Measurement of Transparent Film Using Vertical Scanning White-Light Interferometry

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Abstract. White-light interferometry has a good performance to measure opaque surface profile and step height; While a transparent film is measured, because two beam of lights came from transparent film surface and substrate interfere with the reference light, interference fringe appears twice at the same point and two coherence-peaks be found in the correlogram. The location algorithm of single coherence peak is computed near the maximal intensity and do not judge which interference fringe is come from film surface, so it is not sure to extract the film surface and to know the thickness of film. In this paper, the characteristic of correlogram came from transparent film is utilized to analyze the peak separation algorithms of envelope, and these algorithms are compared through results. Theoretical analysis and experiment result show that the surface and thickness of transparent film measured by white-light interference microscope have high precision when the two coherence peaks at film surface and film substrate are efficiently separated by separation algorithms.

1. Introduction
With the development of white-light interferometric technique, and because of its theoretically unlimited unambiguous height range and high-precise, the white-light interferometry is widely employed in the measurement of surface profile. Many instrument companies have developed such precise, non-contact three-dimensional profiler as Talysurf CCI 3000, ZYGO NewView 5000, Wyko optical 3D profiling systems etc. However, when the surface covered with the transparent film is measured by white-light interferometry, two envelope peaks appear at the two surfaces of transparent film in the correlogram while only one peak is found in the interferogram of opaque surface. If the reflectivity of film substrate is larger than that of transparent film, such as transparent film on Si substrate, the fringe with the maximum intensity detected by CCD is obtained by the interference of two lights reflected from the silicon substrate and reference mirror. The silicon substrate is extracted by the location algorithm of single envelope rather than film surface. So some separation methods are studied in this paper to achieve the surface and thickness measurement of transparent film by white-light interferometry.

2. Measurement Principle
According to the measurement principle of white-light interometry[1], the source light is divided two beams that reach reference mirror and the measured surface respectively, and two beams reflected from reference mirror and the measured surface get together at beam splitter. When the difference
between the reference optical path and the measured optical path is zero, the interference fringe is detected and the intensity for each point at the opaque surface can be written as

\[ i(z) = i_0 + i_0 \gamma(z - z_0) \cos\left(4\pi \frac{z - z_0}{\lambda} + \alpha_0\right) \]  

(1)

Where \( i_0 \) is the background intensity; \( \gamma(z) \) is the interference fringe envelope function; \( z_0 \) is the peak position of intensity; \( \lambda \) is the average wavelength and \( \alpha_0 \) is the phase offset. \( \gamma(z) \) is affected by light source and the numerical aperture of the objective and is approximated as sinc function which holds symmetry at \( z = z_0 \).

\[ \gamma(z) = \sin\left(\frac{2(z - z_0)}{\lambda^2 / \Delta \lambda}\right) \]  

(2)

Where \( \Delta \lambda \) is full width half maximum (FWHM) of light source. The correlogram that is also interference intensity distribution along the Z-axis detected by CCD is shown in Figure 1. The coherence peak position is the best-focus position of surface and the height information could be obtained from the coherence peak location at every pixel. There are many algorithms for finding the coherence peak, such as Fourier transform algorithm [1], Hilbert transform algorithm [2], five-frame algorithm [3], etc.

When transparent film is measured, beam from source light is divided into two beams at film surface, one of which is reflected by film surface and another beam is refracted into film and reflected by film substrate. So the interference fringe is found at the same point twice when OPD is zero at film surface and substrate respectively. The intensity for transparent film is adapted as

\[ i(z) = i_0 + i_0 \gamma_1(z - z_1) \cos\left(4\pi \frac{z - z_1}{\lambda} + \alpha_1\right) + i_0 \gamma_2(z - z_2) \cos\left(4\pi \frac{z - z_2}{\lambda} + \alpha_2\right) \]  

(3)

Where \( i_0 \) is the background intensity, \( \gamma_1(z) \) and \( \gamma_2(z) \) are the interference fringe envelope functions, \( z_1 \) and \( z_2 \) are the peak positions of intensity, \( \alpha_1 \) and \( \alpha_2 \) are the phase offsets. The correlogram is shown in Figure 2. Between the intensity of both peaks, the latter peak is larger, and then the latter peak that reflects the height information of film substrate is located by single peak location algorithm. So the fringe of film surface should be separated from the correlogram before the peak location algorithm is applied. Moreover, the heights of film surface and substrate both can be known from the two peak of correlogram and the thickness could be calculated at anywhere without limiting at discontinuous, so this kind of thickness measurement method has more precision and convenience.

3. Algorithm analysis of coherence peak separation

Envelope function \( \gamma(z) \) of Eq. (1) can be fitted by quadratic polynomial, so the interferogram is approximated by least-squares fitting [4]. However too many parameters are involved and computation is more complex, the correlogram of transparent film are hard to be directly fitted. So the two coherence peaks must be separated before two coherence peaks are located respectively.
Due to the light is divided into two beams at film surface, so the interference fringes found at film surface and film substrate both are weaker than that of opaque surface, and the contrast of interference fringe is comparatively decrease. The contrast of opaque surface in Figure 1 is \( K = 0.2312 \), while those of film surface and film substrate in Figure 2 are \( K_1 = 0.0859 \) and \( K_2 = 0.1468 \). For the efficient separation of interference fringe from correlogram and approximate computation of envelope, the square values of intensity difference between interference fringe and background are considered as original data for approximated computation. The square value of the intensity difference is expressed by the following equation:

\[
\Delta I^2(z) = i_0^2 \gamma_1^2 (z - z_1) \cos^2 \left( 4\pi \frac{z - z_1}{\lambda} + \alpha_1 \right) + i_0^2 \gamma_2^2 (z - z_2) \cos^2 \left( 4\pi \frac{z - z_2}{\lambda} + \alpha_2 \right)
\]  

(4)

The square value of intensity difference \( \Delta I^2(z) \) is shown as Figure 3, and it is divided into two classes: \( \Delta I_1^2(l) \) (\( l = z_1 - \Delta z_1/2, z_1 + \Delta z_1/2 \)), \( \Delta I_2^2(l) \) (\( l = z_2 - \Delta z_2/2, z_2 + \Delta z_2/2 \)).

3.1. Centroid algorithm

In the correlogram of single coherence peak, the central position fringes can be determined by the centroid of the square value \( \Delta I^2(z) \) [5]. Using the assumption \( \Delta z_1 = \Delta z_2 = \Delta z \), the centroid \( z_c \) of correlogram is expressed as

\[
z_c = \frac{\sum_{l = z_1}^{z_1 + \Delta z/2} l \Delta I_1^2(l) + \sum_{l = z_1 - \Delta z/2}^{z_1} l \Delta I_2^2(l)}{\sum_{l = z_1}^{z_1 + \Delta z/2} \Delta I_1^2(l) + \sum_{l = z_1 - \Delta z/2}^{z_1} \Delta I_2^2(l)}
\]

(5)

Clearly \( z_c \) is between the centroids of two classes and \( z_1 < z_c < z_2 \), and shown as Figure 4.

![Figure 3](image1.png)  
**Figure 3.** The square value of intensity difference.

![Figure 4](image2.png)  
**Figure 4.** Centroid method.

3.2. Quadratic polynomial algorithm

Taking \( \Delta I^2(z) \) of Eq.(6) as a class \( (z_i, y_i) \) \( (i = 1, \ldots, L) \), \( y_i = \Delta I^2(z_i) \), the square value of intensity difference \( \Delta I^2(z) \) is fitted by quadratic polynomial

\[
y_i = a_0 + a_1 z_i + a_2 z_i^2
\]

(6)

Where \( a_0, a_1 \) and \( a_2 \) are coefficients. The extremum of quadratic polynomial could be used to separate the two coherence peak of correlogram. Then the separation position is

\[
z_c = -\frac{a_1}{2a_2}
\]

(7)

The coefficients can be worked out in the form of linear matrix equation of
Quadratic polynomial fitting of two peaks correlogram is shown in Figure 5.

3.3. Otsu algorithm
The square value of intensity difference $\Delta \hat{I}(z)$ is considered the histogram of image, and then the automatic threshold selection methods of image process could be applied to separate the two peak of envelope. As a robust method, Otsu method[6] is analyzed and applied in this paper.

The observed number is T and $\Delta \hat{I}(z)$ is divided into two classes $\Delta \hat{I}(z_i)$ ($i=1,\ldots, T$), $\Delta \hat{I}(z_i)$ ($i=T,\ldots, n$). Then the frequencies of the two classes are

$$\sigma_0(T) = \sum_{i=1}^{T} \Delta i^2(z_i) \quad \sigma_1(T) = \sum_{i=T}^{n} \Delta i^2(z_i)$$

(9)

The centroids of two classes are expressed as

$$\mu_0(T) = \frac{\sum_{i=1}^{T} z_i \Delta i^2(z_i)}{\sigma_0(T)} \quad \mu_1(T) = \frac{\sum_{i=T}^{n} z_i \Delta i^2(z_i)}{\sigma_1(T)}$$

(10)

And the intraclass variances of two classes are in the form

$$\sigma_0^2(T) = \sum_{i=1}^{T} (z_i - \mu_0(T))^2 \Delta i^2(z_i) / \sigma_0(T) \quad \sigma_1^2(T) = \sum_{i=T}^{n} (z_i - \mu_1(T))^2 \Delta i^2(z_i) / \sigma_1(T)$$

(11)

So the objective function is expressed by following equation and is the minimum if T is the optimal separation number as shown in Figure 6.

$$F(T) = \sigma_0(T) \sigma_0^2(T) + \sigma_1(T) \sigma_1^2(T)$$

(12)

Figure 5. Quadratic polynomial algorithm.

Figure 6. Otsu algorithm.

3.4. Algorithm comparison
These algorithms are applied to calculate the separation positions of two coherence peaks as shown in Figure 7. The three group of interference fringes have similar shape but different central position. Results show that Otsu algorithm has high-precision to determine the separation and is immune to noise and fringe contrast; while the location errors of centroid algorithm and quadratic polynomial algorithm increase with the deviation of fringe centre from the centre of correlogram. The detailed results are listed in table 1.
4. Experiment and results

The experiment is carried out by WIVS measurement system [7] and a transparent film on Si wafer is measured. The thickness of transparent film is 0.7μm, and the film refractive index is n=1.54. The 3D view of surface and 2D cross-sectional profile of transparent film extracted through separation algorithm of two coherence peaks are shown in Figure 8, and the roughness is Ra=0.0062μm.

\[ h = \frac{z_1 - z_2}{n} \times \text{step} \]  

Where, step is vertical scanning step of white-light interferometry, and then the calculated thickness of the measured film is 0.710μm.

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