Chapter 3
Residual Stress Evaluation in Silicon Wafer Based on the Principle of Superposition and Full-Field Warpage Measurement

Satoru Yoneyama, Keisuke Iizuka, and Mitsuaki Kudo

Abstract A method for estimating residual stresses in silicon wafers from optically measured full-field warpage is proposed. The warpage of a silicon wafer is measured with a surface profilometer equipped with a laser displacement meter. To establish the relationship between warpage and residual stresses, a finite element method is used to calculate the warpage distribution for unit positive stress on the front surface and unit negative stress on the back surface, applied to a single pair of front and back elements. This process is repeated for all such pairs, yielding numerous sets of relationships between warpage and unit initial stresses. Based on the principle of superposition, the measured warpage is expressed as a combination of these unit initial stress-induced warpages. The warpage distribution is then obtained through a least-squares method, with regularization applied to derive appropriate residual stress values. The proposed method is applied to measured warpage distributions of actual silicon wafers, successfully yielding residual stress estimations. The results demonstrate the effectiveness of the proposed method for evaluating residual stresses in silicon wafers.

Keywords Optical method · Residual stress · Silicon wafer · Warpage · Principle of superposition

Introduction

In the manufacturing process of silicon wafers, residual stresses are induced due to the temperature gradients in the wafer and the influence of the surface processing layer generated during grinding. Such residual stresses cause warpage and peeling, which induce defects in products. An X-ray diffraction method or a hole-drilling method is generally used for measuring residual stresses in metallic materials. However, an X-ray diffraction method is usually difficult to measure the residual stresses in single crystals such as silicon. Efforts have been made to measure the residual stresses in silicon single crystals using an X-ray diffraction method, but such special techniques have not yet been generalized. A hole-drilling method is destructive and not suitable for inspecting silicon wafers.

Methods for measuring residual stress in silicon wafers have been studied because of their importance and difficulty. Then, various techniques for evaluating the residual stresses in silicon wafers including simulation have been reported [1]. On the other hand, in the quality inspection of silicon wafers, the warpage is often measured using an interferometer or a laser displacement meter [2]. Therefore, it would be very convenient if the residual stresses in the silicon wafers could be evaluated from the warpage distribution. By achieving this, it is expected that the manufacturing process will be improved based on the evaluation results of residual stresses. In addition, it is important to know the residual stresses in the silicon wafers because they are an important index for predicting the device life. Toyama et al. [3] proposed a method for evaluating stresses inducing the warpage of silicon wafer from warpage measurement. However, they estimated not the residual stresses themselves but the stresses causing the warpage. Obata et al. [4] proposed a method for evaluating residual stresses in a silicon wafer from full field warpage measurement. In their method, the residual stresses are estimated using the regularized least-squares method based on the principle of superposition.

In this study, a method for estimating residual stresses in silicon wafers from optically measured full-field warpage is proposed by improving the previously proposed method. The proposed method is applied to the measured warpage distributions

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Method

The warpage of a 200-mm diameter, 725-micrometer thick silicon wafer is measured with a surface profilometer equipped with a laser displacement meter, providing a measurement resolution of 10 nanometers and a spatial resolution of 1 micrometer. It is assumed that the warpage is caused by residual stresses, with those on the front surface in equilibrium with those on the back. To establish the relationship between warpage and residual stresses, a finite element method is used to calculate the warpage distribution for unit positive stress on the front surface and unit negative stress on the back surface, applied to a single pair of front and back elements. This process is repeated for all such pairs, yielding numerous sets of relationships between warpage and unit initial stresses. Based on the principle of superposition, the measured warpage is expressed as a combination of these unit initial stress-induced warpages. The warpage distribution is then obtained through a least-squares method, with regularization applied to derive appropriate residual stress values.

Results

Figure 1 shows the warpage distribution of a 200-mm diameter, 725-micrometer thick silicon wafer obtained using a surface profilometer. By applying the proposed method, the warpage distribution is obtained from the many sets of the finite element results using the least-squares method, as shown in Fig. 2. The residual between the measured warpage in Fig. 1 and the estimated warpage is 2.72×10^{-2} μm, indicating the measured warpage can be approximated based on the principle of superposition.

The residual stresses are also obtained based on the principle of superposition. However, the coefficients obtained using a least-squares method cannot guarantee the uniqueness of the solution. That is, there exists multiple solutions for a single warpage distribution. Figure 3 shows the residual stress distributions obtained using an ordinary least-squares method. It is observed that the high stress values are obtained, and the distributions are unnatural. The inappropriate variation of the stresses in Fig. 3 indicate the regularization scheme should be introduced into the last-squares method.

The residual stresses obtained using the regularized least squares method are shown in Fig. 4. It can be seen that smooth and appropriate values of stresses are obtained.

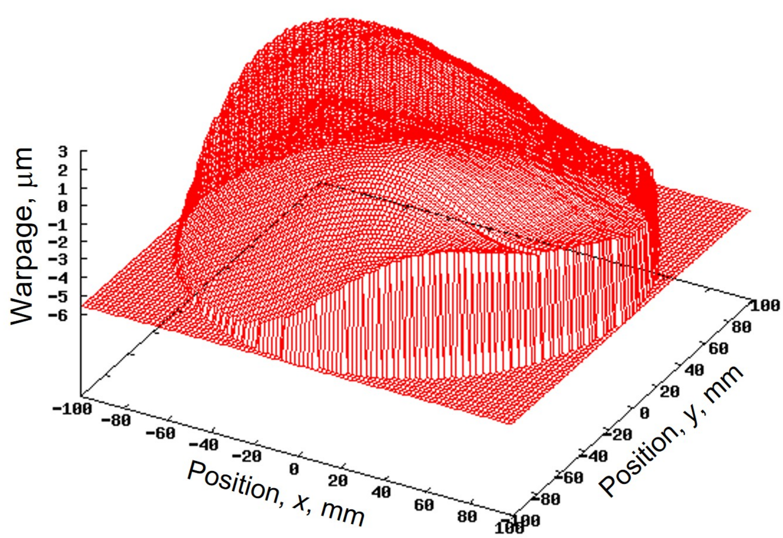

Fig. 1 Warpage distribution of the silicon wafer measured using a surface profilometer equipped with a laser displacement meter

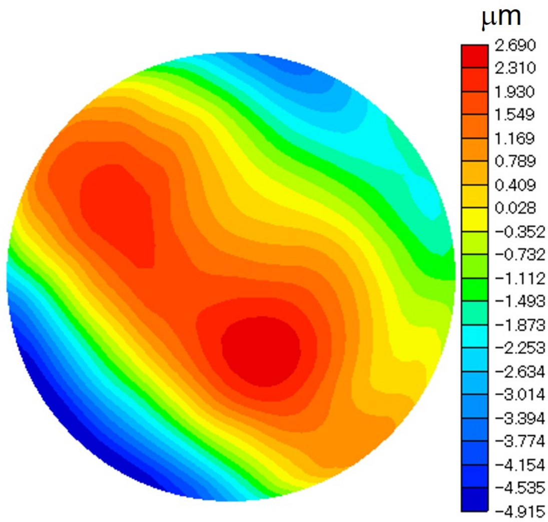

Fig. 2 Contour map of the warpage distribution of the silicon wafer obtained using the least-squares method based on the principle of superposition

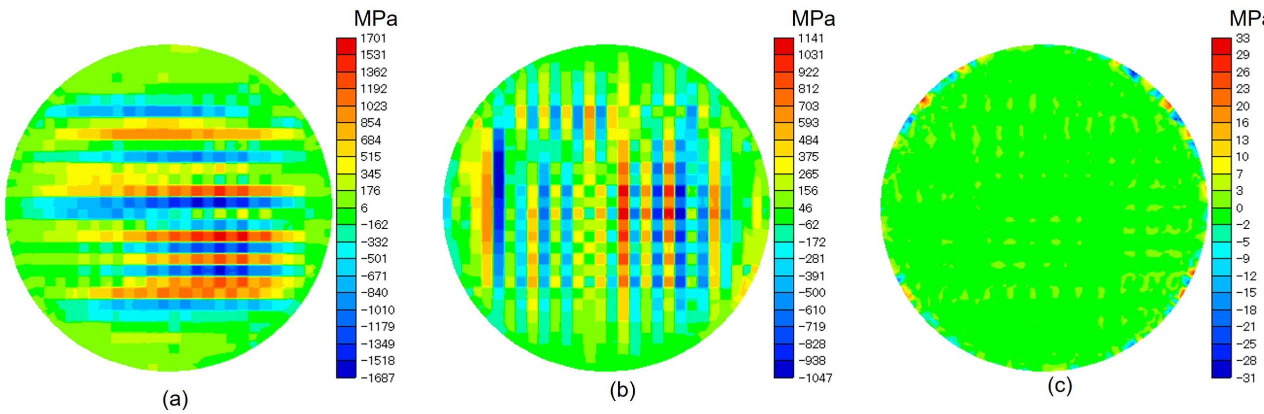

Fig. 3 Residual stresses estimated using the ordinary least-squares method: (a) σ_x; (b)σ_y; (c)τ_{xy}

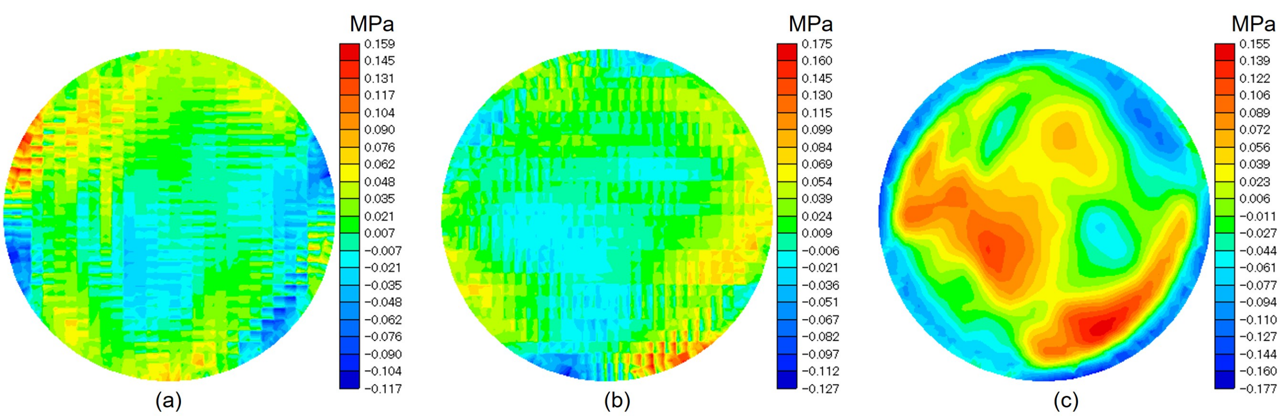

Fig. 4 Residual stresses estimated using the regularized least-squares method: (a) σ_x; (b)σ_y; (c)σ_{xy}

Conclusions

This paper proposes a method for estimating the residual stresses in a silicon wafer from the warpage measurement. The warpage of a finite element model is determined from the measured values using a least-squares method. The residual stresses induced simultaneously with the warpage are estimated. The proposed method is successfully applied to the residual stress evaluation of an actual silicon wafer. Because the warpage of a silicon is often measured in the inspection process, the proposed method which uses the warpage for estimating the residual stresses is useful. Therefore, it is expected that the proposed method can be applied to the inspection process of silicon wafers.

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