

Thin Film Thickness Profile Measurement using an Interferometric Surface Profiler

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ABSTRACT

The technique of surface profile measurement using white-light interferometry is widely used in industry. However, its application to transparent thin films has been limited to date because the reflection signals from the front and back surfaces are mixed and must be separated in order to obtain correct measurements. This paper introduces four of our recent developments in this application field: 1) profiling of a thick transparent film, 2) profiling of a thin transparent film, 3) thickness profiling of a freestanding film, and 4) simultaneous measurement of the thickness and refractive index of a freestanding film.

Keywords: interferometry, white light, surface profiler, transparent film, film thickness, refractive index.

1. INTRODUCTION

The technique of surface profile measurement using optical interference is widely used in industry as a non-contact and non-destructive method of quickly and accurately measuring the profile of microscopic surfaces. However, its application to transparent thin films has been limited because it is difficult to obtain an exact surface profile measurement if the surface to be measured is covered with a transparent film. This is because the interference beam coming from the back surface of the film creates disturbance.

Thickness profile measurement is also of great importance in industry; for example, the measurement of the various kinds of thin film layers on substrates of semiconductors or flat panel display devices. There are several different techniques used to measure these films, of which the most widely used are reflection spectrophotometry and ellipsometry.

In the case of freestanding films such as plastic films, there are also several non-destructive measurement techniques, such as methods using β -rays, infrared (IR) or nuclear gauges, and spectrophotometry.

However, most of these techniques are limited to single-point measurement. To obtain an areal thickness profile, it is necessary to mechanically scan the sample or the sensing device. Another limitation inherent in these techniques is their large spot sizes. For example, spectrophotometers are limited to spot sizes of a few μm or greater because of available light budgets.

It has been the focus of our research to resolve these problems in the surface and thickness measurement of substrate-supported films and freestanding films. The present paper introduces some of the techniques that we have developed to realize surface and thickness profile measurement of a transparent film by means of optical interferometry.

2. PROFILING OF A THICK TRANSPARENT FILM BY WHITE-LIGHT INTERFEROMETRY

2.1 White-light interferometry

Figure 1 shows the optical section of a microscopic surface profiler using white-light interferometry.

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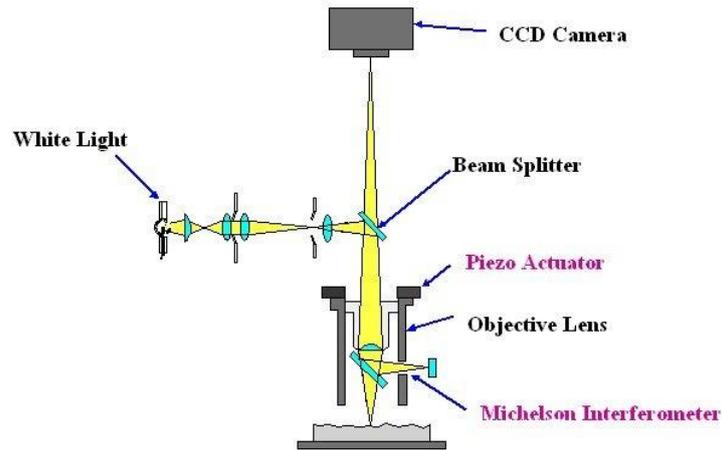


Figure 1. Schematic illustration of an interference microscope.

The equipment uses white light as the light source, and when it performs a vertical scan along the Z-axis of the interference microscope, the intensity signal of one charge-coupled device (CCD) pixel changes, as shown in Figure 2, maximizing the modulation of the interference fringe at the point where the difference in the path length between the measurement light path and the reference light path becomes zero. By determining the Z-axis height that corresponds to the largest interference fringe modulation at every point in the TV camera, this technique measures en bloc the 3-dimensional profile in the field-of-view (FOV) of the camera.

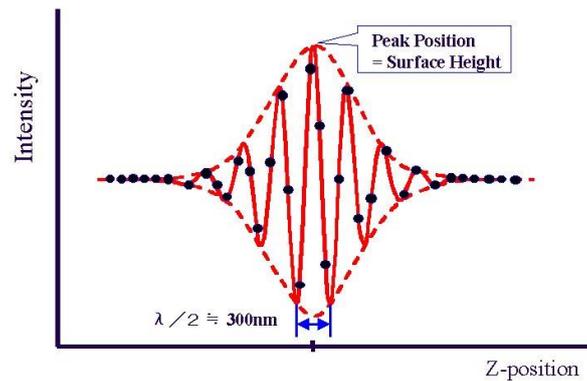


Figure 2. An example of a white-light interferogram. The black dots indicate sampled values, and the dotted line denotes the envelope.

Various algorithms have been proposed to detect the peak position of modulation,¹⁻⁵ most of which assume that the peak is single. Therefore, if a film-covered surface is measured, superposition occurs between the reflected beams from the front surface and the reflected beams from the back surface, hampering correct measurement of the surface profile.

It has long been known that, if the thickness of a transparent film is greater than the coherent length, two peaks of reflection corresponding to the front and back surfaces appear on the interferogram, allowing simultaneous measurement of film thickness and surface height variations from those peak positions.⁶⁻¹⁰

However, the methods reported to date either require visual determination of the peak positions,^{6,7} or use a complex calculation algorithm,^{9,10} and no automatic measuring device was available on the market for practical use until our development of such a device in 2002.¹¹

2.2 KF Algorithm

We developed an algorithm, the thicK Film (KF) algorithm,¹² that is able to automatically detect the positions of two contrast peaks in an interferogram generated by white-light vertical scanning interferometry (VSI). This algorithm calculates the interference amplitudes from an interferogram. The results are interpreted as a histogram, and the

automatic threshold selection method¹³ then finds the optimal threshold for peak separation. Finally, the peak position is determined for each of the distinct peak regions. We will explain this algorithm using a calculation example in the sections that follow.

2.2.1 Interferogram

An oxide film with a thickness of approximately 1 μm formed on a Si wafer was measured. A halogen lamp was used as the light source, and the Z-axis scanning speed was set at 2.4 μm/sec with a sampling interval of 0.08 μm. Figure 3 shows the obtained interferogram.

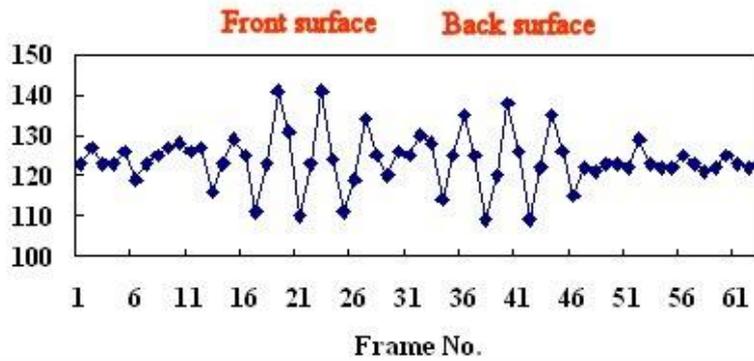


Figure 3. Interferogram used for the KF algorithm test. An oxide film with a thickness of approximately 1 μm on a Si wafer was measured. The sampling interval was 80 nm.

2.2.2 Calculation procedure

(1) Step 1: Calculation of contrast

First determine the average value of the intensity data, and then calculate the AC components by subtracting the average value from each piece of data. By squaring the AC components for the purpose of rectification, we obtain the contrast data of interference shown in Figure 4.

(2) Step 2: Separation of peaks

Taking the contrast data shown in Figure 4 as a histogram, determine the optimal threshold for peak separation, using Otsu's automatic threshold selection method in the field of processing to binary value imagery.¹³

More specifically, given a set of frequency values $n(i)$, ($i = 1, L$), where the number of observed value levels is L , and the observed value level is i , we take the intraclass variance, expressed by the following equation, as an objective function, and choose the threshold that minimizes the function:

$$f = \omega_1 \cdot \sigma_1^2 + \omega_2 \cdot \sigma_2^2, \quad (1)$$

where ω_1 and ω_2 are the frequencies of the classes, and σ_1^2 and σ_2^2 are the variances of the classes.

The values of the objective function are shown by the solid-line curve in Figure 4, with frame number 30 being the threshold.

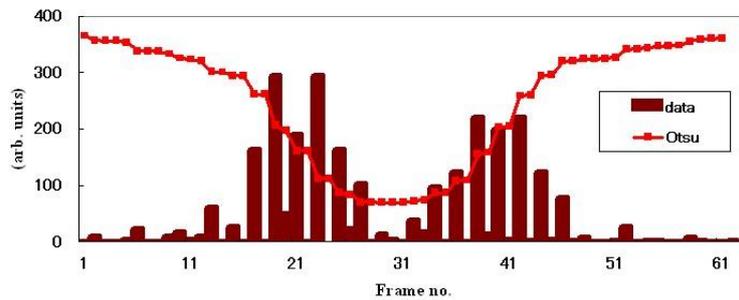


Figure 4. Contrast data and Otsu's objective function for automatic threshold selection.

(3) Step 3: Detection of peak position

Frame number 30 separates the distribution into left and right peak regions. For each region, the peak positions were detected by conventional methods.

(4) Step 4: Calculation of two surface heights and one film thickness

Let the heights converted from the peak positions be z_{p1} and z_{p2} , and let the refractive index of the film be n ; then:

- i) the surface height of the transparent film = z_{p1} ;
- ii) the film thickness $t = (z_{p1} - z_{p2})/n$; and
- iii) the back-surface height of the film = $z_{p1} - t$.

2.3 Film profiler with the KF algorithm

Using the KF algorithm, we developed the non-contact Film Profiler SP-500F shown in Figure 5, which allows simultaneous measurement of the front and back surface topography and the thickness variation of a transparent film.

This development allows the following measurements, which are difficult to perform under conventional methods:

- (1) profiling of a surface covered with a transparent film;
- (2) profiling of a bottom surface through a transparent film; and
- (3) 2-D measurement of film thickness distribution.

This system has already been introduced and used effectively in the semiconductor, LCD and film manufacturing processes.¹¹



Figure 5. SP-500F Film Profiler.

2.4 Range of measurable film thickness

The KF method of measurement has a lower limit of measurable film thickness because it is based on the assumption that interferogram peaks can be separated. Oxide films with a thickness of 0.5-2 μm on a Si wafer were measured, and the minimum measurable thickness was found to be approximately 0.8 μm . Figure 6 shows the interferogram of a 0.77 μm oxide film, which is the lowest measurable range to date.

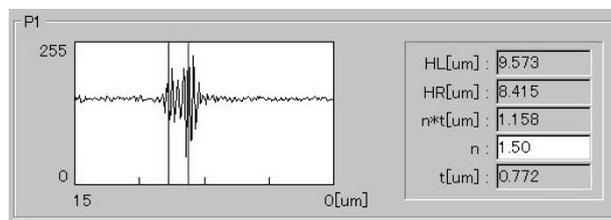


Figure 6. Interferogram of an oxide film on a Si wafer. The measured thickness was 0.77 μm .

2.5 Examples of Measurements

2.5.1 Steps in film thickness

A step in an oxide film formed on a Si wafer was measured, and the results are shown in 3-D representation in Figure 7. The measured surface step was $2.9\ \mu\text{m}$, and the film thickness was $4.0\ \mu\text{m}$ in the higher area and $1.1\ \mu\text{m}$ in the lower area. These thickness values agreed fully with the measurements obtained by ellipsometry. It was also found that the back surface was correctly measured as a flat surface with a supposed refractive index of 1.46.

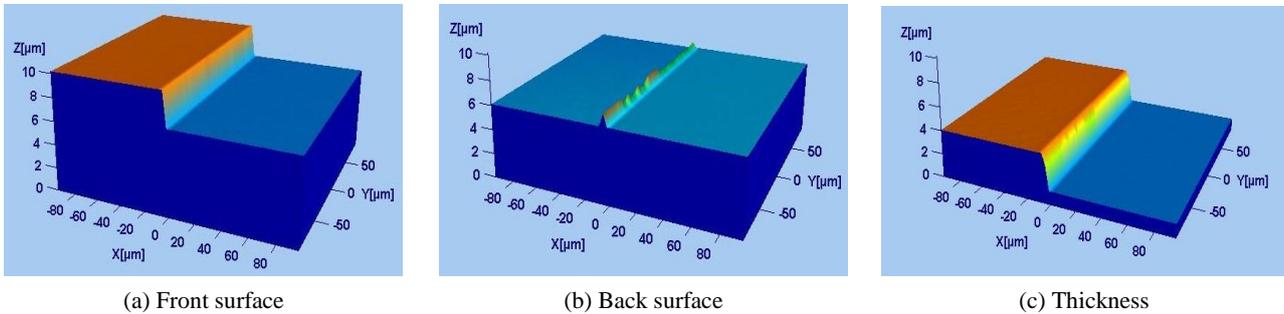


Figure 7. Measurement results of a SiO_2 film step on a Si wafer.

2.5.2 Resist film with an unknown refractive index

The thickness distribution of a resist film on a glass plate was measured. Since the refractive index of the resist film was unknown, part of the film was peeled off, and the film profile was then measured. The surface step, which is equal to the physical thickness (t), was approximately $1.6\ \mu\text{m}$ at the peeled portion, and the optical thickness ($n \cdot t$) was about $3.0\ \mu\text{m}$. These measurements allowed us to estimate the refractive index (n) at approximately 1.9.

The accuracy of the refractive index can be justified by the fact that the plate surface of the peeled portion and the back surface of the film are flush on the same plane. The back surface profiles calculated with three different refractive indexes are shown in Figure 8. A visual estimation gives a result of $n = 1.90 \pm 0.02$.

The film thickness and back surface height were then recalculated with the obtained refractive index; the results are shown in Figure 9.

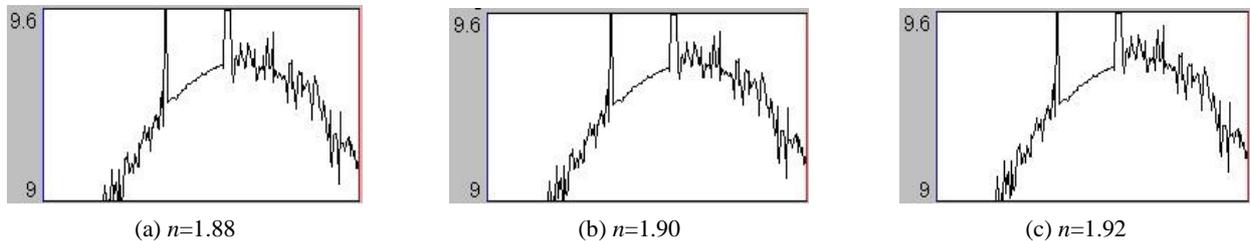


Figure 8. Back surface profiles calculated with different refractive indexes (n). The peeled area is located at center left.

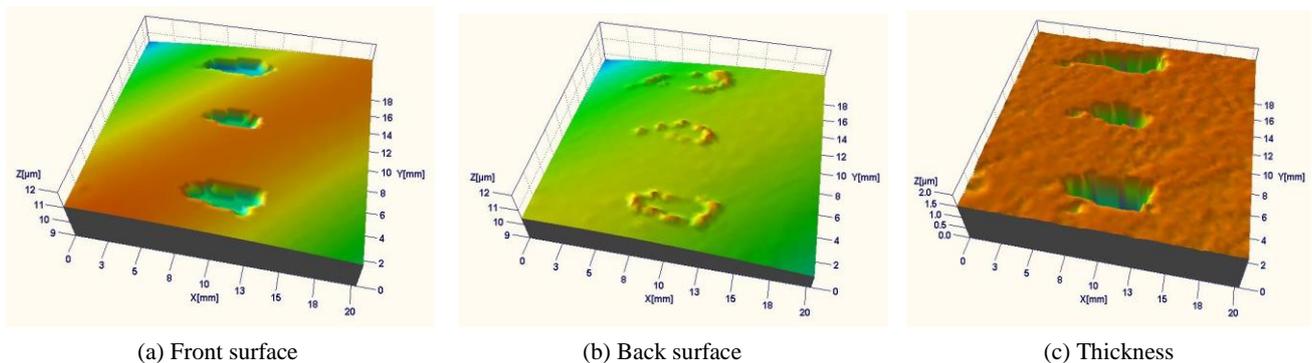


Figure 9. Measurements of a resist film.

2.5.3 Repeatability of measurement

An oxide film on a Si wafer was measured repeatedly, giving the results shown in Figure 10. The measurement of film thickness produced the following data: mean value = 4.609 μm ; standard deviation (σ) = 17 nm; and CV value = 0.36%.

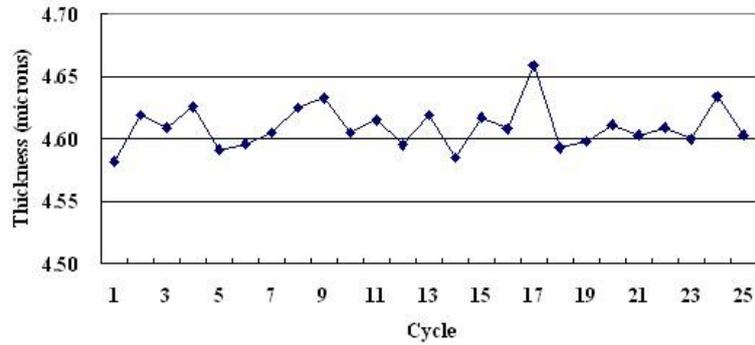


Figure 10. Repeatability of film thickness measurement.

3. PROFILING OF A THIN TRANSPARENT FILM

When a film becomes very thin, the KF algorithm can no longer be applied due to the overlap of two interference peaks. To solve this problem, several methods have been proposed,¹⁴⁻¹⁶ but as yet, there is no appropriate commercial product on the market. We developed an algorithm, the thin Film (NF) algorithm, which can measure the 3-D surface profiles of a surface covered by a thin film, and is robust enough for practical use in industry. Using this algorithm, we developed the non-contact Surface Profiler SP-700 for thin film-covered surfaces. Oxide films with a thickness of 0-2,000 nm on a Si wafer were measured, and the minimum measurable thickness was found to be 10-50 nm.

3.1 Measurement of an oxide thin film step

An oxide thin film step with thicknesses of 100 and 300 nm was prepared on a Si wafer. The test results given in Figure 12 show good agreement between the obtained and predicted values.

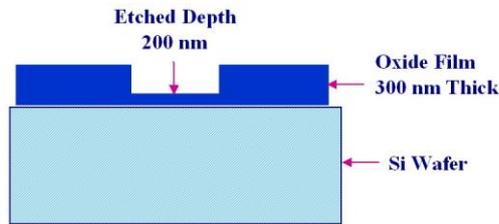
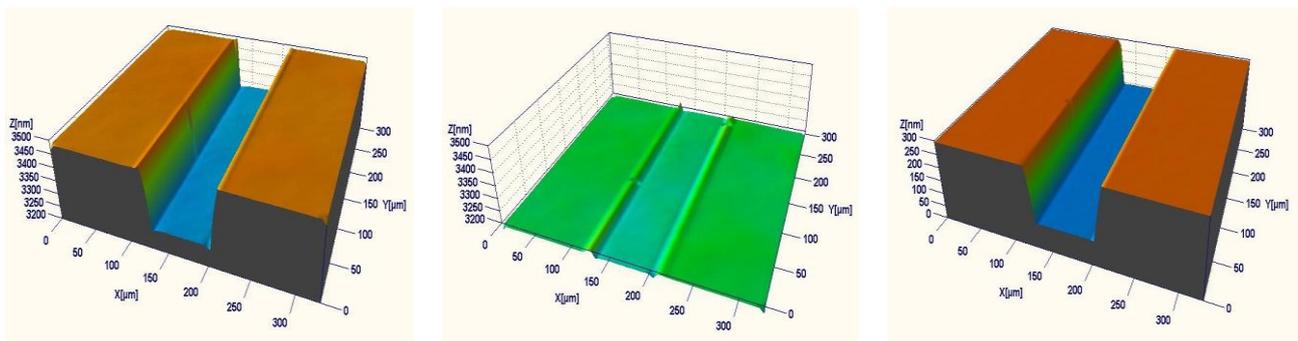


Figure 11. Cross-section of the thin film sample.



(a) Front surface

(b) Back surface

(c) Thickness

Figure 12. Thin film measurement results.

The repeatability of the film thickness measurement is shown in Figure 13. The thickness was an average of 10x10 pixels. The average and sigma of 25 repeated measurements were 301.5 nm +/- 0.21 nm for the thicker film, and 99.3 nm +/- 0.30 nm for the thinner film.

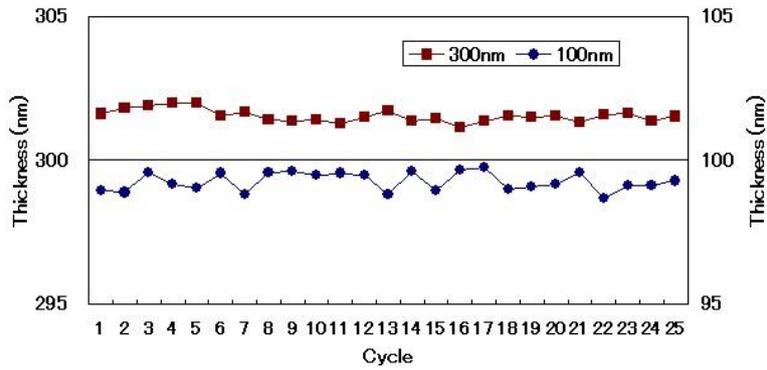


Figure 13. Repeatability of thin film thickness measurement.

3.2 Measurement of CMP samples

Figure 14 shows the measurement results of oxide chemical mechanical polishing (CMP) samples with three different polish times (0 sec, 20 sec and 60 sec). The front surface profiles show rapid change due to the polish. The back surface profiles, on the other hand, show no change because polishing occurs only within the oxide film layer. Figure 15 shows the detailed top surface profile of the 60-sec sample. The film thicknesses underneath are 466 nm at the center area and 740 nm in the surrounding area. From this simultaneous measurement of surface topography and film thickness distribution, we can obtain fast, vital and unique information on the CMP process.

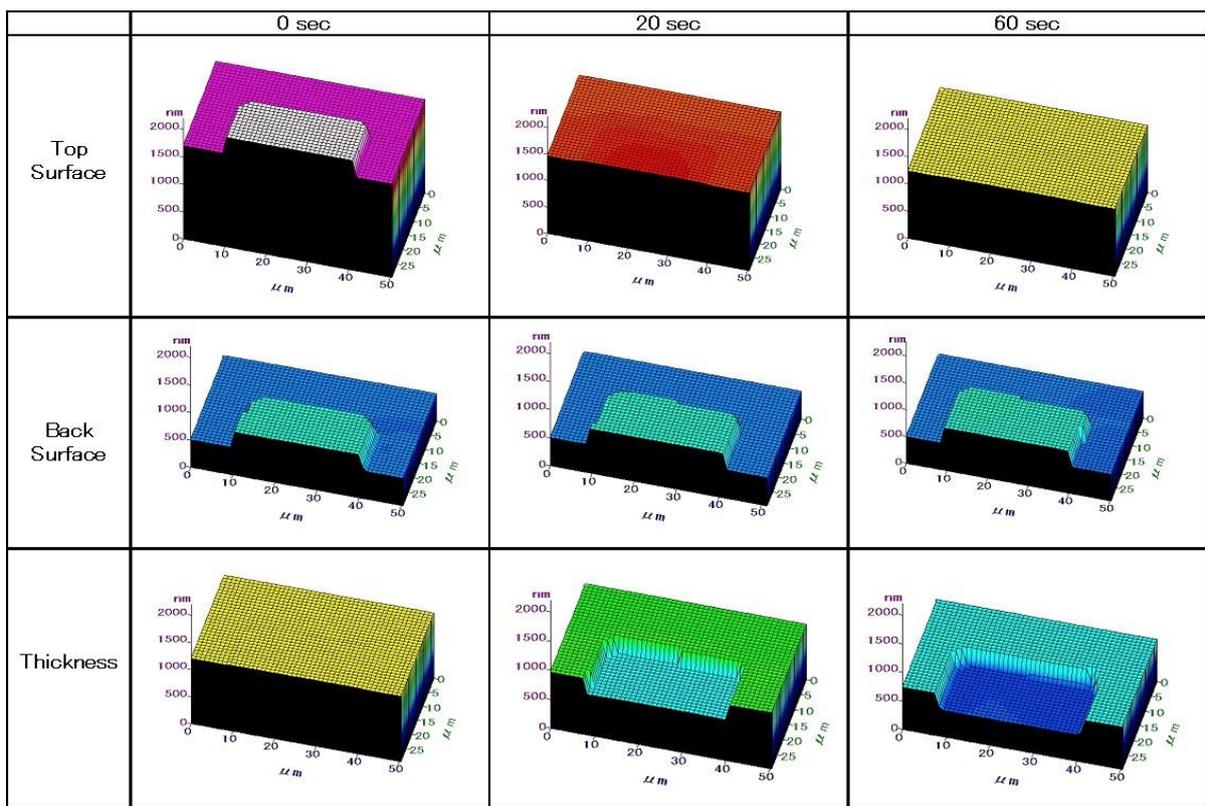


Figure 14. Measurement results of three CMP samples.

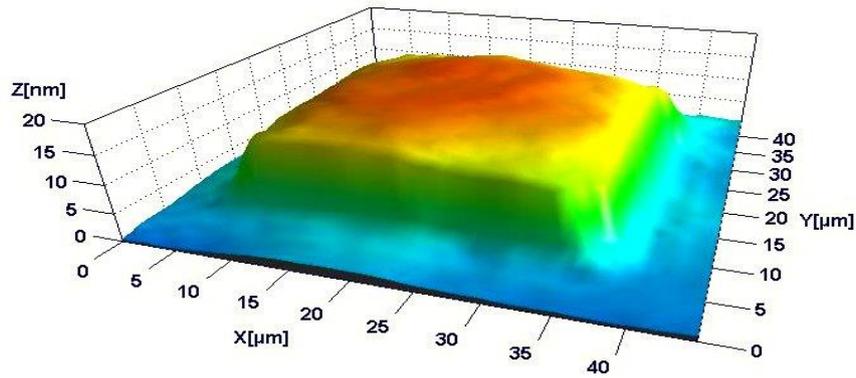


Figure 15. Detailed top surface profile of the 60-sec CMP sample measured by the SP-700. The height of the pattern is on the order of 10 nm, and the film thickness underneath is 460-740 nm.

4. FILM THICKNESS PROFILING BY PSEUDO-TRANSMISSION INTERFEROMETRY

4.1 Principle of the TF method

When we measure a freestanding film like a plastic film, there is another approach. This method, the Transmission Film (TF) method,¹⁷ measures a reasonably flat mirror surface with a sample film placed on it halfway into the FOV. The surface through the film is then measured at a point lower than the surface without the film by $(n-1)*t$, as shown in Figure 16, because of the optical path difference (D) between air and the film. If the refractive index (n) is known, the thickness (t) is calculated from the optical path difference.

If the working distance is not long enough to insert the sample halfway in the FOV, we can obtain the optical path difference by two successive measurements, the first obtained without the film and the second obtained with the sample.

Since any conventional technique for measuring a flat surface, such as phase-shift interferometry, can be used in this technique, measurement of sub-nm thickness is theoretically possible. Another advantage of this technique is its robustness. Since the optical path length does not depend on the film position, its vibration or bending do not affect the measurement.

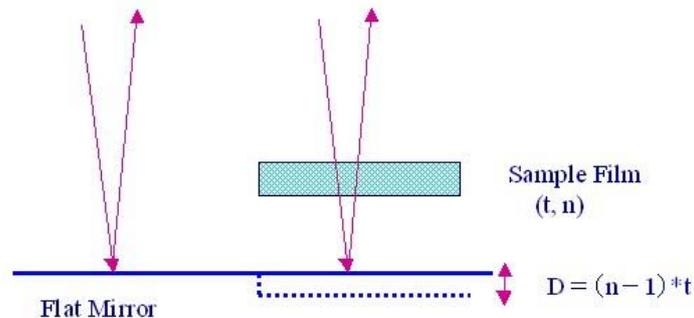


Figure 16. Principle of the TF method.

4.2 Experiments

Polyester (PET) films with thicknesses of 0.9-6.0 μm were measured using this technique. As the reference mirror, we used a metal substrate for hard disk drive. The surface was measured by white-light VSI with a scanning speed of 2.4 $\mu\text{m}/\text{sec}$. The sample was inserted only in the right half of the FOV. Figure 17 shows the measured mirror surface profile, the right half through a PET film with a nominal 0.9- μm thickness.

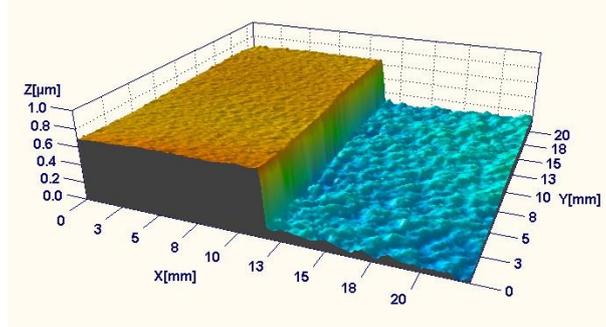


Figure 17. Measured surface profile of a mirror surface, with a PET film of a nominal 0.9- μm thickness inserted in the right half.

The average height difference between the left and right areas was 0.58 μm . From this value and the nominal refractive index of 1.65, we obtained the film thickness of 0.89 μm .

Figure 18 shows the correlation between the measured thicknesses and the nominal values. The obtained film thickness values agree well with the nominal values.

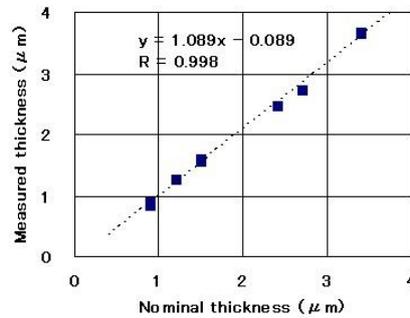


Figure 18. Correlation between the measured values and the nominal values.

5. SIMULTANEOUS MEASUREMENT OF THICKNESS AND REFRACTIVE INDEX

A freestanding polyester film nominally 1.5 μm in thickness was measured using the KF and TF methods. Figures 19 and 20 show the thickness profiles obtained by the KF and TF methods, respectively. These data were obtained using the nominal refractive index value of 1.65. The upper right corner is marker ink. The results are largely consistent with each other with the exception of the error along the film edge in the TF method, which is due to the defocus effect of the microscope.

Figure 21 shows a comparison of two thickness profiles along a certain horizontal line. Note that there is a bias between them, probably due to an error in the nominal refractive index. From this, we observe that it is possible to obtain the thickness and the refractive index simultaneously by combining the results of two measurements: the optical thickness T by the KF method, and the optical path difference D by the TF method.¹⁸

Since $T=n*t$ and $D=(n-1)*t$, the thickness (t) and the refractive index (n) can be obtained by the following equations;

$$t = T-D, \text{ and} \quad (2)$$

$$n = T/(T-D). \quad (3)$$

Figure 22 shows the obtained thickness and refractive index profiles along a horizontal line. This technique was mentioned briefly in the description of an old patent,¹⁹ but seems to have remained almost unknown until now. Compared with other proposed techniques,²⁰⁻²¹ this technique is simple and easily accomplished by a commercial surface profiler.

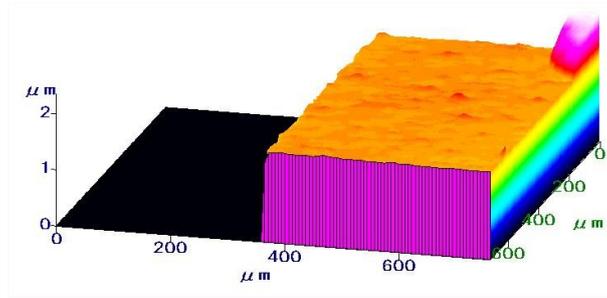


Figure 19. Film thickness profile by the KF method.

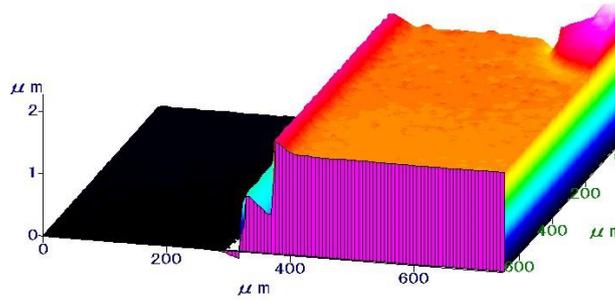


Figure 20. Film thickness profile by the TF method.

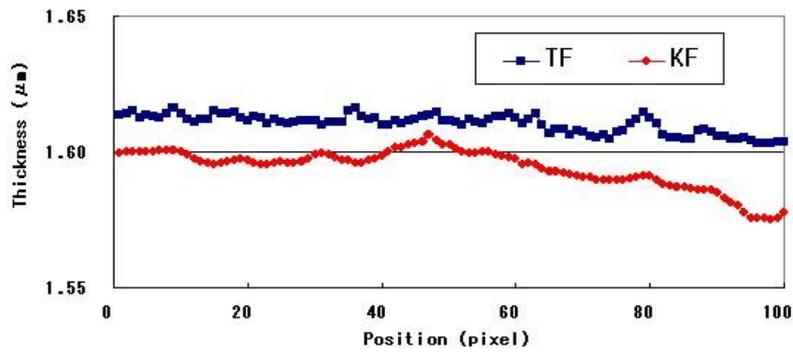


Figure 21. Film thickness profiles obtained by the TF and KF methods with a nominal refractive index.

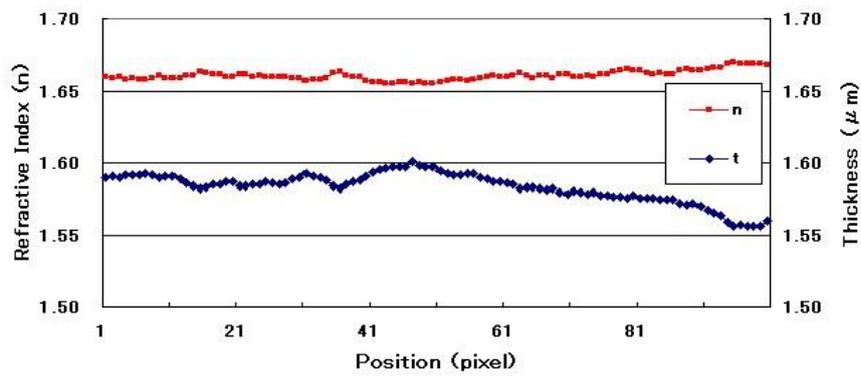


Figure 22. Film thickness and refractive index profiles calculated from the results of the KF and TF methods.

6. CONCLUSION

We have developed four techniques to measure film thickness profiles using optical interferometry: 1) profiling of a thick transparent film, 2) profiling of a thin transparent film, 3) thickness profiling of a freestanding film, and 4) simultaneous measurement of the thickness and refractive index of a freestanding film. All techniques are suitable for practical use, and the first two have already been introduced and used effectively in the semiconductor and LCD manufacturing processes.

Recent rapid advances in electronics and computer technology now allow the incorporation of newly developed, sophisticated algorithms in interferometric profilers, with dramatic results. These advances indicate the superb future potential of this technology and signal the beginning of a '2nd generation of interferometry'.

REFERENCES

1. P.J. Caber, "Interferometric profiler for rough surface," *Applied Optics* 32 (19), 3438-3441, 1993.
2. S.S.C. Chim and G.S. Kino, "Three-dimensional image realization in interference microscopy," *Applied Optics* 31 (14), 2550-2553, 1992.
3. L. Deck and P. de Groot, "High-speed non-contact profiler based on scanning white light interferometry," *Applied Optics* 33 (31), 7334-7338, 1994.
4. R. Dändliker, E. Zimmermann and G. Frosio, "Electronically scanned white-light interferometry: a novel noise-resistant signal processing," *Optics Letters* 17 (9), 679-681, 1992.
5. A. Hirabayashi, H. Ogawa and K. Kitagawa, "Fast surface profiler by white-light interferometry by use of a new algorithm based on sampling theory," *Applied Optics* 41 (23), 4876-4883, 2002.
6. P.A. Flournoy, R.W. McClure and G. Wyntjes, "White-light interferometric thickness gauge," *Applied Optics* 11 (9), 1907-1915, 1972.
7. T. Tsuruta and Y. Ichihara, "Accurate measurement of lens thickness by using white-light fringes," *Proc. ICO Conf. Opt. Methods in Sci. and Ind. Meas., Tokyo*, 369-372, 1974; *Japn. J. Appl. Phys., Suppl.* 14-1, 369-372, 1975.
8. B.S. Lee and T.C. Strand, "Profilometry with a coherence scanning microscope," *Applied Optics* 29 (26), 3784-3788, 1990.
9. O. Nakamura and K. Toyoda, "Coherence probing of the patterns under films," *Kougaku* 21 (7), 481-484, 1992 (in Japanese).
10. M. Itoh, R. Yamada, R. Tian, M. Tsai and T. Yatagai, "Broad-band light-wave correlation topography using wavelet transform," *Optical Review* 2 (2), 135-138, 1995.
11. Toray Inspection Equipment Home Page, (Toray Engineering Co., 2007), <http://www.scn.tv/userp/torayins/>.
12. K. Kitagawa, "3-D profiler of a transparent film using white-light interferometry," *Proc. of SICE Annual Conference 2004 in Sapporo*, 585-590, 2004.
13. N. Otsu, "An automatic threshold selection method based on discriminant and least squares criteria," *Trans. of IECE* 63-D (4), 349-356, 1980 (in Japanese).
14. S.W. Kim and G.H. Kim, "Thickness-profile measurement of transparent thin-film layers by white-light scanning interferometry," *Appl. Opt.* 38, 5968-73, 1999.
15. D. Kim et al., "Fast thickness profile measurement using a peak detection method based on an acousto-optic tunable filter," *Meas. Sci. Technol.* 13, L1-L5, 2002.
16. H. Akiyama, O. Sasaki and T. Suzuki, "Sinusoidal wavelength-scanning interferometer using an acousto-optic tunable filter for measurement of thickness and surface profile of a thin film," *Opt. Express* 13, 10066-10074, 2005.
17. K. Kitagawa, "Film thickness profiling by interferometric optical path difference detection," *Proc. of DIA (Dynamic Image Processing for Real Application) WS 2007*, 137-140, 2007 (in Japanese).
18. K. Kitagawa, "Simultaneous measurement of refractive index and thickness of transparent films by white-light interferometry," *Proc. of JSPE Autumn Conference, 2007* (to be published; in Japanese).
19. K.J. Kalliomaki et al., "Method and interferometer for the measurement of short distances," U.S. Patent 4647205, 1987.
20. T. Fukano and I. Yamaguchi, "Simultaneous measurement of thicknesses and refractive indices of multiple layers by a low-coherence confocal interference microscope," *Opt. Lett.* 21, 1942-1944, 1996.
21. H. Maruyama, S. Inoue, T. Mitsuyama, M. Ohmi and M. Haruna, "Low-coherence interferometer system for the simultaneous measurement of refractive index and thickness," *Appl. Opt.* 41, 1315-1322, 2002.

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