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Journal of Materials Processing Technology 129 (2002) 2–9

Journal of Materials Processing Technology

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Finite element analysis for grinding and lapping of wire-sawn silicon wafers

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Abstract

Silicon wafers are the most widely used substrates for semiconductors. The falling price of silicon wafers has created tremendous pressure on silicon wafer manufacturers to develop cost-effective manufacturing processes. A critical issue in wafer production is the waviness induced by wire sawing. If this waviness is not removed, it will affect wafer flatness and semiconductor performance. In practice, both lapping and grinding have been used to flatten wire-sawn wafers. Although grinding is not as effective as lapping in removing waviness, it has many other advantages over lapping (such as higher throughput, fully automatic, and more benign to environment) and has great potential to reduce manufacturing cost of silicon wafers. This paper presents a finite element analysis (FEA) study on grinding and lapping of wire-sawn silicon wafers. An FEA model is first developed to simulate the waviness deformation of wire-sawn wafers in grinding and lapping processes. It is then used to explain how the waviness is removed or reduced by lapping and grinding and why the effectiveness of grinding in removing waviness is different from that of lapping. Furthermore, the model is used to study the effects of various parameters including active-grinding-zone orientation, grinding force, waviness wavelength, and waviness height on the reduction and elimination of waviness. Finally, the results of pilot experiments to verify the model are discussed.

Keywords: Finite element analysis; Grinding; Lapping; Silicon wafer; Waviness removal

1. Introduction

The majority of semiconductors are built on silicon wafers. The worldwide revenue generated by silicon wafers in 1999 was $5.8 billion, representing a 4% increase from the revenue of 1998 while there was a 26% increase in production [1]. This indicates huge price erosion. The falling price of silicon wafers has created great pressure on silicon manufacturers to develop more cost-effective processes.

Manufacturing of silicon wafers starts with growth of single crystal ingots. A sequence of processes is needed to turn an ingot into wafers. It typically consists of slicing, flattening, etching, polishing and cleaning. More information on these processes can be found in [2–8].

Wire-sawing is the preferred method for slicing ingots of large diameters. An undesirable result associated with wire-sawing is waviness [9,10]. Fig. 1 shows a magic mirror picture of a wafer exhibiting waviness. Information on magic mirror can be found in [11–13] and at website http://www.hologenix.com. The generation mechanism of this waviness is not fully understood yet. This has been the main reason that it is very difficult to eliminate waviness at wire-sawing process. If subsequent processes do not remove this waviness, it will adversely affect wafer flatness, especially site flatness. Site flatness, also called local flatness, is measured by the vertical distance between the highest and lowest points on the wafer surface within a certain area. Typical size of the area is 20 mm × 20 mm for ordinary wafers and 30 mm × 35 mm for advanced applications.

Conventionally, wafers after wire-sawing will go through lapping operations for flattening [14,15]. Despite its widespread use, lapping has the following drawbacks: (1) labor intensive, (2) expensive (due to consumable slurry), and (3) time consuming.

Wafer grinding can be used for grinding wire-sawn wafers to replace or partially replace lapping [16]. Fig. 2 illustrates the wafer grinding process [17]. Its advantages over lapping include the following: (1) the process is fully automatic with cassette-to-cassette operation, (2) it uses fixed-abrasive grinding wheel rather than loose abrasive slurry so the cost of consumables per wafer is lower, and (3) it has higher throughput.

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0924-0136/02/$ – see front matter
PII: S0924-0136(02)00565-4

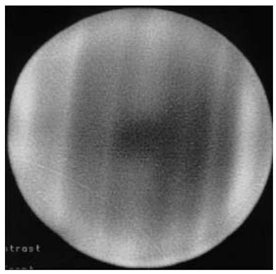


Fig. 1. Waviness.

The main issue with grinding of wire-sawn wafers is waviness, because conventional grinding process cannot effectively remove waviness [9,10,14]. In the literature to date, there are no reports on systematic study of this issue. This paper, through a model of finite element analysis (FEA), aims at providing insight on how waviness is removed or reduced by lapping and grinding and why effectiveness of grinding in removing waviness is different from that of lapping. The knowledge will be useful for industrial practitioners to solve this issue. Industrial implications of simulation results are discussed throughout the paper. The understanding obtained by FEA modeling would be difficult to obtain through empirical approach because of two major obstacles. First, since the generation mechanism of waviness is not clearly understood, its wavelength (the horizontal peak-to-peak, or valley-to-valley distance) and height (the vertical peak-to-valley distance) cannot be changed systematically. Second, experiments with real wafers are costly (both wafers and processes are expensive).

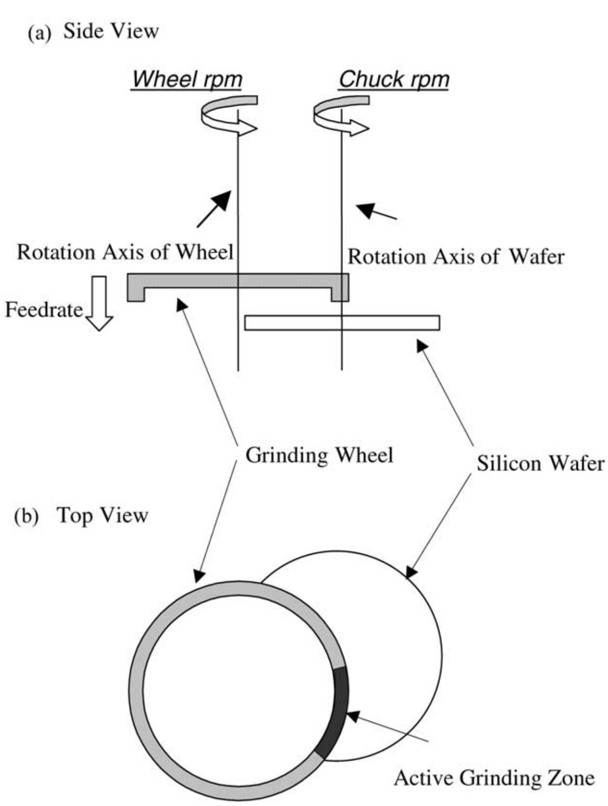


Fig. 2. Illustration of wafer grinding.

This paper is divided into seven sections. Following this section, Section 2 describes the FEA model. In Sections 3 and 4, the model is used to investigate waviness deformation in grinding and lapping and the difference in waviness removal of grinding and lapping. Section 5 presents and discusses effects of various parameters on waviness reduction. Section 6 discusses pilot experiments performed to verify the FEA model. Finally, conclusions are drawn in Section 7.

2. Finite element analysis

The goal of FEA simulation of grinding and lapping processes is to assess effects of various geometry and process parameters (such as wavelength, grinding force) on waviness removal. Commercial software, ANSYS, was used. In order to reduce computational cost, a number of simplifications were made. First, because the focus of this study is the effectiveness of waviness removal, for which the wafer deformation under the impressing grinding wheel is more important than the dynamic or inertial effects, the grinding process was approximated as a static problem instead of a dynamic one. Second, the waviness profile was simplified as sinusoids with uniform wavelength and height, even though in real wafers, waviness strips have approximately the same orientation but wavelength and height change irregularly, as illustrated in Fig. 1. Third, as the thickness dimension of a wafer (0.8 mm) is much smaller than other dimensions (e.g. the wavelength is 15 mm), shell element, instead of 3D solid element, was used in order to capture the effect of both bending and in-plane loading and avoid excessively large number of degrees of freedom (DOF). Fourth, DOF constraint was used to simulate contact instead of using real contact element in ANSYS since the initial contact points between the wafer and its supporting chuck were known (waviness valleys). For the approach to be valid, all nodal displacements were monitored to ensure that none of the unconstrained nodes would move below the chuck surface. The analysis results showed that this condition was satisfied for all simulated cases. This DOF constraint approach significantly reduced the computational cost.

2.1. The FEM model

To generate the mesh, a sinusoid with a certain wavelength (for example, 15 mm) and a certain height (for example, 20 μm) of a total length of 220 mm was extruded (a solid modeling option in ANSYS) into a rectangle wavy area along the depth direction. The depth direction, shown as the Y direction in Fig. 3, is perpendicular to the plane in which the generating sinusoid lies. The area was then intersected (another solid modeling option in ANSYS) with

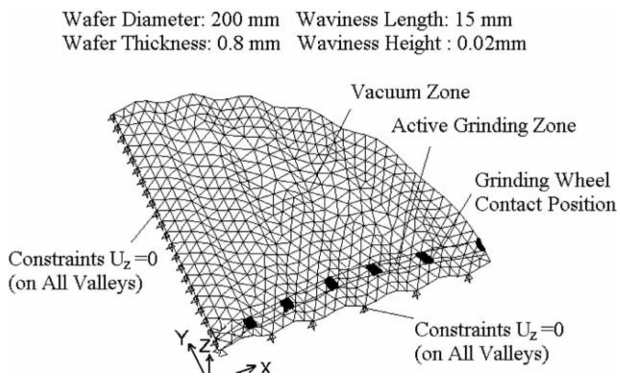


Fig. 3. One-fourth of FEM model including the active grinding zone.

a cylinder with a diameter of 200 mm to form a 3D wafer disk with a diameter of 200 mm. The model was meshed into SHELL63 triangular elements (SHELL63 is a shell element in ANSYS) that have both bending and membrane capabilities, with an average edge length of 2.5 mm to insure adequate mesh resolution within each wavelength. Wafer thickness was introduced through a shell element constant. Elastic modulus of the silicon wafer was 135 GPa, and the Poisson's ratio was 0.3.

In order to demonstrate waviness and boundary conditions, one quarter of the FEA model for wafer grinding is illustrated in Fig. 3 while a full size model was used in simulation. Note that this quarter contains the active grinding zone (the nominal contact area between grinding wheel and wafer, as shown in Fig. 2). There is no active grinding zone in the other three quarters. Also note that, in Fig. 3, the waviness is exaggerated for ease in viewing. The FEA model for lapping is similar except that there is no active grinding zone.

2.2. Boundary conditions

As shown in Fig. 3, the boundary conditions for both grinding and lapping included:

(1) DOF constraints: all nodes at waviness valleys were constrained from moving in the Z direction (the thickness direction), but were free to move in the X and Y directions (the chuck plane) to simulate the support from the ceramic chuck. To prevent rigid body motion, one valley node at wafer center was also constrained in both X and Y directions, and one more node at wafer edge was constrained from moving in the Y direction.
(2) Forces: the grinding forces were loaded at the peak nodes in the $-Z$ direction within the active grinding zone in the case of grinding, and on the entire wafer for lapping. The magnitude of the nodal force was equal to the total force divided by the number of loaded nodes. Since grinding wheel and lapping plates were regarded as rigid objects, the loaded nodes (within active grinding zone for grinding, over entire wafer for lapping) were constrained to always move to the same height in the Z direction. The adjacent nodes were monitored to ensure that they were below the loaded nodes in the Z direction all the time.
(3) Pressure: for grinding, uniform pressure was applied on the top surface of the wafer to simulate the effect of chuck vacuum.

Table 1
Data used in FEA

Parameter	Range	Typical value
Wafer diameter (mm)	150, 200, 300	200
Wafer thickness (μm)	700–950	800
Waviness length (mm)	5–30	15
Waviness height (μm)	5–30	20
Grinding wheel diameter (mm)	200–300	280
Wheel segment width (mm)	1.5–5	2.5
Total grinding force (N)	67–200	160
Chuck vacuum (MPa)	0.006–0.074	0.04
Total lapping force (N)	67–200	160

2.3. Parameters for the FEA model

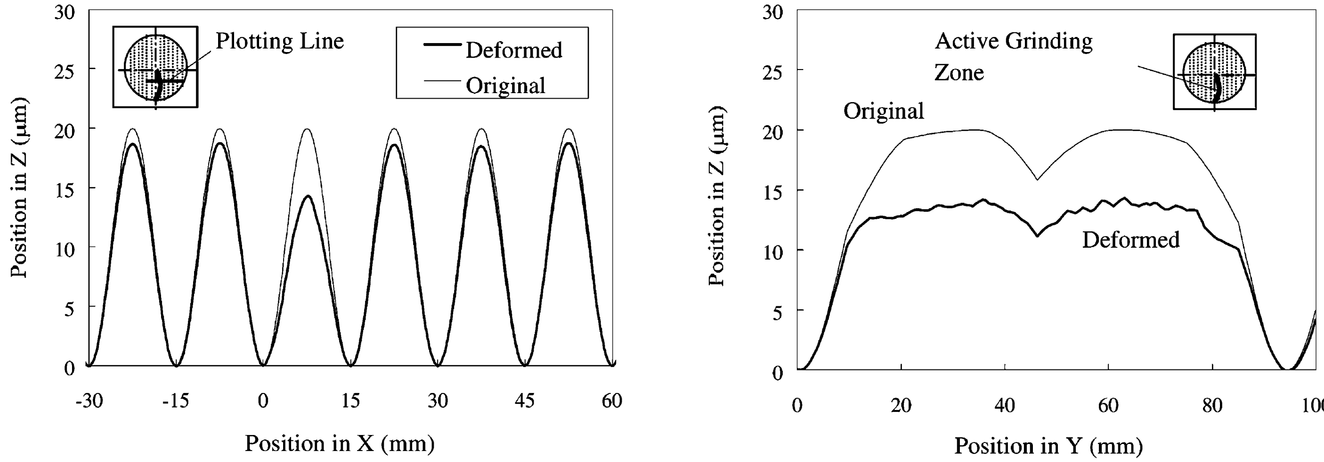
Wafer and waviness dimensions and machining parameters vary within certain ranges, as listed in Table 1. In the following sections, unless otherwise specified, typical values in Table 1 were used in FEA simulations.

3. Waviness deformation in grinding

During grinding, the active grinding zone rotates about the wafer center. For different orientation of the active grinding zone, waviness deformation caused by grinding force is different. Results of three typical orientations of the active grinding zone are presented below. Though the active grinding zone projected onto the wafer plane is an arc, its orientation is approximated by the orientation of an imaginary line passing its two ends. The orientation is indicated in a small insert provided in each relevant figure. Waviness deformation is characterized by the peak displacement defined as the displacement in the $-Z$ direction of peak nodes within the active grinding zone.

3.1. Parallel orientation of active grinding zone

Fig. 4 illustrates the waviness deformation when the orientation of active grinding zone is parallel to waviness strips. In this case, the entire active grinding zone is in contact with only one waviness peak. (Of course, this will change if smaller waviness wavelengths are used in the analysis.) As shown in Fig. 4(b), the positions of the wafer nodes in Z direction within active grinding zone are lower than the original waviness height (20 mm in this example). Because of the discrete nature of the FEA model, the deformed shape of the wafer is a jerky rather than smooth and continuous curve along the active grinding zone. The smoothness can be improved if the mesh density of the FEA model is increased.



(a) Along the plotting line

(b) Along active grinding zone

Fig. 4. Comparison of deformed and original positions at parallel orientation.

As shown in Fig. 4(a), the peak displacement within the active grinding zone is 5.3 μm in the negative Z direction. The peaks outside the active grinding zone displace downward 0.73 μm, caused predominantly by the vacuum. Note that the displacements of the peaks outside the active grinding zone are hardly affected by grinding wheel.

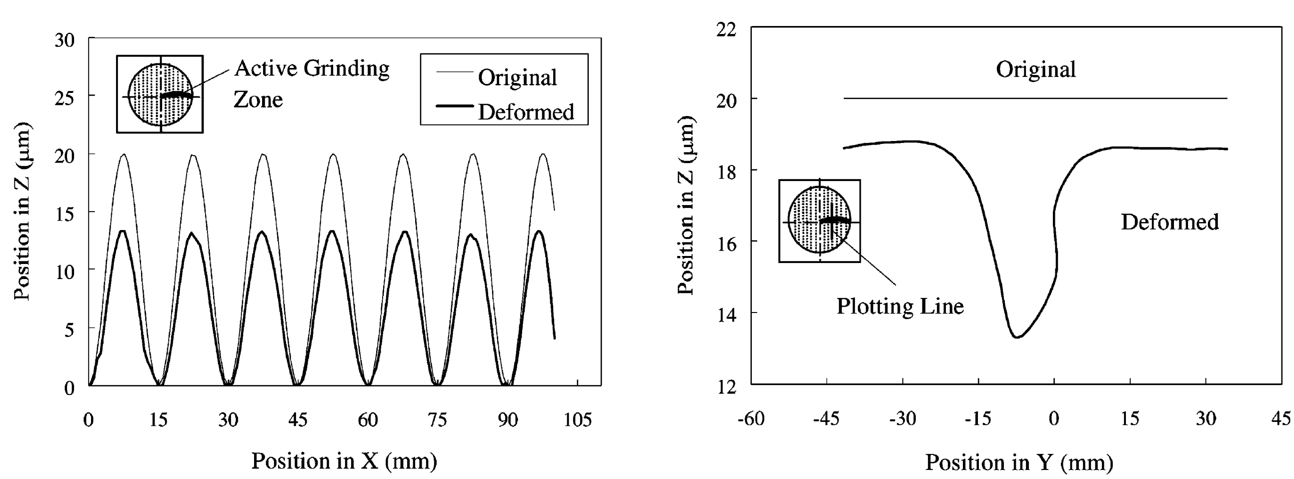
3.2. Perpendicular orientation of active grinding zone

For this orientation, grinding wheel touches every peak of the waviness strips it crosses, as shown in Fig. 5(a). The peak displacement within the active grinding zone is 6.6 μm, slightly larger than that for the parallel orientation. Fig. 5(b) illustrates the peak positions along a waviness strip. Note that not all peak nodes on this waviness strip are in contact with grinding wheel. The dip in the curve corresponds to the contact area between the waviness strip and the active grinding zone.

3.3. Diagonal orientation of active grinding zone

For this orientation, the angle between the active grinding zone and the waviness strips is about 45°. As shown in Fig. 6, within the active grinding zone, the peak displacement is 10.1 μm, larger than those for the parallel and perpendicular orientations. The number of waviness strips contacted by grinding wheel is fewer than that for the perpendicular orientation. As shown in Fig. 6(b), the displacements of the peaks outside the active grinding zone along a plotting line normal to the active grinding zone, indicated by the insert in Fig. 6(b), are hardly affected by the grinding wheel.

The above results make it clear that, during grinding, grinding force causes waviness peaks to displace toward chuck surface. When grinding is done and the grinding force is released, these peaks will spring back toward their original positions. The larger the peak displacement, the more



(a) Along active grinding zone

(b) Along the plotting line

Fig. 5. Comparison of deformed and original positions at perpendicular orientation.

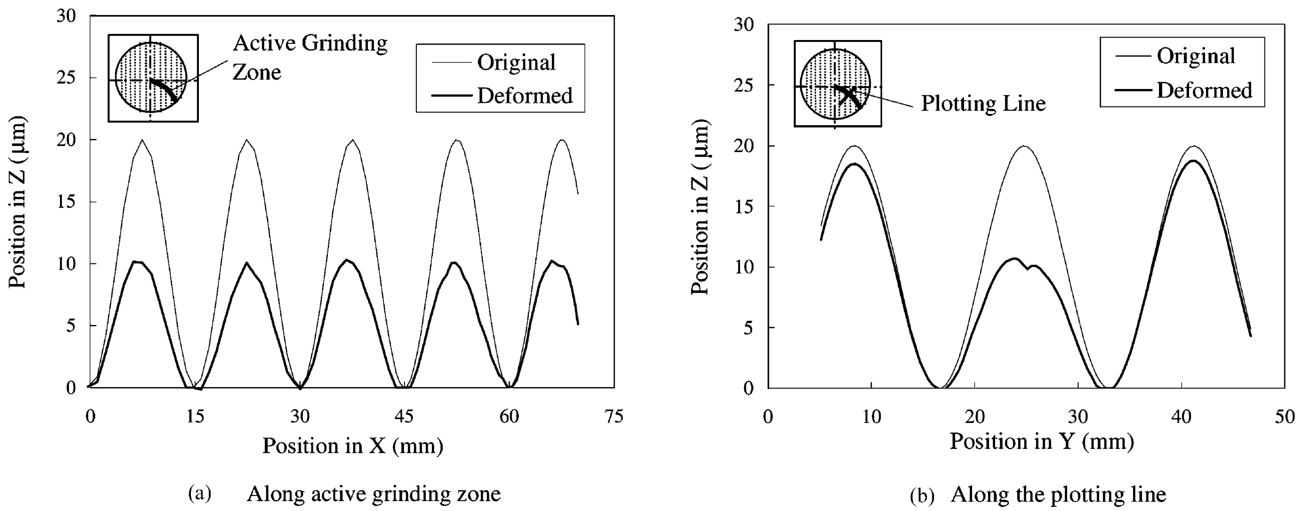


Fig. 6. Comparison of deformed and original positions at diagonal orientation.

difficult it becomes to remove the waviness. The large elastic deformation is the main reason that waviness cannot be removed effectively by conventional grinding.

The preceding analysis shows that waviness deformation during grinding is concentrated around the active grinding zone, and effects of grinding force on peak displacement outside the active grinding zone are negligible. It has the following implication. Any attempt to increase the effectiveness of grinding in removing waviness can be successful only if it can reduce the waviness peak displacement within the active grinding zone. Based on this analysis, the approach of reducing waviness by reducing chuck vacuum [10] might not be as effective as assumed. In that approach, it has been proposed to reduce chuck vacuum to such a value that the elastic deformation of the wafer is substantially reduced. Because the waviness peak displacement within the active grinding zone is primarily caused by grinding force instead of chuck vacuum, waviness cannot be reduced effectively by reducing the chuck vacuum.

4. Difference of waviness deformation in grinding and lapping

In lapping process, if a total force equivalent to the grinding force is applied on the entire surface of a wafer, the waviness peak displacement will be much smaller than that in grinding. Fig. 7 compares the peak displacement in grinding (perpendicular orientation) and lapping. The peak displacement in lapping is only 0.19 µm, less than 1/36 of that in the active grinding zone. The difference is even greater (1/55) for diagonal orientation.

As described in Section 3.2, large deformation of wafer waviness within active grinding zone allows top surface of a wafer to be ground flat at the deformed state. After grinding is done and the grinding force is released, waviness peaks will spring-back toward their original positions, restoring the original waviness to some extent. The greater the deformation during grinding, the more difficult it is to remove the waviness. This analysis explains why lapping is much more effective than grinding in removing waviness. Because the waviness peak displacement during lapping is very small, waviness peaks stay close to their original positions and therefore are easier to remove. When both surfaces are lapped flat, they remain flat even after the wafer is taken out of the lapping machine as there will be little or no spring-back of waviness peaks.

5. Effects of various parameters

5.1. Effects of forces

With increase of applied force, wafer deformation increases approximately linearly for both grinding and lapping. In the ranges investigated (from 67 to 200 N), peak displacement changes from 5.4 to 12.7 µm for grinding, and

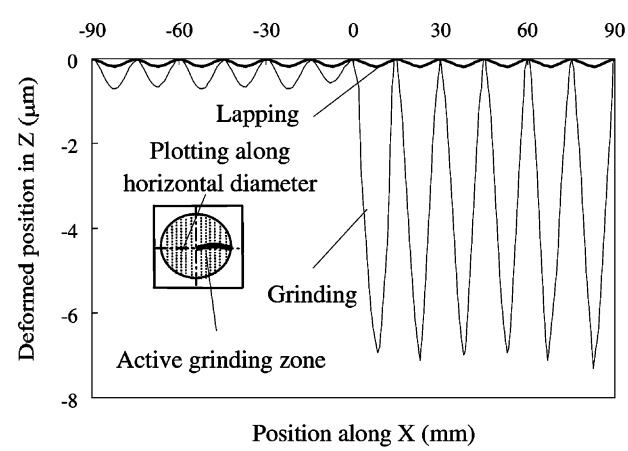


Fig. 7. Comparison of grinding and lapping.

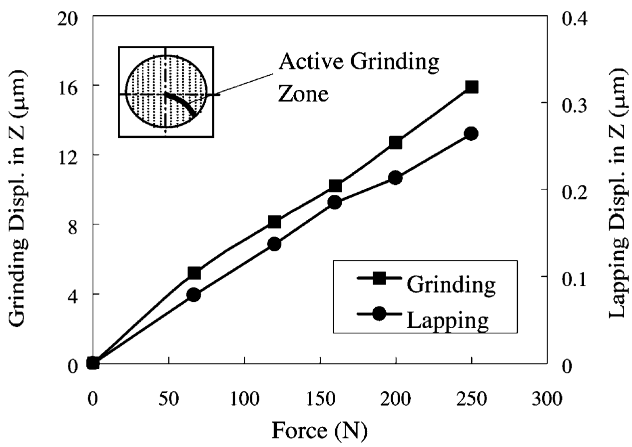


Fig. 8. Effects of grinding and lapping forces.

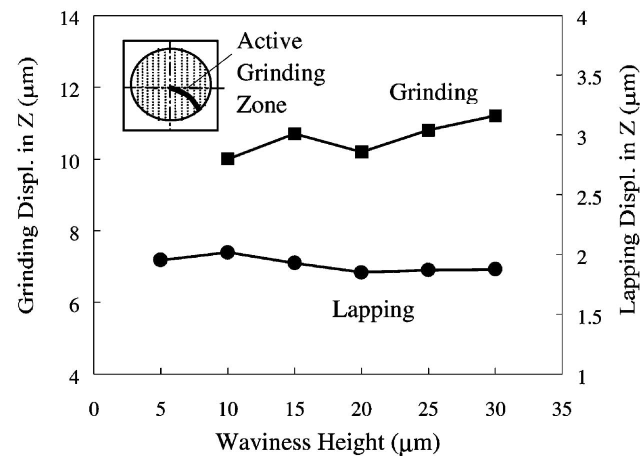


Fig. 10. Effects of waviness height.

from 0.08 to 0.21 μm for lapping, as shown in Fig. 8. Since peak displacement increases as grinding or lapping force increases, smaller force should be employed in order to remove waviness effectively.

5.2. Effects of waviness wavelength

Fig. 9 illustrates the variation of peak displacement with wavelength. With the augment of wavelength, peak displacement increases. When wavelength is above a certain value, peak displacement within the active grinding zone may become so large that the peaks will touch chuck surface. This occurs when wavelength reaches about 20 μm for grinding at grinding force of 160 N. Based on this result, waviness with shorter wavelength is easier to remove than waviness with longer wavelength.

5.3. Effects of waviness height

Variation of waviness height has only little influence on peak displacement with the ratios of waviness height to wavelength within 1:500–1:3000, as shown in Fig. 10. The range of variation in the peak displacement is about 1 μm for grinding, and 0.02 μm for lapping. When the height is smaller than 10.1 μm, the waviness peaks will be in contact with the chuck in grinding.

5.4. Effects of wafer thickness

As shown in Fig. 11, with increase of wafer thickness, peak displacement decreases rapidly. When wafer thickness increases from 700 to 900 μm (a 28% increase), peak displacement drops from 15 to 6.5 μm (a factor of 2.3 reduction). The practical implication is that it is easier to remove waviness when the wafer is thicker. Therefore, after wire-sawing, the grinding or lapping process intended to remove the waviness should be performed before any other processes (such as etching and polishing) that may lead to thickness reduction. If both grinding and lapping are used, lapping should be performed first because the process will remove waviness more effectively.

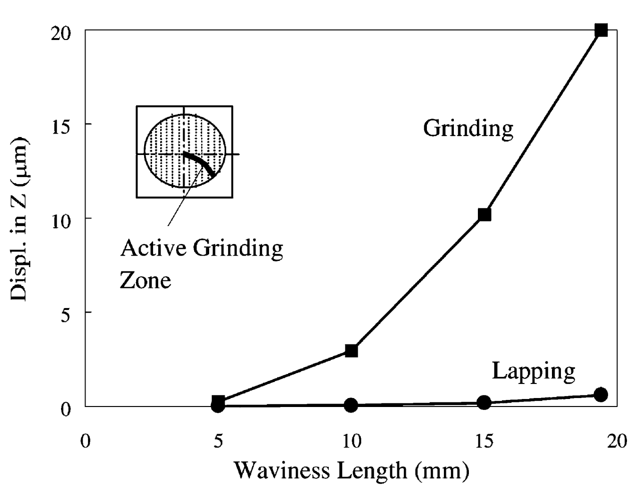


Fig. 9. Effects of waviness length.

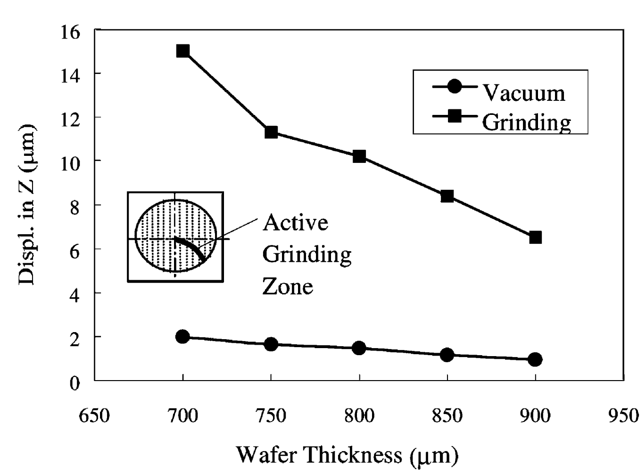


Fig. 11. Deformation with wafer thickness.

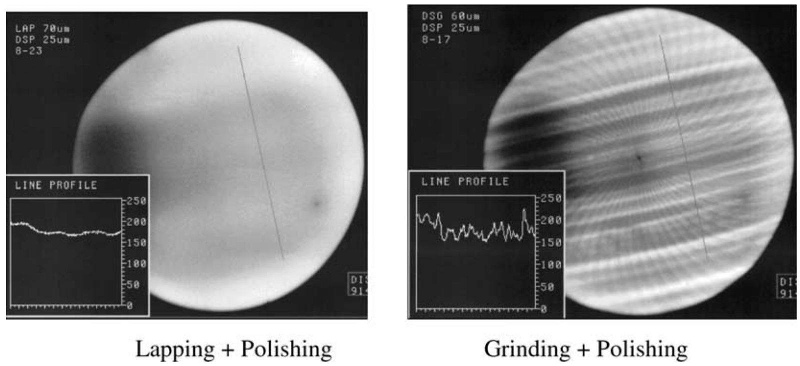


Fig. 12. Results of pilot experiments.

6. Pilot experimental verification

6.1. Experimental procedure

Pilot experiments on grinding and lapping were conducted which agreed qualitatively with the current FEA results. Grinding experiments were conducted on a G&N surface grinder (Nanogrinder, Grinding Machines Nuernberg, Erlangen, Germany). The grinding wheel used is a diamond cup wheel. The grit size is mesh #1200 and the wheel diameter is 300 mm. More details about wafer grinding and grinder are given in [17]. Lapping experiments were conducted on a lapping machine made by Peter Wolters AG (Rendsburg, Germany) with 7 μm Al_3O_2 abrasive slurry.

Single crystal silicon wafers of 300 mm in diameter with the (1 0 0) plane as the major surface were used for the experiments. To block the possible effects of other variations, wafers from the same ingot were used for both grinding and lapping experiments.

Lapping flattens both sides of the wafer simultaneously while surface grinding grinds one side at a time. The total material removal was controlled to be the same for both lapping and grinding. Following lapping and grinding, a polishing operation was performed on these wafers to provide smooth surfaces required for magic mirror inspection. The same amount of material was polished off from both ground and lapped wafers.

6.2. Experimental results

Fig. 12 shows the magic mirror images of wafers processed by lapping and grinding, respectively. Waviness is easily discernable on the image of the ground wafer but hardly visible on the lapped wafer. It shows clearly that lapping is more effective than grinding in removing waviness. This is consistent with the FEA analysis presented in Section 4. It is difficult to verify other simulation results experimentally, mainly because of the lack of control over waviness wavelength and height.

7. Conclusions

Wafer grinding is potentially a more cost-effective process than lapping for flattening wire-sawn silicon wafers. Its success in replacing lapping, however, will depend on whether wire-sawing induced waviness can be effectively removed. FEA modeling has been used to investigate grinding and lapping of wire-sawn silicon wafers. FEA simulations have shed lights on why conventional grinding cannot remove waviness effectively and why lapping is more effective than grinding in removing waviness. They have also provided practical implications that are useful for industrial practitioners. Results of pilot experiments conducted to verify the FEA model agree well with the results of model simulations.

Acknowledgements

Financial support for this work was provided by the Advanced Manufacturing Institute of Kansas State University and a National Science Foundation Award (DMI-0218237).

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