Recent Trends in White-Light Interferometry

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ABSTRACT

The technique of surface profile measurement utilizing white-light interferometry is widely used in industry. However, it has certain shortcomings, such as slow measurement speed and the possibility of error caused by a transparent film on the surface. This paper introduces four of our recent developments in white-light interferometry: 1) speed improvement by sub-Nyquist sampling, 2) accuracy improvement through the use of phase information, 3) profiling of a thick transparent film, and 4) profiling of a thin transparent film.

Keywords: interferometry, white-light, surface profiler, transparent film, sub-Nyquist sampling

1. INTRODUCTION

The technique of surface profile measurement utilizing white-light interferometry (WLI) is widely used in industry as a non-contact, non-destructive method to quickly and accurately measure the profile of microscopic surfaces. However, it has certain shortcomings, including slow measurement speed, poor accuracy in comparison with phase shift interferometry (PSI), and the possibility of error caused by a transparent film on the surface.

Recent rapid advances in electronics and computer technology now allow the use of much more sophisticated algorithms, which would have been impractical ten years ago, to solve these problems. As a result, far more effective commercial products are now possible.

In this paper, we review some of our recent developments in WLI.

2. SPEED IMPROVEMENT BY SUB-NYQUIST SAMPLING

2.1 SEST algorithm

We have developed a new signal processing algorithm named SEST (Squared-Envelope function estimation by Sampling Theory).^{1,2} This algorithm is based on the fact that the interference fringe waveform can be reconstructed from sub-Nyquist sampled data using the sampling theorem for band-pass signals.³ The concept of the SEST algorithm is shown in Figure 1.



Speed-up: Direct Calculation of Envelope

Figure 1. Concept of the SEST algorithm.

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For this algorithm, the wavelength of the white light is limited to a narrow range by a band-pass filter in the illumination. When the frequency bandwidth of the interferogram is limited to $\lambda_c \pm \lambda_b$, the AC component of the interferogram can be reconstructed from its sampled data $y_m \square (m=1,2,...,M)$ by

$$f(z) = \sum_{m=1}^{M} y_m \phi_m(z),$$
 (1)

where f(z) is the AC component of the interferogram, y_m is the sampled data of the AC component defined by $y_m = f(z_m)$, z_m is the *m*-th sampling point, and $\phi_m(z)$ is defined by

$$\phi_m(z) = \sin\left(\frac{\pi(z-z_m)}{2\Delta}\right) \cos\left(\frac{4\pi(z-z_m)}{\lambda_c}\right), \qquad (2)$$

where Δ is the sampling interval, which must satisfy certain conditions, and its maximum Δ_{max} is expressed as

$$\Delta_{max} = \frac{1}{4} \left[\frac{\lambda_c + \lambda_b}{2\lambda_b} \right] (\lambda_c - \lambda_b).$$
(3)

For example, in the case of $\lambda_c = 600$ nm and $\lambda_b = 20$ nm, the maximum interval Δ_{max} becomes 2.175 µm, which is 15 times wider than the Nyquist interval.

By squaring the envelope of the reconstructed interferogram, we obtain a smooth function r(z) (the squared envelope function) to find the peak position.

However, for the purpose of surface profiling, only the peak position of r(z) is needed and the reconstructed interferogram is unnecessary. Therefore, we created a formula to calculate the estimated value $r_B(z)$ of r(z) directly from the sampled data. For example, when z is one of the sampled points, namely $z=z_j$ (j=1,2,...,M), the formula becomes a simple one that requires only algebraic computation:

$$r_B(z_j) = (y_j)^2 + (4/\pi^2) \left\{ \sum_{m=1}^{M} \left\{ y_m / (j-m) \right\} \right\}^2.$$
(4)

The value z where the squared envelope function r(z) becomes the maximum can be obtained by calculating $r_B(z)$ at the sample points by Equation (4) and seeking the peak in the vicinity of the maximum value.

As a result, the number of required sample points can be reduced to one-tenth or less of that of the conventional method.

The utilization of this algorithm led to the world's fastest scanning speed of over 50 μ m/sec, which is seven to fifteen times faster than the speeds obtained with conventional algorithms.

2.2 Measurements

Using this algorithm, we developed the non-contact Surface Profiler SP-500.⁴ Figure 2 shows an example of a reconstructed waveform and envelope; Figure 3 shows the measurement result of integrated circuit (IC) bumps on a Si wafer obtained with a 54- μ m/sec scanning speed; and Figure 4 shows the experimental relation between repeatability and scanning speed. As mentioned above, the sampling interval must satisfy certain conditions theoretically, and the integer multiples of the Nyquist interval fall within unacceptable zones. Thus, repeatability changes periodically with the sampling interval, and the best intervals are the centers of the acceptable zones, that is, odd multiples of half the Nyquist interval.



Figure 2. Sampled data, reconstructed waveform and envelope.



Figure 3. Measurement result of IC bumps using the SEST algorithm with a 54-µm/sec scan speed.



Figure 4. Repeatability vs. scanning speed of the SEST algorithm. Repeatability is shown as one sigma of the pixel-pixel height difference on an 8-µm step under different sampling intervals.

3. ACCURACY IMPROVEMENT BY USING PHASE INFORMATION

3.1 WSI algorithm

Most conventional WLI profilers obtain the surface height by detecting the envelope peak of the interferogram and have poorer accuracy than PSI techniques. Nevertheless, measurement accuracy can be improved by using phase information. This technique, sometimes called WLPSI, first finds the envelope peak frame (N_p) , and then calculates the relative phase (φ_r) at the position, finally obtaining the height (z) by the following equation;

$$z = N_p \cdot \varDelta - (\lambda / 4\pi) \varphi_r, \tag{5}$$

where Δ is the sampling interval, and λ is the wavelength of illumination.

Although this theoretical possibility has been known for a long time ⁵⁻⁷ and has been expected to have the advantages of both the vertical scanning interferometry (VSI) and PSI methods, its practical use was not accomplished until recently, probably because of its weak robustness.⁸ We have developed an algorithm, named WSI (White-light Scanning Interferometry), which utilizes information on both amplitude and phase in an interferogram. Table 1 gives a comparison of the VSI, PSI and WSI methods.

Method	VSI	PSI	WSI
Light	White	Monochromatic	White
Principle	Peak	Phase	Peak & Phase
Surface	Any	Smooth only	Any
Accuracy	10 nm typ.	0.01 nm typ.	1 nm typ.
Scan Speed	Any		2.4 um/sec typ.
Calc. Time	Long	Short	Medium

Table 1. Comparison of three methods.

3.2 Measurement results

Figure 5 shows a comparison of the measurement results of a 1-µm step height obtained by the WSI and VSI methods. Since we used the same image data, the difference depends only on the algorithms, and we found that the WSI method provides approximately 10 times better accuracy than the conventional VSI method.

Although the WSI algorithm gives good results for smooth surfaces, it sometimes exhibits the so-called 2π jump problem for rough surfaces. We have confirmed that this problem is caused by the offset phenomenon between the phase and the fringe peak position, which has been mentioned in some papers.⁸⁻¹⁰ The optical analysis and the algorithm necessary to solve this problem remain to be investigated.



Figure 5. Measurement of step height using the WSI algorithm, compared with the VSI algorithm.

4. PROFILING OF A THICK TRANSPARENT FILM

4.1 KF algorithm

To detect the peak position of modulation, various algorithms have been proposed, most of which assume that the peak is single. Thus, if the target surface is covered with a transparent film, error occurs because of the superposition of the reflected beams from the front surface and the reflected beams from the back surface.

It has long been known 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 simultaneous measurement of film thickness and surface height variations from those peak positions.¹¹⁻¹⁵

However, those traditional methods require visual determination of peak positions^{11,12} or use a complex calculation algorithm, ^{14,15} and no automatic measuring device for practical use was available in the market until our development of such a device in 2002.¹⁶

We have developed an algorithm, named KF (thicK Film), which can automatically detect the positions of two contrast peaks in an interferogram generated by VSI. Using the sampled data of the interferogram as shown in Figure 6, this algorithm first calculates the contrast, which is shown as a bar graph in Figure 7. The optimal threshold for peak separation is then obtained using Otsu's automatic threshold selection method in the field of processing to binary value imagery.¹⁷

More particularly, given a set of frequency values n(i), (i = 1, L), where the n umber 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:

$$f = \omega_1 \cdot \sigma_1^2 + \omega_2 \cdot \sigma_2^2, \tag{6}$$

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 7, with the data number 30 being the threshold. This threshold separates the distribution into left and right peak regions. For each of the separated regions, the peak positions can be detected by conventional methods.

The surface height, back surface height and film thickness are obtained from the peak positions determined for each of the separated peak regions and the known refractive index of the film.

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 $D = (z_{p1}-z_{p2})/n$; and

iii)the back-surface height of the film = z_{p1} -D.

This development allows the following measurements, which are difficult 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.







Figure 7. Contrast data and Otsu's objective function for automatic threshold selection.

4.2 Range of measurable film thickness

The KF method of measurement has a lower limit to 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.

4.3 Examples of measurements

Using this algorithm, we developed the non-contact Film Profiler SP-500F.¹⁷ The following sections give examples of measurements.

4.3.1 Step in film thickness

A step in oxide film formed on a Si wafer was measured, and the results are shown in 3-D representation in Figure 8. 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 agreed fully with 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.



(a) Front surface

Figure 8. Measurement results of a SiO₂ film step on a Si wafer.

4.3.2 Tapered film

A tapered oxide film on a Si wafer was measured, and the results are shown in Figure 9. The conspicuously warped concave front and back surfaces and the tapered thickness profile of the film were measured.



Figure 9. Measurement results of a tapered SiO₂ film on a Si wafer.

4.3.3 Film-covered electric circuit

A flexible circuit partially covered with a transparent film as shown in Figure 10 was measured, and the results are shown in Figures 11a-c. The surface profile in Figure 11a shows the height of bumps above the transparent film layer; the back surface profile in Figure 11b shows the profile of the circuit pattern on the base film; and Figure 11c shows the thickness profile.



Figure 10. Cross-section of a flexible circuit.



Figure 11. Measured profiles of a flexible circuit.

(c) Thickness

4.3.4 Measurement of water droplet surface

The profile of a water droplet on a glass plate was measured, and the results are shown in Figure 12.



Figure 12. Measurement of a water droplet.

5. 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,¹⁸⁻²⁰ but there as yet is no appropriate commercial product in the market. We developed an algorithm, named NF (thiN Film), which can measure the 3-D surface profiles of a surface covered by a thin film, and is robust enough to be practically used 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.

5.1 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 (Figure 13). The test results in Figure 14 show good agreement between obtained and predicted values.



Figure 13. Cross-section of the thin film sample.



(a) Front surface

(b) Back surface Figure 14. Thin film measurement results.

(c) Thickness

The repeatability of the film thickness measurement is shown in Figure 15. The thickness was an average of 10x10 pixels. The average and sigma of 25 repeated measurements were 301.5 nm +/- 0.21 nm for thicker film, and 99.3 nm +/- 0.30 nm for thinner film.



Figure 15. Repeatability of thin film thickness measurement.

5.2 Measurement of CMP samples

Figure 16 shows the measurement results of the oxide chemical mechanical polishing (CMP) samples of 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 17 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 at the surrounding area. From this simultaneous measurement of surface topography and film thicknesses distribution, we can obtain fast, vital and unique information on the CMP process.



Figure 16. Measurement results of three CMP samples.



Figure 17. Detailed top surface profile of the 60-sec CMP sample measured by SP-700. The height of the pattern is on the order of 10 nm, and the film thickness underneath is 460-740 nm.

6. CONCLUSIONS

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'.

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