Whole field curvature and residual stress determination of silicon wafers by Reflectometry

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ABSTRACT

Reflectometry, a simple whole-field curvature measurement system using a novel computer aided phase shift reflection grating method has been improved to certain extend. The similar system was developed from our earlier works on Computer Aided Moiré Methods and Novel Techniques in Reflection Moiré, Experimental Mechanics (1994) in which novel structured light approach was shown for surface slope and curvature measurement. This method uses similar technology but coupled with a novel phase shift system to accurately measure surface profile, slope and curvature.

In our previous paper, “Stress Measurement of thin wafer using Reflection Grating Method”, the surface curvature and residual stresses were evaluated using the versatility of the proposed system.. The curvature of wafers due to the deposition of backside metallization was evaluated and compared with a commercially stress measurement system from KLA-Tencor.

In this paper, some aspects of the work are extended. Our proposed system is calibrated using a reference flat mirror and spherical mirror certified by Zygo Corporation. The mirrors together with the camera calibration toolbox allow the system to acquire measurement accuracy that is demanded by semiconductor industry. Finally, the results obtained from Reflectometry are compared and contrast with results from KLA Tencor System.

1. INTRODUCTION

As the size and thickness of the wafer become thinner and larger, the wafer geometry has become one of the critical aspects to be studied. There is an increased tendency for the wafer to warp and cracks. Monitoring of curvature/flatness is thus necessary to ensure reliability of device and its uses. Residual stresses are induced on the during wafer manufacturing process steps. The localized residual stresses induced cause failures in subsequent processes. These failures are responsible for both material and economical losses. Hence, it is important to be able to monitor and characterize the residual stress of the silicon wafer.

Reflectometry or more commonly termed, phase measuring deflectometry are widely used as inspection tool for semiconductor and packaging industry. This non-contact inspection technique has been actively employed due to its simple setup and its ability to measure surface slope of specular surface, such as silicon wafer. There are plenty of techniques for wafer geometrical and flatness inspection, most of the techniques are point measuring and require time consuming as well as complex scanning technologies. The cost of these equipments cab range from few hundred thousand dollars to few million dollars depends on type applications and requirements of the manufacturing environment. The technique is widely accepted by most silicon based manufacturers due to its relatively low cost configuration, providing resolution and accuracy that meets the requirement for most industry. More important, with the system, one can obtained the whole-field height and curvature distribution information of a particular surface via the slope data.

This paper will focus on a whole field fast out of plane measurement method for thin silicon wafer with reflecting surfaces. By obtaining the surface slope information, height and curvature distributions of the surface can be derived with considerably short cycle time. The phase related to surface slope is derived using the phase shifting method with temporal phase unwrapping. To obtain the absolute phase, a phase to slope transformation is needed. This coefficient is obtained during the calibration process. The height distribution can be obtained by performing integration on the existing slope information and the curvature distributions can be obtained by performing a single order differentiation.

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2. REFLECTOMETRY

The main application of reflectometry is the determination of the surface slope of thin plates. As against majority optical methods which map the out of plane displacement of all point on the surfaces, the reflectometry gives the slopes directly and curvature with one order differentiation. In this way the first and second derivatives of out-of-plane displacement are obtained. Curvature information is important as the small deflection in thin plates is directly related to the bending moments in surface. The main disadvantage of this method is the requirement of specular surface for the specimen under test. Conventionally, the reflected images from the specular surface in deform and reference states can be superimposed to create a moiré pattern equivalent to surface slope. In this paper, four step phase shift algorithm will be employed to deduce the surface slope. A plus point for this method is the easy implementation and equipments needed are minimal compare to other interferometry.

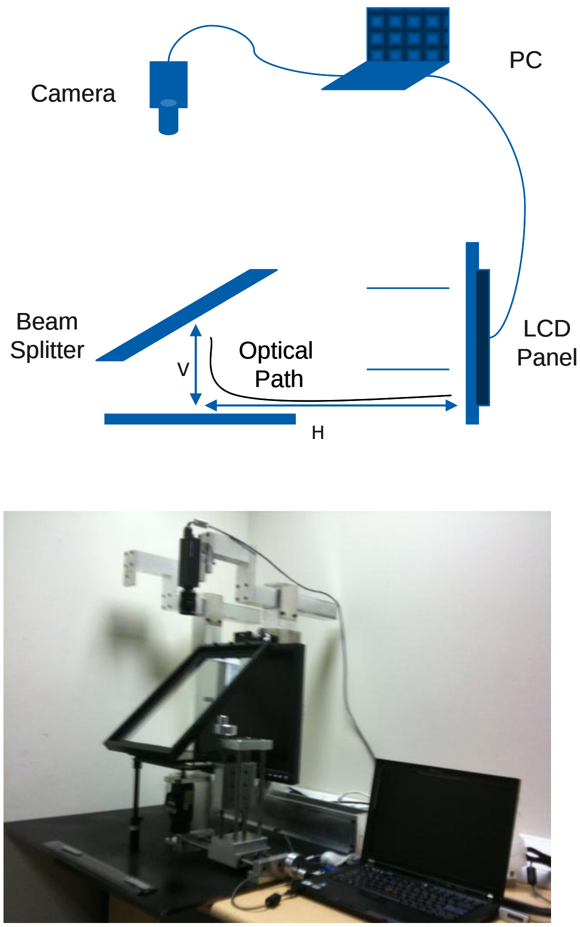

Figure 1: Schematic and photograph of current lab based setup

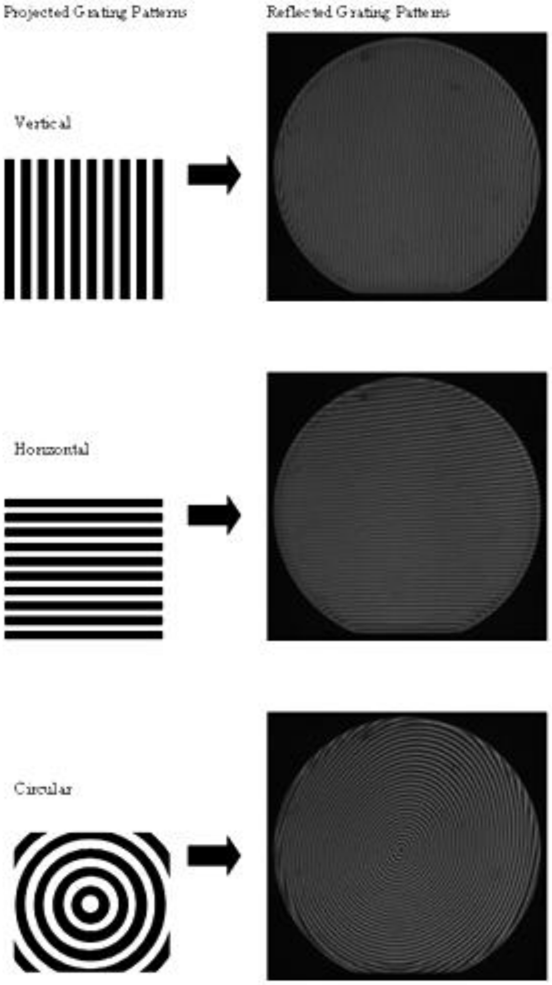

Figure 2: Projected and reflected grating patterns as seen

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2.1. Methodology

Both horizontal and vertical gratings are software generated, display using the LCD panel and projected onto the specimen surface. By using this technique, the pitch of horizontal and vertical grating can be varied and controlled without moving parts, thus reducing the possible error and improving the accuracy. The following algorithm is based on literature [4].

In the four step phase shifting approach, four images of the grating are captured using CCD cameras while the grating is translated in steps of quarter of their pitch (spacing between adjacent dark lines). Two set of four phase shifted images with horizontal and vertical gratings are captured using CCD cameras at 0°, 90°, 180°, and 270° degree intervals.
The 4 phase shifted images have the intensity values as follows:

$$I_0(x,y) = I'(x,y) + I''(x,y)\cos[\Phi(x,y) + 0\pi] \tag{1a}$$

$$I_{90}(x,y) = I'(x,y) + I''(x,y)\cos[\Phi(x,y) + 0.5\pi] \tag{1b}$$

$$I_{180}(x,y) = I'(x,y) + I''(x,y)\cos[\Phi(x,y) + \pi] \tag{1c}$$

$$I_{270}(x,y) = I'(x,y) + I''(x,y)\cos[\Phi(x,y) + 1.5\pi] \tag{1d}$$

A phase shift algorithm is used to deduce the phase of the distorted pattern which can be readily related to the surface slope. With this technique, one can analyze the intensity of the image captured at pixel level. The process is done over the full-field of the wafer simultaneously and in near real-time.

Resultant image of these shifted images are able to provide the phase information of the whole wafer. With some simple mathematical manipulation from set of equations 1, the phase parameter ϕ, which is of interest, can be solved as in equation 2:

$$\Phi(x,y) = \tan^{-1}\left(\frac{I_{270} - I_{90}}{I_0 - I_{180}}\right) \tag{2}$$

Equation two shows the general equation regardless of the direction of the gratings. For general 2-D stress analysis, gratings along two perpendicular directions are generated to get the curvature in the x-and-y-directions. By performing the phase shifting algorithm with grating in two perpendicular directions, two set of phase information are obtained, ϕ_x, ϕ_y. The phase data obtained, ϕ_x, ϕ_y are directly proportional to surface slope. The numerical differentiation is performed in the direction perpendicular to the gratings. The curvature can be obtained by performing a single order differentiation on the slope data. Consequently, residual stresses are related to the curvature through the general Stoney's equation. After taking the derivative, the curvature can be derived as:

$$\text{Curvature}, \kappa_x = \frac{\frac{d^2w}{dx^2}}{(1 + (\frac{dw}{dx})^2)^{\frac{3}{2}}} \tag{3}$$

From the equation above, the slope measured $\frac{dw}{dx}$ or $\frac{dw}{dy}$ is much smaller than unity, in this application, equation (3) can be approximated as:

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$$\text{Curvature}, \kappa_x = \frac{d^2 w}{dx^2} = \frac{1}{R} \tag{4}$$

The height distribution $z(x, y)$ is then calculated with an integration of the slope data [9-10].

2.2. System Calibration

To obtain the absolute slope value, the phase to slope transformation coefficient, γ is needed. To obtain this coefficient, first pixel size calibration procedure is required. This step is to determine the actual distance of the x and y coordinate. The pixel size calibration is obtained using the camera calibration toolbox for matlab in [11]. Figure 3 shows the chessboard used to perform the pixel size calibration. The distance between the black and white boxes are predefined. The real distance in D_x and D_y directions are extracted using this calibration procedure. The pixel size calibration is followed by slope calibration. A concave mirror with known radius of curvature is needed to perform the slope calibration. In this work, a concave mirror certified by Zygo Corporation is used as calibration reference. The phase distributions in Figure 4 are calculated from the reflected grating patterns of the concave mirrors. This phase distributions are used to extract the phase to slope transformation coefficient, γ_x and γ_y. With these factor, both height and curvature distributions are ready to be calculated. Only brief description of the system calibration is covered in this paper.

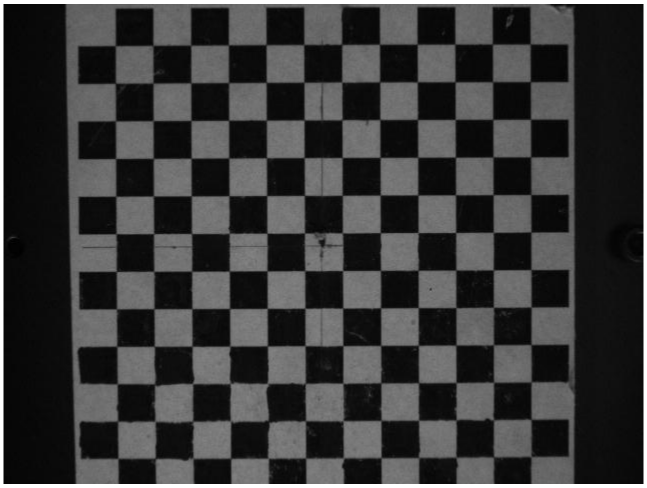

Figure3: Chessboard with predefined box dimension for pixel size calibration

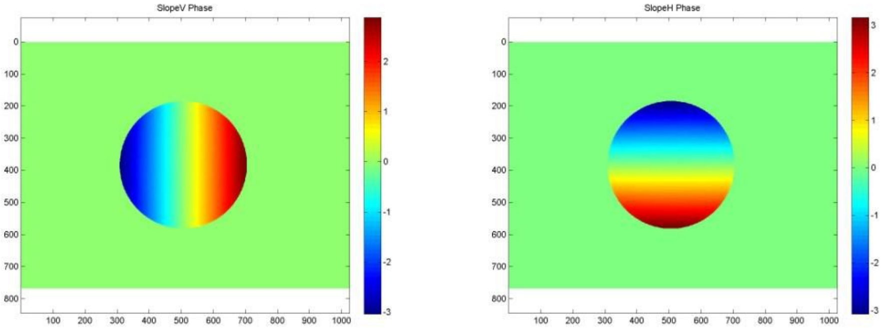

Figure 4: Phase distributions

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3. EXPERIMENTAL FINDINGS

3.1. Curvature and Stress Measurement of Silicon Wafer

The results presented in the previous sub-section proved the measurement capability of the proposed system. In this section, whole-field slope and curvature distributions of bare wafer and wafer with back metallization will be illustrated. For better understanding, wafers with concave and convex surface profile have been chosen to visualize the curvature changes. Curvature data in both directions is needed in order to complete the stress analysis. The bare wafer which has convex surface profile is expected to have negative radius of curvature. As expected, the R_x of bare wafer is measured to be -83.241(m) and R_y of the bare wafer is measured to be -67.176(m). The wafer deposited with Titanium backside has concave surface profile is expected to have positive radius of curvature. Again, the R_x of Titanium wafer is measured to be 28.837 (m) and R_y of Titanium wafer is measured to be 31.364(m). The curvature distributions of bare wafer and wafer with Titanium backside metallization are illustrated in Figure 5 and Figure 6. The experimental figures obtained are verified using KLA-Tencor system. Bare wafer has shown to have more homogeneous distributions than the wafer deposited with back metallization. This may due to the mismatch in coefficient in thermal expansion between the wafer and the metallization after deposition. The sudden changes in temperature gradient experienced by the wafer during the manufacturing processes might induce some residual stress that is irreversible, consequently, warpage results. After analyzing the curvature phase distributions shown in Figure 6, one could say with more confident that points/line measurement are not able to predict the curvature changes of the thin wafer accurately, even if higher accuracy can be obtained for a specific line by these equipment. Curvature changes along the center line might not represent the changes around the circumference. To perform the stress calculation, changes in the average radius of curvature before, R_1 and after, R_2, the back metallization deposition is needed. The stress induced due to back metallization deposition is determined by changes in radius of curvature, R. Since stress is inversely proportional to R, the changes in R can be deduced as follows:

$$\frac{1}{R} = \frac{1}{R_2} - \frac{1}{R_1} \tag{5}$$

or

$$R = \frac{R_1 R_2}{(R_1 - R_2)} \tag{6}$$

Stress induced can only be calculated if the change in radius of curvature before and after back metallization deposition is known. The radius of curvature in Figure 6 (a&b) before deposition process is not known. Only the radius of curvature after deposition is known. Since the bare wafer presented in Figure 6 (a&b) originated from the same batch, it is assumed the wafer in Figure 6 (a&b) has similar radius of curvature before metal deposition.

The stress induced due to back metal deposition can be calculated with the following equation:

$$\sigma = \frac{Eh^2}{(1-v)6Rt} \tag{7}$$

where h is the substrate thickness, R is the radius of curvature and t is the film thickness.

For 100 plane silicon wafer $\frac{E}{(1-v)}$ is equal to 1.805 x 10^{11} Pa [8]. With the assumptions made, the stress induces within the wafer with titanium back metallization is calculated. The average stress induced in x-direction is 1551MPa and the average stress induced in y-direction is 1554MPa.

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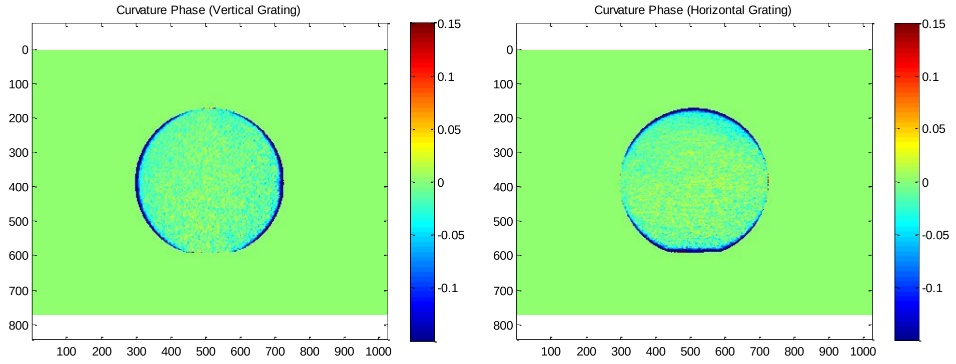
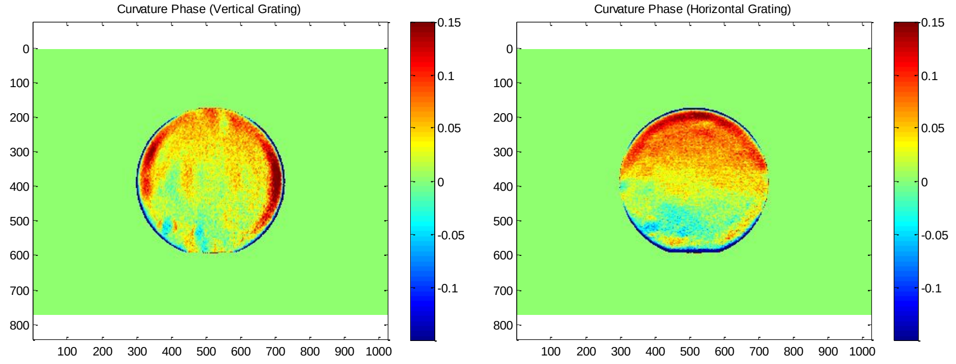


(a) (b)

Figure 5: Curvature distributions of bare wafer (a) vertical grating (b) horizontal grating



(a) (b)

Figure 6: Curvature distributions of wafer with Titanium metallization (a) vertical grating (b) horizontal grating

3.2. Height distribution measurement

Height distribution is obtained by performing the integration on slope data. Information ϕ_x, ϕ_y (Figure 6 (a) & (b) are used to deduce the height distribution. 3-D height distribution in Figure 7 is deduced using least square fit integration. The computation time is longer compare to conventional type integration. However, the errors are significantly reduced. Figure 7(b) shows the line plot through the center of Figure 7(a). The maximum warpage found for the bare wafer is 21um.

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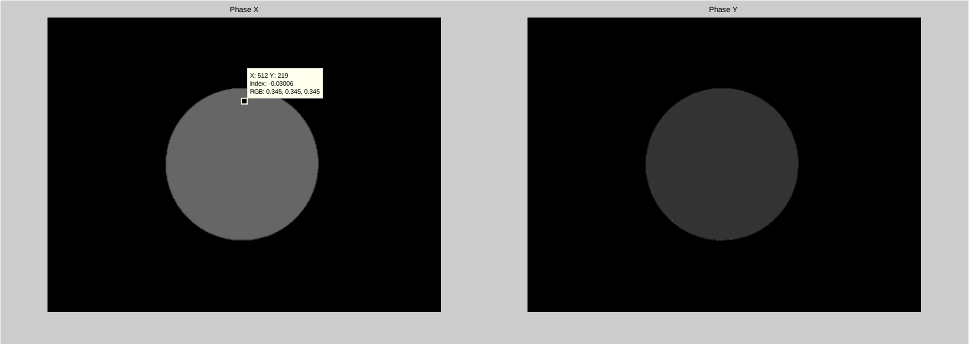
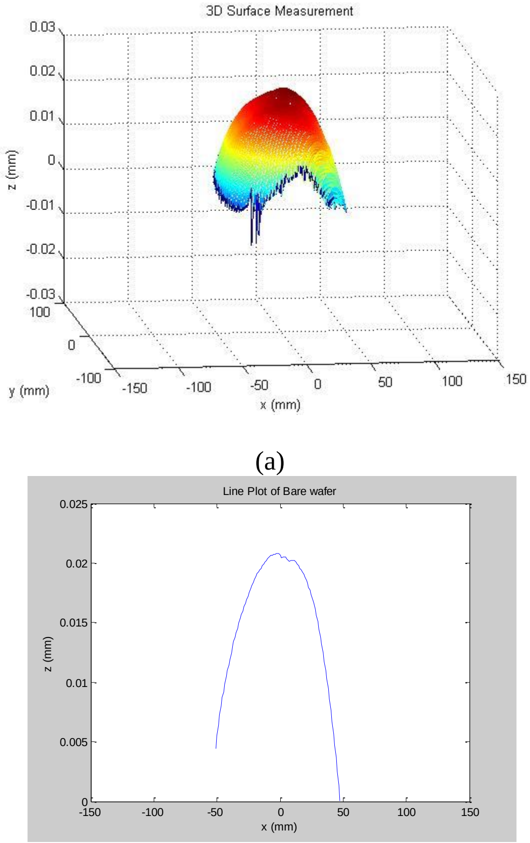


(a) (b)

Figure 6: Slope Map (a) ϕ_x (b) ϕ_y



(a)

(b)

Figure 7: (a) 3D Height Distribution (b) Line plot across the center of (a)

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CONCLUSION

The aim of this research is to prove that our proposed system, Reflectometry, is able to provide correct and accurate height, slope and curvature information when compared to the commercially available surface and stress measurement system. Most of the current techniques are point measuring techniques and require longer scanning time as well as complex scanning technologies. Reflectometry is able to provide whole-field distributions in much shorter cycle time. From the results presented, our current method involves a simple setup but still provides whole-field and sensitive measurement capability. The results from our system show good agreement with the results from KLA-Tencor system.

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