euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

Wafer warpage measurements by stitching lateral shearing interferometry

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Abstract
In this investigation, we describe a wafer warpage measurement system by using a lateral shearing interferometer. The proposed system uses a beam expander to enlarge the beam size and employs two polarization gratings, rotated at 0° and 90° to generate two laterally sheared beams along x- and y- directions. A polarization CMOS camera is used to obtain four phase-shifted interferograms to obtain the wavefront gradient in a single measurement. Then, the wafer warpage is reconstructed using an accumulation-based method. To extend the field of measurement, the stitching technique is adopted, and the proposed system was verified by comparison with measurement results obtained from a Fizeau interferometry.

Wafer warpage measurement, Stitching interferometer, Lateral shearing interferometer

1. Introduction

The wafer size in the semiconductor industry has been increasing for high throughput and productivity. Moreover, 3D stacking technologies have been introduced to confirm multi-functional performance, leading to the fabrication of thinner wafers. However, these structural changes cause the wafer warpage, which induces the alignment errors during semiconductor integration. Subsequently, the wafer warpage alleviates both yield and performance of the devices, and can even result in significant thermal issues. Accordingly, wafer warpage in the entire large surface should be precisely measured. In the conventional large-area surface metrology systems, deflectometry based on the fringe projection [1] and optical interferometry [2] have been used. For the precise measurements, Fizeau interferometry, which offers high stability and reliability, is primarily used, but it is still sensitive to environmental disturbances such as floor vibrations and requires a well-defined reference surface corresponding to the size of the measurement area. On the other hand, shearing interferometry is very attractive to precisely measure the surface figure of a specimen because it does not need a reference mirror. Instead of using the well-defined reference surface, it uses the self-interference by using two spatially sheared wavefronts from the measurement wavefront. Among several shearing interferometers, a lateral shearing interferometer is relatively appropriate for free-form surface measurements because it measures x- and y-gradient maps opposed to other shearing interferometers.

In this investigation, we describe a wafer warpage measurement system by using a lateral shearing interferometer. By using a polarization grating, a very simple lateral shearing unit is configured, and its common path characteristic avoids the use of a spatial coherent light source [3]. Two laterally-shifted beams are parallel to each other, which makes the interference fringes null in the polarization pixelated camera to instantaneously obtain the surface gradient maps. Based on x- and y-directional surface gradient maps, the surface figures of wafers are reconstructed. To reduce the system size and cost, the stitching interferometric principle is adopted.

2. Lateral shearing interferometric module

Figure 1(a) shows the lateral shearing interferometric module, which consists of a polarization grating (PG), a flat mirror (M) and a polarization CMOS camera (PCMOS), with the polarization multiplexing technique [3]. As one of a variety of geometric phase components, the PG enables a circular polarization-dependent diffraction grating, and the beam incident to the PG is diffracted, which is dependent on the polarization status of the incident beam. When a beam with a linear polarization, which can be decomposed into the sum of a right-handed circular polarization and a left-handed circular polarization, is incident to the PG, two diffracted beams are generated of $\pm 1^{st}$ order and propagated with an angle of $\pm\theta$, respectively. In addition, the PG generates phase retardation as a half-wave plate.

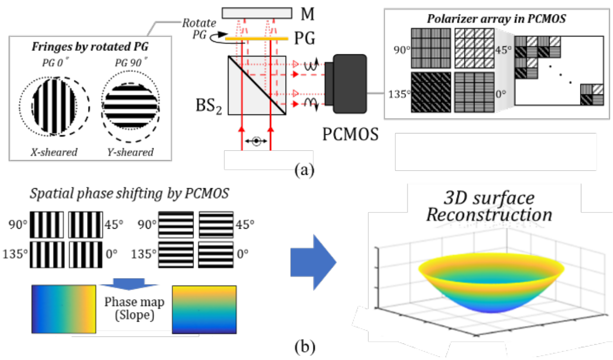

Figure 1. (a) Lateral shearing interferometric module using a polarization grating and (b) wavefront reconstruction; PG, polarization grating; BS, beam splitter; M, flat mirror; PCMOS, polarization CMOS camera.

In the module, therefore, the incident beam is split into two beams by the PG, and the returning beams are laterally shifted after reflecting off the M and passing through the PG again. These two beams are not only laterally shifted, but also their polarization states are orthogonal to each other as circular polarizations. Then, the PCMOS, where a polarizer array with 0°, 45°, 90° and 135° transmission axes is put on the imaging sensor, can obtain four phase-shifted interferograms at once to calculate the phase map based on the spatial phase shifting technique. With a single image obtained by the PCMOS, the proposed module can obtain the phase map corresponding to the x-sheared interferogram, and the other phase map can be calculated from the other single image obtained by the 90° rotation of the PG. These two phase maps indicate the slopes or gradients of the wavefront along x- and y-directions. Then, the original wavefront corresponding to the surface of the specimen can be reconstructed via the wavefront reconstruction algorithms as shown in Fig. 1(b).

3. Wafer warpage measurements by using a lateral shearing interferometer

Figure 2 shows the optical configuration for wafer warpage measurements. As light source, a LED is used, and the beam size is expanded by using a beam expander (BE). The reflected beam from a wafer is incident to lateral shearing interferometric module to obtain x- and y-directional gradient map. In the interferometer, two beam shutters are used for the acquisition of x- and y-sheared interferograms individually.

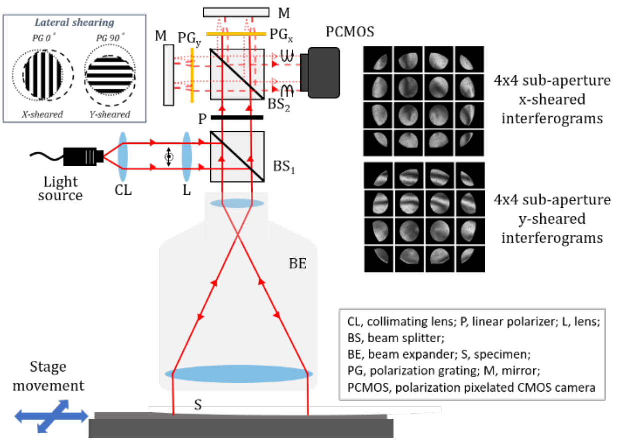

Figure 2. Wafer warpage measurements by using a lateral shearing interferometer.

After obtaining x- and y-directional gradient maps, an accumulative integration technique is used for efficient and rapid calculation of the surface reconstruction. It is based on zonal method proposed by Saunders [4], but it is an expanded version for 2D wavefront reconstruction without minimizing least-squares. Even though the lateral resolution of the surface reconstructed by the accumulative integration technique is relatively low, it is sufficient to evaluate the warpage of a wafer. Furthermore, for the entire surface measurement of a silicon wafer, a stitching method of the sub-aperture measurement results is introduced to the measurement system by using a motorized stage as shown in Fig. 2, and 6 DOF parameters including the lateral positioning errors and the rotational error are considered in the stitching process based the XY stage position measurement results.

To validate the feasibility of the proposed lateral shearing interferometer, we preliminary measured a concave mirror surface, and it was confirmed that the radius of curvature of the reconstructed surface agreed with the designed value within a 2% error margin. By incorporating a beam expander and replacing an imaging telecentric lens, then, we enlarged the effective aperture size as 140 mm such that the system can measure the full area of silicon wafers by using the stitching technique. Figure 3(c) shows the entire wafer warpage measurements results by using 4x4 sub-aperture x- and y-directional gradient maps as shown in Figs. 3(a) and 3(b). As shown in Fig. 3(c), the wafer was bent as 13.2 µm as a peak-and-valley (PV) value, and the validity of the measurement was confirmed by comparing the reconstructed wafer warpages after rotating the wafer by 90° as shown in Fig. 3(d). The measurement repeatability as defined by the mean value of the standard deviation for 10 consecutive surface measurement results was calculated to be on the order of 10 nm. For more rigorous verification of measurement capability, comparative measurements with a 3-inch flat mirror were implemented with a commercialized Fizeau interferometer from Zygo Corp. As a result, the deviation was less than 0.4 µm, attributed to the difference between two measurement procedures and experimental conditions although both of the reconstructed surface profiles were similar to each other.

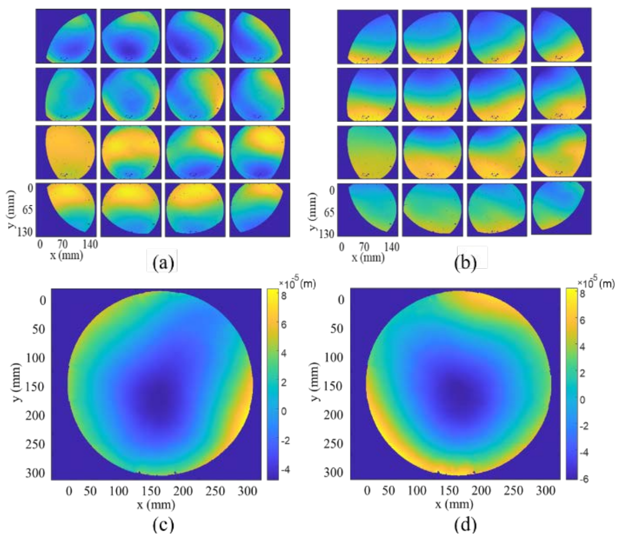

Figure 3. 4x4 sub-aperture measurement results of (a) x-sheared and (b) y-sheared gradient maps, (c) reconstructed wafer warpage measurement result and (d) reconstructed wafer warpage measurement when the specimen was rotated with 90°.

4. Conclusion

To summarize, we proposed and experimentally verified a stitching lateral shearing interferometer based on a polarization grating in this investigation. By the polarization nature of the system, a polarization CMOS camera can directly obtain the surface gradient map with two orthogonally polarized wavefronts. In the experiments, silicon wafers with 300 nm diameter was measured, and the errors of the proposed interferometer were discussed. It is expected that the proposed interferometer can be a good alternative to measure the wafer warpage for the large area when the remaining system errors are minimized..

References

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