

3-D Profiling of a Transparent Film using White-Light Interferometry

Katsuichi KITAGAWA

Toray Engineering Co., Ltd., 1-1-45 Oe, Otsu, Shiga 520-2141, JAPAN

katsuichi_kitagawa@toray-eng.co.jp

Abstract: In the Vertical Scanning White-Light Interferometry, two peaks appear in the interference waveform if a transparent film exists on the surface to be measured. An algorithm has been developed that can detect the position of those peaks quickly and accurately, and a “Film Profiler” has been put into practical use, which is able to measure both the profiles of front and back surfaces and the thickness distribution of a transparent film simultaneously. This technique is applicable to transparent films with the optical thickness of approximately 1 μm or greater, and it is used effectively in semiconductor and LCD manufacturing processes.

Keywords: interferometry, white-light, surface profiler, transparent film, thickness, peak separation

1. Introduction

The technique of surface profile measurement utilizing optical interference is widely used in the industry as a non-contact and non-destructive method to quickly and accurately measure the profile of microscopic surfaces. However, it involves a shortcoming of being unable to obtain an exact surface profile in measurement if the surface to be measured is covered with a transparent film. This is because the interference beams coming from the back surface of the film work as disturbance.

This paper introduces the result of a study about a signal-processing algorithm to realize measurement of the profile of surfaces covered with a transparent film by means of White-Light Interferometry (also called “Vertical Scanning Interferometry”), and it also describes a non-contact Film Profiler, SP-500F, which incorporates the idea.

2. Principle of Measurement

The optical section of the equipment is shown in Figure 1.

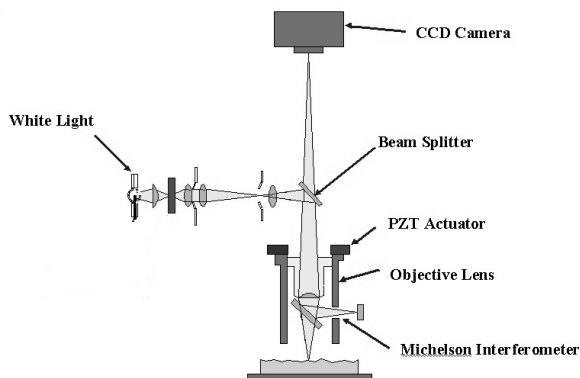


Figure 1. Schematic of an interference microscope

The equipment uses white light having a short coherent length as the light source, and when it performs vertical scan along the Z-axis of interference microscope, the intensity signal of one CCD pixel changes as shown in Figure 2 (called an interferogram), maximizing the modulation of interference fringe at the point where the difference in the path length between the measurement light path and the reference light path becomes zero. Determining the Z-axis height that brings the largest modulation of interference fringe 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.

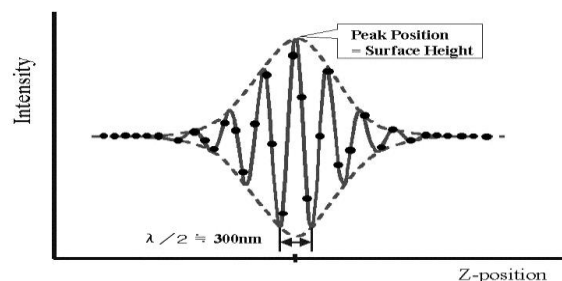


Figure 2. An example of a white-light interferogram. Black dots show sampled values, and dotted line denotes the envelope.

For the algorithm to detect the peak position of modulation, various methods have been proposed, including the smoothing method ¹⁾, Hilbert-transform method ²⁾, Fourier-transform-phase method ³⁾, centroid method (center of gravity method) ⁴⁾, and signal restoration method ⁵⁾, most of which assume 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 been known for long that, if the thickness of a transparent film is greater than the coherent length, two peaks of reflection on the front and back surfaces appear in the interferogram, enabling measurement of thickness and profile of the film from those peak positions.^{6) - 10)}

However, those methods reported so far require visual determination of peak positions^{6) 7)}, or use a complex calculation algorithm^{9) 10)}, and now no automatic measuring devices for practical applications are found in the market. The author tried to develop a practical algorithm that detects plural peak positions in the interferogram to enable fully automatic measurement of thickness and profiles of a film-covered surface.

3. Development of Algorithm and Result of Experiment

3.1 Test data

Using the surface profiler, SP-500^{5) 11)}, a transparent film was measured and an interferogram was collected as shown in Figure 3. The measurement was conducted under the following conditions:

- (1) Illumination: A halogen lamp was used as the light source because a shorter coherent length is convenient for separation of peaks. The coherent length was approximately 1 μm .
- (2) Speed of Z-axis scanning: The speed was set to 2.4 $\mu\text{m}/\text{sec}$ (sampling interval = 0.08 μm). This interval broadly corresponded to a quarter of the period of interferogram.
- (3) Subject for measurement: An oxide film with thickness (D) of about 1 μm formed on a Si wafer was measured. The optical thickness (n·D) was about 1.5 μm because the refractive index (n) was about 1.5. Since the coherent length was about 1 μm , the value was considered to be near to the lower limit that still permits separation of peaks. In addition, semiconductor and LCD processes use various kinds of transparent films having a several- μm thickness, such as resist films and coating films, and therefore, it was meaningful in a practical sense to select films with thickness of several micrometers as the subject for measurement.
- (4) Range of scanning: 5 μm . Since the number of images is $5/0.08 = 63$, the time of measurement (scanning) is approximately 2 seconds when a standard camera of 30 fps is used.

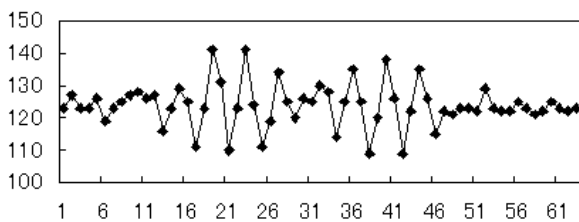


Figure 3. Interferogram used for algorithm test

3.2 Calculation algorithm: Peak separation method¹²⁾

This algorithm calculates the interference amplitudes from interferogram, and takes the result as a histogram, and then the automatic threshold selection method finds out the optimal threshold for peak separation, and finally the peak position is determined for each of the separated peak regions.

3.2.1 Procedure of calculation

- (1) Step 1: Calculation of AC components

First determine the average value of intensity data, and then calculate the AC components by subtracting the average value from each data. The result is shown in Figure 4.

- (2) Step 2: Calculation of amplitude

Square the AC components for the purpose of rectification. The result is shown in Figure 5.

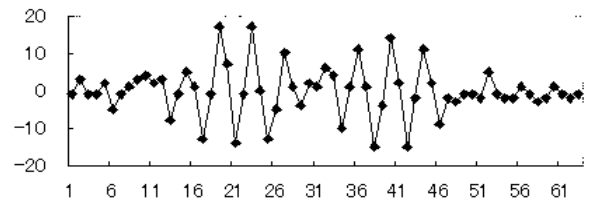


Figure 4. AC components of intensity signals

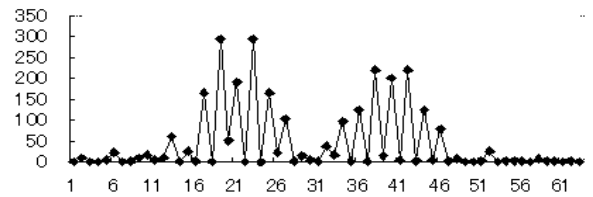


Figure 5. Squared values of AC components

- (3) Step 3: Separation of peaks

Taking the waveform data of Figure 5 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 particularly, 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 , 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 : the frequency of the classes, and

σ_1^2 and σ_2^2 : the variance of classes.

The values of the objective function are shown by the solid-line curve in Figure 6, with the data number 30 being the threshold.

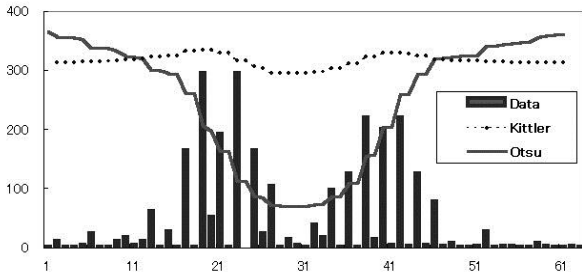


Figure 6. Two objective functions for threshold selection. Solid line denotes the Otsu's method; Dotted line denotes the Kittler's method.

(4) Step 4: Detection of peak position

Data number 30 separates the distribution into left and right peak regions. For each of the separated regions, the peak positions were detected by a conventional method. Here the waveform was smoothed, using the low-pass filter method, the most common method of peak position detection. The calculation equation used in a smoothing method was a 19-point quadratic polynomial equation, as expressed by the following equation:

$$y(n) = (1/W) \sum [w(i) \cdot x(n+i)] \quad (2)$$

where $i = 0, \pm 1, \pm 2, \dots, \pm 9$; W , a normalizing coefficient, is the sum total of $w(i)$; $w(i)$ is the weighting factor, and the actual values are 269, 264, 249, 224, 189, 144, 89, 24, -51, and -136 starting from $w(0)$ for 19-point method.

This calculation resulted in a smoothed curve, as shown in Figure 7, with two peak positions located at data numbers 21 and 40. Further, a quadratic curve was applied to three data points in the vicinity of peaks in order to determine interpolated peak positions, with the resolution being smaller than the sampling interval, obtaining values of 21.17 and 39.61.

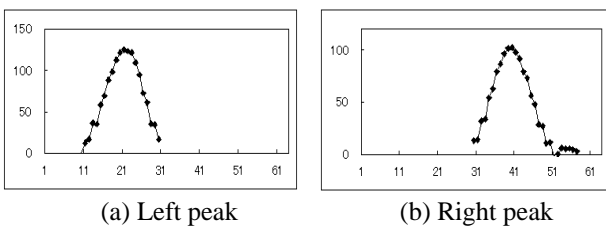


Figure 7. Result of peak smoothing after peak separation

(5) Step 5: Calculation of two surface heights and 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 , and then:

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

This test, carried out with the peak positions at 21.17 and 39.61, the sampling interval of $0.08 \mu\text{m}$, and the film refractive index of $n = 1.5$, brought a surface height = $3.31 \mu\text{m}$, a film thickness = $0.98 \mu\text{m}$, and a back surface height = $2.33 \mu\text{m}$.

3.2.2 Comparison of peak separation algorithms

Besides the above-mentioned Otsu's method, we have a method of Kittler et al.¹³⁾ as another algorithm for automatic threshold selection based on the gray-level histogram.

The Kittler method takes the following equation as the objective function in stead of equation (1):

$$f = \omega_1 \cdot \log(\sigma_1/\omega_1) + \omega_2 \cdot \log(\sigma_2/\omega_2) \quad (3)$$

Comparison was made between these two methods for various cases. For the data of this experiment, both methods make no difference as shown in Figure 6. Figures 8(a) to 8(c) show other cases. A case of greater difference between peak heights is shown in Figure 8(a), and a case of smaller peak interval is shown in Figure 8(b). In both cases, the Otsu's method is better than the Kittler's method. The Kittler method is more effective when the variances of two peaks are much different from each other as shown in Figure 8(c). For interference waveform, however, little difference is found normally in the variances. Therefore, the Otsu's method was adopted.

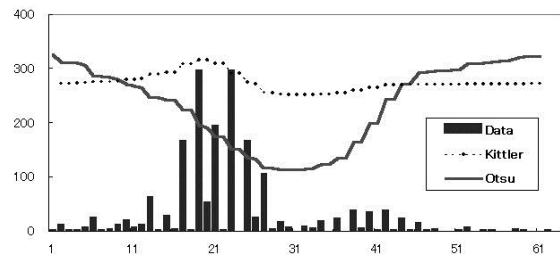


Figure 8(a). Two objective functions for threshold selection: A case of greater difference between peak heights. Solid line denotes the Otsu's method; Dotted line denotes the Kittler's method.

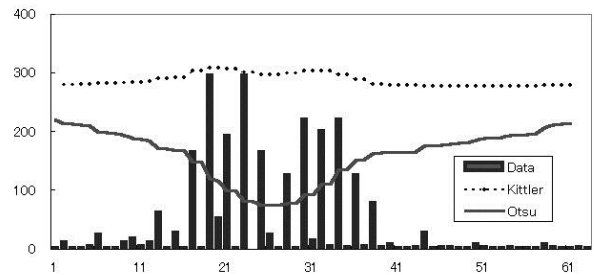


Figure 8(b). Two objective functions for threshold selection: A case of smaller peak interval: Solid line denotes the Otsu's method; Dotted line denotes the Kittler's method.

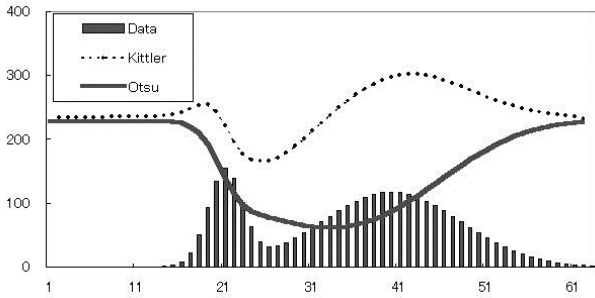
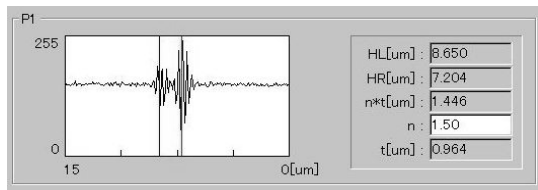


Figure 8(c). Two objective functions for threshold selection: A case with large difference in variance: Solid line denotes the Otsu's method; Dotted line denotes the Kittler's method.

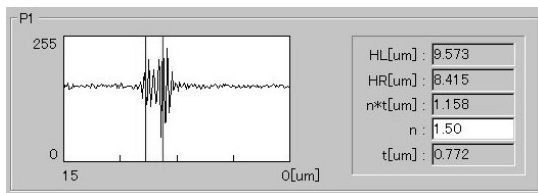
4. Range of Measurable Film Thickness

This method of measurement has a lower limit to measurable film thickness because it is based on an assumption that peaks of interferogram can be separated.

Oxide films with 0.5-2 μm thickness on a Si wafer were measured, and the minimum measurable thickness was found to be about 0.8 μm . Figure 9 shows two example of interferograms.



(a) Thickness = 0.96 μm



(b) Thickness = 0.77 μm

Figure 9. Interferograms of oxide films on Si wafer

5. Film Profiler, SP-500F

A piece of software that deals with transparent films, based on the above Algorithm, was installed in the surface profiler SP-500¹¹⁾, and a Film Profiler SP-500F, shown in Figure 10, was developed. Major specifications are listed in Table 1.

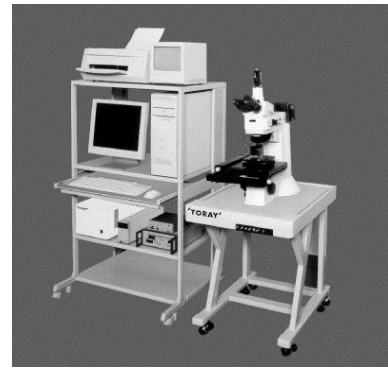


Figure 10. Film Profiler SP-500F

Table 1. Major specifications of Film Profiler, SP-500F

Measurement Technique	Vertical Scanning Interferometry
Algorithm	Film Surface & Thickness Profiling Algorithm; Patent-Pending
Measurement Functions	Surface Profile, Back Surface Profile and Film Thickness Profile
Range of Measurement	0 to 100 μm (Optional: 0 to 350 μm)
Thickness Range	1 to 50 μm (optical thickness)
Objectives	Selectable from 2.5 \times , 5 \times , 10 \times , 20 \times , 50 \times
Measurement Speed	Dependent on the various parameters (typ. 10 sec)
Vertical Resolution	1 nm (Display Unit)
Thickness Measurement Repeatability	on the order of 0.1 % (CV)
Measurement Array	Selectable from 512 \times 480, 256 \times 240, 128 \times 120 (Optional: max. 1376 \times 1040)
Computer System/OS	PC/Windows NT

6. Examples of Measurements

6.1 Step in film thickness

A step in oxide film formed on a Si wafer was measured, and the result is shown in 3-D representation in Figure 11. The measured surface step was 2.9 μm , and the film thickness was 4.0 μm in the higher area and 1.1 μm in the lower area. These thickness values completely agreed with the measurement by ellipsometry. It is also shown that the back surface was correctly measured as a flat surface, with the supposed refractive index of 1.46.

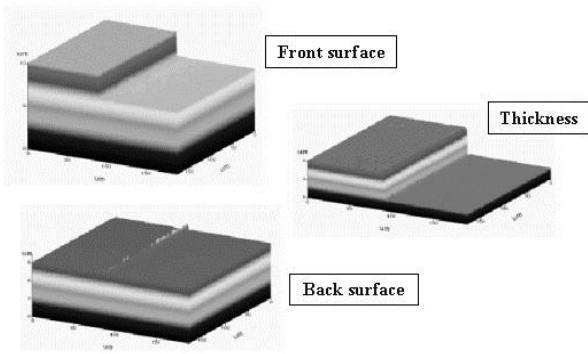


Figure 11. Measurement of a step in film thickness

6.2 Tapered film

A tapered oxide film formed on a Si wafer was measured, and the result is shown in Figure 12. Conspicuously warped concave front and back surfaces, and tapered thickness profile of the film were measured.

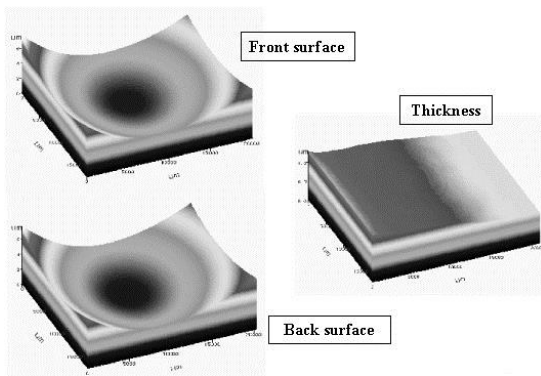


Figure 12. Measurement of a tapered film

6.3 LCD cell gap

Measurement result of cell gap of an 8-segment LCD is shown in Figure 13. A 20 mm field-of-view interferometer was used. The cell gap distribution of approximately $5\ \mu\text{m}$ was measured en bloc through the thick glass plate.

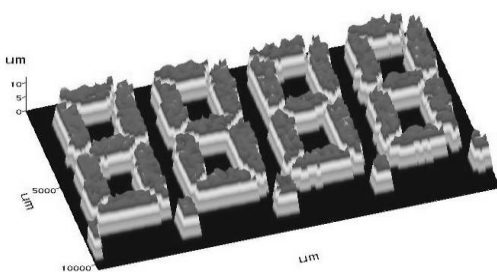


Figure 13. Measurement of cell gap

6.4 Measurement of resist film with 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 then the film profile was measured. The surface step, which is equal to the physical thickness (D), at the peeled portion was about $1.6\ \mu\text{m}$, and the optical thickness ($n \cdot D$) was about $3.0\ \mu\text{m}$. These measurements allowed us to estimate the refractive index (n) to be about 1.9.

The correctness 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 14. Visual estimation can suppose it to be $n = 1.90 \pm 0.02$.

Then the film thickness and the back surface height were recalculated with the obtained refractive index, and the results are shown in Figure 15.

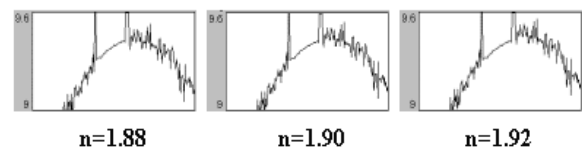
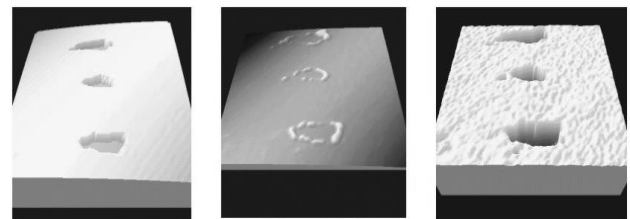


Figure 14. Back surface profiles calculated with different refractive indexes (n). Peeled area is located at center left.



(a) Front surface (b) Back surface (c) Thickness

Figure 15. Measurement of resist film

6.5 Measurement of water droplet surface

The profile of water droplet on a glass plate was measured, and the result is shown in Figure 16.

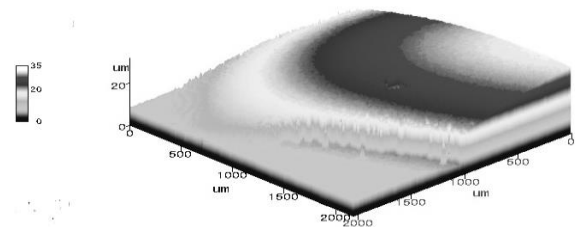


Figure 16. Measurement of water droplet

6.6 Repeatability of measurement

An oxide film formed on a Si wafer was measured repeatedly, of which result is shown in Figure 17. The measurement of film thickness produced the following data:

mean value = 4.609 μm ; standard deviation(σ) = 17 nm; and CV value = 0.36%.

In practical cases, the area-average thickness is often significant, and therefore, on a resist film, averaging was made in the area consisting of approximately 4000 pixels, which obtained the mean value = 1.526 μm ; standard deviation(σ) = 3.4 nm and CV value = 0.2%.

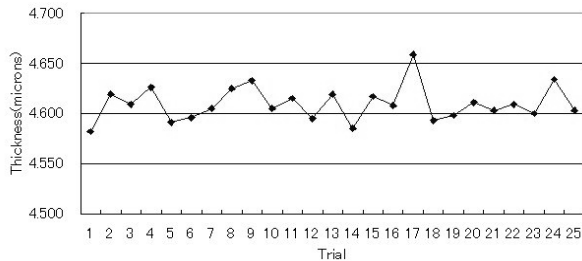


Figure 17. Repeatability of film thickness measurement

7. Conclusion

An algorithm has been devised that can automatically detect the positions of two contrast peaks in an interferogram generated by vertical scanning white-light interferometry. Using this algorithm, we have developed a non-contact Film Profiler, SP-500F, which enables simultaneous measurement of the front and back surface topography and the thickness variation of a transparent film.

This development enables the following measurement, which conventionally could hardly be available:

- (1) Measurement of profile of a surface covered with a transparent film, and
- (2) 2D measurement of film thickness distribution.

This system has already been introduced and effectively used in semiconductor and LCD manufacturing processes.

Acknowledgements

The author would like to thank Prof. Hidemitsu Ogawa of Tokyo Institute of Technology for valuable discussions.

References

- [1] P.J.Caber, Interferometric profiler for rough surface, Applied Optics, Vol.32, No.19, pp.3438-3441, 1993.
- [2] S.S.C.Chim and G.S.Kino, Three-dimensional image realization in interference microscopy, Applied Optics, Vol.31, No.14., pp.2550-2553, 1992.
- [3] P. de Groot and L.Deck, Three-dimensional imaging by sub-Nyquist sampling of white-light interferograms, Optics Letters, Vol.18, No.17, pp.1462-1464, 1993.
- [4] R.Dändliker, E.Zimmermann and G.Frosio, Electronically scanned white-light interferometry: a novel noise-resistant signal processing, Optics Letters, Vol.17, No. 9, pp.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, Vol.41, No.23, pp.4876-4883, 2002.
- [6] P.A.Flournoy, R.W.McClure and G.Wyntjes, White-Light Interferometric Thickness Gauge, Applied Optics, Vol.11, No. 9, pp.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, pp.369-372, 1974.; Japn. J. Appl. Phys., Suppl., Vol.14-1, pp.369-372, 1975.
- [8] B.S.Lee and T.C.Strand, Profilometry with a coherence scanning microscope, Applied Optics, Vol.29, No. 26, pp.3784-3788, 1990.
- [9] O.Nakamura and K.Toyoda, Coherence Probing of the Patterns under Films, Kougaku, Vol.21, No. 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, Vol.2, No. 2, pp. 135-138, 1995.
- [11] Toray Inspection Equipment Home Page: <http://www.scn.tv/corp/torayins/>
- [12] Patent Pending
- [13] M.Takagi and H.Shimoda ed., Handbook of Image Analysis, Tokyo Univ. Press, pp.503-504, 1991. (in Japanese).

This is the final manuscript of

Katsuichi Kitagawa: 3-D profiling of a transparent film using white-light interferometry, Proc. of SICE Annual Conference 2004 in Sapporo, TAI-7-2, 585-590 (August 2004)