# Optical Microscopy Study of Topological Insulators Using Ellipsometry

Amber Schedlbauer

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## 1 Abstract

An optical setup based on normal-incidence reflectivity allows the Magneto Optic Kerr Effect (MOKE) to be observed. This microscopy study analyzes different materials to see their responses to an applied magnetic field. Due to their unique surface states, topological insulators have recently become a new topic of study. While different materials were examined, the $Bi_2Se_3$ sample, which is a topological insulator, was the main specimen of interest.

## 2 Introduction

Recently, topological insulators have become an exciting new topic of research in quantum physics. These materials have curious properties, which have been predicted to reveal certain quantum events or particles. Topological insulators differ from regular insulators because while the bulk of the material is insulating and the conduction and valence bands are separate, the surface can conduct charge due to the absence of a band gap [1]. When an external magnetic field is introduced under specific conditions, the surface may exhibit certain changes, which could reveal magnetic monopoles [2]. Using an optical technique called ellipsometry, the surface changes can be observed and analyzed without contact or degradation of the surfaces. By analyzing the change in the polarization of light due to the Magneto Optic Kerr Effect (MOKE), this process can provide information about a sample smaller than the wavelength of the probing light. Due to the sensitive nature

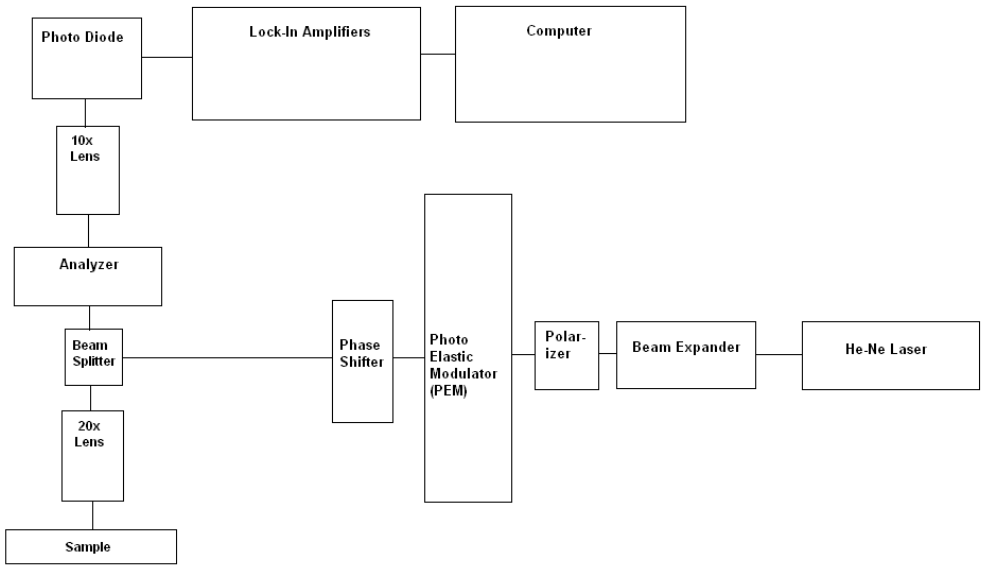



Figure 1: Ellipsometric setup used to detect MOKE.

of the topological insulators, ellipsometry provides an ideal approach to examining the properties of these unique insulators. The purpose of this study was to prepare and calibrate the experimental setup, so the process could be replicated in vacuo with far-field optics.

# 3 Experimental Setup and Theory

Ellipsometry is a useful optical technique used to observe dielectric properties of thin films or bulk materials without destruction of or contact with the sample. This light modulation method measures the changes in polarization of the electromagnetic wave, both magnitude and phase, after the wave has reflected off the sample at normal incidence. The reflectivity difference between the p-polarized (parallel to the plane of incidence) and s-polarized (perpendicular to the plane of incidence) components of the wave is detected. This specific experimental setup is shown in Figure 1.

Light from a plane polarized monochromatic source (He-Ne Laser) passes first through a polarizer and then a Photo Elastic Modulator (PEM), which introduces a variable phase shift between the p- and s- polarized components at a specific frequency. The wave passes through a wave plate to introduce a constant phase shift between the components, and the first harmonic of the wave can be adjusted. After passing through the second polarizer, the wave travels through a beam splitter and an objective, and then reflects off the sample. The sample is mounted to two PI stages that allow the system to scan larger areas of the sample. The wave then travels back through the objective and beam splitter to an analyzer. This analyzing polarizer allows the second harmonic of the wave to be adjusted. Finally, the wave travels through a converging objective to a photodiode where the wave is converted to an electronic signal that is received by two Stanford Research Systems Lock-In Amplifiers (Model SR830 and Model SR850) and then analyzed by a computer.

After the microscope was configured to accurately scan samples, a solenoid with an iron core was introduced to the optical setup. Using a Hewlett Packard DC Power Supply LVR Series Model 6268B to supply the variable current, the solenoid produced variable magnetic fields near the sample. Alternatively, a giant Neodymium magnet was also used to produce a large magnetic field.

The Kerr effect takes place when a linearly polarized beam of light is incident upon a magnetic sample in an external magnetic field. After reflection, the light is elliptically polarized and rotated with respect to the incident angle of polarization [3]. In our specific setup, the Kerr effect is measured with a polar geometry, where the magnetic field is perpendicular to the sample under observation. To observe MOKE for a thin magnetic film, consider the following dielectric tensor describing the response of the magnetized sample to an external field.

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \epsilon_\omega & i\alpha M & 0 \\ -i\alpha M & \epsilon_\omega & 0 \\ 0 & 0 & \epsilon_\omega \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} \tag{1}$$

Because linearly polarized light is the superposition of left and right circularly polarized light, the eigen-electromagnetic waves are given by $\vec{E}_L = \frac{E}{2}(\hat{x} + i\hat{y})$ with effective dielectric constant $\epsilon_L = \epsilon_\omega - \alpha M$ and $\vec{E}_R = \frac{E}{2}(\hat{x} - i\hat{y})$ with effective dielectric constant $\epsilon_R = \epsilon_\omega + \alpha M$, where $E^{(i)} = E_L^{(i)} + E_R^{(i)} = E^{(i)}\hat{y}$. Because the reflection of the incident wave components have well-defined indices of refraction, $n_L = \sqrt{\epsilon}_L$ and $n_R = \sqrt{\epsilon}_R$. Also if $d \ll \lambda$, then the reflection coefficients derived from the boundary conditions and properties of the materials are

$$r_L = r_o + \frac{4\pi d r_o i}{\lambda_o}\frac{\epsilon_2 - \epsilon_L}{\epsilon_2 - \epsilon_o} \tag{2}$$

$$r_R = r_o + \frac{4\pi d r_o i}{\lambda_o}\frac{\epsilon_2 - \epsilon_R}{\epsilon_2 - \epsilon_o} \tag{3}$$

where r$_o$ is the reflection coefficient of the substrate, d is the thickness of the film, and $\epsilon_2$ and $\epsilon_o$ are properties of the dielectrics. Thus,

$$\begin{aligned}
\vec{E}_L^{(r)} &= r_L \vec{E}_L^{(i)} \\
&= \vec{E}_L^{(i)} r_o \left(1 + \frac{4\pi d i}{\lambda_o}\frac{\epsilon_2 - \epsilon_\omega}{\epsilon_2 - \epsilon_o}\right) + \vec{E}_L^{(i)} r_o \frac{4\pi d i}{\lambda_o}\frac{\alpha M}{\epsilon_2 - \epsilon_o} \\
\vec{E}_R^{(r)} &= r_R \vec{E}_R^{(i)} \\
&= \vec{E}_R^{(i)} r_o \left(1 + \frac{4\pi d i}{\lambda_o}\frac{\epsilon_2 - \epsilon_\omega}{\epsilon_2 - \epsilon_o}\right) - \vec{E}_R^{(i)} r_o \frac{4\pi d i}{\lambda_o}\frac{\alpha M}{\epsilon_2 - \epsilon_o}
\end{aligned}$$

resulting in,

$$\vec{E}_{total}^{(r)} = \vec{E}_L^{(r)} + \vec{E}_R^{(r)} \tag{4}$$

$$= \vec{E}^{(i)} r_o \left(1 + \frac{4\pi d i}{\lambda_o}\frac{\epsilon_2 - \epsilon_\omega}{\epsilon_2 - \epsilon_o}\right) + \vec{E}^{(i)} r_o \frac{4\pi d}{\lambda_o}\frac{\alpha M}{\epsilon_2 - \epsilon_o}\hat{x} \tag{5}$$

Because the reflected electric field component orthogonal to the incident electric field is proportional to the magnetization, the resulting detected light intensity is

$$I^{(r)} = |r_o E^{(i)}|^2 sin^2\theta + 2|r_o E^{(i)}|^2 sin\theta \frac{4\pi d \alpha M}{\lambda_o(\epsilon_2 - \epsilon_o)} \tag{6}$$

where the first term, $|r_o E^{(i)}|^2 sin^2\theta$, corresponds to the small y-component that is also detected due to flaws in the components of the system.

To observe MOKE using the optical setup described above, the light encounters a series of transformations that can be described by Jones vectors. After the light travels through the system and reflects off the sample, the intensities of the first and second harmonics should be

$$I(\omega) = I_{inc}|r_o|^2\Delta_{M2}J_1(\pi)sin\omega t \quad (7)$$

$$I(2\omega) = -I_{inc}|r_o|^2\Delta_{M1}J_2(\pi)sin2\omega t \quad (8)$$

with

$$\Delta_M = \frac{4\pi d}{\lambda_o}\frac{\alpha M}{\epsilon_2 - \epsilon_o} = \Delta_{M1} + i\Delta_{M2} \quad (9)$$

By being able to detect the signals of the first and second harmonics from MOKE, surface properties of the sample can be discovered. Using software written by Dr. Zhu's group, images of sample surfaces were obtained, and changes in the surfaces show how the samples respond to external conditions, like an introduced magnetic field.

# 4 Experimental Methods

## 4.1 System Paratmeters - Beam Width and Depth of Focus

To calibrate and learn the parameters of our system, scans were run on different samples with Mitutoyo M Plan Apo SL 20x (NA=0.28) and Mitutoyo M Plan Apo 10x (NA=0.28) objectives. The samples consisted of bovine serum albumin (BSA) deposited on a reflective surface, a metal sheet with 5 $\mu$m holes, a reflective surface with a surface defect, and a thin metal sheet. Each sample provided a distinct feature upon which the beam could be focused. By measuring the change in intensity of the light reflected from the surface, the system produced outputs that indicated the resolution and depth of focus of our setup. Due to the scattering effects, the change in intensity was quite apparent and was an appropriate way to obtain information about the surface of the sample.

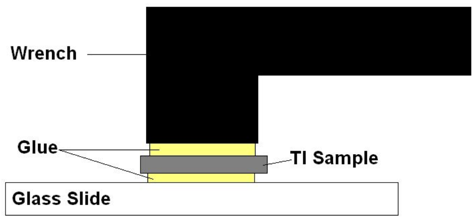


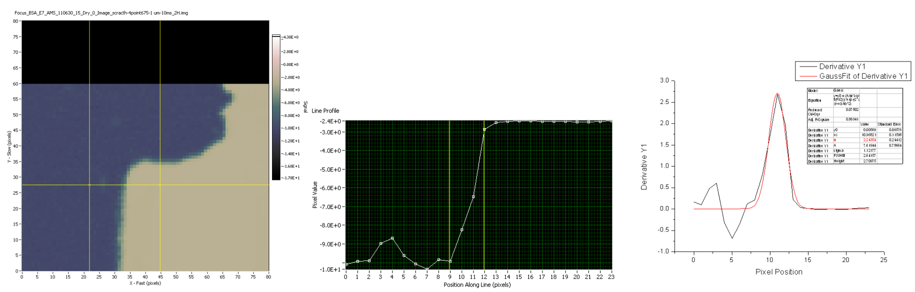

Figure 2: The configuration of the components used to cleave the crystal and reveal a clean surface of the topological insulator.

## 4.2 Topological Insulator Sample Preparation

To prepare the topological insulator (TI) for observation and measurement, the $Bi_2Se_3$ crystal has to be cleaved, so a fresh surface layer free of impurities can be exposed. A TI sample with a surface area of  1-2 $mm^2$ was fixed to a glass substrate using a small quantity of epoxy: Varian Torr Seal. After allowing the epoxy to set for two hours, another small quantity of the adhesive was placed on the end of an Allen wrench with  1 mm diameter. The wrench was carefully placed on the top surface of the TI sample and held in place with a small clamp. Once the epoxy set after two hours, the wrench was given a sharp tap or pealed to cleave the crystal and reveal a fresh surface. Great care was taken to ensure that no glue between the glass substrate and the sample and between the sample and the wrench touched the sides of the TI sample. The final setup is shown in Figure 2. The glass substrate with the sample was then secured to a mount and placed in the optical setup. It then could be scanned to find the focus position on a flat surface or terrace, where the beam could be placed to observe MOKE.

## 4.3 Magneto Optic Kerr Effect

To observe MOKE, an external magnetic field had to be introduced. A giant neodymium permanent magnet was used to produce a constant magnetic field perpendicular to the sample surface. The magnet was placed at the same height as the sample and 1 mm away from the surface being observed to ensure the largest magnetic field incident upon the area being probed.




(a) (b) (c)

Figure 3: a) An image from the optical setup of a feature from the reflective surface with a defect b) The line profile of the feature (a) showing a 3 $\mu$m step giving the resolution or beam diameter of the probing beam c) Graph of a Gaussian curve (red) fit to the the data (black) from (b). The table with the number in red indicates the beam width calculated from the Gaussian fit.

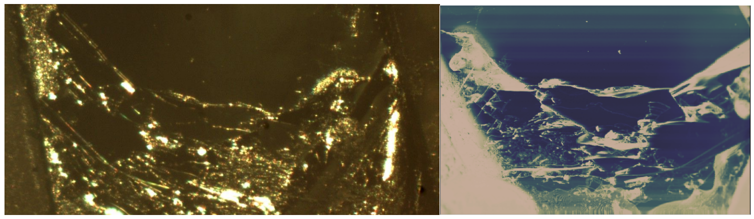
# 5 Results and Discussion

## 5.1 System Parameters - Beam Width and Depth of Focus

An excerpt of the images, line profiles, and Gaussian curves obtained for the determination of the resolution of our system is assembled in Figure 3. Using 20x and 10x objectives, the probing beam diameter and the depth of focus was 2-3 $\mu$m and 20 $\mu$m and 5 $\mu$m and 70 $\mu$m, respectively. The data from the line profiles was matched with the Gaussian curves fit to each data set. A range of other graphs at different micrometer positions of the objective, which are not provided, determined the focus range, or depth of focus of the probing beam.

## 5.2 Topological Insulator Sample Preparation

The cleaving of the crystal by methods outlined above exposed a fresh, even surface that was devoid of impurities. Using our optical system, an image of a large terrace and other surface characteristics on the topological insulator was obtained and is shown in Figure 4.

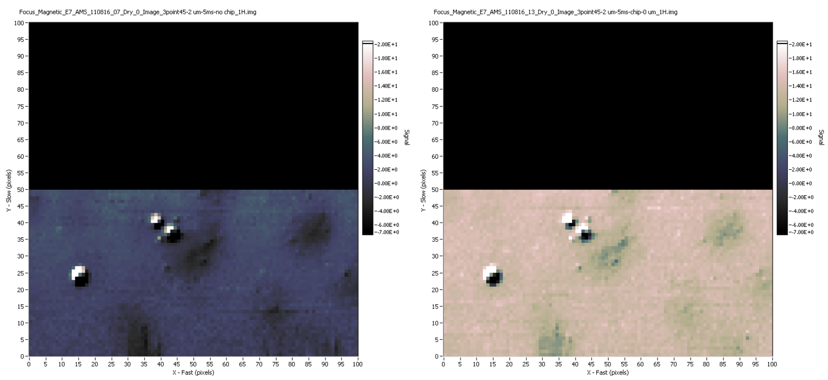


(a) (b)

Figure 4: a) An image obtained by a microscope of the entire topological insulator sample after it had been cleaved to expose a clean terrace b) An image obtained by our optical setup of the same topological insulator sample (Note: The image is a mirror image of (a).)

## 5.3 Magneto Optic Kerr Effect

To observe MOKE, a variety of samples were used to test their responses to the external magnetic field. At first, an electromagnet was used to produce the introduced field, but all three samples (a glass slide, a topological insulator, and a magnetic film grown on a silicon substrate) returned the same magnetic response. Because the dielectrics are temperature sensitive, the heat from the solenoid could have altered the responses of the materials in the same way. Alternatively, a giant neodymium permanent magnet was used to produce a constant magnetic field on the order of 5,000 G. The effect of changing the direction of the magnetic field was observed on the magnetic film grown on a silicon substrate (Si/SiO2/Pd(20nm)/[Co(0.3nm)/Pd(0.9nm)]$_{52}$/ Pd(0.9nm)). The response of the domains from saturation in one direction of the magnetic field to saturation in the opposite direction of magnetic field are shown in Figure 5. For the magnetic film, the change in phase was on average 10 mV. This translates to a quarter degree phase shift, which is expected for this material. From this data, the magneto optical response of the magnetic film was observed, and as a result, it is determined that our optical setup is an effective technique to detect MOKE. However, large drift in the signals occurs, so this would need to be reduced or eliminated for future experiments to obtain more accurate results.




(a) (b)

Figure 5: a) An image of a scan of a thin magnetic film at saturation after exposure to an applied magnetic field. b) An image of a scan of a thin magnetic film at saturation after exposure to an applied magnetic field in the opposite direction of (a).

# 6 Outlook and Future Work

The results obtained and conclusions drawn above have been made in effort to prepare for the next experiment. Dr. Zhu's group will be placing and revealing a fresh surface of the topological insulator sample in a vacuum and proceed to take optical measurements from a distance, which could lead to the discovery of magnetic monopoles under specific conditions.

# 7 Acknowledgments

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# 8 References

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