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3D Nano Object Recognition based on Phase Measurement Technique

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Spectroscopic ellipsometry (SE) has become an important tool in scatterometry based nano-structure 3D profiling. In this paper, we propose a novel 3D nano object recognition method by use of phase sensitive scatterometry. We claims that only phase sensitive scatterometry can provide a reasonable 3D nano-object recognition capability since phase data gives much higher sensitive 3D information than amplitude data. To show the validity of this approach, first we generate various 0th order SE spectrum data (Ψ and Δ) which can be calculated through rigorous coupled-wave analysis (RCWA) algorithm and then we calculate correlation values between a reference spectrum and an object spectrum which is varied for several different object 3D shape.

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I. INTRODUCTION

Optical correlation techniques have been proved to be very useful in various two and three dimensional pattern recognition applications. Recently, there were increasing interests in various imaging based 2D and 3D optical information sensing and recognition [1-5]. Especially, 3D information processing based on digital holography has been proposed to extend optical correlation techniques to 3D object recognition [4-5]. However, all such approaches were mainly based on an imaging technique which has an inherent optical diffraction limit and for that reason, recognition capability of nano-size patterns smaller than around 1 μm could not be handled through such an imaging based optical approach. So far, a general possible way we could use was an SEM (Scanning Electron Microscope) based 2D imaging approach. However, due to some shortcomings of SEM technology in the sense that it can provide only 2D imaging information and it requires a vacuum environment, SEM has not been that preferable in industrial fields. Recently, to complement those drawbacks of SEM based nano-object measurement approach, a more practical optical method called scatterometry emerged in the semiconductor industry. While traditional optical imaging techniques cannot resolve features smaller than the wavelength of the illumination beam, scatterometrry enables physical parameters of sub-wavelength periodic structures to be extracted from the spectroscopic signature [6-8].

In this paper, we propose a novel recognition method that can be applied for nano size 3D objects. For obtaining both amplitude and phase information through the reflected spectrum, we employ spectroscopic ellipsometry. In this study, we deal with only grating-like periodic nano patterns since scatterometry can be applied only for periodic structures. Although we prove the recognition capability of this study only for one dimensional periodic case, we expect two dimensional periodic patterns also would be able to be handled with this concept. In section 2, we first describe the basic principle of scatterometry. And then, the rigorous coupled-wave analysis (RCWA) theory is introduced to explain how the diffraction of electromagnetic waves from the periodic surface of grating structures can be handled accurately with numerical analysis [9]. In section

3, we deal with the proposed 3D nano-object recognition method which is based on phase sensitive scatterometry. Finally, we show that the proposed method can provide a moderate 3D nano-object recognition capability for various nano object shapes.

II. RCWA BASED SCATTEROMETRY THEORY

Spectroscopic ellipsometry depicted in Fig. 1 has been recognized as a highly suitable tool for determining 3D shape of nano-patterns in semiconductors and photonic crystals. The incident light diffracts into positive and negative orders. Only the 0th order diffracted beam is collected by a spectroscopic system. The collected light is a linear combination of two linearly polarized components with a phase difference between p and s polarization. The polarization mode when the electric field is in the direction parallel to the grating lines is called TE mode, and the polarization mode when the electric field is in the direction perpendicular to the grating lines is the TM mode.

RCWA is a rigorous analysis algorithm utilizing Maxwell's equations with some boundary conditions. Fig. 2 illustrates the geometry of the diffraction configuration of a 1D periodic pattern for the RCWA. The whole structure can be divided into an incident region (Region I), a grating (or patterned) region, and an exit region (Region II). The electric fields can be obtained from Maxwell's equations by using boundary conditions of the grating region [9]. In this grating region ($0 < z < d$), the periodic dielectric function is expandable with Fourier series with period L as

$$\varepsilon(x) = \sum_h \varepsilon_h \exp\left(j\frac{2\pi h}{L}x \right) \quad (1)$$

where ε_h is the h-th Fourier component of the dielectric function in the grating region.

For TE mode, the electric field in region I and II can be represented as follows:

$$\begin{aligned} E_{I,y} &= E_{inc,y} + \sum_i R_i \exp[-j(k_{xi}x - k_{I,zi}z)], \\ E_{II,y} &= \sum_i T_i \exp\{-j[k_{xi}x + k_{II,zi}(z-d)]\}, \end{aligned} \quad (2)$$

where k_{xi} is determined from the Floquet condition and is given by

$$k_{xi} = k_0[n_I \sin\theta - i(\lambda_0 / L)] \quad (3)$$

where,

$$k_{l,zi} = \begin{cases} k_0[n_l^2 - (k_{xi}/k_0)^2]^{1/2} & k_0 n_l > k_{xi}, \\ -jk_0[(k_{xi}/k_0) - n_l^2] & k_{xi} > k_0 n_l \end{cases} \quad l = I, II. \quad (4)$$

R_i in Eq. (2) is the normalized electric-field amplitude of the i-th backward diffracted (reflected) wave in Region I while T_i is the normalized electric-field amplitude of the forward diffracted (transmitted) wave in Region II. By applying the Maxwell's equations in the grating region and matching the boundary conditions at the interfaces of the three regions, one can determine the unknown amplitudes R_i and T_i of the diffracted waves. Those parameters are related to the ellipsometric parameters Ψ and Δ as

$$\rho = \frac{r_p}{r_s} = \left|\frac{r_p}{r_s}\right| e^{i(\delta_p - \delta_s)} = \tan\Psi e^{i\Delta} = \frac{TM}{TE}. \quad (5)$$

where, r_p and r_s are reflection coefficients of TE and TM polarization, respectively. Also, δ_p and δ_s represent phase shifts of the TE and TM polarization modes, respectively. The phase difference between p and s polarization, Δ means $\delta_p - \delta_s$.

III. THREE-DIMENSIONAL NANO-OBJECT RECOGNITION

Figure 3 (a) shows the reference pattern we use for

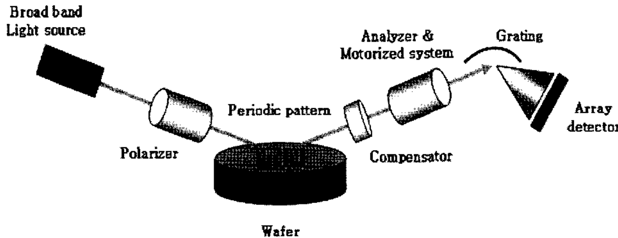

FIG. 1. Schematic of spectroscopic ellipsometer which consists of broadband light source, polarizer, compensator, analyzer and spectrometer.

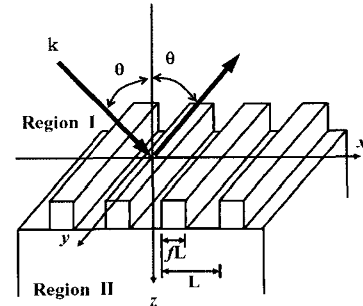

FIG. 2. 3D geometry of nano-patterns used for scatterometry.

testing the object recognition capability. Figure 3 (b) and 3 (c) are two object patterns (upper width: 470 nm and 0 nm) among 8 different object patterns that have various upper widths, i.e., 490 nm, 480 nm, 470 nm, 400 nm, 300 nm, 200 nm, 100 nm, 0 nm. However, for simplicity, the period of all patterns was set to be 1000 nm with fill factor of 0.5 and all the height is set to be 55 nm. First, for each pattern, we calculate SE parameters $\Psi(\lambda)$ and $\Delta(\lambda)$ by using the RCWA for using them in testing recognition capability. The angle of incidence defined by the angle between the normal axis of the pattern sample and the incident light is set to be 10 degree just for simulating at a specific condition. However, it can be any value between 0 to around 90 degree. 3-D nano object recognition has been performed through a conventional correlation technique that uses a matched filter. We will present some correlation results for the two input objects as shown in Fig. 3 (b) and 3 (c) to show that it can provide a practical capability for 3-D nano object recognition.

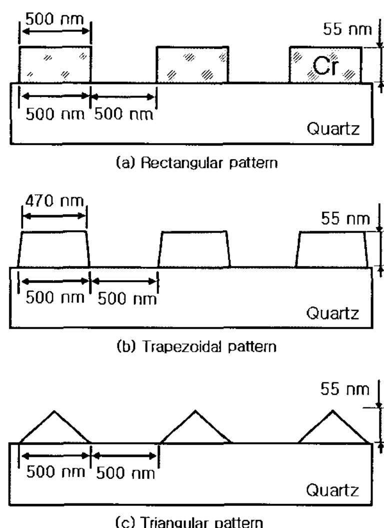

FIG. 3. Patterns used for validation of scatterometry based recognition capability [(a) Rectangular pattern (reference pattern), (b) Trapezoidal pattern (the third input target object) and (c) Triangular pattern (the 8th input target object)].

As the first step, we generate 0th order Ψ and Δ spectrum for the rectangular shape by using RCWA. It corresponds to the reference data $u_i^R(\lambda)$ which is used for making the matched filter. Then, 0th order Ψ and Δ spectrum for the 8 different trapezoidal input objects are generated. The 8 corresponding generated input target object spectrum data are denoted as $u_i^T(\lambda)$.

Figure 4 (a)-(b) represent the 0th order Ψ and Δ

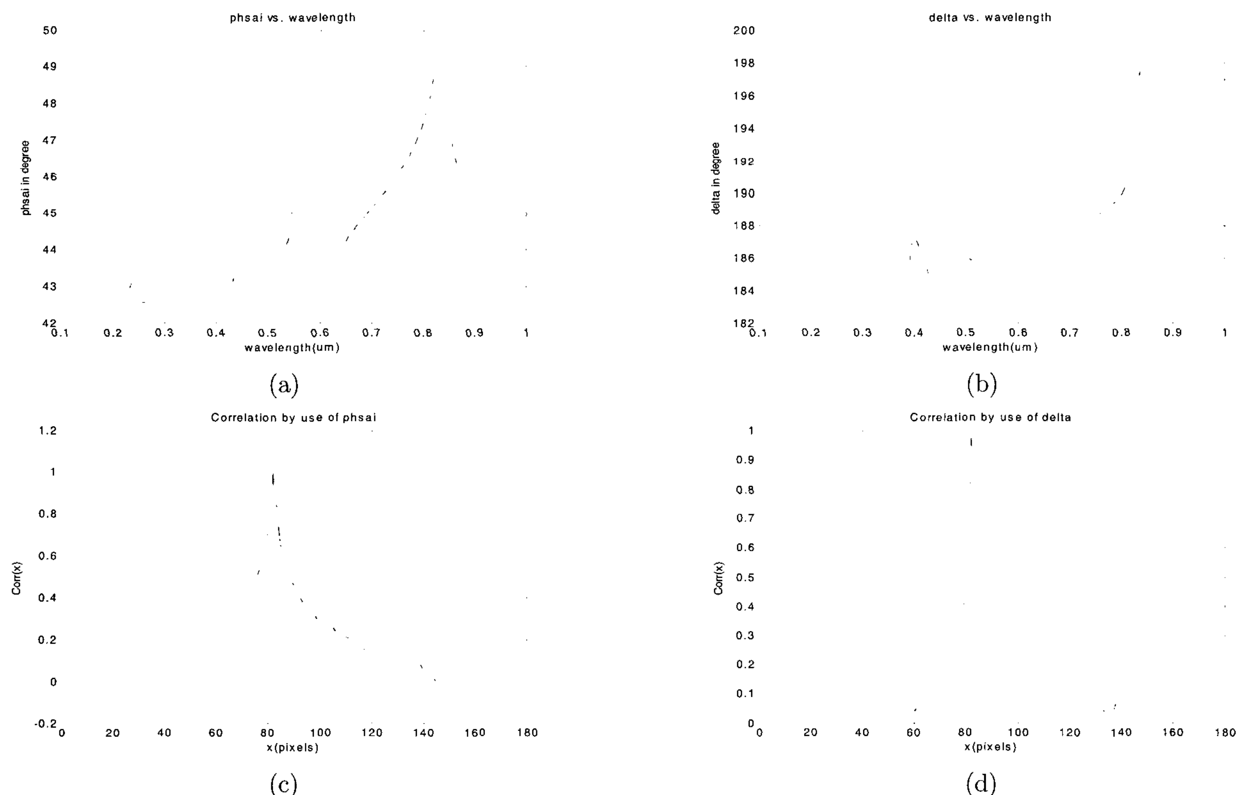

FIG. 4. Simulated results obtained by using rectangular and trapezoidal patterns (upper width: 470 nm) [(a)-(b) $\Psi(\lambda)$ and $\Delta(\lambda)$, respectively (solid line: rectangular pattern, dotted line: trapezoidal pattern), and (c)-(d) Amplitude correlation (λ) obtained by using the two $\Psi(\lambda)$ spectrums represented by solid and dotted line in Fig. 4 (a) and phase correlation (λ) obtained by using the two $\Delta(\lambda)$ spectrums denoted by solid and dotted in Fig. 4 (b), respectively].

spectrum. Here, solid line corresponds to the reference spectrum of the rectangular shape described in Fig. 3 (a), and dotted line represents that of the trapezoidal input object in Fig. 3 (b). The correlation function $C(\lambda)$ between the reference spectrum and the input object spectrum can be represented as follows:

$$C(\lambda)=\left|\boldsymbol{F}^{-1}\{\boldsymbol{F}[u_i^T(\lambda)]\times \boldsymbol{F}^*[u_i^R(\lambda)]\}\right|^2 \qquad (6)$$

Here, spectrum data can be either Ψ or Δ. Figure 4 (c) represents the auto-correlation (solid line) and the cross correlation (dotted line) results when we used Ψ spectrums as the reference and input target object. Similarly, Figure 4 (d) denotes the auto-correlation (solid line) and cross correlation (dotted line) results when we use Δ spectrums as the reference and input target object data. We can see that there is strong correlation between the rectangular and trapezoidal pattern with upper width of 470 nm as expected for both Ψ and Δ cases. Likewise, we do the same procedure with the triangular pattern shape that has upper width of 0 nm as the second input target.

As can be seen in Fig. 5 (c) and 5 (d), there still exists strong correlation between the rectangular and triangular pattern when we use Ψ spectrum, while Δ spectrum case does not. Figure 6 (b) shows how the correlation peak values are varied as the side angle θ defined in Fig. 6 (a) increases from 0 degree to around 80 degree for the Ψ and Δ spectrum cases. This result clearly shows that the amplitude based scatterometry is much less likely to recognize input object 3D shape correctly while the phase sensitive approach can provide a moderate capability.

We need to notice that only phase based Δ spectrum can provide a reasonable 3D nano-object recognition capability. Scatterometry based 3D object recognition theory seems to be very similar to that of digital holography based recognition in the sense that the phase information measurement capability of digital holographic technique gives much higher sensitive 3D recognition capability than the amplitude based approach. The proposed scatterometry method enables us to recognize nano patterns up to the size of around sub 100 nm with UV region scatterometry technology [10]. Also, we can say that it can provide a very fast recognition capability since such Δ spectrum can be measured almost in real time with the current state of art

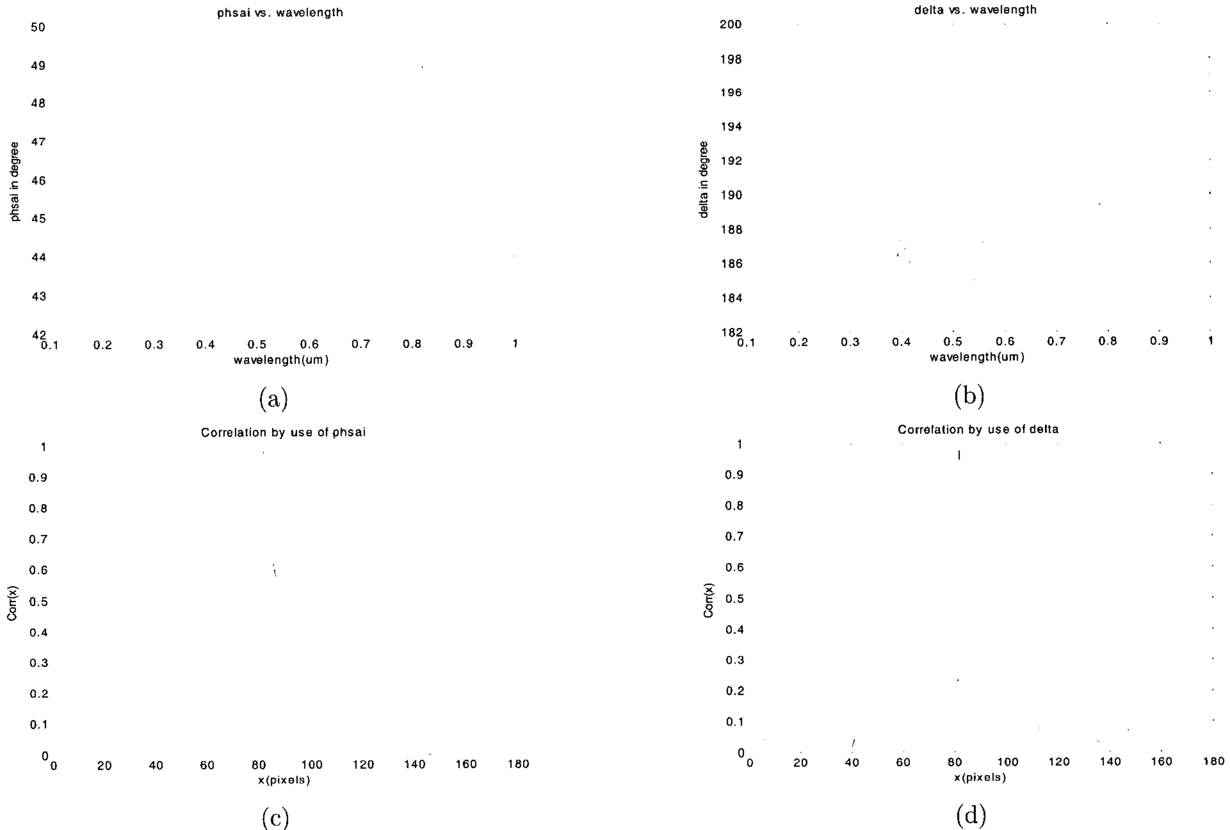

FIG. 5. Simulated results obtained by using rectangular and triangular patterns (upper width: 0 nm) [(a)-(b) $\Psi(\lambda)$ and $\Delta(\lambda)$, respectively (solid line: rectangular pattern, dotted line: trapezoidal pattern), and (c)-(d) Amplitude correlation (λ) obtained by using the two $\Psi(\lambda)$ spectrums represented by solid and dotted line in Fig. 5 (a) and phase correlation (λ) obtained by using the two $\Delta(\lambda)$ spectrums denoted by solid and dotted in Fig. 5 (b), respectively].

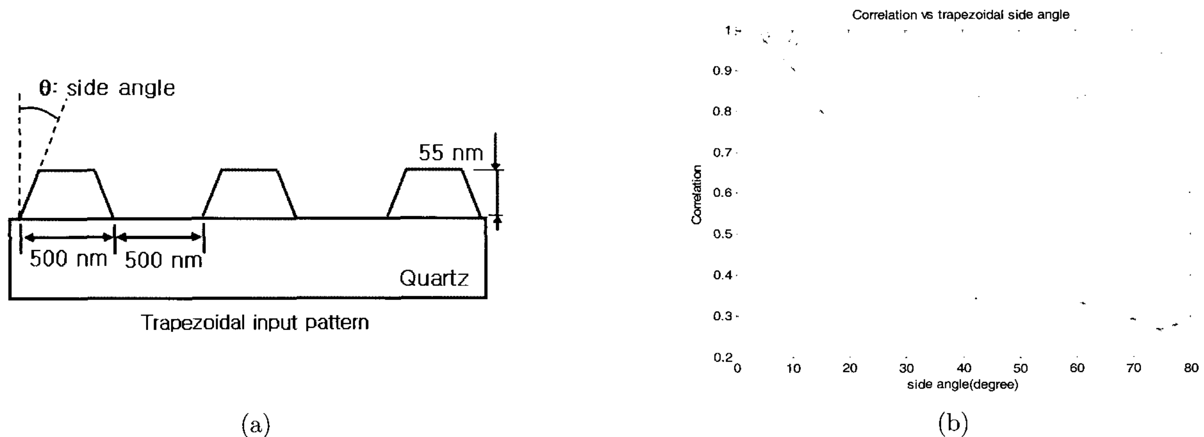

FIG. 6. (a) Definition of trapezoidal pattern side angle and (b) Correlation peak value versus pattern side angle as defined in Fig. 6 (a) [o: when we used Ψ spectrum, *: when we used Δ spectrum].

SE technology. Although this kind of nano-object recognition application is not that popular yet in nano technology industry, we expect that it would play an important role in various nano technology fields such as photonic crystal, semiconductor and NEMS (Nano Electro-Mechanical System) applications in the near future.

IV. CONCLUSION

A novel method for nano size 3D object recognition by use of phase sensitive scatterometry has been described. In this study, we have obtained a meaningful conclusion that the amplitude based scatterometry is much less likely to recognize 3D nano-object correctly while phase sensitive scatterometry can provide a reasonable moderate recognition capability. We expect that this kind of scatterometry based real time nano-object recognition technology will be more and more important as various nano technology fields grow gradually.

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