Development of 2D Angle Probe for Flatness Metrology of Large Silicon Wafer

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1. INTRODUCTION

Flatness is a critical parameter of silicon wafers for making integrated circuits, and measurement of wafer flatness is an essential process for both wafer manufactures and device manufacturers. Meanwhile, to make devices with improved functionality at a reduced cost, the design rule (width of the device pattern) has been becoming smaller and the silicon wafer size has been becoming larger. It is predicted that the design rule and wafer size will be 130nm, 300mm in 2002, and 35nm, 450mm in 2014, respectively [1]. This brings a big challenge to the metrology of wafer flatness. The site flatness of a wafer is required to be at the same level as the design rule, and the tolerance for the global flatness over the whole wafer is also very tight. To properly evaluate the flatness of such large wafers, improved metrology techniques with nanometric accuracy and high measurement speed must be developed.

In this project, we aim to develop a new scanning multi-probe system based on the concept of error separation [2], which can measure the flatness of 300mm and/or 400mm silicon wafers with high accuracy and high measurement speed. Two two-dimensional angle probes are used for error separation [3][4]. The probes detect the two-dimensional local surface slopes at two points on the wafer surface. The profile (flatness) of the wafer can be separated from the motion errors of the scanning stage (Z-directional error, pitching and rolling) by using the probe outputs. To realize nano-metrology of wafer flatness, two-dimensional angle probes with high resolution and high accuracy must be used. Since there are no commercially available angle probes that can detect the two-dimensional local slope of a surface, development of such probes is of high priority in this project.

In this paper, a prototype angle probe was designed and built. The probe utilizes the principle of autocollimation [5]. Different optical detection devices (photo-detectors) were used in the probe for the purpose of comparison. Principle and calibration results of the probe are reported.

2. PRINCIPLE OF 2D ANGLE PROBE

A two-dimensional (2D) angle probe is basically used for detecting the two-dimensional tilt of a surface as shown in Figure 1. Two-dimensional local slopes of the surface can also be detected by such a probe. The simplest way to construct a 2D angle probe is to utilize the method of optical lever. As can be seen in Figure 1, a laser beam is projected onto the sample surface. The optical spot of the reflected beam on a photo-detector with a distance L from the sample surface will move in the X and Y directions if the sample tilts around the X and Y axes. The two-dimensional components of the tilt $\Delta\alpha$ and $\Delta\beta$ can be calculated from the moving distances Δx and Δy of the spot on the photo-detector as follows:

$$\Delta\alpha = \Delta y / L \tag{1}$$
$$\Delta\beta = \Delta x / L \tag{2}$$

This method is simple but errors arise when distance L changes. In this study, we employ the technique of autocollimation to solve this problem. As shown in Figure 2, an objective lens is placed between the sample and the photo-detector. If the photo-detector is placed at the focal position of the lens, the relationship between the tilt and the readout of the photo-detector becomes:

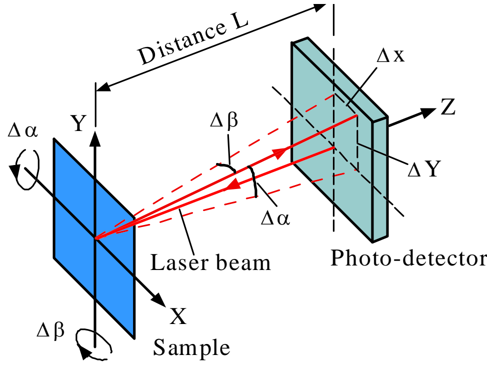

Figure 1 Two-dimensional tilt of a surface

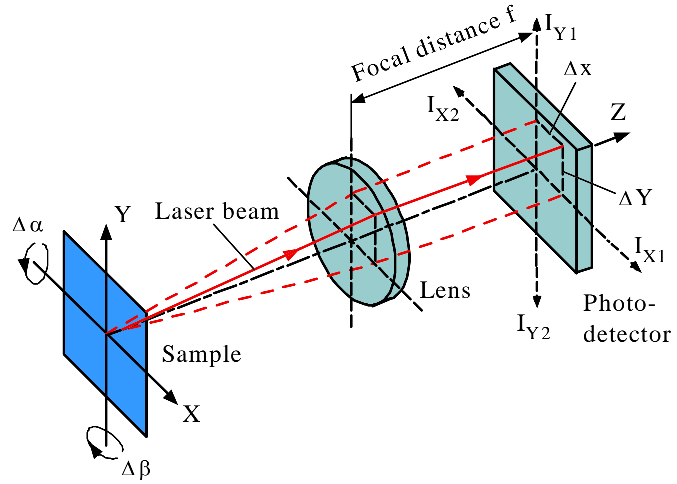

Figure 2 Detection of 2D tilt by autocollimation

$$\Delta\alpha = \Delta y / f \quad (3)$$
$$\Delta\beta = \Delta x / f \quad (4)$$

where f is the focal distance of the lens. As can be seen in Equations (3) and (4), the distance between the sample surface and the autocollimation unit consisting of the lens and the photo-detector does not affect the angle detection.

In the case of flatness metrology of silicon wafer, local slopes of the wafer surface are very small and the sensitivity of the angle probe is required to be very high. The sensitivity of the angle probe based on autocollimation can be improved by choosing a lens with a long focal distance. However, this will influence the compactness of the angle probe. In this paper, we discuss how to improve the sensitivity of the angle probe without increasing the focal distance of the lens by choosing proper photo-detectors.

The two-dimensional position sensing device (PSD) is widely used to detect the position of a light spot in two dimensions. PSDs have the advantage of good linearity. Position detection is also not affected by the intensity distribution of the light spot. Let the sensitive length of the PSD be L_P in both X and Y directions, the two-dimensional position can be calculated from the optical-electric currents I_{X1}, I_{X2}, I_{Y1}, and I_{Y2} through the following equations:

$$\Delta x = \frac{L_P}{2} \frac{(I_{X1} - I_{X2})}{(I_{X1} + I_{X2})} \quad (5)$$

$$\Delta y = \frac{L_P}{2} \frac{(I_{Y1} - I_{Y2})}{(I_{Y1} + I_{Y2})} \quad (6)$$

It can be seen that the sensitivity of a 2D PSD is mainly determined by the sensitive length. A PSD with short sensitive length is preferred for getting high sensitivity. A sensitive length of 0.1mm is proper for our purpose but commercially available PSDs typically have sensitive length of several millimeters. That means the required sensitivity of angle detection is difficult to achieve by choosing a PSD as the photo-detector. Another parameter to determine the sensitivity of a PSD is the noise current. The noise current level of a 2D PSD is several times larger than that of a one-dimensional (1D) PSD. From this point of view, it is easier to achieve higher sensitivity by using 1D PSDs. Figure 3 shows a 2D angle probe using two 1D PSDs. The sensitive directions of the PSDs are set along the X-axis and Y-axis, respectively.

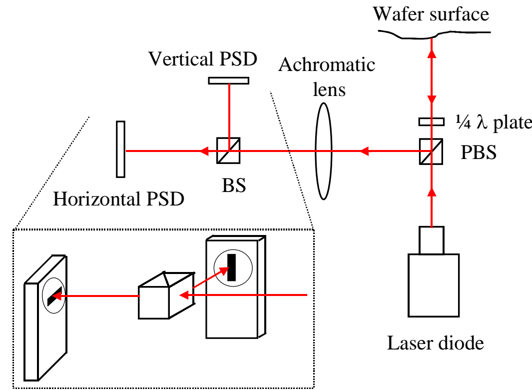

Figure 3 Two-dimensional angle probe using two one-dimensional PSDs

Another possible photo-detector is the quadrant photodiode (PD). As shown in Figure 4, a quadrant PD is placed at a position that is slightly apart from the focal point of the lens so that a light spot with a width of D_P is generated on the PD. For simplicity, the light spot is assumed to be rectangular. The two dimensional position of the light spot can be calculated by:

$$\Delta x = \frac{D_P}{2} \frac{(I_1 + I_4) - (I_2 + I_3)}{(I_1 + I_2 + I_3 + I_4)} \quad (7)$$

$$\Delta y = \frac{D_P}{2} \frac{(I_1 + I_2) - (I_3 + I_4)}{(I_1 + I_2 + I_3 + I_4)} \quad (8)$$

It can be seen that the sensitivity of the quadrant PD for position detection is mainly determined by the width of the light spot on the sensitive window of the PD. The width of the light spot can be changed to get a proper sensitivity of position detection by adjusting the position of the PD relative to the focal position of the lens along the optical axis of the autocollimation unit. Extremely high sensitivity can be achieved by using this technique.

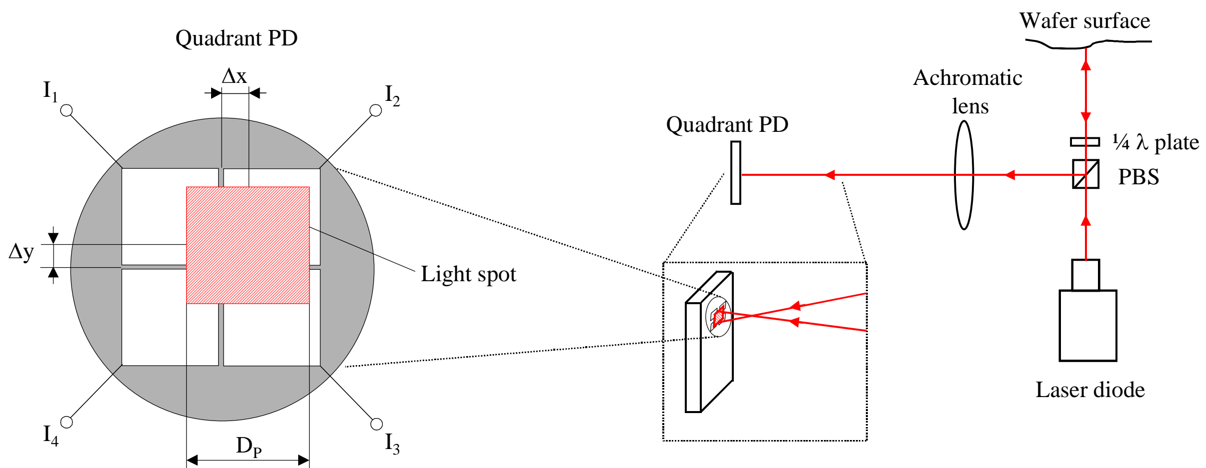

Figure 4 Two-dimensional angle probe using a quadrant PD

It should be pointed out that if the shape of the light spot is not rectangular but round, the relationships shown in Equations (7) and (8) will be nonlinear.

3. EXPERIMENTS

A prototype 2D angel probe was designed and built to investigate the basic characteristics of using different photo-detectors. Figure 5 shows a schematic view of the probe. Two one dimensional PSDs and a quadrant PD were used as the photo-detectors in the same probe for comparison. A laser diode was used as the optical source for compactness. The probe was designed to be within 90mm x 60mm x 20mm in size. An achromatic lens with a focal distance of 40mm was employed as the objective lens.

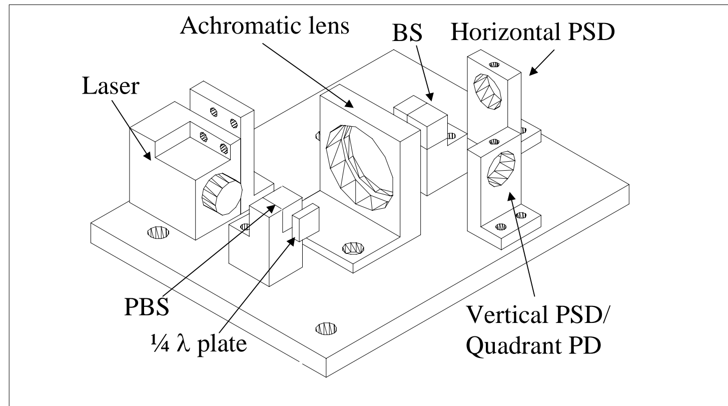

Figure 5 A prototype 2D angle probe

Figure 6 shows the result of calibration. The position of the PD was carefully adjusted to get high sensitivity of angle detection. It can be seen that the sensitivity of using quadrant PD is much higher than that of using PSD. The non-linearity of the PD output was caused by the round shape of the light spot.

4. CONCLUSIONS

A two-dimensional angle probe has been designed for measuring the flatness of large wafers. To improve the sensitivity of angle detection, the method of using two one-dimensional PSDs, and that of using a single quadrant PD as the photo-detectors have been theoretically discussed and experimentally investigated. It has been confirmed that the method of using a quadrant PD could reach higher sensitivity.

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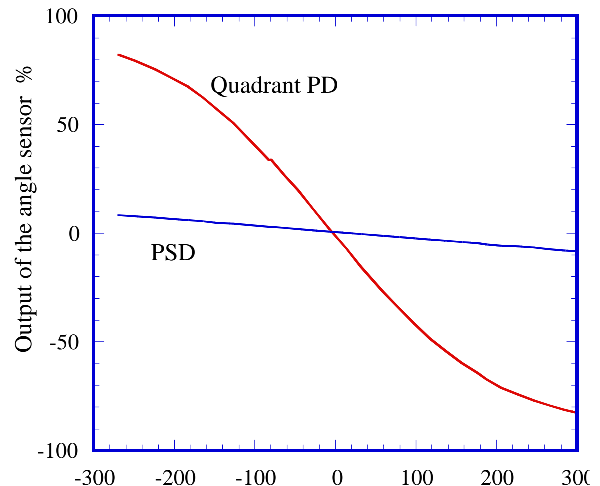

Figure 6 Calibration result

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