Validation of correction method for gap shape measurement
by vertical-objective-type ellipsometric microscopy
with rotating-compensator ellipsometry

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Abstract
Correction method for improving the accuracy of gap shape measurement using vertical-objective-type ellipsometric microscopy (VEM) was investigated. This method can provide observation with 0.1-µm-order lateral resolution. Since VEM-based measurement uses an optical microscope with high lateral resolution, the measured ellipsometric signal includes polarization change and incident angle unevenness when applying rotating compensator ellipsometry (RCE) to gap shape measurement. The effect of the variations of the ellipsometric signals on the gap measurement accuracy had been theoretically investigated and these could cause errors of more than 10 nm in gap measurements with RCE. Corrections of these errors were necessary for gap shape measurements with nm-accuracy. The proposed method enabled to correct the polarization change and the incident angle distribution due to using optical devices. Evaluation using gaps filled with air or lubricant (poly-α-olefin) demonstrated gap measurement accuracy of about 1 nm. The VEM gap shape measurement using the correction method showed the highest sensitivity for gaps around the contact region, and enabled observation of the differences in the contact state, which depended on small variations in surface roughness of less than 1 nm. This method also achieved to observe confined lubricant film of less than 1 nm in the contact area, which is possible to reduce the contact points between surfaces.

Keywords: Nanometer gap, Film thickness measurement, Ellipsometry, Tribology, Contact mechanics

1. Introduction

Recent refinement of mechanical elements due to advances in precise processing technology has led to narrower sliding gaps between these elements. For more advanced precision machines, forming lubrication films in the gap is necessary to reduce friction and wear due to sliding (Dowson, 1992; Spikes, 2001). The sliding gaps have been reduced to nanometer-order thickness because the viscosity of lubricants has become lower with growing social demands for energy saving. The lubrication phenomena in nm-size gaps has been found to greatly depend on the gap size, and lubricant confined in nanometer gaps shows different properties than when it is in the bulk state (Granick, 1991; Luengo et al., 1997; Israelachivili, 1973; Luo et al., 1996; Matsuoka and Kato, 1997). Furthermore, in micro machines such as the head-disk interface of computer hard disk drives, the area of lubrication between solid surfaces is on the order of µm². Therefore, measuring the thickness distribution of lubrication film or the gap shape on the micro-scale is needed to clarify the lubrication phenomena.

Optical-interferometry-based methods have been widely used to measure gap shapes and have produced valuable results in tribology. Particularly, spacer-layer imaging or ultra-thin film interferometry method using a multi-layer solid substrate was proposed to measure a gap with a size of 1–10 nm (Johnston et al., 1991; Glovnea et al., 2003). The other
method named relative optical interference intensity uses a semi-reflective metal-coated surface to improve the interferometric intensity (Luo et al., 1996; Guo and Wong, 2002; Liran and Chenhui, 2009). However, these gap measurements based on optical interferometry need carefully controlled special layers for test surfaces, which cause to differ from practical ones.

Ellipsometry can measure gaps without any special layers on test surfaces. Ellipsometer is used to measure the thickness of thin film at a resolution of 0.1 nm based on ellipsometry (Azzam and Bashara, 1987; Fujiwara, 2007). Unlike ellipsometers, ellipsometric microscopy (EM) uses an imaging device such as a CCD camera as a light detector to obtain a two-dimensional thickness distribution (Beaglehole, 1988; Jin et al., 1996). Since EM can obtain a thickness distribution in one measurement as an image, it can be applied to dynamic measurement such as lubrication measurement. EM measurement initially used an oblique optical configuration to obliquely illuminate the sample plane, which is essential for ellipsometry. However, this type of EM has low lateral resolution because the oblique observation narrows the focused area, so a high-resolution objective lens cannot be used.

Vertical-objective-type EM (VEM) has improved lateral resolution due to using vertical observation with off-axis Köhler illumination (Neumaier et al., 2000; Linke and Merkel, 2005; Fukuzawa et al., 2008; Fukuzawa et al., 2013). The vertical configuration of the objective lens enables the focused area to include the whole field of view. It can achieve high lateral resolution (0.1-μm order) and a large field of view (100 μm in diameter) (Fukuzawa et al., 2017). Furthermore, VEM has been successfully applied to measuring sliding gap shapes (Fukuzawa et al., 2018).

In VEM-based gap measurement, it is necessary to convert the measured ellipsometric signals into the gaps. To obtain the ellipsometric angles $\Psi$ and $\Delta$ showing the sample polarization state, the rotating compensator ellipsometry (RCE) method is widely used in ellipsometers. The film thickness or sample gap can be derived from the measured ellipsometric angles. The RCE method provides a resolution of the order of 0.1 nm for thickness measurement of thin films and has been used for VEM gap shape measurement to attain high gap resolution (Fukuzawa et al., 2018).

Unlike conventional ellipsometers, a VEM microscope includes optical devices such as lenses and mirrors. These devices may cause additional polarization changes and incident angle unevenness in the field of view. Correction of these errors is needed in order to apply the RCE method to VEM gap shape measurement with nm-order accuracy. The concept of the correction method for the additional polarization change and incident angle unevenness has been proposed, and its feasibility was demonstrated (Namba et al., 2018). However, the details of its performance were not investigated. In this paper, we have validated the performance of VEM gap shape measurement using this correction method and demonstrated examples of application of the VEM measurement; study of contact mechanics.

2. VEM gap measurement using RCE method

Figure 1 shows the schematic setup for VEM gap shape measurement. Oblique illumination is necessary for ellipsometric measurement, and the optimum incident angle of the illumination light to the sample plane for obtaining maximum ellipsometric signals is about 60–70°. In VEM, the illumination light is focused on an off-axis point on the back focal plane of the objective lens, and thereby generating a parallel light incident to the sample obliquely, as shown in the inset of Fig. 1. The incident angle of the illumination light can be changed by adjusting the distance between the objective lens axis and the focused point on the back focal plane.
The VEM optical system is similar to that of the PCSA-type ellipsometer (Fujiwara, 2007); the main components are a light source, polarizer (P), compensator (C), sample (S), analyzer (A), and detector. An electron multiplying (EM) CCD camera was used as the detector. The sample gap was contained between a reflective solid surface and a transparent one. As the reflective solid, a plano-convex glass lens was used. This convex surface was coated with a metal (stainless steel) layer to simulate a practical surface. As the transparent solid, a glass substrate was used. The light illuminating the sample passed through the glass substrate and the gap and was reflected at the metal surface on the lens, as shown in Fig. 1. Finally, the reflected light was detected by the EM-CCD camera. The polarization state of the reflected light from the gap sample is expressed as the amplitude reflectivity ratio of the p- and s-polarization lights, \( r_p \) and \( r_s \), respectively. The complex reflectivity ratio of the p- and s-polarization lights, \( \rho \), is given by (Azzam and Bashara, 1987)

\[
\rho = \frac{r_p}{r_s} = \tan \Psi(h, \theta) e^{i \Delta(h, \theta)},
\]

where \( \tan \Psi \) and \( \Delta \) are the absolute value and phase shift of \( \rho \), respectively. The ellipsometric angles \( \Psi \) and \( \Delta \) are functions of gap \( h \) and incident angle \( \theta \) and can be obtained by analyzing of the intensity of the captured image. The \( \theta \) is determined by the arrangement of the VEM optical devices. Therefore, by converting \( \Psi \) and \( \Delta \) into gap \( h \) at each pixel of the image, we can obtain the gap shape.

The \( \Psi \) and \( \Delta \) are obtained by using the RCE-based method. The details were described by Fukuzawa et al. (2018). In this method, the angles of the polarizer and analyzer are respectively set to 0 and 45° with respect to the p-polarization direction, and \( \Psi \) and \( \Delta \) are analyzed from the detected light intensity during continuous rotation of the compensator in the VEM.

The conversion curve from \( \Psi \) and \( \Delta \) to gap is theoretically obtained from an optical model expressing a sample with gap (Fukuzawa et al., 2018). In our experiment, the sample can be expressed as a three-layer model (glass substrate/gap/metal surface of lens) shown in the inset of Fig. 1. The ellipsometric angles at gap \( h \), \( \Psi(h) \) and \( \Delta(h) \), are given by Fresnel equations (Azzam and Bashara, 1987):

\[
\tan \Psi(h) \exp(i\Delta(h)) = \frac{r_{01p} + r_{21p} \exp(-2ih)}{1 + r_{01p}^* r_{21p} \exp(-2ih)} \times \frac{1 + r_{01s} r_{21s} \exp(-2ih)}{r_{01s}^* + r_{21s} \exp(-2ih)},
\]

\[
h = 2\pi N_i h \cos \theta_i / \lambda, \quad r_{ijp} = \frac{N_j \cos \theta_j - N_i \cos \theta_i}{N_j \cos \theta_j + N_i \cos \theta_i}, \quad r_{ifs} = \frac{N_i \cos \theta_i - N_j \cos \theta_j}{N_i \cos \theta_i + N_j \cos \theta_j}.
\]

Subscripts \( p \) and \( s \) indicate p- and s-polarized light, respectively; \( \lambda \) is the wavelength of the illumination light; \( N_0, N_i, \) and \( N_s \) are the complex refractive indices of the glass substrate, gap, and metal layer, respectively; and \( \theta_0, \theta_i, \) and \( \theta_s \) are the incident angles in the glass substrate, gap, and metal layer, respectively, which can be calculated using Snell’s law (Fujiwara, 2007). Substituting the wavelength, complex refractive indices, and incident angles into Eqs. (2) and (3), the theoretical relationships between gap \( h \) and ellipsometric angles \( \Psi \) and \( \Delta \) are given. Since \( \Delta \) had higher sensitivity than \( \Psi \) for small gaps in our experiment, only the relationship between \( \Delta \) and \( h \) was used as a conversion curve to calculate the gap. For example, Fig. 2(a) shows a theoretically obtained relationship between \( \Delta \) and \( h \). Using this relationship, a measured \( \Delta \) with the RCE method can be converted into \( h \), as shown in Fig. 2(a). Furthermore, converting \( \Delta \) at each pixel of VEM image, the gap shape can be obtained.

However, the optical devices in VEM caused an additional polarization change of \( \Delta \), which generated an error in the gap. For example, Fig. 2(b) shows the relationship between \( \Delta \) and \( h \) when \( \Delta \) includes \( \Delta \) of 2°. The difference between the theoretical relationship and measured one including \( \Delta \) caused a gap conversion error, as shown in Fig. 2(b). In addition, the optical devices also caused the uneven incident angle distribution in the field of view, because the illumination light became slightly non-parallel in the actual setup. Figure 2(c) shows the relationships between \( \Delta \) and \( h \) for different incident angles \( \theta \) and \( \theta' \). Thus, the uneven incident angle also caused the gap conversion error. Therefore, to improve the accuracy of VEM gap shape measurement using the RCE method, a method is needed to correct the additional polarization change of \( \Delta \) and incident angle \( \theta \) at each pixel.
consisting of a glass substrate, a gap, and a metal-coated lens. The gap was filled with air or lubricant. Poly-α-olefin (PAO) was used as the lubricant; its viscosity is about 0.07 Pa s, and its complex refractive index is $1.47 - 0i$. A high-refractive index glass (K-LASFN23) was used as the substrate; its complex refractive index is 1.93–0i according to the manufacturer (Sumita Optical Glass, Japan). Its thickness was 0.8 mm. The lens composed of BK7 glass (SLB-05-30P, Sigmakoki, Japan) and had a radius of 15.6 mm. It was coated with 53-nm stainless steel film by sputtering to increase reflectivity. The complex refractive index of the stainless steel was $1.43 - 2.59i$ as measured with a commercial spectroscopic ellipsometer (FE-5000S, Otsuka Electronics, Japan). Since surface roughness ($R_g$) may affect the measured gap shape, the roughness of the glass substrate and that of the metal-coated lens were measured with an atomic force microscope (Dimension Icon, Bruker, USA). The $R_g$ of the glass substrate was 0.3 nm. Two metal-coated lenses with different surface roughnesses were prepared, a smoother one ($R_g$ 0.8 nm; $R_{\text{max}}$ 9.4 nm) and a rougher one ($R_g$ 1.0 nm; $R_{\text{max}}$ 11.8 nm).

A modified inverted optical microscope (IX-71, Olympus, Japan) was used for the VEM. An objective lens with a numerical aperture of 0.8 (M iPLAN APO LCD NIR HD50, Shibuya Optical, Japan) was modified for gap observation through the 0.8-mm-thick glass substrate. The angle of the light radiated from the objective lens was set to $50.8^\circ$, which was theoretically estimated from the off-axis distance of the light source using the geometric optics illustrated in Fig. 1. That corresponded to an incident angle of $23.7^\circ$ in the glass substrate by Snell’s law. The incident angle was determined so as to maintain the lateral resolution of the objective lens. An LED with a wavelength of 460 nm (X-Cite, Lumener Dynamics, USA) was used as the light source, and a high sensitive EM-CCD camera (Cascade II, Photometrics, USA) was used as the detector. The exposure time of the camera for one image frame was set to 0.1 s. For ellipsometric measurement, a polarizer, compensator (quarter-wave plate), and analyzer were added to the microscope. The polarizer and analyzer were respectively set at 0 and $45^\circ$ with respect to the p-polarization direction. The compensator was attached to a stepping motor, and the rotation period was set to 1.6 s. In our experiment using the RCE method, because the ellipsometric angle $\Delta$ can be obtained during one rotation of the compensator, we could acquire one gap image for each 1.6 s, which corresponds to frame rate of 0.625 frames/s.

To control the distance and the load between the glass substrate and metal-coated lens, a z-piezo stage with displacement feedback from a capacitive sensor was used (P-753, Physik Instrumente, Germany). Its displacement resolution is 0.05 nm. The metal-coated lens was attached to the stage through a double cantilever, whose spring constant was obtained in advance by measuring the relationship between applied displacement and load using a micro-stage and an electronic balance. In the gap measurements, the applied load to the lens was obtained by multiplying the spring constant by the displacement of the double cantilever measured with a spectral interference sensor (SI-F1000V, Keyence, Japan) shown in Fig. 1. The VEM gap measurements were conducted at room temperature, and the temperature near the contact area was not controlled.

![Graphs](image)

**Fig. 2** Examples of relationships between $\Delta$ and gap. (a) Theoretical relationship used to convert $\Delta$ into gap. (b) Theoretical relationship and measured one that includes the polarization change of $\Delta$ due to optical devices. (c) Theoretical relationship at the incident angle of $\theta$ and measured one at $\theta'$; $\theta'$ is different from $\theta$ due to unevenness of incident angle in the field of view.

### 3. Materials and methods

For our evaluation of correction method for the VEM gap shape measurement with RCE method, we used a sample consisting of a glass substrate, a gap, and a metal-coated lens. The gap was filled with air or lubricant. Poly-α-olefin (PAO) was used as the lubricant; its viscosity is about 0.07 Pa s, and its complex refractive index is $1.47 - 0i$. A high-refractive index glass (K-LASFN23) was used as the substrate; its complex refractive index is 1.93–0i according to the manufacturer (Sumita Optical Glass, Japan). Its thickness was 0.8 mm. The lens composed of BK7 glass (SLB-05-30P, Sigmakoki, Japan) and had a radius of 15.6 mm. It was coated with 53-nm stainless steel film by sputtering to increase reflectivity. The complex refractive index of the stainless steel was $1.43 - 2.59i$ as measured with a commercial spectroscopic ellipsometer (FE-5000S, Otsuka Electronics, Japan). Since surface roughness ($R_g$) may affect the measured gap shape, the roughness of the glass substrate and that of the metal-coated lens were measured with an atomic force microscope (Dimension Icon, Bruker, USA). The $R_g$ of the glass substrate was 0.3 nm. Two metal-coated lenses with different surface roughnesses were prepared, a smoother one ($R_g$ 0.8 nm; $R_{\text{max}}$ 9.4 nm) and a rougher one ($R_g$ 1.0 nm; $R_{\text{max}}$ 11.8 nm).

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4. Method for correcting VEM gap measurement

4.1 Correction of measured $\Delta$

Measured $\Delta$ using the RCE method includes an additional polarization change due to the VEM optical devices. This polarization change causes an error of $\Delta_m$ in the measured $\Delta$. $\Delta_m$, which are independent on the sample and the gap size. In our experiment, the gap between a glass substrate and a metal-coated lens was measured. For example, Fig. 3(a) shows cross-sectional profiles of $\Delta_m$ along the center line of the lens. In this experiment, the lens was loaded to the glass substrate, so the central part of the lens was flattened due to Hertzian contact. The gap filled with air and the one after injecting lubricant while the contact was maintained were measured. Although the central parts of $\Delta_m$ in Fig. 3(a) should have been even, they were declined due to the additional polarization change. For both cases, the differences of $\Delta_m$ in the flattened parts were about 1°, which meant that the $\Delta_m$ had $\Delta_e$ of at least about 1°. To estimate $\Delta_e$ in the whole field, a glass substrate coated with the same metal film as that coating the lens was prepared to make the gap between metal and glass completely 0. The metal film on the glass substrate was formed in the chamber used to form the lens-coating film. The measured $\Delta$ with the metal-coated glass substrate, $\Delta_{m}(0)$, is shown in Fig. 3(a). This result showed $\Delta_e$ of about more than 2° in the measurement area. Here, $\Delta_e$ is the difference between the maximum and minimum $\Delta$.

Using the wavelength and complex refractive indices of samples described in chapter 3, the theoretical relationships between $\Delta$ and $h$ filled with air or lubricant are shown in Fig. 4. The incident angle in the glass substrate was set to 23°. These curves can be approximated to lines with gradients of 0.87 and 0.25 deg/nm at the gap range of 0–10 nm for gaps filled with air or lubricant, respectively. This means that the measured $\Delta_e$ of 2° induces gap errors of about 2 nm and about 8 nm, respectively. Furthermore, at the gap range of 50–60 nm, gradients of approximation lines are −0.11 and −0.16 deg/nm, so that $\Delta_e$ of 2° induces gap errors of about 19 nm and about 13 nm for gaps filled with air or lubricant, respectively. Thus, to obtain $h$ with 1-nm accuracy, we need to correct $\Delta_e$ in the measured $\Delta_m$.

Here, the measured complex reflectivity ratio $\rho_m$ of the sample is expressed using true value $\rho_t$ and error $\rho_e$:

$$\rho_m = \rho_t \cdot \rho_e = (\tan \Psi_t \cdot \tan \Psi_e) \exp(i(\Delta_t + \Delta_e)), \quad (4)$$

where the subscripts $t$ and $e$ mean true value and error, respectively. Therefore,

$$\Delta_m(h) = \Delta_t(h) + \Delta_e. \quad (5)$$

Since $\Delta_t$ does not depend on the gap, to remove $\Delta_t$ from $\Delta_m(h)$, we focused on the difference between $\Delta_t(h)$ and $\Delta_t(0)$, which is $\Delta$ at a gap of 0. The difference, $\delta \Delta(h)$, is given by

$$\delta \Delta(h) = \Delta_m(h) - \Delta_m(0) = (\Delta_t(h) + \Delta_e) - (\Delta_t(0) + \Delta_e) = \Delta_t(h) - \Delta_t(0). \quad (6)$$

![Fig. 3 Cross-sectional profiles of $\Delta$ along the centerline of lens. (a) Measured $\Delta$ for gaps filled with air (red line) or lubricant (blue line) and for metal-coated glass substrate without gap (black line). (b) Corrected $\delta \Delta$ for air-filled gap (red line) and lubricant-filled gap (blue line).](image-url)
Subtracting measured $\Delta_m(0)$ from $\Delta_m(h)$, $\delta \Delta(h)$ was experimentally obtained without $\Delta_e$. Since the relationship between $\delta \Delta$ and $h$ is theoretically obtained from $\Delta_e(h)$ and $\Delta_e(0)$ using Fresnel equations (Eqs. (2) and (3)), as shown in Eq. (6), the gap can be obtained from the corrected $\delta \Delta(h)$ without $\Delta_e$.

To obtain $\Delta_m(0)$ at each pixel of the VEM image, the metal-coated glass substrate was also used, whose gap between metal and glass was completely 0 (Fig. 3(a)). $\delta \Delta(h)$ can be obtained by subtracting $\Delta_m(0)$ from $\Delta_m(h)$ at each pixel. After subtracting, a constant $\Delta$ was added for all pixels so as to make $\delta \Delta(h)$ in the flattened region equal to 0. This means the contact point between the lens and glass substrate corresponds to the contact between the metal film and flat substrate for the metal-coated glass substrate. The results of corrected $\delta \Delta(h)$ for gaps filled with air or lubricant are shown in Fig. 3(b). Comparing the profiles of $\delta \Delta$ after the correction in Fig. 3(b) to the ones of $\Delta_m$ before the correction in Fig. 3(a), the flattened region of the central part of $\delta \Delta$ became even for both gaps filled with air and lubricant. This means that $\Delta_e$ could be successfully reduced from $\Delta_m$ with the correction using the metal-coated glass substrate.

**4.2 Correction of incident angle distribution**

In the RCE method, the incident angle of the illumination light should be determined accurately in order to obtain the true relationship between $\Delta$ and $h$ theoretically. $\delta \Delta$ also depends on the incident angles; therefore, inaccurate incident angle causes an error in the gap measurement. Theoretical relationships between $h$ of lubricant-filled gaps and $\delta \Delta(h)$ for several incident angles were calculated using the wavelength and samples described in chapter 3. The results are shown in Fig. 5. To estimate gap errors due to inaccurate incident angles, gaps for several $\delta \Delta$ were calculated with respect to the incident angle of 21–25° using the results of Fig. 5. The results are shown in Fig. 6. The variation in calculated gap with respect to the incident angle means the gap error due to inaccurate incident angle. As shown in Fig. 6, the $\delta \Delta$ of 3.2° caused larger gap error, which corresponds to the maximum peak of $\delta \Delta$ at an incident angle of 21° in Fig. 5. For the worst case, Fig. 6 shows that the difference in the incident angle of 4° can cause the gap error of more than 10 nm at the $\delta \Delta$ of 3.2°. Therefore, the incident angle should be obtained with an accuracy of much less than 1° to
measure the gap with nm-accuracy.

Moreover, in the VEM measurement, the incident angles can vary at each pixel due to the illumination light not being perfectly parallel. Therefore, to measure the gap shape with nm-accuracy by VEM, we need to obtain the distribution of incident angle and correct the theoretical relationships between \( h \) and \( \delta \Delta \) at each pixel.

As shown in Fig. 5, the \( \delta \Delta \) takes the maximum peak at a certain gap, and the maximum values, \( \delta \Delta_{\text{max}} \), depend on the incident angle. To experimentally obtain \( \delta \Delta_{\text{max}} \), the change in \( \delta \Delta \) with the gap was measured using the RCE method while bringing the lens closer to the glass substrate by moving a z-piezo stage shown in Fig. 1 at slow speed. For example, the measured change of \( \delta \Delta \) at a pixel for a lubricant-filled gap with the piezo stage extension \( l \) is shown in Fig. 7, and \( \delta \Delta_{\text{max}} \) can be obtained. As shown in Fig. 5, \( \delta \Delta \) has a maximum peak at the gap of 20–30 nm for gaps filled with lubricant, so that \( \delta \Delta_{\text{max}} \) was obtained at each pixel when the lens was apart from the glass substrate. Here, note that, at the pixels far from the center of lens, the gaps will not attain less than 20–30 nm when the center of lens contacts to the substrate. This means that \( \delta \Delta_{\text{max}} \) cannot be obtained for the point far from the center of the lens. Therefore, by applying larger load to the lens to get larger Hertzian contact area and smaller gap at the pixels far from the center, \( \delta \Delta_{\text{max}} \) can be obtained in the whole filed. Then, the relationships between \( \delta \Delta_{\text{max}} \) and the incident angle in a glass substrate, \( \theta_0 \), were calculated using Fresnel equations (Eqs. (2) and (3)) for gaps filled with air or lubricant. The results are shown in Fig. 8. Therefore, measuring \( \delta \Delta_{\text{max}} \) at each pixel using the piezo stage, the spatial distribution of \( \theta_0 \) can be obtained using the relationship shown in Fig. 8.

The measured incident angle distributions using this correction method for gaps filled with air or lubricant are shown in Figs. 9(a) and (b), respectively. These incident angle distributions were expressed in color contour maps with 16 levels, which colors showed an angle range of 0.375°. The average incident angles were 21.7° and 20.1° for air and lubricant, respectively, in the circular corrected area (diameter of 90 \( \mu \)m). These values differ greatly from the designed incident angle of about 23.7° estimated from the VEM setup described in chapter 3. As shown in Fig. 9(b), the variation in the incident angle for lubricant-filled gap over the whole field was about 4.5°; the difference between the maximum...
incident angle of 23.1° and the minimum one of 18.6°. The variation in the incident angle of 4.5° can cause a gap error of more than 10 nm without the correction of the incident angle, as estimated from Fig. 6.

As shown in Figs. 9(a) and (b), the incident angle distributions for gaps filled with air or lubricant were almost symmetric with respect to the y-axis, whereas they were asymmetric with respect to the x-axis. In this setup, the y-direction was the direction of the VEM incident light; therefore, an oblique incidence to the sample was possible to cause the incident angle to vary. Moreover, the incident angle distributions for gaps filled with air or lubricant differed greatly from one another. This means that the measured incident angle distribution should be regarded as a correction parameter including the variations in the measurement factors, such as light intensity, wavelength, and complex refractive indices besides the incident angle.

4.3 Result of correction for gap shape measurement
For a validation of the correction for the additional polarization change of $\Delta e$ and incident angle distribution, a gap shape after injecting lubricant was measured. The smoother surface lens ($R_a$ of 0.8 nm) was used, and the load was 8.4 mN. Gap shapes were expressed in color contour maps with 16 levels, which colors showed a gap range of 4.25 nm. Figure 10(a) shows the gap shape before the correction. Here, measured $\delta\Delta$ was converted to $h$ by assuming that the incident angle was even in the whole field. The incident angle was set at 20.1°, which was the average value over the field of Fig. 9(b). In Fig. 10(a), unmeasurable area existed (the black dots), because the relationship between $\delta\Delta$ and $h$ differed from the true one due to the incorrect incident angle. Figure 10(b) shows the gap shape after the correction using the measured incident angle distribution shown in Fig. 9(b). Compared to Fig. 10(a), the unmeasurable area became much smaller in Fig. 10(b), which indicates the validity of our correction method. However, the black dots were slightly remained after correction in Fig. 10(b) (around the yellow area) by the limitation of the measurement sensitivity in the gap range of 20–30 nm, as described in section 5.1.

![Fig. 10 Contour maps of measured gap shapes filled with lubricant (a) before and (b) after correction of incident angle distribution.](image)

5. Gap measurement results
5.1 Measured gap shape
VEM gap shape measurement with RCE using the correction method was evaluated as follows. In our experiment, the $\Delta e(0)$ of the metal-coated glass substrate was measured at each pixel in order to subtract $\Delta e$ from the measured $\Delta m$ (Eq. (6)) at first. Next, the gap between the glass substrate and lens was measured. The lens was made to contact the substrate using the z-piezo stage at a certain load, and the $\Delta m$ of a static air-filled gap was measured. Then, lubricant (PAO) was injected around the gap, and the $\Delta m$ of the lubricant-filled gap was measured. In these measurements, the static gaps filled with air and lubricant should have had the same shape. Prior to these measurements, the $\delta\Delta_{\text{max}}$ for gaps filled with air or lubricant were acquired using the z-piezo stage. By the correction method described in chapter 4, we obtained the $\delta\Delta(h)$ without $\Delta e$ and the incident angle $\theta_0$ for air- and lubricant-filled gaps at each pixel. The gap shapes were then obtained by converting $\delta\Delta(h)$ using each theoretical relationship at the obtained incident angles. In our static gap measurements, light intensity images of the gap were continuously measured for 8 s to obtain five images of $\Delta m$ for the five images at each pixel to reduce noise.

By using the measured incident angle distributions shown in Fig. 9, we measured the static gap shape filled with air.
and the one after injecting lubricant while the contact was maintained. The results are shown in Figs. 11(a) and 11(b) (correspond to Fig. 10(b)), respectively. In these measurements, the smoother surface lens (R_a of 0.8 nm) was used, and the load was 8.4 mN. As shown in Figs. 11(a) and (b), the gap shapes were flattened due to the load in the contact area at the center. The gap shapes in the non-contact area were concentric, corresponding to the spherical shape of the lens.

Figures 11(c) and (d) show cross-sectional views of the gaps along the centerline of the lens shown in Figs. 11(a) and (b), respectively. The gap shapes calculated using Hertzian contact theory at the load of 8.4 mN are also shown in Figs. 11(c) and (d) (Johnson, 1985). Young’s moduli of the lens and glass substrate were 79.9 and 124.9 GPa, and the Poisson ratios were 0.209 and 0.295, respectively, according to the manufacturer. Both the measured air-filled and lubricant-filled gaps showed good agreement with those obtained by Hertzian theory. This means that gap shapes can be accurately measured by using the RCE method along with our correction method.

For the air-filled gap of 40–50 nm and the lubricant-filled gap of 20–30 nm, the measurements had errors, as shown by the tiny black dots of unmeasurable pixels in Figs. 11(a) and (b), respectively. And, the gaps around these ranges had larger errors than those of Hertzian theory, which caused different gap images of Figs. 11(a) and (b). This is because the gap sensitivity is low in these ranges, which correspond to the vicinity of the Δ peak in Fig. 4. To improve gap measurement accuracy in the low-sensitivity ranges, it is helpful to use Ψ along with Δ because the low-sensitivity regions of Ψ and Δ are located at different positions, although, the calculation is more complicated. Furthermore, the air-filled gap shape in Fig. 11(a) showed larger unmeasurable area than the lubricant-filled one in Fig. 11(b). This is because the air-filled gap was more sensitive to Δ and larger gap errors were caused by the same errors of Δ than the lubricant-filled gap. And, particularly in the y-direction which corresponds to the incident light direction, larger errors in measured Δ were caused due to the uneven incident angle distribution.

Fig. 11 Contour maps of measured gap shapes filled with (a) air or (b) lubricant at the load of 8.4 mN. Cross-sectional views of gap along centerline of lens in x-direction for gaps filled with (c) air (red line in (a)) or (d) lubricant (blue line in (b)). Black lines in (c) and (d) show the Hertzian theoretical shape.
5.2 Gap measurement accuracy

To obtain measurement accuracy with the RCE method, static gaps filled with air or lubricant were measured ten times. The $\delta\Delta$ variations for air and lubricant were similar: 0.17° on average over the whole image. Here, the variations were defined as the standard deviation for ten $\delta\Delta$-images at each pixel. This accuracy is the accuracy for one measurement. In our experiments, all the static measurement gaps were obtained from the average $\delta\Delta$ for five consecutive measurements. Therefore, the accuracy of the measurement $\delta\Delta$ should be obtained by dividing the standard deviation of $\delta\Delta$ by the square root of five. The obtained accuracy of the measurement $\delta\Delta$ was 0.076° with the required measurement time of 8 s.

The relationship between $\delta\Delta$ and $h$, as shown in Fig. 5, indicates that the sensitivity of $h$, i.e., the gradient of the curve, varies with the gap. The accuracy of the gap measurement can be obtained by dividing the accuracy of the $\delta\Delta$ measurement by the sensitivity of gap. Figure 12 shows the measurement accuracies for air-filled and lubricant-filled gaps calculated using the $\delta\Delta$ accuracy of 0.076° at the averages of the measured incident angles of 21.7° and 20.1°, respectively. The results show that we can measure gaps with an accuracy of less than 1 nm in the gap range of 0–34 nm for air-filled gaps and in the gap range of 0–16 nm for lubricant-filled gaps. And, these results also shows that we can measure gaps around the contact region ($h = 0$) with an accuracy of about 0.08 nm for air and about 0.3 nm for lubricant. Therefore, the gap measurement using the RCE method shows the highest precision at a gap of around 0 nm, which enables measurement of gaps of the order of 1 nm. However, at the gap of about 41 nm (air) and about 26 nm (lubricant), gap sensitivities are low, as shown in Fig. 11. These results suggest that the VEM gap measurement will be useful for investigation of the contact state including the absorption of lubricant additives.

The gap profiles for air and lubricant in Figs. 11(c) and (d) had accuracies of 0.26 and 0.66 nm, respectively, in the contact region, which were the calculated standard deviations from zero. The standard deviations for gaps with air or lubricant calculated from the Hertzian theoretical curve were 0.7 and 1.0 nm for gaps of 0–20 nm, respectively. Thus, we successfully achieved gap shape measurement with an accuracy of about 1 nm. However, the gap accuracies in the contact region and for gaps of 0–20 nm were larger than the theoretically predicted ones, as shown in Fig. 12. This may be because the surface roughnesses of the lens and substrate were not considered in the Hertzian shape.

6. Demonstrations of VEM gap measurement with correction method

6.1 Surface roughness effect

Two lenses with the different surface roughness were used for gap measurement to investigate the effect of surface roughness on the gap shape. The surface profiles of the smoother lens (Ra of 0.8 nm) and the rougher one (Ra of 1.0 nm) measured with an atomic force microscope are shown in Figs. 13(a) and (b), respectively. The scan area was $20 \times 20 \, \mu$m. The surface profile of the smoother lens shows polished grooves in similar direction, whereas that of the rougher lens shows random grooves.

Figure 14 shows the measured gap shapes filled with air around the contact regions; Fig. 14(a) shows the gap shape with the smoother lens, and Fig. 14(b) shows the shape with the rougher one. These gap shapes were expressed in color contour maps with 16 levels, which colors showed 0.375 nm. The load was set to 17.6 mN for both cases. The gap shape with the smoother lens shows the contacts with low-height ridges in similar direction, whereas the shape with the
rougher one shows the contacts with random asperities. These features of the gap shapes correspond to the surface profiles shown in Figs. 13(a) and (b).

For the gap shape with the smoother lens (Fig. 14(a)), the flattened region at the gap of about 0 nm was circular, whereas that with the rougher one (Fig. 14(b)) was irregular. This is because the real contact areas for these measurements differed due to the difference in the surface profiles of the lenses. These show the VEM gap measurement can measure the difference of contact states on the nm-scale.

6.2 Lubricant confinement effect

Figure 15(a) shows the cross-sectional views of the measured gap shapes filled with lubricant around the contact region using the smoother lens. The blue line shows the measured gap just after injecting lubricant, and the red line shows the gap when the lens was separated from the glass substrate and brought into contact again. The both loads were set to 17.6 mN. At these loads, the mean Hertzian pressure was calculated at 0.023 GPa, which was much smaller than the yield stress of the lens (BK7 glass, 3.5 GPa) (Antunes et la., 2006). Therefore, plastic deformations of the samples can be ignored during these measurements. The average gaps around the contact region were 0.72 nm after injecting lubricant and 1.34 nm after re-contact. Figure 15(b) shows the measured gaps at the load of 17.6 mN with the rougher lens. The average gaps around the contact region were 0.89 nm after injecting lubricant and 1.80 nm after re-contact. For both cases with the smoother lens and the rougher one, the re-contact gaps became slightly larger than the gaps after injecting lubricant. Interestingly, a few contact points of the re-contact gaps at locally minimum gaps ($h \approx 0$) penetrated the lubricant film, as indicated by arrows in Fig. 15.

These gap increases around the contact region less than 1 nm can be considered that the lubricant was confined in the grooves of the lens surface. This led to reduce the contact points between the surfaces, and the gap increase around the contact region resulted. The confined lubricant film is possible to contribute to reduce friction and wear for sliding surfaces.
7. Conclusion

We investigated the improvement of the VEM gap shape measurement along with RCE using the proposed correction method. This method was shown to correct the polarization change and incident angle distribution due to using optical devices in the microscope. Evaluation using gaps filled with air or lubricant (PAO) demonstrated gap measurement accuracy of about 1 nm. Since the gap measurement using the correction method has high accuracy for gaps around the contact region, this enables investigations of the contact state, which depends on the surface roughness and the presence of lubricant in the gap. The differences of the measured gap shape due to the small variation in the nanometric surface roughness and the local lubricant confinement were observed by VEM. This improved VEM-based gap-shape measurement is thus useful for clarifying the lubrication phenomena in nm-order gaps.

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