A grinding-based manufacturing method for silicon wafers: generation mechanisms of central dimples on ground wafers

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Abstract

Silicon wafers are the fundamental building blocks for most integrated circuits. The lapping-based manufacturing method currently used to manufacture the majority of silicon wafers will not be able to meet the ever-increasing demand for flatter wafers and lower prices. A grinding-based manufacturing method has been investigated experimentally to demonstrate its potential to manufacture flat silicon wafers at a lower cost. It has been demonstrated that the site flatness on the ground wafers (except for a few sites at the wafer center) could meet the stringent specifications for future silicon wafers. This paper, as a follow up, addresses one of the reasons for the poor flatness at the wafer center: central dimples on ground wafers. A finite element model is developed to illustrate the generation mechanisms of central dimples. Then, effects of influencing factors (including Young’s modulus and Poisson’s ratio of the grinding wheel segment, dimensions of the wheel segment, grinding force, and chuck shape) on the central dimple sizes are studied. Pilot experimental results will be presented to substantiate the predicted results from the finite element model. This provides practical guidance to eliminate or reduce central dimples on ground wafers.

1. Introduction

The majority of semiconductors are built on silicon wafers [1]. About 150 million silicon wafers of different sizes are manufactured each year worldwide [2]. In year 2004, worldwide revenue generated by silicon wafers was $7.3 billion [3], and worldwide sales of semiconductors reached a record $213 billion [4].

As the starting materials for fabrication of most semiconductor devices, silicon wafers must be very flat in order to print circuits on them by lithographic processes. Wafer flatness directly impacts device line-width capability, process latitude, yield, and throughput [5,6]. The feature sizes of semiconductor devices will continue to decrease and this will demand increasingly flatter wafers [7].

The lapping-based manufacturing method currently used to manufacture silicon wafers will not be able to meet the ever-increasing demand for flatter wafers and lower prices. Its drawbacks were discussed in a prior paper [8].

A grinding-based manufacturing method, as shown in Fig. 1, has been investigated experimentally to demonstrate its potential to manufacture flat silicon wafers at a lower cost [8]. Note that some processes are omitted in Fig. 1 for simplicity; for example, edge grinding, edge polishing, laser marking, and final cleaning. Additional related information is available in the literature [9–11] and at www.memc.com.

Experiments have shown that the site flatness on the ground wafers (except for a few sites at the wafer center) could meet the stringent specifications for future silicon wafers [8]. This paper, as a follow up, addresses one of the reasons for the poor flatness at the wafer center: central dimples on ground wafers. The objectives of this study are to understand the generation mechanisms of the central dimples and to provide practical guidance to eliminate or reduce central dimples on ground wafers.

There are five sections in this paper. Following this introduction section, Section 2 provides some background information about wafer grinding. In Section 3, procedures to develop the finite element model are presented. The developed model is used in Section 4 to predict the relations...
between the influencing factors (including Young’s modulus and Poisson’s ratio of the grinding wheel segment, dimensions of the wheel segment, grinding force, and chuck shape) and the size of the central dimple. Section 5 provides the pilot experimental results to substantiate the predicted results from the finite element model. Section 6 comprises the conclusions.

2. Wafer grinding and central dimples

Fig. 2 illustrates wafer grinding, the cornerstone process for the grinding-based manufacturing method shown in Fig. 1. Grinding wheels are diamond cup-wheels. The wafer is held on a porous ceramic chuck by means of vacuum. 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.

The ceramic chuck is typically ground to a conic shape with a very small slope, as shown in Fig. 3(b). The graphs in Fig. 3 are cross-sectional views along the centerline of the wheel segment. When the wafer is held onto the chuck, it elastically deforms to the chuck’s conic shape, thus ensuring that the grinding wheel only contacts half of the wafer. This contact area is marked as ‘Active Grinding Zone’ in Fig. 2.

Central dimples have been observed on some ground wafers. Fig. 4 illustrates the central dimple. 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).

The hypothesis for the generation mechanisms for central dimples is as follows. During grinding, due to the grinding force, the portion of the grinding wheel segment that is in contact with the silicon wafer (or, the portion of the wheel segment that is within the active grinding zone) will elastically deform. This deformation will cause the portion of the wheel segment that is next to the active grinding zone to contact with (cut into) the silicon wafer near the wafer center. The cutting action of this portion of the wheel segment (outside the active grinding zone) will remove material from the silicon wafer near the wafer center, in addition to the material removed by the portion of the wheel segment within the active grinding zone. The additional removal of material near the wafer center (on the opposite side of the active grinding zone) generates the central dimples.

Fig. 1. The grinding-based manufacturing method.

Fig. 2. Illustration of wafer grinding.

Fig. 3. Cross-sectional views of the wheel segment, wafer, and chuck (the magnitude of $\delta$ is greatly exaggerated for illustration purpose).

Fig. 4. Illustration of a central dimple (the depth of the central dimple is greatly exaggerated for illustration purpose).
In the following two sections, a finite element model is developed based on this hypothesis. Then, the developed model is used to predict the relationships between the influencing factors (including mechanical properties and geometry of the grinding wheel segment, chuck shape, and grinding force) and the dimple size.

3. Development of the finite element model

Commercial software, ANSYS (ANSYS, Inc., Canonsburg, PA), was used for this study. Fig. 5 schematically displays the two-dimensional (2D) model developed. Please note that the height of the cone, \( d \), the measure of the chuck shape, is greatly exaggerated for illustration purpose.

A 2D element model was built on the cross-section shown in Fig. 3. Please note that the cross-section is along the centerline of the wheel segment. The reasons that a 2D (instead of 3D) finite element model was used include the followings. Firstly, the focus of this study is the elastic deformation of the grinding wheel segment. Since the wheel segment is about 2–5 mm wide, 3D models will not add significantly more insights than the 2D model. Secondly, the 2D model requires a much smaller number of total nodes and much less computing time.

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

1. The grinding process was modeled as a static problem (i.e. any dynamic effects were ignored), since the focus of this study was the elastic deformation of the wheel segment under the grinding force (i.e. the reaction force between the wheel segment and the wafer).
2. Since silicon wafers have much higher (two to three magnitude higher) Young’s modulus than the wheel segment, the silicon wafer in the finite element model was modeled 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.

The radius of the central dimple on a ground wafer was computed as the contact length (measured from the wafer center) between the wheel segment and the wafer on the other side of the active grinding zone.

Since the areas around the wafer center were of major interest, finer meshes were employed for the portion of the wheel segment near the wafer center. Contact elements were used to model the wafer-wheel interface. Since the wafer was treated as a rigid body, the contact elements for the wafer-wheel pair were of rigid-flexible type.

As shown in Fig. 5, the boundary conditions include the followings.

1. Degree-of-freedom constraints: the top line of the wheel segment was constrained from moving in the \( X \) direction. For the silicon wafer, its pilot node (whose motion governs the motion of the entire 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. The grinding force would cause a portion of the wheel segment to contact the wafer and even deform elastically.
3. Contacts: a contact element pair was created between the wafer and the wheel segment. The pair consists of TARGE169 and CONTAL72 elements (both are standard elements in the ANSYS package).

Six influencing factors were considered in the finite element model. Typical ranges for these influencing factors and their default values used in the finite element model are listed in Table 1. 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.

4. Effects of influencing factors on dimple size

4.1. Mechanical properties of the grinding wheel segment

Fig. 6 shows how the mechanical properties of the grinding wheel segment affect the dimple radius. It can be
seen from Fig. 6(a) that, as Young’s modulus increases, the dimple radius will decrease. If Young’s modulus of the wheel segment is sufficiently high, the dimple radius can be reduced to practically zero, and therefore there will be no central dimples on the ground wafers. The interaction effects of Young’s modulus of the wheel segment and the chuck shape can also be clearly seen in Fig. 6(a). The effects of Young’s modulus are enhanced for the chuck shape with a smaller conic height. However, the effects of Poisson’s ratio on the dimple radius are relatively trivial, as shown in Fig. 6(b). The dimple radius changes very little as Poisson’s ratio changes from 0.2 to 0.4.

The practical implication of the results is as follows. In order to eliminate or reduce the central dimples on ground wafers, grinding wheels whose segments have sufficiently high Young’s modulus should be used.

4.2. Geometry of the grinding wheel segment

Fig. 7 shows the effects of the geometry (width and height) of the grinding wheel segment on the dimple radius. It can be seen from Fig. 7(a) that, as the wheel segment becomes wider, the dimple radius becomes smaller. Please note that this conclusion is obtained based on a constant grinding force. When the grinding force is constant, a wider wheel segment will have a larger contact area with the silicon wafer and hence a smaller stress. Consequently, the elastic deformation will be smaller, resulting in a smaller dimple radius. However, if the grinding force also changes as the wheel segment gets wider, it is possible that this conclusion will no longer be true.

Fig. 7(b) shows the relationship between the wheel segment height and the dimple radius. It can be seen that when the wheel segment is higher, the dimple radius will be larger.

The interaction effects between the chuck shape and the wheel segment width (as well as height) are obvious in Fig. 7. When the chuck is flatter (δ is smaller), the change in the wheel segment width (or height) causes a larger change in the dimple radius.

In summary, central dimples can be lessened if the wheel segment is made shorter and/or wider. (Please note that a wider wheel segment can reduce the dimple radius only if the grinding force is kept the same.)

4.3. Chuck shape

The effects of the chuck shape on the dimple radius are shown in Fig. 8. As the chuck gets flatter, the dimple radius increases exponentially. A chuck with a conic shape whose conic height is sufficiently large can effectively prevent the occurrence of central dimples on ground wafers.

The above results have provided an effective, yet relatively inexpensive, solution to the central dimple
problem in grinding of silicon wafers. It involves using a conic chuck with a sufficiently large cone height. It does not involve any modifications on grinding wheels.

4.4. Grinding force

Fig. 9 shows the relationship between the grinding force and the dimple radius. As the grinding force increases, the wheel segment will deform more. This will increase the dimple size. Therefore, from the perspective of reducing the central dimples on ground wafers, smaller grinding forces are desirable.

The interaction effects between the chuck shape and the grinding force can be observed from Fig. 9. When the chuck is flatter (δ is smaller), the change in the grinding force causes a larger change in the dimple radius.

5. Pilot experimental verification

5.1. Experimental conditions

Grinding experiments were conducted on a Strasbaugh Model 7AF wafer grinder (Strasbaugh, Inc., San Luis Obispo, California). The grinding wheels used were diamond cup-wheels. The grit size for the coarse grinding wheel was mesh #320. The grit size for the fine grinding wheels was mesh #2000. One of the fine wheels had a larger Young’s modulus than the other fine wheel. The radius of the wheels was 140 mm.

Single crystal silicon wafers of 200 mm in diameter with the (100) plane as the major surface (the front or back surface of the wafer) were used for this investigation. To ensure the consistency of test wafers, all wafers were lapped using the same lapping conditions prior to grinding.

Grinding parameters and their values are listed in Table 2. Note that there were three feedrate values, used for three sequential steps, respectively. During grinding, deionized (purified) water was used to cool the grinding wheel and the wafer surface. The coolant was supplied to the inner side of the cup-wheel, at a flow rate of 11.4 l min⁻¹ (or, 3 gallon min⁻¹).

The chuck shape used for the experiments was fairly flat, close to the chuck shape with δ = 1 µm. Due to limitations of currently available measurement tools [12], the exact chuck shapes were not known. However, based on the mathematical model for the chuck shape [12–14], it is possible to know approximately the chuck shape once the setup parameters are determined.

Central dimples were measured on flatness gages, Model Ultra gage 9500 (ADE Corporation, Westwood, MA). More information on the UltraGage 9500 flatness gage can be found at www.ade.com.

5.2. Experimental results

Fig. 10 shows two wafers ground by two grinding wheels (A and B). For wheel A, the Young’s modulus of the wheel segment was larger. The wafer ground by this wheel does not have a central dimple, as shown in Fig. 10(a). The wafer ground by wheel B (its wheel segment has a smaller Young’s modulus) shows a central dimple, as shown in Fig. 10(b).

This experimental result is consistent with observations of many grinding tests conducted by other industrial
practitioners. They reported that central dimples always appeared on the wafers ground by grinding wheels whose segments had very small Young's modulus.

The pilot experimental results and the reports from industrial practitioners have substantiated the predicted effects of the wheel segment’s Young’s modulus.

6. Conclusions

This paper has addressed one of the critical issues in silicon wafer grinding: central dimples on ground wafers. A finite element model has been developed to illustrate the generation mechanisms of central dimples and to predict the effects of influencing factors on the dimple size. Pilot experimental results are consistent with model predictions. Major conclusions from the study are:

1. Central dimples on the ground wafers are due to the elastic deformation of the wheel segment, causing additional material removal at the wafer center outside the active grinding zone.
2. The size of central dimples will increase as the wheel segment’s Young’s modulus decreases, as the segment height increases or the segment width decreases. The effects of those factors will be much stronger for a flat chuck shape.

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**Fig. 10. Results of pilot experiments.**

(a) Wafer ground by wheel A (with a large Young’s modulus)

(b) Wafer ground by wheel B (with a small Young’s modulus)
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.

The results of this study have provided the practical guidance for eliminating or reducing the problem of central dimples on ground wafers. The most effective measure is to use a conic-shaped chuck with a sufficiently large slope. The second measure involves design and manufacturing of grinding wheels: more rigid segments (larger Young’s modulus, larger width, and smaller height for the wheel segments). Finally, it is beneficial to choose grinding conditions that minimize the grinding force (for example, to select a lower feedrate).

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