Real-time Visualization of Lubricant Films on Head Slider Using an Ellipsometric Microscope

Q Liu and F Yan

C-MEIC & CICAET, School of Information and Control, Nanjing University of Information Science & Technology, Nanjing, China
E-mail: sherryliuqq@163.com

Abstract. As the recording density increased in hard disk drives (HDDs), the head disk interface (HDI) spacing has been decreased to 2-3 nm during its operation. The head slider may pick up the lubricant at this contact or near-contact HDI. Therefore, a real-time visualization of lubricant thickness distribution on a slider surface is essential to study the physical mechanisms for reducing the head disk interface spacing. A vertical-objective-based ellipsometric microscope (VEM) was presented as the effective method for real-time visualization of nm-thick lubricant films on disks with high lateral resolution. However, extinction coefficient of head slider is low, which means the intensity of reflected light may be reduced. In this report, the feasibility of VEM used for head observation is discussed, and the images of polar perfluoropolyether (PFPE) lubricant Zdol4000 applied on head slider are obtained by the current setup. It indicates that this method can be used in real-time visualization of nm-thick lubricant films on head slider.

1. Introduction
Recently, the study on physical mechanisms of the nm-thick liquid lubricant films plays an important role in the performance of HDDs due to decrease of head-disk interface spacing to 2 to 3nm with the increasing of recording density. The contact or near-contact HDI is needed to increase the recording density. However, lubricant pick-up by a head slider will occur. Therefore, a real-time observation of lubricant thickness distribution on a slider surface is essential to study the physical mechanisms or phenomena for reducing the head disk interface spacing. High lateral resolution is required for this observation because the contact area is small, of the order of 1μm[1-5]. Ellipsometry is widely used for the investigation for thin films[6-8]. Ellipsometric microscopes (EMs), which are based on ellipsometry, can provide thickness distribution as a dark-bright contrast image by using an imaging device as a photo detector. In conventional EMs, a parallel light source is set oblique to the sample with well-defined polarization, as well as the objective lens. Narrow field of view can be involved by this oblique setup when using high lateral resolution lenses. Therefore, a vertical-objective-based EM (VEM) has been improved to solve this problem. In the VEM, the illumination light comes from the lubricant film side and the off-axis light is focused onto the back focal plane of the objective lens to obtain the oblique illumination. This VEM can provide both high lateral resolution and thickness resolution on disks; however it has not been applied to the head slider observation since the low extinction coefficient of head slider may cause extremely low reflectivity. In this report, the feasibility and the improved method of VEM used for head observation is discussed.

2. Setup of VEM

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
Based on ellipsometry, in EMs, a sample is illuminated by parallel, oblique light with well-defined polarization. The measured quantity is the change of polarization due to reflection of light at the sample. The polarized conditions are different due to different film thicknesses, so on the captured image, the light intensity changes depend on the film thickness. Figure 1 shows the schematic of our VEM. As the oblique illumination is necessary to get ellipsometric contrast in EMs, in our VEM, the objective lenses are set vertically and the off-axis light is focused onto the back focal plane of the objective lens. A commercial microscope was modified and an objective lens at NA = 0.95 and WD = 0.3 mm was used. A LED was used as the light source, with wavelength of $\lambda = 546$nm. The light reflected from the sample was imaged through the objective and imaging lenses onto a highly sensitive electron multiplying CCD camera. This type of VEM the has the thickness resolution of about 0.4 nm, which has a large field of view of $160 \times 160$ μm², and can be used for real-time observation\textsuperscript{[9-10]}. However, it has not been proved whether this type of VEM can be used for head observation.

![Figure 1. Schematic of vertical-objective-based ellipsometric microscope.](image)

3. Method

A schematic structure of the head with the lubricant film on the slider surface is shown in figure 2. The incident light travels through the lubricant film on the slider surface and is then reflected by the slider surface. Different film thicknesses result in different reflected light intensity which can be detected by the system.

As mentioned before, the measured quantity is the change of polarization due to reflection of light at the sample. The ellipsometric angles $\psi$ and $\Delta$, which are used to describe the change in polarization, are given by

$$
\tan \psi \cdot \exp(i \Delta) = \frac{R_s}{R_p} = \left| \frac{R_s}{R_p} \right| \exp[i \left( \phi_p - \phi_s \right)]
$$

where $R_p$ and $R_s$ are the complex reflection coefficients of the p- and s-polarized lights, which can be calculated by $2 \times 2$ matrix method\textsuperscript{[11]}. $2 \times 2$ matrix method is well used in the film thickness measurement, especially for multilayer structures. When light incidents on the multilayer structure, the change of the reflected light can be decomposed into the effects of the propagation through the interface between different layers and the inside of a layer. Using different $2 \times 2$ matrices to describe these effects, the complex reflection coefficients are obtained by the matrix operations.

Moreover, the intensity signal of ellipsometric microscope $I$ is generally given by\textsuperscript{[12]}
\[ I = \frac{R_s^2 I_0}{2} \times [r^2 \cos^2 A + 2r \sin A \cos A \sin(2P + \Delta) + \sin^2 A], \]  

where \( r \) is the amplitude ratio for p- and s-polarized lights, \( I_0 \) is the intensity of incident light, and \( P \) and \( A \) are the angles of the polarizer and analyzer.

In our simulation, the layer model of the head slider consisted of air, lubricant film and head slider as a substrate, the refractive indices were 1, 1.3, and 1.98+0.377i, respectively. Moreover, a lubricated magnetic disk for HDDs was used for comparison. The layer model consisted of air, lubricant film and magnetic disk as a substrate, the refractive indices were 1, 1.3, and 2.35+3.93i, respectively. For both simulations, the thicknesses of lubricant and substrate were 1-10 nm and \( \infty \), respectively. The light source with the wavelength \( \lambda \) of 546 nm and the incident angle \( \theta \) of 60deg was used as well.

4. Results and discussion

4.1. Simulation results

In figure 2, the simulated relationships between ellipsometric intensity \( I \) and film thickness \( h \) for head and disk are shown, which are in the extinction condition, which means the reflected ellipsometric intensity \( I = 0 \), when the film thickness \( h = 0 \). It should be noted that the reflected ellipsometric intensity \( I \) has been normalized by the intensity of incident light \( I_0 = 1 \) in all the simulations. From this simulation, we know both the situations have the same tendency when film thickness comes from 0 to 10 nm; however the amplitude of ellipsometric intensity \( I \) of head is about 1/4 of the magnetic disk for the same \( h \). As the thickness resolution is determined by the signal-to-noise ratio, and the signal-to-noise ratio of the observed image is proportional to the square root of the intensity of the illumination light, which means the thickness resolution of head observation is about 2 times of the one of disk observation, theoretically. For example, if the thickness resolution is about 0.4 nm for the disk observation, it is about 0.8 nm for head observation. As the lubricant film is just a few nanometers thick, the thickness resolution of 0.8 nm is low and should be improved.

For 2×2 matrix method, the complex reflection coefficients \( R_p \) and \( R_s \) are not only the functions of refractive indices \( n \) of each layer, but also the incident angle \( \theta \) and wavelength \( \lambda \), so we did the simulations for different incident angles and wavelengths.

**Figure 2.** Simulated relationships between ellipsometric intensity \( I \) and film thickness \( h \) for head and disk (wavelength \( \lambda = 546 \) nm and the incident angle \( \theta = 60\text{deg} \)).

**Figure 3.** Simulated relationships between ellipsometric intensity \( I \) and film thickness \( h \) of different incident angles \( \theta \) for head.
Figure 3 shows the results of simulation of the relationships between the ellipsometric intensity $I$ and film thickness $h$ for head at different incident angles with wavelength $\lambda = 546$ nm. This calculation indicates that the ellipsometric intensity varies depending on the incident angle for each film thickness. It reaches the maximum when the incident angle $\theta = 70$deg.

The simulation of the relationships between the ellipsometric intensity $I$ and film thickness $h$ with different wavelength has been done as well. Commonly used wavelengths of visible light were calculated, and the result at the incident angle $\theta = 70$deg is shown figure 4. For example, the film thickness $h = 3$nm, the difference of ellipsometric intensity $I$ for different wavelengths is shown in figure 5. It is obviously concluded that shorter wavelength leads to larger intensity of the reflected light. The thickness resolution of the VEM is inversely proportional to the square root of the intensity of the illumination light as mentioned before, therefore the thickness resolution can be improved by decreasing the wavelength of the incident light, which means more information can be obtained in the observation. Thus, in our simulation, by choosing wavelength of 385nm and incident angle of 70deg for head observation can get the optimal measurement effect.

![Figure 4](image1.png)  
**Figure 4.** Simulated relationships between ellipsometric intensity $I$ and film thickness $h$ of different wavelength $\lambda$ for head.

![Figure 5](image2.png)  
**Figure 5.** Simulated relationships between ellipsometric intensity $I$ and wavelength of the incident light $\lambda$ for head (film thickness $h = 3$nm).

Comparing the simulated optimum of head with disk, as shown in figure 6, the amplitude of intensity $I$ of head is improved and becomes about 2/3 of magnetic disk observation for the same film thickness $h$. That means if the disk observation has the thickness resolution of 0.4nm, it is about 0.5nm for head observation. This means that the improved VEM is feasible if signal-to-noise ratio of $I$ is improved. And if incident light intensity $I$ is improved by 1.5 times, it can get the same thickness resolution as disk observation.

In the previous work, the linear relationship between the ellipsometric intensity $I$ and film thickness $h$ has been obtained by both simulation and experiment method for disk observation. In disk observation, the ellipsometric intensity $I$ is approximately proportional to the film thickness $h$, when the angle of analyzer $A$ has been set in the extinction condition and the angle of polarizer $P$ has been adjusted. This means that the intensity can be directly converted into film thickness by the VEM, which enables real-time observation. Therefore, in this study the same simulation has been done for head observation. The wavelength of 385nm and incident angle of 70deg has been used for this simulation. The result is shown in figure 7. When the angle of analyzer $A$ has been set at 8.7deg, as well as the angle of polarizer $P = 65$deg, the linear relationship between ellipsometric intensity $I$ and film thickness $h$ for head observation has been obtained. However, the intensity is inversely proportional to the thickness comparing with disk observation.
4.2. Real-time visualization of head slider

Figure 8 shows the dewetting images of the 6.7nm-thick films on head slider observed in real time taken by the VEM. The observation was started at about 5min 30sec after the film applied to the slider. The lubricant in this experiment was Zdol4000 which was polar lubricant. Therefore, the lubricant on the disk was unstable and spontaneously dewetted the slider. The thickness of the lubricant was measured by AFM. The figure shows that dewetting started from the right to the left on the slider, and the part of slider with lubricant films was darker than the bared part, which was consistent with the simulation result. The temporal change of the nm-thick lubricant film on the head slider can by observed by VEM.

Figure 8. Dewetting images of lubricant film on head slider taken by VEM, (a)-(d) are the images obtained at 5min30s, 5min50s, 6min10s and 6min30s after film applying, respectively (h=6.7nm).

5. Summary

The VEM is expected to be a useful method for real-time observation of the lubrication phenomena and physical mechanisms that uses thin liquid lubricants. However, it has low thickness resolution for head slider observation due to the low extinction coefficient of head slider. An improved VEM is presented, of which the thickness resolution can be increased by choosing the suitable wavelength and incident angle of the incident light and the feasibility of this type of VEM has been proved. The linear relationship between the ellipsometric intensity and film thickness for head observation has been
obtained. However, the intensity is inversely proportional to the thickness, which is confirmed by the visualization of lubricant films on head slider by VEM.

6. References

[1] Marchon B, Guo X, Moser A, Spool A, Kroeker R and Crimi F 2009 J Appl. Phys. 105 074313
[2] Mate C, Marchon B, Murthy A and Kim S 2010 Tribol. Lett. 37 581
[3] Tani H, Kubota M, Tsujiguchi Y and Tagawa N 2011 Microsyst. Technol. 17 1175
[4] Vangipuram S Canchi and Bogy D 2010 IEEE Trans. Magn. 46 764
[5] Vangipuram S Canchi and Bogy D 2012 Microsyst. Technol. 18 1517
[6] Henon S and Meunier J 1991 Rev. Sci. Instrum. 62 936
[7] Gang J, Roger J and Hans A 1996 Rev. Sci. Instrum. 67 2930
[8] Linke F and Merkel R 2005 Rev. Sci. Instrum. 76 063701
[9] Liu Q, Fukuzawa K, Kajihara Y, Zhang H and Itoh S 2011 Tribology Online 6 251
[10] Fukuzawa K, Q Liu, Tarukado T, Kajihara Y, Watanabe R, Itoh S and Zhang H 2013 IEEE Trans. Magn. 49 2530
[11] Azzam R M A and Bashara N M 1987 Ellipsometry and Polarized Light (Amsterdam: North-Holland) p 332
[12] Fukuzawa K, Noda T and Mitsuya Y 2003 IEEE Trans. Magn. 39 898
[13] Fukuzawa K, Yoshida T, Itoh S and Zhang H 2008 Langmuir 24 11645

Acknowledgments

This project has been supported by National Natural Science Foundation of China (No. 61701244), and the Scientific Research Foundation of Nanjing University of Information Science & Technology (No. 2013r106).