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Warping of silicon wafers subjected to back-grinding process

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ABSTRACT

This study investigates warping of silicon wafers in ultra-precision grinding-based back-thinning process. By analyzing the interactions between the wafer and the vacuum chuck, together with the machining stress distributions in damage layer of ground wafer, the study establishes a mathematical model to describe wafer warping during the thinning process using the elasticity theory. The model correlates wafer warping with machining stresses, wafer final thickness, damage layer thickness, and the mechanical properties of the monocrystalline silicon. The maximum warp and the warp profile are measured on the wafers thinned to various thicknesses under different grinding conditions, and are used to verify the modeling results.

1. Introduction

Silicon has been the predominant substrate material for integrated circuits. Because of the required package thickness, a silicon wafer is normally back-thinned after the completion of integrated circuits. Ultra-precision grinding based on the principle of wafer rotation grinding is currently utilized as a major back-thinning technique due to its high efficiency, low cost, and good flatness [1–4]. However, a back-thinned wafer is often deflected after grinding, which can impose problems in the subsequent handling and transportation processes, leading to wafer breakage.

Wafer warping from a grinding-based thinning process is reportedly related to grinding damage and residual stresses. Assuming a uniform layer of grinding-induced damage, Zhou et al. [5] proposed a mathematical model using the Stoney formula, in which wafer warp was a function of damage depth, residual stress and wafer thickness. Also using the Stoney formula and the assumption of a uniform damage layer, Chen et al. estimated residual stress through warp measurement [6]. Similarly, Draney et al. found a relationship between wafer warp and wafer thickness [7]. In the wafer thinning research so far, it has been common to (a) assume a uniform damage layer; and (b) use the Stoney formula to correlate wafer warp with residual stress, damage layer thickness, wafer thickness and diameter, etc. But in Stoney formula, wafer bottom in grinding is assumed to be not constrained in every direction, which implies that wafer holding mechanics on the vacuum chuck is ignored. In addition, residual stress is considered to be the only force responsible for wafer warp. Stoney formula is not comprehensive to analyze wafer warp in grinding and presents large disagreement. Unfortunately, few reports are found on mechanics-based warp prediction and prevention.

This study uses the finite element analysis (FEA) to first investigate wafer holding mechanics on a vacuum chuck and grinding-induced stress distribution during a wafer thinning process, and then establish a wafer warp model based on the elasticity theory under a small deflection. The model is verified by a grinding-based back-thinning experiment.

2. Warp model in wafer back-thinning

2.1. Force analysis

The grinding-based back-thinning process is featured with a rotating wafer which is held by a vacuum chuck [3,8]. The wafer is induced with stresses by grinding which are partially released when the wafer is removed from the chuck. Residual stresses are thus left in the ground wafer.

In this study, FEA is used to analyze the mechanics between the vacuum chuck and wafer during the back-thinning process.

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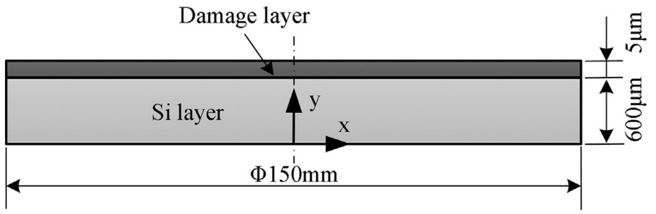

Fig. 1. FEA model.

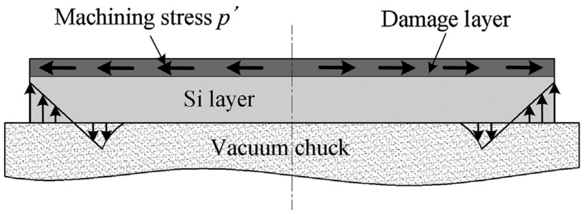

Fig. 3. Mechanical loading to the wafer being chucked and machined.

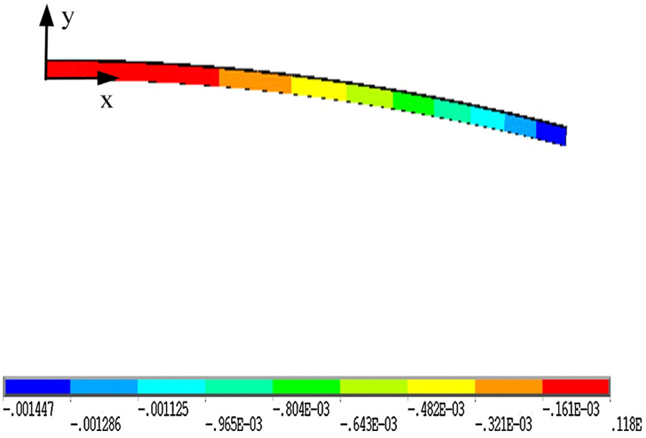

Fig. 4. Wafer warp after being loosened the bottom constrains.

Compressive stress is usually formed in the surface damage layer of a wafer after the thinning process [5–7,9,10]. In the FEA process, thermal stress is assumed to simulate both grinding-induced stress (also called machining stress in this paper) and residual stress since these stresses are technically difficult to handle in the FEA loading process. In the FEA model, a uniform damage layer of 5 μm thickness [11,12] and the bulk silicon wafer of 600 μm thickness are represented by two different materials of linear thermal expansion coefficients of 0 K^{-1} and $2.6 \times 10^6\ \mathrm{K}^{-1}$ respectively, as shown in Fig. 1. The surface damage layer of FEA model expands in the radial direction (*x*-direction) under thermal loading, whereas the bulk silicon layer does not, which causes a compressive stress in the damage layer. In the FEA model, the nodal points in the wafer bottom are all constrained in every direction to reflect the vacuum chucking conditions. Upon thermal loading, the FEA model is arranged with a thermal stress at the interface of the two layers, which tends to warp the wafer and results in a mechanical loading at the wafer–chuck interface.

Fig. 2 presents an FEA result of *y*-stress distribution in the radial direction at the wafer–chuck interface, which depicts that the vacuum resultant force (including supporting force and attracting force) acting on the wafer only exists in a narrow band around the wafer circumferential portion (the outer circumferential portion of the wafer is subjected to a supporting force, and the inner circumferential portion to an attracting force from the vacuum chuck), while the rest wafer is nearly zero. Based on the findings from the previous FEA result, three forces (machining stress, supporting force and attracting force) act on the wafer subjected to back-grinding, as shown in Fig. 3. When subjected to grinding, the wafer surface is loaded with a machining stress p' which is assumed to have a uniform distribution in the FEA model, as shown in Fig. 3. Machining stress p' is produced by the mechanical interaction between the grinding wheel and workpiece, and is related to grinding conditions. For given grinding conditions, machining stress p' remains constant. In addition, the wafer circumferential band is loaded with a supporting force and an attracting force exerted by the vacuum chuck. After thermal loading, in the FEA model, the all constraints in wafer bottom are loosened to reflect the wafer removing from the vacuum chuck after grinding and the wafer warps in order to partially release stresses in damage layer until the new equilibrium occurs (the resultant force acting on the wafer is zero), as shown in Fig. 4. Fig. 5 presents the FEA result of *x*-stress distribution in the thickness direction of the bulk wafer with warp. In the FEA model, the maximum tensile stress is found at the uppermost edge of the bulk wafer while the maximum compressive stress is located at the lower edge of the bulk wafer, and the stresses between these two opposing maxima vary linearly. Fig. 6 shows the schematic stress distribution in the thickness direction of a wafer with warp. Residual stress p within the damage layer was assumed uniform since this layer thickness was much smaller than the bulk wafer. In addition, a transient stress distribution around interface of the damage layer and the bulk wafer is complicated and is simplified to zero at the interface.

2.2. Wafer warp modeling

Wafer warp is assumed to be small in the elastic range, i.e., the total deflection being a linear superposition of the individual ones. The wafer warps when removed from the vacuum chuck after

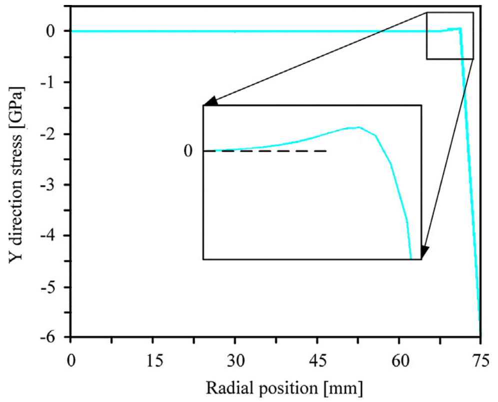

Fig. 2. *y*-Stress distribution in the radial direction at the wafer–chuck interface.

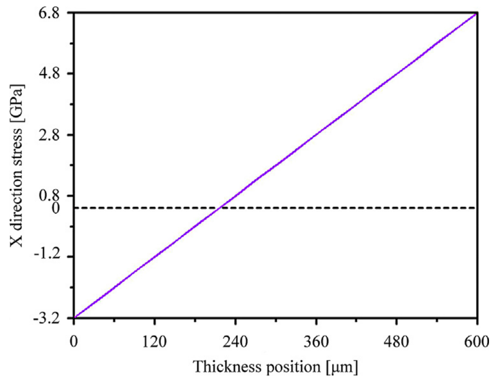

Fig. 5. *x*-Stress distribution in the thickness direction of the bulk wafer with warp.