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Measurement of highly reflective surface shape using wavelength tuning Fizeau interferometer and polynomial window function

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ABSTRACT

In this study, a $5N-4$ phase shifting algorithm comprising a polynomial window function and a discrete Fourier transform is developed to measure interferometrically the surface shape of a silicon wafer, with suppression of the coupling errors between the higher harmonics and the phase shift error. A new polynomial window function is derived on the basis of the characteristic polynomial theory by locating five multiple roots on the characteristic diagram. The characteristics of the $5N-4$ algorithm are estimated with respect to the Fourier representation in the frequency domain. The phase error of the measurements performed using the $5N-4$ algorithm is discussed and compared with those of measurements obtained using other conventional phase shifting algorithms. Finally, the surface shape of a 4-in. silicon wafer is measured using the $5N-4$ algorithm and a wavelength tuning Fizeau interferometer. The accuracy of the measurement is discussed by comparing the amplitudes of the crosstalk noise calculated by other algorithms. The uncertainty of the entire measurement was 34 nm, better than that of any other conventional phase shifting algorithms.

1. Introduction

Silicon wafers have been widely used in the semiconductor industry because of their excellent performance and the ease of fabricating integrated circuits on their surface and controlling the value of resistance [1]. The surface shape of a silicon wafer must be measured precisely when estimating the performance of semiconductor devices [2]. The semiconductor industry uses atomic force microscopy (AFM) to measure the surface shape of a silicon wafer; however, using AFM to measure the entire surface shape is time consuming. Wavelength tuning Fizeau interferometry is another method for measuring the surface shape distribution of a silicon wafer. In wavelength tuning interferometry, phase shifting is used to vary the phase difference between a sample beam and a reference beam, and the signal irradiance is acquired at equal phase difference intervals [3]. The phase distribution of a fringe pattern can be calculated with a phase shifting algorithm.

When using wavelength tuning interferometry to measure the surface shape of a silicon wafer, not only the phase shift errors that occur during wavelength tuning and the harmonics resulting from the high reflectivity of the surface, but also the coupling errors between the phase shift errors and the higher harmonics must be considered because the surface reflectivity is high (30%) [4]. These systematic errors influence the calculated phase and appear as crosstalk noise obtained by subtracting successive results.

Many studies [5–23] have reported on error-compensating algorithms that can eliminate the effect of systematic errors. Systematic approaches to the design of such phase shifting algorithms include averaging over successive samples [5,9,11], using a Fourier representation [7] or analytical expansion [10,16,17,19,20], using data-sampling windows [12,18], and characteristic polynomial theory [13,21–23]. The prominent Schwider–Hariharan 5 sample algorithm [5,6] can compensate for phase shift miscalibration but not for coupling errors. The $2N-1$ algorithm, developed by Surrel [13], uses characteristic polynomial theory to compensate for phase shift miscalibration and the coupling error between the higher harmonics and the phase shift miscalibration; however, this algorithm cannot compensate for the nonlinearity in the phase shift error. Hibino et al. [16], who derived two kinds of 19 sample algorithms [19,20] by considering the refractive index dispersion in the transparent plate, proposed a phase shifting algorithm that can compensate for the coupling error. However, Hibino algorithms do not satisfy the condition for maximum fringe contrast [22]. Phase shifting algorithms should satisfy the maximum fringe contrast condition when a highly reflective surface such as that of a silicon wafer is measured [22]. We developed the $4N-3$ algorithm that can compensate for up to second-order nonlinearity and coupling errors [23]. The surface shape and variation in the optical

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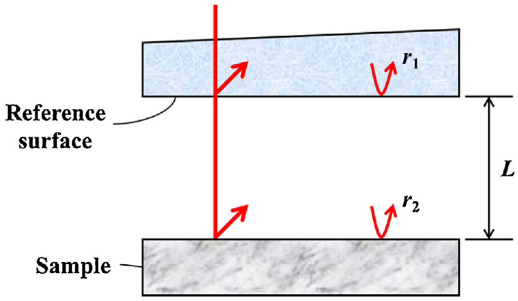

Fig. 1. Laser Fizeau interferometer.

thickness of a lithium niobate (LNB) crystal wafer were measured simultaneously using wavelength tuning and the $4N-3$ algorithm. However, the ripples that result from the residual phase shift error and coupling errors were clearly observed in the measured surface shape and the variation in the optical thickness [23]. The ripples that resulted from the imperfect suppression of the coupling errors were observed when one subtracted the successively measured surface shapes or the variations in optical thickness.

We developed and present here a new $5N-4$ phase shifting algorithm that comprises a polynomial window function and a discrete Fourier transform (DFT) term to measure the surface shape of a silicon wafer with suppression of the coupling errors. The characteristics of the $5N-4$ algorithm are discussed with respect to the Fourier representation of the phase shifting algorithm in the frequency domain. We show that our $5N-4$ algorithm yields the smallest phase error compared with those of five conventional phase shifting algorithms. Finally, the surface shape of a 4-in. silicon wafer was measured using a wavelength tuning Fizeau interferometer and the $5N-4$ algorithm. The accuracy of the measurement of the surface shape was 2.2 nm. The accuracy of the conventional phase shifting algorithms also is discussed with respect to the crosstalk noise.

2. 5*N* – 4 phase shifting algorithm

2.1. Laser Fizeau interferometer

A laser Fizeau interferometer (Fig. 1) allows the interference of multiple reflections between a sample surface and a reference surface by virtue of the high degree of coherence of the light. Let the reference and sample surface reflectivities be r_1 and r_2, respectively.

The observed signal irradiance $I(\alpha_r)$ in the interference fringe pattern that occurs during phase shifting is given by [4,17]

$$\begin{aligned} I(\alpha_r) &= \sum_{m=1}^{\infty} A_m \cos(\varphi_m - m\alpha_r) \\ &= I_0 \left[1 + \sum_{m=1}^{\infty} \gamma_m \cos(\varphi_m - m\alpha_r) \right] \\ &= I_0 + I_0\gamma_1 \cos(\varphi_1 - \alpha_r) + I_0\gamma_2 \cos(\varphi_2 - 2\alpha_r) + \cdots, \end{aligned} \tag{1}$$

where α_r is the phase shift parameter and A_m and φ_m are the amplitude and phase of the mth harmonic component, respectively. The DC component I_0 of the signal irradiance and the fringe contrast γ_m of the mth harmonic component are given by [4]

$$I_0 = \frac{r_1 + r_2 - 2r_1r_2}{1 - r_1r_2}, \tag{2}$$

$$\gamma_1 = \frac{2(1-r_1)(1-r_2)}{r_1 + r_2 - 2r_1r_2}\sqrt{r_1r_2}, \tag{3}$$

$$\gamma_2 = -\gamma_1\sqrt{r_1r_2}, \tag{4}$$

$$\gamma_3 = \gamma_1 r_1 r_2. \tag{5}$$

The fringe contrast γ_m for each successive harmonic of order m decreases in strength by the multiplicative factor $-\sqrt{r_1r_2}$. The phase distribution can be determined using a phase shifting algorithm. Consider an M-sample phase shifting algorithm, where the reference phases are separated by $M-1$ equal intervals of $\delta = 2\pi/N$ rad and N is an integer. A general expression for the calculated phase in this algorithm is given by [24]

$$\varphi^* = \arctan \frac{\sum_{r=1}^{M} b_r I(\alpha_r)}{\sum_{r=1}^{M} a_r I(\alpha_r)}, \tag{6}$$

where a_r and b_r are the rth sampling amplitudes and $I(\alpha_r)$ is given by Eq. (1). When the phase shift is nonlinear, each α_r value is a function of the phase shift parameter and can be expressed as a polynomial function of the unperturbed phase shift value α_{0r} [16]:

$$\begin{aligned} \alpha_r = \alpha_{0r}[1 + \varepsilon(\alpha_{0r})] = \alpha_{0r} \Bigg[1 + \varepsilon_0 + \varepsilon_1 \frac{\alpha_{0r}}{\pi} \\ + \varepsilon_2 \left(\frac{\alpha_{0r}}{\pi}\right)^2 + \cdots + \varepsilon_p \left(\frac{\alpha_{0r}}{\pi}\right)^p \Bigg], \end{aligned} \tag{7}$$

where p is the maximum order of the nonlinearity, ε_0 is the error coefficient of the phase shift miscalibration, ε_q $(1 \le q \le p)$ is the error coefficient of the qth nonlinearity of the phase shift, and $\alpha_{0r} = 2\pi[r-(M+1)/2]/N$.

The phase error $\Delta\varphi$ in the calculated phase is a function of the amplitude ratio A_m/A_1 and the error coefficient ε_q and can undergo a Taylor expansion as follows:

$$\Delta\varphi = \varphi^* - \varphi_1 = o(A_k) + o(\varepsilon_q) + o(A_k\varepsilon_q), \tag{8}$$

for $k = 2, 3, \ldots, m$ and $q = 0, 1, \ldots, p$. In Eq. (8), $o(A_k)$, $o(\varepsilon_q)$, and $o(A_k\varepsilon_q)$ are the error in the harmonics, the phase shift error, and the coupling error between the higher harmonics and the phase shift error, respectively. For example, $o(\varepsilon_0)$ is the phase shift miscalibration and $o(A_2\varepsilon_1)$ is the coupling error between the second harmonic and first-order nonlinearity of the phase shift error.

When measuring the surface shape of a highly reflective sample such as a silicon wafer, the coupling error is large because the higher harmonics components considerably influence the calculated phase distribution, even though the phase shift miscalibration is extremely small [4].

2.2. Derivation of 5N – 4 phase shifting algorithm

The characteristic polynomial $P(x)$ proposed by Surrel [13] is defined as

$$P(x) = \sum_{r=1}^{M} (a_r + ib_r)x^{r-1}, \tag{9}$$

where i is the imaginary number, $x = \exp(im\delta)$, and $\delta = 2\pi/N$. Surrel noted that the locations and multiplicities of the roots of the polynomial in the characteristic diagram determine the sensitivity of the algorithm to higher harmonics and phase shift miscalibration [13].

First, to suppress the mth harmonic component, the characteristic polynomial of the phase shifting algorithm should have single roots in the characteristic diagram, as shown in Fig. 2(a) [13]. This is the synchronous detection algorithm proposed by Bruning [3] and it does not compensate for $o(\varepsilon_q)$ and $o(A_k\varepsilon_q)$ specified in Eq. (8). To suppress $o(\varepsilon_0)$ and $o(A_m\varepsilon_0)$, the double roots should be located on the characteristic diagram as shown in Fig. 2(b), the $2N-1$ algorithm proposed by Surrel [13], which uses the triangular window