Proceedings of Asia International Conference on Tribology 2018, pp. 305-306, September 2018

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

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Keywords: Gap measurement; vertical-objective-type ellisometric microscopy; rotating compensator ellipsometory

ABSTRACT – Correction methods to improve accuracy of measurement of gap shape using vertical-objective-type ellipsometric microscopy (VEM), which can provide 0.1-μm-order lateral resolution, were proposed. Since the VEM-based measurement uses an optical microscope with a high lateral resolution, the correction of measured ellipsometric signal is needed when applying rotating compensator ellipsometry to gap shape measurement. In this paper, we proposed correction methods of the polarization change and the incident angle distribution due to the optical devices. Demonstrating the correction methods, the gap-measurement accuracy of less than 1-nm was achieved.

1. INTRODUCTION

Recent progress of measurement methods has shown that the lubrication phenomena at narrow gaps significantly depend on the size of gap. Therefore, measuring gap shape is indispensable to clarify these phenomena. Ellipsometric microscopy (EM) was proposed to measure two-dimensional thickness distribution based on ellipsometry. Moreover, a new type of EM, called vertical-objective-type EM (VEM), was developed to improve the lateral resolution up to 0.1 □m order, and has been attempted to apply to measuring gap shape [1].

In VEM-based measurement of the gap, conversion of the measured ellipsometric image to the gap shape is necessary. Rotating compensator ellipsometry (RCE) method was introduced for the gap measurement [1]. The RCE method is widely used in ellipsometers,and provides thickness resolution of the order of 0.1 nm. Unlike usual ellipsometers, the microscope for the VEM includes optical devices such as lenses and mirrors. The optical devices may cause additional polarization changes and unevenness of incident angles in the field of view. Therefore, when applying the RCE method to the gap measurement by VEM, correction of these errors is needed. In this paper, we proposed correction methods for the polarization change and the incident angle distribution to improve the accuracy of the gap shape measurement by VEM with RCE method.

2. GAP MEASUREMENT BY VEM WITH RCE METHOD

Figure 1 shows a schematic set up of the gap measurement using VEM. The illumination light focused onto the off-axis point on the back focal plane of the objective lens, which can generate oblique light illumination and provide sufficient ellipsometric signal.

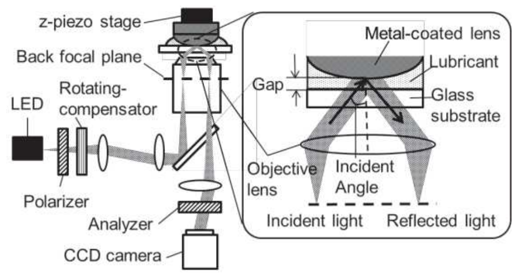


Figure 1 Schematic setup for measuring gap shape by VEM. The inset is magnified view of the around gap.

The optical system is configured of a light source, polarizer, compensator, sample, analyzer and detector. An LED with a wavelength of 460 nm was used as the light source, and an electron multiplying CCD camera was used as the detector. The light reflected at the gap between the metal-coated lens and glass substrate was detected. The complex reflectivity ratio of sample, ρ, is given by

$$\rho = \tan\Psi(h)\exp\{i\Delta(h)\}. \quad (1)$$

$\tan\Psi$ and Δ are the absolute value and argument of ρ at a gap of h, respectively. Since ρ changes with the gap, analysing ρ by polarization devices provides the gap.

The procedure of the RCE method was based on that reported by Fukuzawa et al. in detail [1]. In this method, the change of the intensity of ellipsometric image with continuous rotation of compensator was measured, and analyzing this change of intensity, Ψ and Δ were obtained at each pixel. In this paper, only Δ was used to calculate the gap, because Δ had higher sensitivity than Ψ for small gaps. The relationship between Δ and gap h is theoretically obtained by Fresnel equations from incident angle of illumination light and refractive indices of materials composed the gap. Using this relationship, measured Δ at each pixel was converted to the gap shape.

3. CORRECTION METHOD

3.1 Correction of measured Δ

The measured $\Delta_m(h)$ includes the error Δ_e due to the optical devices. Therefore, to obtain the true value $\Delta_t(h)$, correction of $\Delta_m(h)$ is necessary. The measured complex refractivity ratio ρ_m is the sum of the true value ρ_t and error ρ_e, and is given by

$$\rho_m = \rho_t \cdot \rho_e = (\tan\Psi_t \cdot \tan\Psi_e)\exp\{i(\Delta_t(h) + \Delta_e)\}. \quad (2)$$

Therefore, $\Delta_t(h)$ is given by $\Delta_t(h)$=$\Delta_m(h)$-Δ_e. To eliminate Δ_e from $\Delta_m(h)$, we focused on the difference between $\Delta_t(h)$ and $\Delta_t(0)$, $\delta\Delta(h)$, given by

$$\delta\Delta(h) = \Delta_t(h) - \Delta_t(0) = \{\Delta_m(h) - \Delta_e\} - \{\Delta_m(0) - \Delta_e\} \\ = \Delta_m(h) - \Delta_m(0). \quad (3)$$

To obtain measured $\Delta_m(h)$ at each pixel, the phase shift of metal-coated glass substrate, Δ_{Ref}, whose gap between metal and glass is completely zero, was measured. $\Delta_m(h)$ was adjusted so that $\Delta_m(0)$ in the contact region coincides with Δ_{Ref}. Thus, $\delta\Delta(h)$ with reduction of error was obtained at each pixel.

3.2 Correction of incident angle distribution

In the RCE method, the incident angle of light should be determined accurately to obtain the true relationship between Δ and gap theoretically. To measure the gap around 15 nm within 1-nm accuracy, the incident angle is necessary to determine within 0.4 degree accuracy. In the VEM-based measurement, the incident angles at each pixel have unevenness in the field of view due to the optical devices.

With the RCE method, the change of Δ with the gap was measured while bringing the lens closer to glass substrate by a z-piezo stage at a slow speed. $\Delta_m(h)$ took the maximum value, Δ_{max}, at a particular gap as shown in Fig. 2(a). The differential value of $\delta\Delta_{max}$ between Δ_{max} and $\Delta_m(0)$ was obtained by $\delta\Delta_{max}=\Delta_{max}-\Delta_m(0)$. Using the relationship between $\delta\Delta_{max}$ and the incident angle in the glass substrate θ_0, the approximate function $\theta_0(\delta\Delta_{max})$ can be theoretically calculated from Fresnel equations. Thus, measuring $\delta\Delta_{max}$ at each pixel with change of the piezo displacement, the distribution of θ_0 was determined in the observed area by VEM.

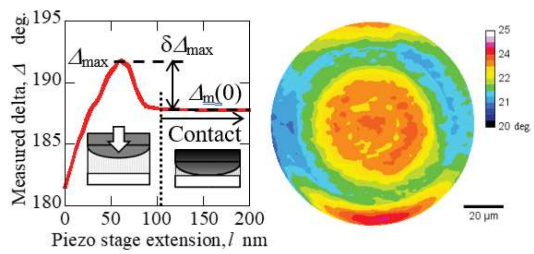
4. MATERIALS AND METHODS

For VEM-based measurement of the gap shape, the sample consisted of lens/lubricant/substrate. The lens had a radius of 15.6 mm and was coated with 53-nm stainless steel film to increase the reflectivity. Poly-α-olefin (PAO) was used as the lubricant sample, and a high refractive index glass (K-LASFN23) was used as the substrate. A glass substrate coated with stainless steel film in the same process of the lens was used as the reference sample to obtain Δ_{Ref}. Since surface roughness may affect the accuracy of gap measurement, we used the smooth surfaces with Ra of 0.7 nm and 0.3 nm of the lens and substrate, respectively.

In the experiment, Δ_{Ref} was measured with RCE method. Changing the sample, the lens was made contact with the substrate using the z-piezo stage. Lubricant PAO was injected, and $\Delta_m(h)$ of the static gap was measured. Then, with the piezo stage method, Δ_{max} was measured. Using the correction methods described in sections 3.1 and 3.2, $\delta\Delta(h)$ and the incident angle in glass θ_0 were obtained at each pixel.

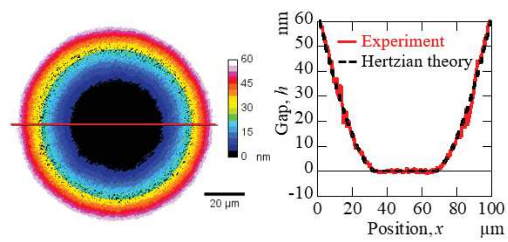
5. RESULTS AND DISCUSSION

The incident angle distribution θ_0 was obtained as shown in Figure 2(b). This showed the maximum difference of about 3 degrees in the observed area, which corresponds to a gap error of about 7 nm at a measurement of gap around 15 nm.



(a) (b)

Figure 2 (a) Measured change of Δ during approach of lens to substrate. (b) Measured incident angle distribution in glass substrate θ_0.



(a) (b)

Figure 3 Measured static gap shape filled with PAO. (a) Image of gap shape. (b) Cross sectional view of the gap on centerline of lens (red line in (a)).

Figure 3(a) shows the measured gap shape filled with PAO, and Fig. 3(b) shows the cross-sectional view of the gap on the centerline of lens and that calculated using Hertzian contact theory. The measured gap with lubricant shows good agreement with the theoretical one. By contrast, in the contact without lubricant, the deformation caused by the adhesion was observed. In the gap range around 20 to 30 nm, however, gaps had more error as shown in black dots of Fig. 3(a). This is because the sensitivity became low in this range. Eventually, the accuracy of our method was estimated at 0.8 nm in the gap range of 0 to 20 nm as the standard deviation from the theoretical curve.

Additionally, a measurement of metal-to-metal gap would be required for practical application. In our VEM-based method, it could be achieved by using a glass substrate coated with semi-transparent thin-metal film and analysing the gap composed of metal/lubricant/metal/substrate.

6. CONCLUSIONS

We developed a new method to correct the polarization change and the incident angle distribution due to the optical devices. Using the correction methods, the gap-measurement accuracy less than 1-nm was achieved. This method is useful to clarify the lubrication phenomena at nm-sliding gaps.

REFERENCE

[1] Fukuzawa, K., Sasao, Y., Namba, K., Yamashita, C., Itoh, S., & Zhang, H. (2018). Measurement of nanometer-thick lubricating films using ellipsometric microscopy. *Tribology International*, *122*, 8-14.