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Thickness Profiling of a Large-aperture Transparent Plate immune to nonlinear errors

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According to the increased demand for large-aperture silicon wafers, a transparent plate, used as a mask for patterning a silicon wafer, should be thoroughly measured for the high performance of the semiconductor chips. In the wavelength-tuning interferometry, the optical thickness of the large-aperture transparent plate can be precisely measured without destruction, but it is inevitable to avoid the occurrence of nonlinear errors by environmental factors. The nonlinearities generate uniform and nonuniform errors in the final phase distorting the original phase information. In this paper, for suppressing the nonlinearities, uniform, and nonuniform errors, a new algorithm designing method, extended averaging method, is developed. With the use of the minimum number of interferograms, we can get the extended averaging phase-extracting algorithm which has immunity to nonlinearities, uniform, and nonuniform error. Two types of numerical error analyses show the novel algorithm has superior error-suppression ability.

1. Introduction

A transparent plate is used as a mask for patterning a silicon wafer in the semiconductor industry. Several geometrical properties of the transparent plate such as thickness variation, absolute thickness, and sagging are directly related to the quality of the semiconductor chips [1]. Also, the necessity of large-aperture silicon wafers has been increasing for mass production and cost reduction in the industry. Therefore, the thickness of the large-aperture transparent plate should be thoroughly measured for the high performance of the semiconductor chips.

Wavelength-tuning interferometry has been widely used for thickness profiling which has non-destructive inspection and a wide measurable range [2, 3]. With this technique, a phase difference between beams reflected from reference and sample surface is linearly shifted and equivalent interferograms are acquired with the same phase-shift intervals. However, during the wavelength tuning, environmental factors such as vibration and temperature variation cause nonlinear errors in the phase shift [4]. The nonlinearities in the phase shift generate uniform and nonuniform errors in the final phase distorting the original phase information. Therefore, a new phase-extracting algorithm is needed which has immunity to the nonlinearities, uniform and nonuniform errors.

In this paper, for suppressing the phase-shift nonlinearities, uniform and nonuniform errors, a new algorithm designing method, the extended averaging method, is developed. The averaging method is successively applied twice for suppressing the nonlinearities uniform and nonuniform errors. In this method, with the use of the minimum number of interferograms, we can get a novel extended averaging phase-extracting algorithm which can suppress the phase-shift nonlinearities, uniform and nonuniform errors. Two types of numerical error analyses show the novel algorithm has superior error-suppression ability.

2. Advanced averaging phase-extraction algorithm

2.1 Wavelength tuning interferometry

The intensity of the interferograms acquired by the wavelength tuning can be expressed as

$$I\left(a_r\right)=S_0+\sum_{m=1}^{\infty}S_m\cos\left(\varphi_m-m\alpha_r\right), \tag{1}$$

where S_0 is the DC component of intensity, S_m and φ_m are the intensity and phase of the mth harmonics, respectively. The phase-shift parameter α_r can be expressed as [5]

$$\alpha_r=\alpha_{0r}\left[1+\varepsilon_0+\varepsilon_1\left(\frac{\alpha_{0r}}{\tau}\right)+\varepsilon_2\left(\frac{\alpha_{0r}}{\tau}\right)^2+\ldots\right], \tag{2}$$

where α_{0r} = $(2\pi/N)[r - (M + 1)/2]$, τ = $(\pi/N)(M - 1)$ (N is phase-distribution integer), ε_0 is the coefficient of the phase-shift miscalibration and ε_k is the coefficient of the phase-shift nonlinearity.

For measuring the optical thickness of the transparent plate, the phase of fundamental signal φ_1 should be detected by the M-sample phase-extraction algorithm, generally given by

$$\tan(\varphi_1) = \frac{\sum_{r=1}^{M} b_r I(\alpha_r)}{\sum_{r=1}^{M} a_r I(\alpha_r)}, \tag{3}$$

where r is the sampling number, M is the number of interferograms, and a_r and b_r are sampling amplitudes.

By substituting Eqs. (1) and (2) into Eq. (3) and using the Taylor series, calculated phase error $\Delta\varphi$ can be expressed as [5]

$$\begin{aligned}\Delta\varphi &= \frac{\pi}{2}(X_0\varepsilon_0 + X_2\varepsilon_2 + \cdots)\sin 2\varphi_1 \\ &+ \frac{\pi}{2}(Y_1\varepsilon_1 + Y_3\varepsilon_3 + \cdots) + \frac{\pi}{2}(Z_1\varepsilon_1 + Z_3\varepsilon_3 + \cdots)\cos 2\varphi_1,\end{aligned} \tag{4}$$

where X_{2q}, Y_{2q+1}, and Z_{2q+1} (q = 0, 1, 2, …) are the error coefficients. On the right side of Eq. (4), the first and the third terms, including the target phase φ_1, are the nonuniform errors distorting the entire configuration. The second term, not including the target phase φ_1, is the uniform error, moving the configuration apart from the zero-error axis.

2.2 Algorithm design

The M-sample phase-extraction algorithm, Eq. (3), can be expressed as below form:

$$\tan(\varphi_1) = \frac{N_1}{D_1}. \tag{5}$$

By applying the averaging method to M samples having $2\pi/N$ phase shifts, two algorithms are merged in the following form:

$$\tan\left(\varphi_1 - \frac{\pi}{N}\right) = \frac{N_1 + N_2}{D_1 + D_2}, \tag{6}$$

where N_2 and D_2 are the numerator and denominator of the $2\pi/N$ shifted M-sample algorithm. Also, for the symmetric form of the phase shift and sampling amplitudes, the phase center should be moved by π/N, half of the phase shift interval. The averaging method can be applied twice in a row, called as an extended averaging method, and followed the below form:

$$\tan\left(\varphi_1 - \frac{2\pi}{N}\right) = \frac{N'_1 + N'_2}{D'_1 + D'_2} = \frac{(N_1 + N_2) + (N_2 + N_3)}{(D_1 + D_2) + (D_2 + D_3)}. \tag{7}$$

By applying the averaging method to M samples, the nonlinearities can be suppressed as much as using $2M$ interferograms with the advantage of using the minimum number of samples, M + 1 interferograms. In the extended averaging method, applying the averaging method twice in succession as Eq.(7), only M + 2 interferograms are required instead of $3M$ interferograms. The effect of nonlinearities is reduced in each averaging step [6]. By the extended averaging method, the nonlinearities can be suppressed which results in the suppression of the nonuniform error as well.

However, the extended averaging method cannot suppress the uniform error. The constant error, the second term on the right side of Eq. (4), can be suppressed by adjusting the constant error coefficient Y_q to zero. In this paper, the first nonlinearity, the dominant error, is considered and the error coefficient Y_1 is adjusted to zero. To adjust Y_1 to zero, the characteristic polynomial approach and window function expression are used. The M-sample phase-extraction algorithm can be expressed by the characteristic polynomial [7]:

$$P(x) = \sum_{r=1}^{M}(a_r - ib_r)x^{r-k}, \tag{8}$$

where k is $(M + 1)/2$, and the sampling amplitudes a_r and b_r can be expressed by the window function:

$$a_r = w_r \cos\alpha_{0r}, \tag{9}$$

$$b_r = w_r \sin\alpha_{0r}. \tag{10}$$

According to the Eqs.(9) and (10), the constant error coefficient Y_1 can be written as

$$Y_1 = -\frac{2}{N(M-1)}\sum_{r=1}^{M}(r-k)^2 w_r. \tag{11}$$

Given the similarity of the Eqs. (8) and (11), Eq. (8) is differentiated two times:

$$D^2P(x) = \sum_{r=1}^{M}(r-k)^2(a_r - ib_r)x^{r-k}, \tag{12}$$

where derivative operator $D = x \cdot d/dx$. By substituting x with the fundamental frequency $\zeta = \exp(2\pi i/N)$ and utilizing Eqs. (9) and (10), we can obtain:

$$D^2P(\zeta) = \sum_{r=1}^{M}(r-k)^2 w_r, \tag{13}$$

where the right side is the same as that of Eq. (11). Provided that the characteristic polynomial has two roots at the fundamental frequency, the error coefficient Y_1 is set as zero.

However, the characteristic polynomial $P(x)$ cannot have roots at the fundamental frequency because the fundamental frequency possesses the optical thickness information as mentioned in Section 2.1. Therefore, a novel characteristic polynomial is required, having two roots at the fundamental frequency whose radii are not unity and different from each other:

$$Q(x) = P(x)\frac{1}{x}(x - \rho_1\zeta)(x - \rho_2\zeta), \tag{14}$$

where ρ_1 and ρ_2 are positive real numbers, and $1/x$ is added to maintain the Hermitian form. According to the assumption that $\rho_1\rho_2$ = 1 and none of them are unity, Eq. (14) can be rewritten as below:

$$Q(x) = P(x)\left(x - C\zeta + \frac{\zeta^2}{x}\right). \tag{15}$$

With the condition $D^2Q(\zeta) = 0$ for eliminating the coefficient Y_1, we can get the equation of C:

$$C = \frac{2P(\zeta)}{D^2P(\zeta)} + 2. \tag{16}$$

Finally, we can get the $(M + 4)$-sample phase-extraction algorithm that can suppress the nonlinearities, uniform, and nonuniform errors by the above novel method, named as an advanced averaging method.

2.3 Example

Now, to verify the error-suppression ability of the advanced averaging method, a 7-sample algorithm is used as an example. The algorithm considers up to the second harmonics and second nonlinearities, and can be expressed as

$$\tan(\varphi_1) = \frac{I_1 - 7I_3 + 7I_5 - I_7}{-4I_2 + 8I_4 - 4I_6}. \tag{17}$$

After applying the extended averaging method to the 7 samples, (7 + 2)-sample algorithm can be given by

$$\tan(\varphi_1) = \frac{-6I_2 + 26I_4 - 26I_6 + 6I_8}{-I_1 + 16I_3 - 30I_5 + 16I_7 - I_9}. \tag{18}$$

Then, a novel characteristic polynomial can be calculated by the advanced averaging method:

$$Q(x) = -\frac{1}{x^5}(x-1)(x+1)(x-i)^6\left(x^2 + \frac{14i}{5}x - 1\right). \tag{19}$$

By expanding Eq. (19) and extracting the coefficients, the sampling amplitudes of (7 + 4)-sample phase-extraction algorithm are obtained:

$$a_r = [0,-16,0,-64,0,160,0,-64,0,-16,0], \tag{20}$$

$$b_r = [-5,0,1,0,134,0,-134,0,-1,0,5]. \tag{21}$$

During the process, additional interferograms are obtained as Fig. 1.

The nonlinearities in wavelength tuning generate nonlinear errors in the target phase and in the harmonics. The nonlinearity-suppression ability of the algorithm can be examined by the root-mean-square (RMS) value of these two errors as shown in Fig. 2 [8]. The (7 + 4)-sample algorithm has a superior ability to suppress nonlinearities compared with the Jeon 11-sample algorithm [9] which uses the same number of interferograms. Also, it is certain that due to the advanced averaging method, the error is reduced by almost 96% compared with the base 7-sample algorithm.

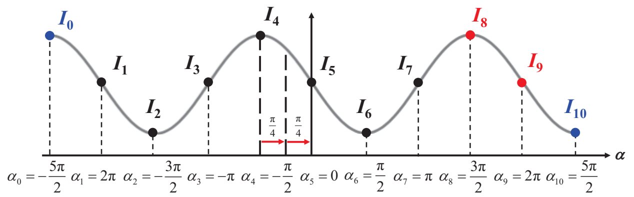

Fig. 1 Phase shift of the (7 + 4)-sample algorithm obtained from the advanced averaging method. Red indicates the extended averaging method and Blue indicates the advanced averaging method.

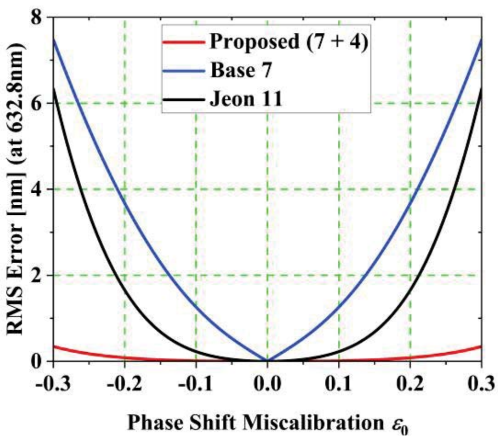

Fig. 2 Calculated RMS error as a function of the phase shift miscalibration ε_0.

Table 1 Mean value of the uniform error in case of 5% miscalibration and 3% first nonlinearity in phase calculation

algorithm	constant error with λ_1 for optical variation	constant error with λ_s for absolute optical thickness
(7 + 4)	0.039 nm	4.446 nm
Base 7	1.568 nm	178.7 nm
Jeon 11 [9]	1.784 nm	203.4 nm

The constant error can be estimated by the synthetic wavelength since the constant error should be considered when measuring the absolute optical thickness. The calculated phase should be multiplied by the synthetic wavelength $\lambda_s = \lambda_1\lambda_2/(\lambda_2 - \lambda_1)$ when the wavelength linearly changes from λ_1 to λ_2. For example, in case of λ_1 = 632.8 nm and λ_2 = 638.4 nm, the synthetic wavelength λ_s is 72.14 μm which amplifies the constant error. Table 1 shows the mean value of the constant error when 5% miscalibration and 3% first nonlinearity exist in the phase. In Table 1, it is obvious that when using the synthetic wavelength for measurement of the absolute optical thickness, the uniform error is amplified approximately 100 times. The advanced averaging (7 + 4)-sample algorithm shows the improved error-suppression ability compared with the base algorithm.

3. Conclusions

This paper proposes a novel algorithm designing method, an advanced averaging method, suppressing the nonlinearities, uniform, and nonuniform errors with the minimum number of interferograms. First, the extended averaging method is applied to M samples, then (M + 2) samples are obtained which can suppress the effect of the nonlinearities and nonuniform error. Second, the novel characteristic polynomial is calculated to suppress the uniform error which gives a significant effect on the absolute optical thickness, then (M + 4) samples are obtained. This entire procedure is named as advanced averaging method and an algorithm derived from this method is called as an advanced averaging algorithm. Finally, the error-suppression ability of the proposed algorithm is analyzed by two types of numerical methods. The advanced averaging algorithm shows improved ability compared with the base algorithm.

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