (Xe or tungsten) and a grating based monochromator. Unlike a laser, such a beam is typically much wider and cannot be transported over long distances without significant divergence. Therefore, sending and retrieving such a beam through a long narrow hole in the pole piece would lead to an unacceptable loss of light and errors in the measurement. Geerts et al. have described a three-mirror and multiple reflection based arrangement for performing polar MOKE measurements.6 However, a quantitative analysis of the effect of the mirrors on the measurement was not presented.

Here, we describe a single mirror based polar MOKE arrangement which eliminates the need for an electromagnet having a pole piece with an axial hole. The arrangement allows for the use of a normal, monochromator dispersed, light beam for wavelength-dependent MOKE spectroscopy and can be easily adapted for measurements at low temperatures. Our theoretical analysis shows that the mirror has a significant influence on the rotation and ellipticity measurements. We experimentally verify it by measuring optical activity of sugar solution using this arrangement and describe a procedure to correct for the influence of the mirror. Finally, using this arrangement, polar MOKE spectroscopy was performed on Ni films and the results are compared with reports in the literature.

II. EXPERIMENTAL DETAILS AND SIGNAL ANALYSIS

For measuring the MOKE signals, we have adopted the photo-elastic modulator (PEM) based polarization modulated measurement technique.7 This technique helps

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determine both the magneto-optical Kerr parameters $\phi_k$ and $\eta_k$ simultaneously, with very high sensitivity down to $\sim 0.002^\circ$. A schematic of our polar MOKE arrangement is shown in Fig. 2. The main element of this arrangement is the cylindrical sample holder finger placed between the pole pieces of a conventional H-frame electromagnet. The sample holder has a $45^\circ$ cut on it exposing two surfaces, one parallel to the length of the finger and the other inclined at $45^\circ$ to it. The sample is mounted on the flat surface and a thin Al mirror is mounted on the inclined surface. The sample holder is introduced within the pole pieces in a manner such that the sample (dotted rectangle on the sample holder in Fig. 2) surface is parallel to the electromagnet pole pieces, ensuring that $\mathbf{B}$ is normal to the sample surface as required for polar MOKE geometry.

According to the coordinate system shown in Fig. 2, the plane of incidence is the horizontal $x$-$z$ plane and the polarization axis orientations are relative to this plane. The top right inset in Fig. 2 shows the light trajectory close to the sample in detail. Here, $\alpha_1$ ($\alpha_2$) is the angle of incidence on the mirror before (after) the light hits the sample, consequently the angle of incidence on the sample is $(\alpha_2 - \alpha_1)/2$, which is also equal to half the angle between the light beams coming into and leaving the pole piece region. We have worked with an angle of incidence on the sample close to $5^\circ$. We note here that by replacing this sample holder finger with a flat top finger, one can easily change to the longitudinal MOKE geometry. With a flat top finger, one can also perform transverse MOKE measurements as follows. Consider the $x$-$z$ plane as passing through the vertical center of a sample mounted on such a flat top finger. If the incident beam travels towards the sample at an angle to the $x$-$z$ plane such that it hits the sample from below the $x$-$z$ plane, then upon reflection it will turn back and move progressively away from the $x$-$z$ plane. This represents a transverse MOKE measurement geometry and the optics can be appropriately arranged to achieve it.

Our sample holder finger was made from a 11 mm diameter copper rod and attached to the cold finger of a closed-cycle He refrigerator. There is a provision for a vacuum jacket with a fused silica window in front, for doing measurements at low temperatures. We can cool samples down to 15 K in our setup. In a conventional polar MOKE arrangement, a relatively large and unwanted background rotation signal can arise due to Faraday effect in the cryostat window material. In our arrangement, the plane of the cryostat window is parallel to the magnetic field direction and the angle of incidence on the window is small. These result in a significantly reduced window related background rotation signal.

The Al mirror was made by depositing a 150 nm thick layer of Al on Si substrate followed by a 10 nm thick protective cap layer of SiO$_2$, using electron beam evaporation technique. For the probe beam, light from a broadband Xe lamp was dispersed using a 0.5 m focal length monochromator (bandpass 0.5 nm) and then collimated, before being made incident on the first polarizer whose pass axis was aligned at $-45^\circ$ to the horizontal. The PEM axis was horizontal at $0^\circ$ and the analyzer axis was at $90^\circ$. We used Glan-Taylor polarizers in our measurements. The PEM used was Model II/IS42 from Hinds Instruments, which operates at a modulation frequency $f = 42$ kHz with frequency stability better than 25 ppm. The detector was an infrared sensitive PMT and the signals were detected using a Model SR-830 Lock-in amplifier from Stanford Research Systems.

Magnetic fields up to 1.8 T can be used in our measurements. Note that the Al mirror is in a high magnetic field region. It is known that the Kerr effect in a non-ferromagnetic material is about 1/1000 that for a ferromagnetic material under similar magnetic fields. Therefore, one can neglect the Kerr effect in Al influencing the signals. However, since $s$ and $p$ polarized light would be reflected differently by the Al mirror (the two angles of incidence on the mirror are close to $45^\circ$), it can influence the measurement and to understand this we performed a theoretical analysis of the measured signals as described below.

For analysis we use the Jones matrix formalism. The electric field vector of light polarized linearly at an angle $\theta$ relative to the horizontal $x$-$z$ plane in Fig. 2 is given by the Jones vector,

$$\hat{E}(\theta) = |E| \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix}. \tag{1}$$

After the polarizer in Fig. 2, the incident light would be represented by $\hat{E}(-45^\circ)$. The Jones matrix for the PEM with its
modulation axis in the x-z plane can be represented by
\[ \tilde{C} = \begin{pmatrix} e^{i\delta/2} & 0 \\ 0 & e^{-i\delta/2} \end{pmatrix}, \]
where \( \delta = \delta_0 \cos(2\pi ft) \) is the sinusoidally varying retardation of the PEM at the modulation frequency \( f \). Next assuming that light is incident on the mirror surface at an angle \( \alpha \) relative to the normal, its normalized Jones matrix is given by
\[ \tilde{M}(\alpha) = \begin{pmatrix} \tan \Psi(\alpha) e^{i\Delta(\alpha)} & 0 \\ 0 & 1 \end{pmatrix}, \]
where \( \tan \Psi(\alpha) \) and \( \Delta(\alpha) \) are the ellipsometry parameters of the mirror which depend on \( \alpha \). The Fresnel reflection matrix for the sample can be written as
\[ \tilde{S} = \begin{pmatrix} r_{pp} & r_{ps} \\ r_{sp} & r_{ss} \end{pmatrix}, \]
where \( r_{ij} \) is the ratio of incident \( j \) polarized electric vector and the reflected \( i \) polarized electric vector. For near normal angle of incidence \( r_{ps} \approx r_{pp} \), and this matrix becomes
\[ \tilde{S} = \begin{pmatrix} 1 & -i\eta_k \frac{(\phi_k + i\eta_k)}{1} \\ i\eta_k & \eta_k \end{pmatrix}. \]
where \( r_{ps}/r_{pp} = -r_{sp}/r_{pp} = -(\phi_k + i\eta_k) \) defines the Kerr rotation \( \phi_k \) and ellipticity \( \eta_k \) parameters for near normal incidence. The normalized Jones matrix for the analyzer with pass axis oriented at an angle \( \phi \) with the x-z plane is given as
\[ \tilde{A}(\phi) = \begin{pmatrix} \cos^2 \phi & \cos \phi \sin \phi \\ \sin \phi \cos \phi & \sin^2 \phi \end{pmatrix}. \]
The Jones vector of the light reaching the detector is obtained from the dot product of the Jones matrices of the optical components encountered by the light as
\[ \tilde{E}_d \propto \tilde{A}(90^\circ) \tilde{M}(\alpha_2) \tilde{S} \tilde{M}(\alpha_1) \tilde{C} \tilde{E}(-45^\circ) \]
\[ = |E| \frac{e^{-i\delta/2}}{\sqrt{2}} \begin{pmatrix} 0 \\ -1 + e^{i[\delta + \Delta(\alpha_1)]} \tan \Psi(\alpha_1)(\phi_k + i\eta_k) \end{pmatrix}. \]
(7)
As mentioned before, \( \alpha_1 \) is the angle at which light hits the mirror before hitting the sample and \( \alpha_2 \) is the angle of incidence on the mirror after reflection from the sample. We note that \( \alpha_2 \) does not appear in the final equation above and hence the second reflection from the Al mirror does not affect the measurements in this particular geometry. The intensity of the light \( I \) as measured by the detector can now be expressed as
\[ I \propto |\tilde{E}_d|^2 \]
\[ \propto |E|^2 \frac{1}{2} [1 - 2\tan \Psi(\phi_k \cos(\Delta) - \eta_k \sin(\Delta))] \]
\[ = I_0 [1 - 2\tan \Psi(\phi_k \cos(\Delta) - \eta_k \sin(\Delta))], \]
(8)
where \( I_0 \) is a constant depending on the source intensity and detector response and is wavelength-dependent. In the above we have only retained terms linear in \( \phi_k \) and \( \eta_k \). Using the expansion formulas
\[ \sin(\delta_0 \cos(2\pi ft)) = 2J_0(\delta_0) \cos(2\pi ft) + \ldots, \]
\[ \cos(\delta_0 \cos(2\pi ft)) = J_0(\delta_0) - 2J_2(\delta_0) \cos(4\pi ft) + \ldots, \]
(9)
where \( J_n(\delta) \) is the \( n \)th order Bessel function at \( \delta_0 \). Eq. (8) can be written as
\[ I = I_0[I_{dc} + I_f \cos(2\pi ft) + I_{2f} \cos(4\pi ft) + \ldots], \]
(10)
where
\[ I_{dc} = 1 + 2\tan \Psi J_0(\delta_0)(\phi_k \cos\Delta - \eta_k \sin\Delta), \]
(11)
\[ I_f = 4\tan \Psi J_1(\delta_0)(\eta_k \cos\Delta + \phi_k \sin\Delta), \]
(12)
\[ I_{2f} = 4\tan \Psi J_2(\delta_0)(-\eta_k \sin\Delta + \phi_k \cos\Delta). \]
(13)
Here, \( I_f \) and \( I_{2f} \) represent the components of the detector signal at the PEM modulation frequency \( f \) and its second harmonic \( 2f \). They are measured using the lock-in amplifier. The dc component of the detector signal \( I_{dc} \) is measured using a voltmeter. With the peak retardation of the PEM set at \( \delta_0 = 2.405 \) one gets \( J_0(\delta_0) = 0 \) and following relations are obtained for the ratios of the ac to dc signals:
\[ \frac{I_f}{I_{dc}} = 2\sqrt{2}J_1(\delta_0)(\eta_k \cos\Delta + \phi_k \sin\Delta) \tan \Psi, \]
(14)
\[ \frac{I_{2f}}{I_{dc}} = 2\sqrt{2}J_2(\delta_0)(-\eta_k \sin\Delta + \phi_k \cos\Delta) \tan \Psi. \]
(15)
The above includes a factor of \( 1/\sqrt{2} \) since the lock-in measures the root-mean-squared value of the ac signal. Equations (14) and (15) suggest a strong intermixing of signals corresponding to \( \phi_k \) and \( \eta_k \) through the ellipsometry parameters \( \tan \Psi \) and \( \Delta \) of the mirror. Such an influence of the ellipsometry parameters has also been reported for unmodulated Faraday rotation measurements involving mirrors.\(^{10}\)

In the absence of the mirror \( \tan \Psi = 1, \Delta = 0 \) and the above equations simplify to the usually considered relations,
\[ \frac{I_f}{I_{dc}} = 2\sqrt{2}\mathcal{A}J_1(\delta_0)\eta_k, \]
(16)
\[ \frac{I_{2f}}{I_{dc}} = 2\sqrt{2}\mathcal{B}J_2(\delta_0)\phi_k. \]
(17)

We note here that in general, while using a PEM it is important to properly calibrate the peak retardance \( \delta_0 \) as well as the ratios \( I_f/I_{dc} \) and \( I_{2f}/I_{dc} \), as a function of wavelength. The errors in the ratios arise from the frequency response of the detection electronics and also from the temporal response of typical semiconductor photo-diode detectors which can vary with the wavelength of the incident light. We also note that during low temperature measurements with the vacuum jacket on, errors can be introduced if there is significant strain in the fused silica windows.\(^{11}\) The influence of the mirror will also vary if impurities get adsorbed on it at low temperatures and it is therefore advisable to mount the mirror such that it has poor thermal contact with the copper sample holder.

In order to verify the influence of the mirror on rotation and ellipticity measurements, we first studied optical activity of sugar solution using this arrangement. Sugar solution was chosen since one can get a fairly large optical rotation.
in this system. Sugar solution of concentration 120 g/l was taken in a glass cuvette with a path length of 10 mm. The measurements were performed using two arrangements. The first was the conventional arrangement with no mirrors as shown in Fig. 3(a). In the second arrangement in Fig. 3(b), the light suffered an extra reflection from an Al mirror (40° angle of incidence on the mirror) before passing through the sugar solution. Since the above analysis showed that the influence of the mirror on the measurements arise through the ellipsometric parameters $\tan \Psi$ and $\Delta$ of the mirror at the given angle of incidence, these were also measured as a function of wavelength using a separate conventional ellipsometry arrangement. Finally, in order to verify the working of our polar MOKE arrangement, measurements were performed on electron beam deposited 500 nm thick Ni films on Si substrate which were capped with a 5 nm thick SiO$_2$ layer.

III. RESULTS AND DISCUSSION

Figure 4 shows the results of optical rotation and ellipticity measurements as a function of wavelength on sugar solution, which were performed to study the role of the extra mirror in our arrangement. The solid lines are results of a measurement using the conventional arrangement in Fig. 3(a) where the signals were analyzed using Eqs. (16) and (17). As expected for sugar solution, we see a large rotation but negligible ellipticity in the spectral region from 340 nm to 800 nm. The dashed lines are results of a measurement using the arrangement with an additional mirror as in Fig. 3(b) where the signals were again analyzed using Eq. (16) and (17). These two sets clearly do not match, the ellipticity measurement in particular shows a very large error in the mirror based configuration. Thus, the added mirror clearly has a very strong influence on the measurements. The inset of Fig. 4 shows the measured ellipsometry parameters $\tan \Psi$ and $\Delta$ of the Al mirror at 40° angle of incidence. Using these values of $\tan \Psi$ and $\Delta$ along with Eq. (14) and (15), we again calculated the rotation and ellipticity from the data obtained through measurements involving the additional mirror. These values are depicted by the dotted lines in Fig. 4 and are in fairly good agreement with the results obtained with the conventional arrangement that did not use the mirror. Thus using the ellipsometry parameters $\tan \Psi$ and $\Delta$ of the Al mirror, one can easily correct for the influence of the additional mirror on the rotation and ellipticity measurement signals. We note here that according to Eq. (14) and (15), if instead of a metallic mirror one used an appropriate dielectric mirror for which $\Delta$ is close to 180°, then one can minimize the intermixing of the $\phi_k$ and $\eta_k$ signals.

Our polar MOKE arrangement shown in Fig. 2 involves two reflections of the light from the Al mirror before it hits the analyzer. The theoretical analysis above showed that the second reflection (after the sample) does not influence the results. This was also experimentally verified through optical activity measurements on sugar solution as follows. We added a second mirror to again reflect the light after it emerged from the cuvette. Here too the rotation and ellipticity estimated by using Eqs. (14) and (15) gave the similar results (data not shown here) as obtained for the case without any mirror, thereby proving that the second reflection does not influence the measurements.

As a test of proper functioning of this single mirror based polar MOKE arrangement, we present Kerr rotation and ellipticity spectra of Ni films measured using this setup. The measurements were performed at 295 K in the photon energy range of 1.5 eV–3.75 eV, under 1 T magnetic field. Such magnetic field strengths are sufficient to saturate magnetization in Ni. Figure 5 shows three sets of MOKE rotation and ellipticity spectra of Ni films. (i) The dashed lines are results obtained...
FIG. 5. Polar MOKE rotation and ellipticity spectra of a 500 nm thick Ni film under 1 T magnetic field. The dashed lines were obtained using the analysis that did not account for the Al mirror while the dotted lines take into account the influence of the Al mirror. For comparison, the continuous lines show the results obtained by Visnovsky et al. The inset shows the Kerr hysteresis loops obtained at a photon energy of 1.55 eV ($\lambda = 800$ nm).

by using Eqs. (16) and (17) for the analysis of the measured signals, these do not take into account the influence of the Al mirror. (ii) The dotted lines are results obtained by using Eqs. (14) and (15) to analyze the measured signals. These account for the influence of the Al mirror through the ellipsometry parameters $\tan \Psi$ and $\Delta$ of the Al mirror. The values of $\tan \Psi$ and $\Delta$ used were measured at $40^\circ$ angle of incidence, to match with the first reflection from the mirror in our polar MOKE arrangement. (iii) The solid lines represent the MOKE spectra of Ni obtained by Visnovsky et al. We see that by using the analysis that takes into account the influence of the mirror, we get MOKE rotation and ellipticity spectra for Ni that is in fairly good agreement with the spectra obtained by Visnovsky et al. This agreement also shows that the second reflection from the mirror does not influence the results. We note that an exact agreement is unlikely because the MOKE rotation and ellipticity parameters are influenced by several parameters of the film including its quality. The inset of the Fig. 5 shows the polar MOKE rotation and ellipticity hysteresis loops for the Ni film, obtained at a photon energy of 1.55 eV ($\lambda = 800$ nm). Here the signals were analyzed using Eqs. (14) and (15). It reveals the saturation magnetization field for Ni to be close to 0.5 T, which again agrees well with the value reported by Visnovsky et al.

In conclusion, we have demonstrated an arrangement for performing polar MOKE spectroscopy measurements with a conventional electromagnet that uses one additional mirror. This arrangement eliminates the need for a special electromagnet with a narrow hole in one of its pole pieces and associated complications in transporting light back and forth through such a hole. It also reduces the unwanted background Faraday rotation signal associated with optical windows on a cryostat, when performing measurements at low temperatures. The significant influence of the mirror on the measurements was analyzed theoretically and demonstrated experimentally. A procedure to correct for the influence of the mirror by using appropriate ellipsometric parameters of the mirror, has also been described.

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Next assuming that light is incident on the mirror surface at an angle $\alpha$ relative to the normal, its normalized Jones matrix is given by

$$
\hat{M}(\alpha) \propto \begin{pmatrix}
\tan \Psi(\alpha) e^{i\Delta(\alpha)} & 0 \\
0 & 1
\end{pmatrix}
$$

(3)

where $\tan \Psi(\alpha)$ and $\Delta(\alpha)$ are the ellipsometry parameters of the mirror which depend on $\alpha$. The Fresnel reflection matrix for the sample can be written as

$$
\hat{S} = \begin{pmatrix} r_{pp} & r_{ps} \\
r_{sp} & r_{ss}
\end{pmatrix} = r_{ss} \begin{pmatrix} r_{pp}/r_{ss} & r_{ps}/r_{ss} \\
(r_{sp}/r_{pp})(r_{pp}/r_{ss}) & 1
\end{pmatrix}
$$

(4)

where $r_{ij}$ is the ratio of incident $j$ polarized electric vector and the reflected $i$ polarized electric vector. For near normal angle of incidence $r_{ss} \approx r_{pp}$, and this matrix becomes

$$
\hat{S} \propto \begin{pmatrix} 1 & -(\phi_k + i\eta_k) \\
\phi_k + i\eta_k & 1
\end{pmatrix}
$$

(5)

where $r_{sp}/r_{pp} = -r_{ps}/r_{ss} = \phi_k + i\eta_k$ defines the Kerr rotation ($\phi_k$) and ellipticity ($\eta_k$) parameters for near normal incidence. The normalized Jones matrix for the analyzer with pass axis oriented at an angle $\phi$ with the $x$-$z$ plane is given as

$$
\hat{A}(\phi) = \begin{pmatrix}
\cos^2 \phi & \cos \phi \sin \phi \\
\sin \phi \cos \phi & \sin^2 \phi
\end{pmatrix}
$$

(6)

The Jones vector of the light reaching the detector is obtained from the dot product of the Jones matrices of the optical components encountered by the light as

$$
\tilde{E}_d \propto \hat{A}(90^\circ) \hat{M}(\alpha_2) \hat{S} \hat{M}(\alpha_1) \hat{C} \hat{E}(-45^\circ) \\
\propto |E| e^{-i\delta/2} \begin{pmatrix}
0 \\
-1 + e^{i(\delta + \Delta(\alpha_1))} \tan \Psi(\alpha_1)[\phi_k + i\eta_k]
\end{pmatrix}
$$

(7)

As mentioned before, $\alpha_1$ is the angle at which light hits the mirror before hitting the sample and $\alpha_2$ is the angle of incidence on the mirror after reflection from the sample. We note that $\alpha_2$ does not appear in the final equation above and hence the second reflection from the Al mirror does not affect the measurements in this particular geometry. The intensity of the light ($I$) as measured by the detector can now be expressed as

$$
I \propto \tilde{E}_d^* \tilde{E}_d \\
\propto |E|^2 \left[1 - 2 \tan \Psi \left\{ \phi_k \cos(\delta + \Delta) - \eta_k \sin(\delta + \Delta) \right\} \right] \\
I = I_0 \left[1 - 2 \tan \Psi \left\{ \phi_k \cos(\delta + \Delta) - \eta_k \sin(\delta + \Delta) \right\} \right]
$$

(8)