Abstract—This paper presents a back focal plane microellipsometer combined with a polarized shifting interferometer. This system is used for the determination of optical phase shift on reflection of a slider's air bearing surface. These optical properties are essential parameters for the flying height measurements in a HDD manufacturing process. The resulting phase shifting images were processed by using Windowed Fourier filters and phase unwrapping techniques, in order to precisely determine the phase of a back focal plane image. The phase images were then used to determine the optical phase shift on reflection values. The results from an aluminum sample show that the measured optical phase shift on reflection values are comparable to the standard values.

I. INTRODUCTION

With the increasing recording density of the hard disk drives (HDD), the decrease in magnetic recording bit size and the increase in recording track density requires that the slider and read/write heads fly at almost contact condition with the media surface. The flying height between the heads and media is currently in the order of sub-10 nm. Although, in current HDD technology, there is the feedback control system to ensure the optimal flying height of slider, the requirement of the absolute measurement of flying height distance is still essential for the validation of the air bearing surface (ABS) design. Up till now, various optical interferometric techniques have been developed to accurately measure slider flying height. These include a white light interferometry using color distribution [1], a homodyne interferometry using interference light intensity [2], and a polarization interferometry using rotation of light vibration plane [3]. Measurement systems utilized these methodologies are in commercial use.

According to the current technology of flying height measurement, the attainable precision is about 0.4 nm [4]. The demand for a FH tester with better precision is becoming critical in order to support the slider air bearing design. One of the major challenges for the optical flying height measurement techniques is the difficulty to simultaneously distinguish phase shifts those are due to slider-to-media spacing and the local variations in the refractive index. The routine procedure is to subtract the measured phase shifts with the calibrated value. Such calibrated value is obtained from the measurement of phase shift on reflection by using an offline ellipsometer. Resulted values from an ellipsometer are in the complex form (n&k values). However, this compensation method creates another problem associated with the measured position on the slider where the optical constants were measured. Such position may not match with the measured spot of the flying height measurement. Since local n&k values cannot be determined at the exact flying height measurement spot, an average n&k value is usually applied for phase shift on reflection calculation. This problem leads to inaccuracies in the calibrated values due to differences in reflectivities [4] caused by local n, k variation at test spot. Leong et al. proposed the technique based on an empirical linear relationship between calculated reflectivity and ellipsometric-measured n and k properties. They demonstrated that the improvement in precision of flying height values could be obtained. In this paper, we propose the different approach based on a back focal plane microellipsometer combined with a polarization shifting interferometer. This system is used for the determination of phase shift on reflection of a slider’s air bearing surface at relatively small spot size comparable with the flying height measurement spot size. Therefore, the local phase shift on reflection measurements with the position closed to the flying height measurement spot can be possible.

II. PRINCIPLE OF BACK FOCAL PLANE MICROEILLLIPSMETRY

In conventional ellipsometers, the optical constant (n&k) can be measured by using the ratio of the Fresnel reflection coefficients for a beam reflected at a single oblique angle. However, such ellipsometers has major challenge in their lateral resolution which is approximately 20 μm. By using back focal plane microellipsometry, diffraction-limited resolution may be achieved. The principle of microellipsometry is the measurement of the amplitude and phase distributions of the reflected light in the back focal plane of an objective lens. For the analysis of a back focal plane interferometry, we start by considering a collimated beam that is linearly polarized as shown in Figure 1. The
electric vector \( E_1 \) of the illuminating light at the input to the quarter waveplate \( Q_i \) is given by:

\[
E_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
\]

(1)

\[
T^+ = (r_p r_{p_i} + r_s r_{s_i}) \cos \theta \\
T^- = (r_p r_{p_i} - r_s r_{s_i}) \cos \theta
\]

where \( r_p \) and \( r_s \) are the Fresnel transmission coefficients. In the case of a single objective lens or so-called reflection mode, \( T^+ \) and \( T^- \) can be written as:

\[
T^+ = r_p + r_s e^{i\pi/4} \\
T^- = r_p - r_s e^{i\pi/4}
\]

(3)

(4)

where \( r_p \) and \( r_s \) are the reflection coefficients for s-polarized and p-polarized light respectively.

The purpose of using a half waveplate \( H_j \) positioned at the azimuthal angle of \( 3\pi/8 \) (Fig. 1) is to optically manipulate of \( T^+ \) and \( T^- \) in equation 2 and 3. Therefore, the electric vector of the light \( E_j \) after passing the half waveplate \( H_j \) can be written as:

\[
E_j = \frac{1}{\sqrt{2}} \begin{bmatrix} -T^+ + T^- \\ T^+ - T^- \end{bmatrix}
\]

(5)

At the azimuthal angle of \( \phi = \pi/4 \), the electric vector \( E_1 \) can be determined by:

\[
E_3 = \sqrt{2} \begin{bmatrix} r_p \\ r_s \end{bmatrix}
\]

(7)

Using equation (7), ellipsometric parameters \( \Psi, \Delta \) are defined by the Fresnel reflection coefficients \( r_p, r_s \) can be calculated by

\[
\tan \Psi = \frac{r_p}{r_s}
\]

\[
\exp i\Delta = \exp i(r_p - r_s)
\]

(8)

(9)

### III. EXPERIMENTAL SETUP

Figure 2 shows the diagram of the experimental setup for the microellipsometer combined with the polarization shifting interferometer. A He-Ne laser beam with random polarization is transmitted through the polarizer \( P_1 \) and beam expander \( BX_1 \). The polarized beam is then passed to a quarter waveplate \( Q_i \) and steered on to the objective lens (Nikon, M Plan Apo, NA = 0.95). The beam is focused onto the sample. The reflected beam is collected again by the objective and passed to a quarter waveplate \( Q_3 \) and a half waveplate \( H_j \) consecutively. At this point after the half waveplate \( H_j \), the electric vector \( E_3 \) contains substantial information about the Fresnel reflection coefficients of a sample as described in equation (7).

The ellipsometric parameter \( \Delta \) is defined as the difference of the phases of the \( p \) and \( s \) complex reflection coefficients as shown in equation (9). In this research, such a parameter is optically determined by using a technique so-called polarization shifting interferometer [6]. The basic principle is based on the optical phase shift by modifying the polarization state of composite components of the original light wave. The phase shifting is achieved by adjusting the polarization state of the output beams with a rotating quarter wave plate \( Q_3 \). The rotation can be more precisely controlled and free from nonlinear behavior and hysteresis comparing with the phase shifting technique reported in [7]. The ellipsometric parameter \( \Delta \) can be determined by the intensity profile at azimuthal angle \( \phi = \pi/4 \) of the resulting image of [6].

\[
\Delta(\phi = \pi/4) = \arctan \frac{|I_2 - I_4|}{2(I_1 - I_3)}
\]

(10)
Where \( I_1, I_2, I_3, I_4 \) are the focal plane images captured by the CCD camera (CCD2) at the quarter waveplate azimuthal angle of \( \pi/8, \pi/4, 3\pi/8 \) and \( 3\pi/4 \) respectively.

![Fig. 2 Diagram of the back focal plane microellipsometry.](image)

The ellipsometric parameters \( \Delta \) is then used to calculate the optical phase shift on reflection \( \phi_0 \) by using the relationship [7]:

\[
\Delta \equiv \phi_0 (\theta_i^2 + \theta_j^2) / 6 \tag{11}
\]

where \( \theta_i \) is the incident angle.

**IV. RESULTS AND DISCUSSION**

In this paper, the aluminum thin film deposited onto the glass substrate was used as a sample. The azimuthal angle of quarter waveplate was set at the position of \( \pi/8, \pi/4, 3\pi/8 \) and \( 3\pi/4 \). The captured back focal plane images by CCD camera (CCD2) are shown in Figure 3. All of the four images are then processed by using equation (10). The intensity profile at the azimuthal angle \( \phi = \pi/4 \) of the resulted image is then plotted against the incident angle \( \theta_i \) of objective lens as shown in Figure 4.

The numerical fitting of the experimental data (shown as dotted curve) to the equation (11) is performed using the curve fitting toolbox in MATLAB. The resulted optical phase shift on reflection \( \phi_0 \) from the fitting procedure is shown in Table 1 comparing with the theoretical values [7]. The good agreement between theoretical and experimental values is achieved.

![Fig. 3 The focal plane images captured by the CCD camera (CCD2) at the quarter waveplate azimuthal angle of \( \pi/8, \pi/4, 3\pi/8 \) and \( 3\pi/4 \).](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Theoretical</th>
<th>Fitting Curve (Degree)</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>14.1</td>
<td>13.5</td>
</tr>
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</table>

**V. CONCLUSIONS**

In this paper, we have demonstrated the back focal plane microellipsometer combined with a polarized shifting interferometer to measure optical phase shift on reflection. An aluminum thin film deposited on a glass substrate sample was used as the sample. The good agreement between the resulted phase shift on reflection values and that of the theoretical values was demonstrated.
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