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Thickness and Surface Measurement of Transparent Thin-Film Layers using White Light Scanning Interferometry Combined with Reflectometry

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Surface profiling and film thickness measurement play an important role for inspection. White light interferometry is widely used for engineering surfaces profiling, but its applications are limited primarily to opaque surfaces with relatively simple optical reflection behavior. The conventional bucket algorithm had given inaccurate surface profiles because of the phase error that occurs when a thin-film exists on the top of the surface. Recently, reflectometry and white light scanning interferometry were combined to measure the film thickness and surface profile. These techniques, however, have found that many local minima exist, so it is necessary to make proper initial guesses to reach the global minimum quickly. In this paper we propose combing reflectometry and white light scanning interferometry to measure the thin-film thickness and surface profile. The key idea is to divide the measurement into two states; reflectometry mode and interferometry mode to obtain the thickness and profile separately. Interferogram modeling, which considers transparent thin-film, was proposed to determine parameters such as height and thickness.

With the proposed method, the ambiguity in determining the thickness and the surface has been eliminated. Standard thickness specimens were measured using the proposed method. Multi-layered film measurement results were compared with AFM measurement results. The comparison showed that surface profile and thin-film thickness can be measured successfully through the proposed method.

Keywords : Transparent thin film, Thickness, Interferometry, Reflectometry, Interferogram modeling
OCIS codes : (120.0120) Instrumentation, measurement, and metrology; (120.3180) Interferometry

I. INTRODUCTION

Thin films have been increasingly used in the optics, semiconductors and material industries to provide specific functions to the coated devices. Effective measurement of the profile and the film thickness are important to achieve special functions. To measure the thickness and surface, optical methods such as white-light interferometry and reflectometry have been widely used. Recently, white light scanning interferometry has extended its application from the surface measurement to the thin film thickness measurement. However, due to the phase distorting effect of the transparent thin-film, it is very difficult to measure a transparent thin-film on the top of the 3-D surface by conventional metrology.

Reflectometry is more popular in industries for its fast throughput. Reflectometry is a well-established and powerful technique for measuring film thickness [1, 2]. It measures reflectance for different wavelengths to calculate thickness. But, this technique can only determine the film thickness and it is limited to only one point detection. Recently, volumetric thickness profile has been measured using a CCD camera [3].

To measure the 3-D profile of a transparent surface, a white light interferometry technique which gets spectrally resolved analysis by Fourier transform was proposed [3-4]. It determines both surface profile and film thickness in the spectral domain. Kim's method extracted thickness information from the interferogram. It has the merit that it does need additional spectral units, but spectral information usually is not enough for calculating the thickness in a practical measurement. And it has the limitation of spectral resolution, which is most important in calculating thickness. To compensate for the ambiguity in spectral analysis, reflectometry and

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spectrally resolved white light interferometry were combined [5, 6]. But this method was too sensitive to the detection of the peak signal. Modeling based researches also had been proposed recently [7-10]. And several researchers have used different techniques to measure the thin film thickness and height accurately [11-20]. However, there still remains ambiguity in detecting surface height due to the thin film effect. They had practical limitations of uncertainty and measurement speed. To overcome those problems we have combined a spectrometer into an interferometry system. As a result, the proposed method can gather more accurate and highly resolved spectral information for thickness calculation.

In this paper we combine the white light scanning interferometry and reflectometry for determination of film thickness and surface profile. The key idea is to divide the measurement into two states, reflectometry mode and interferometry mode, to get the two unknowns of thickness and surface profile separately. The experiment was performed in two steps. First the film thickness was determined in reflectometry mode. For the next step, the thickness and surface profile are calculated by white light scanning interferometry mode using the thickness value which is determined by reflectometry mode. It saves calculation time for least-square fitting because it does not need an initial guess for the thickness value. For reflectometry mode, a normal objective lens and spectrometer were used to measure the thickness of the specimen. For interferometry mode, an interferometric lens (mirau type) and CCD sensor were used to measure the film thickness and surface profile. The shape and position of an interferogram varies depending on several parameters such as the height and thickness of the specimen. And it can be modeled using the theory of interferometry and reflectometry. The optimum model provides the surface profile and the thin-film thickness simultaneously. The final thin-film and surface profile were measured by obtaining the best matching model using the non-linear least square fitting. For the interferometry mode, we considered the phase changing effect of the thin-film on the top of the surface for accurate and simultaneous measurements of the film thickness and surface profile.

By separating the thickness measurement from the surface profile measurement using reflectometry, we enhanced the accuracy of both surface profiling and thickness measurement. The most important advantage of the proposed technique is the elimination of the ambiguity in determination of thickness and surface by separating measurement of thickness and surface profile.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. A vertical movement in the z direction was implemented using the piezoelectric actuator toward the test surface located in the x-y plane. The test surface is observed through objective (Nikon ELWD 10X/20X/50X) lenses and an interferometric (Nikon 20X/50X Mirau type) objective. The light source is a halogen lamp with a broad and continuous spectrum.

The setup can be used both for reflectometry measurement mode or interferometry measurement mode. When it uses a normal objective lens and spectrometer, it does not allow the light reflected on the reference surface to reach the spectrometer because a normal objective lens does not have a reference mirror inside. So, under this condition, the spectrometer records interference between the top and bottom surface of the film in the specimen. This is known as reflectometry mode. When the interferometric lens and the CCD camera were used, the light reflected on the reference surface. The reflection interfered with the test surface beam. Now the CCD camera records the interference signal between the test and reference signals. This mode is known as white light interferometery mode. In this mode, the interferogram gives information about the thin film thickness d and surface height h simultaneously.

For the measurement of reflectometry mode, the spectrometer (Ocean Optics QE65000; 1024 pixels), which has a detecting range from 200 nm to 1100 nm, was used. The spectrometer is aligned at the center of the camera so that the light reflected from the center of the specimen can enter the spectrometer. By implementing a normal objective lens and 50 μm optical fiber (Ocean Optics) between the beam splitter and the spectrometer, a 2.5 μm spot for reflectometry measurement was implemented.

For the measurement of interferometry mode, the interferometric objective was fitted with a PZT. The control voltage to shift the PZT for phase shifting was produced by a Micom with PID control. The camera (Vieworks VG264, 250 fps) gives an 8-bit digital output. The interferograms were transferred to the PC through an image acquisition board.

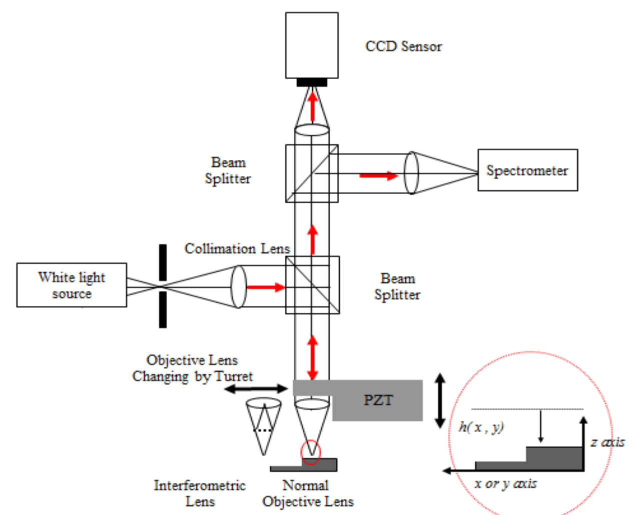

FIG. 1. Experimental setup.

III. PRINCIPLE

3.1. Multiple Reflection

When incident light is upon a surface with a transparent thin-film layer, multiple reflection takes place, as illustrated in Fig. 2. If we take account of the multiple reflections inside the transparent thin film layer, the parameter R (total reflection coefficient) can be derived as Eq. (1) [1]

$$R = \frac{r_{01} + r_{12}\exp(-j2\beta)}{1 + r_{01}r_{12}\exp(-j2\beta)} \tag{1}$$

$$\beta = 2\pi \frac{d}{\lambda} N_1 \cos(\theta_1) \tag{2}$$

where r_{01} and r_{12} represents the Fresnel reflection coefficients of the top and the bottom boundaries of the film, respectively. β denotes the phase change of the reflected wave as it traverses the thin-film. β can be expressed explicitly as Eq. (2) where θ_1 is the propagation angle of the incident beam and d and N_1 are the thickness and the refractive index of the thin-film layer, respectively. The parameter R (the reflection coefficient of the surface) is a complex number which can be expressed in the standard form of

$$R = a + bi \tag{3}$$

where a and b are real numbers. Then the total phase difference of the reflected beam relative to the incident beam is determined as

$$\psi = \tan^{-1}(b/a) \tag{4}$$

3.2. Interferogram Modeling

Considering the reflection of the specimen, interference signals can be expressed as a sum of reference light and objective light as,

$$E_{ref}(z,k) = E_{i(k)}\, \rho(1-\rho)\left|R_{ref}(k)\right| * e^{-i(2kl - \psi_{ref})} \tag{5}$$

$$E_{obj}(z,k) = E_{i(k)}\, \rho(1-\rho)\left|R_{obj}(k)\right| * e^{-i(2k(l+h-z) - \psi_{obj})} \tag{6}$$

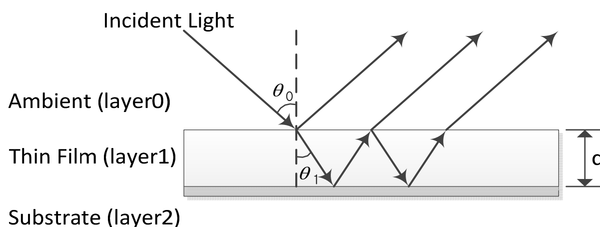

FIG. 2. Multiple reflections in thin film.

$$\varphi(z,k) = (E_{ref} + E_{obj})\overline{(E_{ref} + E_{obj})} \tag{7}$$

$$\Delta\psi = \psi_{ref} - \psi_{obj} \tag{8}$$

where, z is the position of PZT, k is the wavenumber, $E_{ref}(z,k)$ is the wave equation of reference light, $E_{obj}(z,k)$ is the wave equation of measurement light. ρ is the reflection coefficient of the beam splitter, $\left|R_{ref}(k)\right|$ is the reflection coefficient of the reference light, $\left|R_{obj}(k)\right|$ is the reflection coefficient of the objective. l is the length difference between the reference mirror and the objective lens, h is the height of the sample, z is the position of scanning optics. ψ_{ref} and ψ_{obj} are the initial phase in reference mirror and sample. Here we need to remember that ψ_{obj} is the function of the film thickness and wavenumber.

Considering incoherent superposition of monochromatic lights, the interference intensity sampled from a surface point (x,y) of height h is generally described as the integral of the effective wave number from k_1 to k_2

$$\varphi(z) = \int_{k1}^{k2} I_0[1 + \gamma\cos(2k(h-z) - \Delta\Psi)] * F(k)dk \tag{9}$$

where γ denotes the modulation amplitude and $F(k)$ and dk are, respectively, the central wave number and the bandwidth of the white-light source. In Eq. (9), the integral is related to the broad spectral distribution of the source light. To simplify the analysis, the numerical aperture of the objective is assumed to be small enough for approximating $\cos(\theta_0) = 1$ and $\sin(\theta_0) = 0$. $\Delta\Psi$ is the initial phase difference between ψ_{ref} and ψ_{obj}. Calculating ψ_{obj} using Eq.(4) and substituting $\Delta\Psi$ in Eq. (9) by Eq. (8), for each wavelength from k_1 to k_2, an interferogram considering the phase change due to the thin-film can be modeled. The spectral distribution of the light source is considered from 400 nm to 800 nm. For comparison, the interferogram shape without film was modeled, as shown in Fig. 3(a) and the interferogram with a 408 nm SiO_2 film on Si, as shown in Fig. 3(b).

In the case of Fig. 3(a), the psi of the sample does not vary because there is no thin-film on the top layer. In the case of 3(b), the interference of the top layer is affected by the signal from the bottom surface. As the thin film gets thinner, the interference signal of the bottom surface affects the interference signal of the top surface.

3.3. Non-linear Least Square Fitting

In reflectometry mode, after the data acquisition process is completed, a regression method, such as the Levenberg-Marquardt non-linear fitting algorithm, is used for searching the best-matching theoretical reflectance. The aim of the fitting process is to find the thin film thickness that minimizes the difference between the measured reflectance

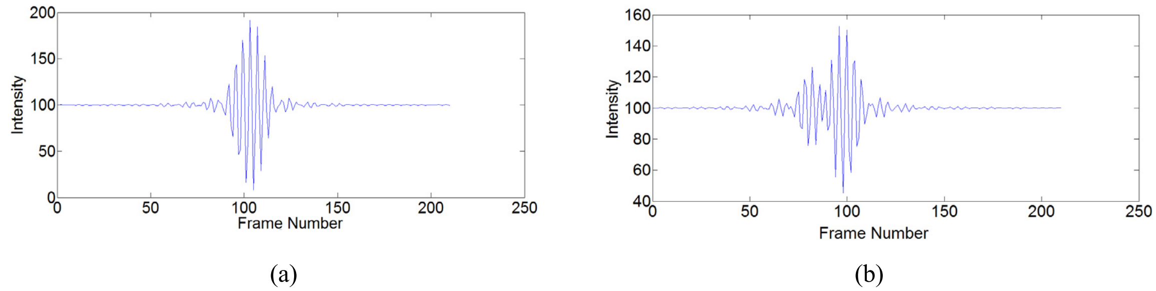

FIG. 3. Modeled interferograms of (a) no film (b) SiO_2 408 nm film on Si.

and the theoretically calculated reflectance. In order to evaluate the difference, the error, e(d), in Eq.(10) is used. The difference is squared and integrated in wavelength range. As the error gets close to zero, the theoretical reflectance gets more similar to the measured reflectance.

$$e(d) = \int_{-\infty}^{\infty} [R_{experiment}(d) - R_{theory}(d)]^2 d\lambda \tag{10}$$

In interferometry mode, surface height h and thickness d can be determined using Non-Linear Least Square Fitting. In this work, measured $\varphi_{measured}$ denotes the actual data gathered from the system and φ_{theory} is the modeled interferogram result. An error function is defined as the sum of squared deviations.

$$\chi(d,h) = \sum_{z=FrameStart}^{FrameEnd} (\varphi_{measured}(z) - \varphi_{theory}(z;d,h))^2 \tag{11}$$

The optimum model shows the surface profile h and thin-film thickness d simultaneously. The phase component in the Eq. (9) turns out to be highly nonlinear with respect to the unknowns; thus an appropriate multidimensional nonlinear least-squares technique with fast convergence capability is necessary. In searching for the true values of h and d, we found that many local minima exist, so it was necessary to make proper initial guesses for these values to reach the global minimum quickly. For determination of thickness and surface in interferometry mode, thickness data measured by reflectometry mode was applied as the initial thickness value d. Finally the best matching interferogram gives height and thickness information of the measured specimen.

IV. EXPERIMENTAL RESULTS

The experiment was performed in two steps. First, thin film thickness was determined in reflectometry mode and then the film thickness and the surface profile was calculated by interferometry mode. For interferometry measurement, the thickness value determined by reflectometry mode was used as the initial thickness value d.

4.1. Reflectometry Mode Result

A regression method like Levenberg-Marquardt nonlinear fitting algorithm is used for searching for the best-matching theoretical reflectance. The aim of the fitting process is finding the thickness of thin film which minimizes the difference between measured reflectance and theoretically calculated reflectance. The procedure of finding the best matching model is shown in Fig. 4.

Using the reflectometry mode, the proposed reflectance and phase modeling was verified. SiO_2 film of 408 nm thickness was deposited on a Si substrate by NIST; NIST 400-100, CRADA, CN-1364, 1998[4]. Figure 5 shows the fitting result between the measured reflectance signal and

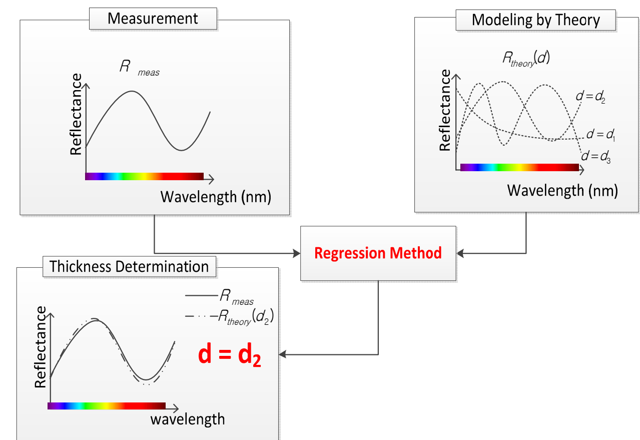

FIG. 4. Procedure of regression algorithm.

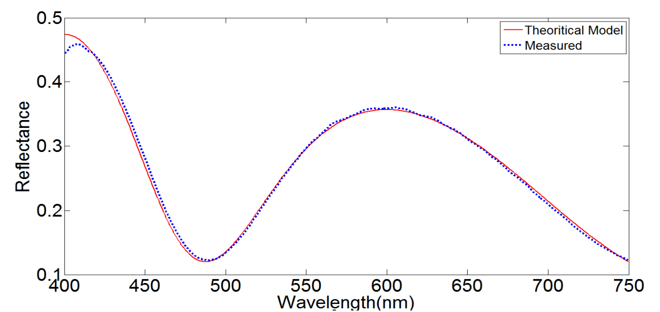

FIG. 5. Fitting of experimental and modeled reflectances for SiO_2 408 nm on Si.

modeled reflectance signal. We searched for the optimal thickness of the film thickness '*d*' that would minimize the error function e(d) in Eq. (10). Figure 5 shows the fitted reflectance.

4.2. Interferometry Mode Result

The thickness *'d'* measured in reflectometry mode was set as the initial thickness value of interferometry mode. Fig. 6 shows the fitting result of the sample. Matching results of the actual interferogram and the modeled signal were plotted. Thickness of the interferometry mode was analyzed by averaging 10*10 pixels at the center of the specimen.

To verify the effectiveness of the interferogram modeling, reference specimens which have SiO_2 film layers on silicon have been analyzed; NIST reference specimen for 408 nm (NIST 400-100, CRADA, CN-1364, 1998[4]) and Mikropack-ID0076 specimen for the others (from 40 nm to 1000 nm).

To verify the performance of the proposed technique, samples of thickness lower than 200 nm also have been investigated. Fig. 7 shows the comparison of the true value and measured thickness value. When the thickness is lower than 150 nm, correct measurement result is not guaranteed; it shows the limitation of the proposed method. The reason for the limitation is when the deposited film gets thinner than 150 nm, thicknesses can no longer be distinguished from one to the other because the phase change within the thin-film layer becomes very small regardless of wave number when thickness *d* is smaller than 150 nm.

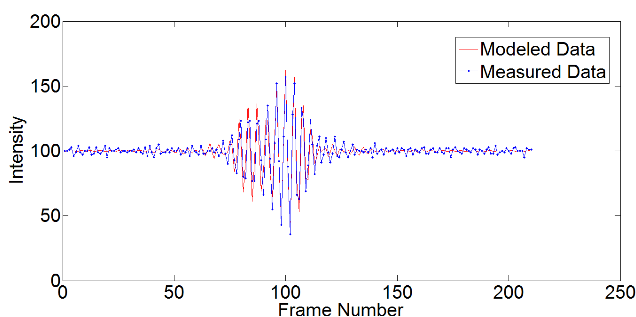

FIG. 6. Experimental and fitted interferograms for SiO_2 408 nm on Si.

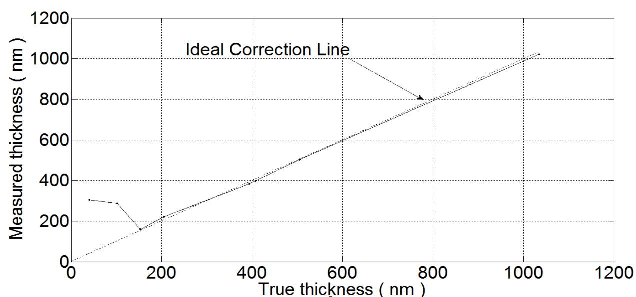

FIG. 7. Comparison of true and measured thickness values.

For verifying proposed reflectometry, we measured samples in Table 1 using three objectives with different magnification. The test result indicates that the maximum deviation reaches; 0.6% when the thickness value is in the range 350 nm - 1100 nm. It shows enhanced thickness measurement accuracy compared with previous research; 3% [4]

The thin-film-transistor (TFT) supporting structure, which is a very important structure in the Liquid Crystal Display panel illustrated in Fig. 8, was measured by using the proposed method for industrial application. The sample has two layers from the bottom. The first layer is relatively thick with opaque material and the second layer consists of transparent thin film. These kinds of samples could be measured to evaluate the performance of the proposed method. Table 3 shows the measured results for

TABLE 1. Comparison of sample thicknesses measured by two methods (unit : nm)

	True Value	Reflectometry	Proposed Interferferometry
Sample1	42	41	312
Sample2	83	84	298
Sample3	168	169	172
Sample4	205	206	221
Sample5	394	401	384
Sample6	408	409	398
Sample7	505	507	503
Sample8	1035	1040	1022

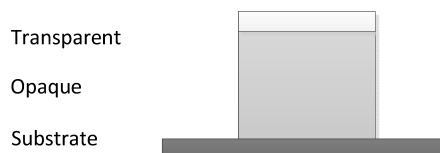

FIG. 8. Structure of specimen to verify simultaneous measurement performance using the interferometry mode.

TABLE 2. Comparison of sample thicknesses measured by reflectometry mode with three objectives (unit : nm)

	10X	20X	50X
Sample1	42	41	42
Sample2	85	84	86
Sample3	169	169	168
Sample4	206	206	206
Sample5	401	401	399
Sample6	409	409	408
Sample7	506	507	504
Sample8	1039	1040	1038

the sample shown in Fig. 8. AFM measurement results are also provided in Table 3 for comparison. The conventional bucket algorithm by Larkin [17] gave a different value from the true value due to the thin-film effect on the top of the surface. On the other hand, the proposed method showed a maximum difference of 9 nm from the AFM results. Accuracy of the conventional method is not guaranteed when transparent film exists; 22.1% error (Table 3). On the other hand the proposed method showed enhanced accuracy; 0.7%. It shows enhanced surface measurement accuracy compared with previous research; 3% [4].

In searching for the true values of h and d we have found that many local minima exist, so it is necessary to make good initial guesses at these values to reach the global minimum. Figure 9 shows a series of calculation for Eq.(11) that we performed to verify the convergence of the least-squares technique for Sample 1 in Table 3. 20 times iteration has been performed for each calculation to perform a feasibility test. The computation result reveals that global minimum is attained within 20 iterations for proper initial guess. However, when the inappropriate initial guess value had been given, correct convergence is not guaranteed; it depends a great deal on the initial guesses of d. If we do not apply initial value d in the equation, we cannot expect correct result for both h and d. Also it took some tens of seconds to determine the thickness and height of the single point without proper initial guess value. For these reasons, the measurement range of the thickness was set to be in range from *(d -100)* nm to *(d+100)* nm. It gives a huge decrease in calculation time because it does not need an initial guess for the thickness. When we applied the proposed method, it took less than 3 seconds to analyze the target area of 100*100 pixels including nonlinear least square fitting. As the calculation time has been decreased, 3-D surface with transparent thin-film can be measured in practice.

TABLE 3. Comparison between the conventional method and the proposed method (unit: nm)

	AFM	Conventional Interferometry	Proposed method
Sample1	1113	1359	1120
Sample2	1702	1467	1693
Sample3	2106	1874	2097

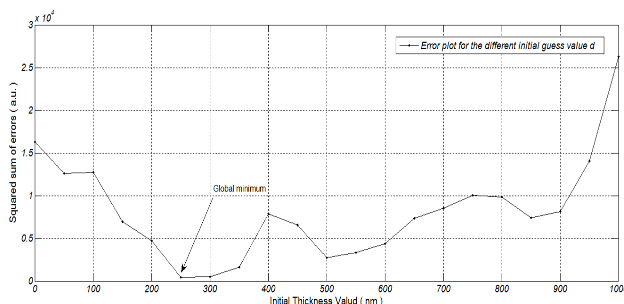

FIG. 9. Error plot for the different initial value.

For verifying proposed methods, we measured samples of Table 2 using two objectives with different magnification. The test result indicates that the maximum deviation reaches; 0.5% when the magnification varies from 20X to 50X (Table 4).

The profile of the sample was compared with the AFM measurement result, as shown in Fig. 10.

The comparison showed fairly good matching profile. Finally, a 3-D surface profile measured using the proposed algorithm is shown in Fig. 11.

V. CONCLUSION

White light scanning interferometry is a well-established technique in surface profiling applications. The resolution

TABLE 4. Comparison of sample heights measured by interferometry mode with three objectives (unit: nm)

	20X	50X
Sample1	1120	1124
Sample2	1693	1692
Sample3	2097	2099

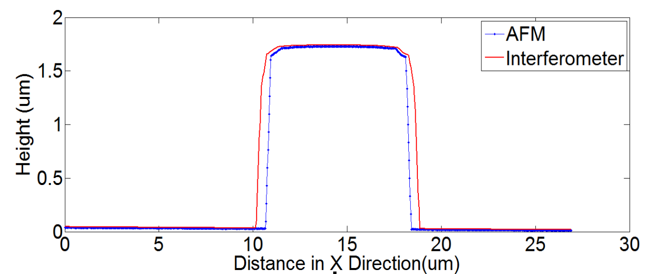

FIG. 10. Comparison between interferometry- and AFM-measured profiles.

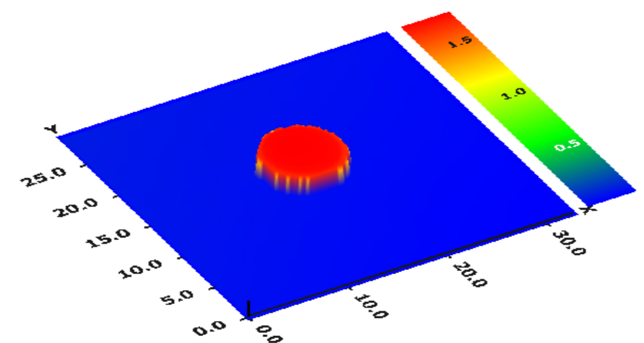

FIG. 11. 9 3-D measurement of TFT-support by proposed method.

in this technique is of the order of a nanometer. But when a transparent thin film exists, the reflection signals from both the top and bottom surfaces of the film will interfere with the reference signal. At the same time, the multiple reflection signals between the two film surfaces will also interfere with the others. Effective separation of the interference signals from each other is the key to achieving a successful measurement. In this paper, measurement of the surface profile and thin-film thickness by interferometry combined with reflectometry was proposed. The key idea is to divide the measurement into two states using reflectometry mode and interferometry mode to obtain the two unknowns separately; thickness d and height h. The final thin-film surface profile information is measured by obtaining the best matching model using the non-linear least square fitting. The proposed method gave the proper initial guess for the accurate measurement and it saves calculation time in finding the most adequate interferogram. It took less than 3 seconds to analyze target area of 100*100 pixels.

The maximum difference between the measured height and the reference height was more than 250 nm under the conventional bucket algorithm, but the difference was reduced to 16 nm under the proposed method. Accuracy has been enhanced from 22.1% to 0.7% for height measurement using the proposed method. The modeling method was more effective when it was used for a thin-film (< 1 μm) because the phase distortion of the thin-film gets worse as the thin film gets thinner. The AFM profile showed a fairly good matching result with the profile of the proposed method. This technique is available not only probing the thickness point by point but also providing complete volumetric film profiles digitized in three dimensions. At present, this measurement technique provides nanometer resolutions of the vertical height when the transparent film thickness exceeds 150 nm. The limitation occurs when the deposited film gets thinner than 150 nm. The reason is that the interferogram can no longer be distinguished from one to the other because the phase change within the thin-film layer becomes very small regardless of the wave number when thickness d is small. A more rigorous reflection model is required to improve a measurement accuracy lower than 150 nm. In conclusion, the most important advantage of the proposed technique is the elimination of the ambiguity in determining the thickness and surface profile. By separating measurement of thickness and surface profile, the proposed method effectively eliminated the ambiguity of thickness determination.

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