Investigations of silicon wafer grinding using finite element analysis

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Abstract: Silicon wafers are used as substrates to build more than 90% of integrated circuits. One of the manufacturing processes for silicon wafers is grinding. This paper reports the investigations of silicon wafer grinding using Finite Element Analysis (FEA). FEA models are first used to study the effects of process parameters on waviness reduction in the grinding of wire-sawn wafers on a rigid chuck. Then, soft-pad grinding of wire-sawn wafers is modelled using FEA to study the effects of pad properties on waviness reduction. Finally, FEA is used to study the elastic deformation of the grinding wheel, providing an explanation for the central dimples on ground wafers.

Keywords: dimple; finite element analysis; grinding; semiconductor material; silicon wafer; waviness removal.


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Introduction

As silicon wafers are the starting materials for fabrication of most integrated circuits (Pei, Xin and Liu, 2003; Sun, Pei and Fisher, 2005), they must be very flat to print circuits on them by lithographic processes (Zhang, Pei and Fisher, 2006). The feature sizes of integrated circuits will continue to decrease and this will require increasingly flatter wafers (Sun, Pei and Fisher, 2005).

1.1 Wafer grinding

A sequence of processes is required to manufacture high-quality silicon wafers. Some typical processes are listed below (Pei and Strasbaugh, 2001; Liu, Pei and Xin, 2002; Matsumura, Misumi and Hotta, 2003; Xin, Pei and Liu, 2004).

1 Slicing: Slicing silicon ingot into wafers of thin disk shape.
2 Flattening (lapping or grinding): Achievement of higher degree of flatness of the wafer.
3 Etching: Chemical-based removal of the damage induced by slicing and flattening.
4 Polishing: Attainment of a smooth wafer surface.
5 Cleaning: Removal of the polishing agent or dust particles from the wafer surface.

Grinding can be used for flattening sliced wafers to replace or partially replace lapping (Xin, Pei and Liu, 2004). As shown in Figure 1, the wafer is held on a porous ceramic chuck by means of vacuum. Grinding wheels are diamond cup-wheels. The rotation axis for the grinding wheel is offset by a distance of the wheel radius relative to the rotation axis for the wafer. During grinding, the grinding wheel and the wafer rotate about their own rotation axes simultaneously and the wheel is fed towards the wafer along its axis (Liu, Pei and Xin, 2002; Pei, Xin and Liu, 2003; Sun et al., 2004; Xin, Pei and Liu, 2004; Zhang, Pei and Fisher, 2006).

Figure 1 Illustration of wafer grinding
Wafer flatness is affected by several factors. One is the waviness of the wire-sawn silicon wafers before the grinding process. Another is the central dimples on ground wafers introduced by grinding.

1.2 Waviness of the wire-sawn silicon wafers

A major drawback of wire sawing is the waviness induced by it (Xin, Pei and Liu, 2004). Figure 2 shows a magic mirror picture of a wafer exhibiting waviness. The strips of wire-sawing induced waviness have approximately the same orientation but the wavelength and height change irregularly (Pei, Xin and Liu, 2003). The wavelength of such waviness typically ranges from 0.5 to 30 mm (Sun et al., 2004). The generating mechanism of such waviness is not yet fully understood and therefore it is very difficult to prevent (Sun et al., 2004). If subsequent processes do not remove the waviness, it will adversely affect the flatness, especially the site flatness, of the wafers (Pei, Xin and Liu, 2003).

Figure 2  Waviness induced by wire-sawing

1.3 Central dimples on ground wafers

Some ground wafers have central dimples, as shown in Figure 3. Typically, for a silicon wafer with a diameter of 200 mm, its thickness is about 0.75 mm. The size of central dimples ranges from 10 to 30 mm in diameter, with a depth of less than 0.2 µm (0.0002 mm) (Zhang, Pei and Fisher, 2006).

Figure 3  Illustration of a central dimple

The hypothesis for the generation mechanisms for central dimples is as follows (Zhang, Pei and Fisher, 2006): The ceramic chuck is typically ground to a conic shape with a very small slope. As shown in Figure 4, the wafer elastically deforms to the chuck’s conic shape, thus ensuring that the grinding wheel only contacts half of the wafer. During
grinding, the portion of the grinding wheel segment that is in contact with the silicon wafer would elastically deform. This deformation will cause the portion of the wheel segment that is next to the active grinding zone to contact with the silicon wafer near the wafer centre. The cutting action of this portion of the wheel segment will remove the material from the silicon wafer near the wafer centre, in addition to the material removed by the portion of the wheel segment within the active grinding zone.

**Figure 4**  Cross-sectional views of the wheel segment, wafer and chuck

This paper reports some results of the research on silicon wafer grinding using FEA. Commercial software, Analysis System (ANSYS), was used. One model is used to study the effects of process parameters on waviness reduction in the grinding of wire-sawn wafers on a rigid chuck. The other is a model of soft-pad grinding of wire-sawn wafers to study the effects of pad properties on waviness reduction. Finally, an approach to model the central dimples on ground wafers is discussed.

### 2 Model for grinding of wire-sawn wafers on a rigid chuck

A FEA model, as shown in Figure 5, was built with the waviness profile simplified as sinusoids with uniform wavelength and height. Since the thickness dimension of the wafer is much smaller than the diameter dimension, the shell element was used for this model (Pei, Xin and Liu, 2003). For the approach to be valid, all nodal displacements were monitored to ensure that none of the unconstrained nodes move below the chuck surface.

**Figure 5**  Finite element analysis model for wafer grinding on a rigid chuck
The boundary conditions for the FEA model are listed below.

1. **Degree-of-freedom (DOF) constraints.** All nodes at the valleys of waviness are constrained from moving in Y direction (along the wafer thickness dimension) to simulate the support from the ceramic chuck.

2. **Forces.** Grinding force is loaded at the peak nodes in Y direction within the active grinding zone. Since the grinding wheel is regarded as a rigid object, the degree of freedom in Y direction of the loaded nodes in the active zone has been constrained such that they always move to the same height and the adjacent nodes are always below the loaded nodes.

3. **Pressure.** The pressure is applied on the upper surface of wafer to simulate the effect of vacuum.

Four factors (wafer thickness, waviness wavelength of the wafer, waviness height of the wafer and grinding force) were taken into consideration during this study. A $2^4$ (four factors, two levels, 16 tests) full factorial design was used for the experiments. The output variable was the displacement of the peak nodes in the active grinding zone.

The following conclusions have been obtained.

1. The main effects of wafer thickness, waviness wavelength and grinding force are significant. It becomes more difficult to remove the waviness as the wafer thickness decreases, as the waviness wavelength increases or as the grinding force increases.

2. The effect of wafer thickness is greatly enhanced at the high level of waviness wavelength and at the high level of grinding force. Also, the effect of waviness wavelength at the high level of grinding force is larger than that at the low level of grinding force.

3. Waviness height does not show any significant effects on either the main effect or the two-factor interactions.

### 3 Model for grinding of wire-sawn wafers using a soft pad

Soft-pad grinding is a newly patented approach that involves using a ‘soft pad’ or a resilient pad (Kassir and Walsh, 1999). When grinding the first side of a wire-sawn wafer, a perforated resilient pad is inserted in-between the wafer and the ceramic chuck (Xin, Pei and Xin, 2004). The soft pad accommodates and supports the wavy surface of the wafer and holds the wafer in an undeformed condition. As a result, the waviness of the top surface is removed effectively by grinding. This ground surface will be the flat reference plane for grinding the other side of wafer on the conventional ceramic chuck.

#### 3.1 2D model

As shown in Figure 6, the 2D model simulated the cross-section that passes through the active grinding zone and perpendicular to the longitudinal direction of the waviness strips (Xin, Pei and Liu, 2004). The waviness profile was simplified as sinusoids with uniform wavelength and height.
Figure 6  An approximate finite element model for soft-pad grinding

The following boundary conditions were imposed for this model.

1 **DOF constraints.** All nodes at the bottom of the soft pad were constrained from moving in the Z direction (along the wafer thickness dimension), but were free to move in the X direction to simulate the support from the ceramic chuck. In addition, one node at the wafer centre was constrained from moving in the X direction.

2 **Forces.** Grinding force was loaded at the peak nodes of the wafer in the Z direction within the active grinding zone. The force applied on each peak node was assumed to be 7 N. Under this loading condition, the waviness peaks were pressed down to touch the chuck surface when grinding on rigid chuck. All loaded peak nodes were constrained to deform always to the same height for reflecting the rigidity of the grinding wheel.

3 **Pressure.** The chuck vacuum was neglected since its effect is very small compared with the grinding force.

4 **Contact.** A contact element pair was created between the wafer and the soft pad.

Three types of soft pad materials were investigated. The first were linear elastic with Young’s modulus $E$ and Poisson’s ratio $v$. The second were bilinear elastic with Young’s modulus $E_1$ and $E_2$, inflection point $e_{ip}$ and Poisson’s ratio $v$. The third type was a hyperelastic material. The final deformation was directly obtained by carrying out a static analysis. However, to understand the deformation mechanism of the interface between the wafer and pad, the transient analysis was used to investigate the whole process of deformation during loading.

Relative peak displacement in the active grinding zone was used as the measure of effectiveness in the removal of waviness. The relative peak displacement is the average displacement of the peaks relative to the valleys along the grinding force direction (the Z direction). A smaller relative peak displacement is desirable to remove or reduce waviness.

The following conclusions have been drawn.

1 The use of soft pads can significantly reduce the relative peak displacement during grinding, thereby enhancing the ability of removing the wire-sawing induced waviness.

2 The effectiveness of soft pads in removing waviness varies dramatically when the pad properties change.

3 For linear elastic pads, with the increase of $E$ and $v$, the relative peak displacement will also increase. A small Young’s modulus (close to 2 MPa) is preferable.
4 Thicker pads are more effective in removing wire-sawing induced waviness.

5 If a bilinear elastic pad is used, the inflection point should be smaller than the effective strains of every location of the pad. In addition, with large $E_1$, small $E_2$ and $\epsilon_0$ in the range of small inflection point, the relative peak displacement can be efficiently reduced.

6 Hyperelastic materials as incompressible materials are not suitable to be used as a soft pad for waviness removal purpose.

3.2 3D model

The static 3D model is shown in Figure 7 (Sun et al., 2004). Similarly, to simplify the problem, the waviness was assumed to have a sinusoidal profile. The eight-node 3D solid elements in ANSYS were used for the wafer and the soft pad. 3D contact elements were used to model the wheel-wafer and wafer-soft pad contacts. The contact elements for the wheel-wafer pair were rigid–flexible type, while the contact elements for the wafer-pad pair were flexible–flexible type.

Figure 7 Solid model of 3D finite element analysis

In this model, a solid disk of 220 mm in diameter and 1 mm in thickness was created to present the soft pad. The bottom surface of the soft pad was fixed in all directions. Grinding wheel was modelled by a segment of a hollow cylinder with a diameter of 280 mm, a width of 2.5 mm and a height of 4 mm. In simulation, the grinding wheel was treated as a rigid contact body and had a total grinding force of 50 N on its pivot node of rigid-flexible contact. The centre of the wafer was constrained from moving in the Y direction in order to prevent the wafer rigid body movement along the Y direction.

Four factors (pad Young’s modulus, pad Poisson’s ratio, pad thickness and waviness wavelength of the wafer) were taken into consideration during this study. A $2^4$ (four factors, two levels, 16 tests) full factorial design was used for the experiments.

The following conclusions have been drawn from this study.

1 The main effects of pad Young’s modulus, pad thickness and wafer waviness wavelength on the relative peak displacement are significant. It becomes more difficult to remove the waviness as pad Young’s modulus and Poisson’s ratio increase, or as wafer waviness wavelength increases. The effect of pad Young’s modulus is greatly enhanced at the high level of waviness wavelength.
2 The valley displacement becomes larger as the pad Young’s modulus and Poisson’s ratio decrease, or as the pad thickness increases.
3 The effect of pad Young’s modulus is greatly enhanced at the high level of pad Poisson’s ratio.

4 Model for the study of central dimples on ground wafers

A 2D FEA model was built on the cross-section (along the centreline of the wheel segment) as shown in Figure 8. This model has been developed to illustrate the generation mechanisms of central dimples and to study the effects of influencing factors on the central dimple sizes (Zhang, Pei and Fisher, 2006). Finer meshes were employed for the portion of the wheel segment near the wafer centre and contact elements for the wafer–wheel pair were of the rigid–flexible type.

**Figure 8** Illustration of the finite element model

The finite element model was based on the following assumptions and simplifications.

1 The grinding process was modelled as a static problem, since the focus of this study was the elastic deformation of the wheel segment under the grinding force.
2 Since silicon wafers have much higher Young’s modulus than the wheel segment, the silicon wafer was modelled as a rigid body.
3 The grinding wheel was assumed to have a single segment.
4 Material removal would occur wherever the wheel segment was in contact with the wafer.
5 The radius of the central dimple on a ground wafer was computed as the contact length (measured from the wafer centre) between the wheel segment and the wafer on the other side of the active grinding zone.

The boundary conditions for this FEA model include the followings.

1 **DOF constraints.** The top line of the wheel segment was constrained from moving in the X direction and the pilot node on the silicon wafer was constrained from moving in the X or Y directions to simulate the support from the ceramic chuck.
2 Forces. The grinding force was loaded on the top line of the wheel segment in the Y direction.

3 Contacts. A contact element pair was created between the wafer and the wheel segment.

Six influencing factors (Young’s modulus of the grinding wheel segment, poisson’s ratio of the grinding wheel segment, chuck shape, wheel segment width, wheel segment height and grinding force) were considered in the finite element model. When studying the effects of one factor on the dimple size, only that factor was changed within a suitable range while the other factors were fixed at their default values unless specified otherwise. The following conclusions have been drawn.

1 Central dimples on the ground wafers are due to the elastic deformation of the wheel segment.

2 The size of central dimples will increase as the wheel segment’s Young’s modulus decreases, as the segment height increases or as the segment width decreases.

3 The size of central dimples will increase as the chuck shape gets flatter.

4 The size of central dimples will increase as the grinding force increases.

5 Summary

1 FEA model for grinding of wire-sawn wafers on a rigid chuck shows that the main effects of wafer thickness, waviness wavelength and grinding force are significant. The best scenario for removing waviness is the combination of thicker wafer, shorter wavelength and lower grinding force.

2 FEA model for the grinding of wire-sawn wafers using a soft pad shows that the use of soft pads can significantly reduce the relative peak displacement during grinding. The effectiveness of soft pads in removing waviness varies dramatically when the pad properties change.

3 FEA model for the study of central dimples on ground wafers shows that wheel segment’s Young’s modulus, height and width, the chuck shape and grinding force have significant effects on the size of central dimples.

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