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Fine grinding of silicon wafers

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Abstract

Silicon wafers are used for the production of most microchips. Various processes are needed to transfer a silicon crystal ingot into wafers. As one of such processes, surface grinding of silicon wafers has attracted attention among various investigators and a limited number of articles can be found in the literature. However, no published articles are available regarding fine grinding of silicon wafers. In this paper, the uniqueness and the special requirements of the silicon wafer fine grinding process are introduced first. Then some experimental results on the fine grinding of silicon wafers are presented and discussed. Tests on different grinding wheels demonstrate the importance of choosing the correct wheel and an illustration of the proper selection of process parameters is included. Also discussed are the effects of the nozzle position and the flow rate of the grinding coolant. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Single-crystal silicon, the most important building block of semiconductors, is found in every type of microelectronic application, including computer systems, telecommunications equipment, automobiles, consumer electronics products, industrial automation and control systems, and analytical and defense systems. In 1997, approximately 150 million silicon wafers of different sizes were manufactured, representing a worldwide revenue of US$6.2 billion [1].

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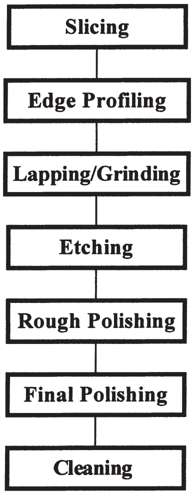


Fig. 1. Typical process flow for making silicon wafers (after Bawa et al. [2], Fukaml et al. [3] and Tonshoff et al. [4]).

To turn a silicon crystal ingot into wafers of satisfactory quality, a sequence of machining processes are needed. As shown in Fig. 1, this typically consists of the following [2–4]:

1. slicing: to slice single-crystal silicon ingot into wafers of thin disk shape;
2. edge profiling or chamfering: to chamfer the peripheral edge portion of the wafer;
3. flattening (lapping or grinding): to flatten the surface of the wafer;
4. etching: to chemically remove processing damage of the wafer without introducing further mechanical damage;
5. rough polishing: to obtain a mirror surface on the wafer;
6. fine polishing: to obtain the final mirror surface; and
7. cleaning: to remove the polishing agent or dust particles from the wafer surface.

Besides being a major flattening process, surface grinding has also been proposed to replace etching [5], even for producing 400 mm silicon wafers [6].

In addition to its applications in silicon wafer manufacturing, surface grinding has also been used for “backgrinding”. In backgrinding, silicon wafers containing completed devices on their frontside are ground on their backside, before being sliced into individual chips for the final package.

Due to its importance, surface grinding has attracted more and more interest among investigators. The reported investigations can be classified into the following categories:

(a) Flatness and surface roughness. Matsui [7] compared the experimental results of silicon wafer surface grinding (he called it the “wafer rotation grinding method”) with those obtained by conventional and creep-feed grinding. He concluded that surface grinding is superior as far as flatness, surface roughness, scratches and chipping are concerned.
(b) Subsurface damage (SSD). Lundt et al. [8], Pei et al. [9], Tonshoff et al. [10], Van De Merwe [11], and Zarudi and Zhang [12] have studied the subsurface damage induced by

surface grinding. It was reported that the size of the diamond grits has a most significant effect on the SSD. As grit size increases, the depth of the subsurface cracks increases.

(c) Wafer strength. Lee et al. [13] studied the influence on the chip fracture strength of the mesh size of the grinding wheel, and of the orientation of the grinding lines. They concluded that the fracture strength of silicon chips was much more sensitive to the orientation of the grinding lines than the flaw depth. McGruire et al. [14] also reported the dependence of wafer strength on the orientation of grinding lines. (Though the grinding employed by McGuire et al. was not exactly the same as the surface grinding referred to in this paper.)

(d) Wheel development. Tonshoff et al. [15] discussed the effects of the topography of the abrasive layer, particularly the height distribution of the single grains on the grinding wheel. Their tests revealed that both plastic deformation and micro brittle fracture occurred during surface grinding. They attributed this to the unevenness of the grinding wheel.

However, to our best knowledge, reports on fine grinding of silicon wafers are not currently available in the public domain.

Fine grinding of silicon wafers refers to the grinding operations with #2000 mesh (3~6 μm grit size) or finer diamond wheels. The wafer surfaces to be fine-ground generally have no damage or very little damage and the surface roughness is less than 0.03 μm in Ra.

Fine grinding of silicon wafers requires high predictability and consistency, which requires the grinding wheel to possess self-dressing ability, i.e., after initial truing, the wheel should not need any periodic dressing by external means. In other words, there should be “a perfect equilibrium between the rate of wear of the abrasive grains and the rate of release of worn abrasive grains” [16], hence maintaining the grinding force to be relatively constant.

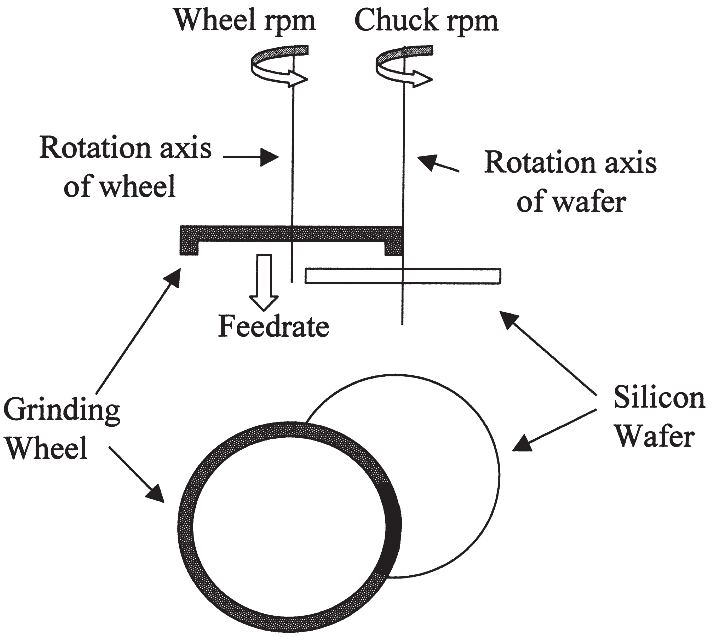


Fig. 2. Illustration of wafer surface grinding.

The other major requirements for fine grinding of silicon wafers include:

(a) the grinding wheel should have a reasonable life;
(b) the grinding force should be low and constant;
(c) surface and sub-surface damage should be minimized; and
(d) the ground wafers should have very good flatness. This usually means sub-micron GBIR (or TTV, total thickness variation).

Due to its unique requirements, fine grinding of silicon wafers presents big challenges to grinding wheel manufacturers, grinder machine builders and process engineers. To ensure the successful development of fine grinding of silicon wafers, a large amount of research work is needed.

As the first of a series of papers dealing with fine grinding of silicon wafers, this paper reports and discusses some experimental work on the effects of grinding wheels, process parameters and grinding coolant. The second paper will report a factorial experimental study on the fine grinding of silicon wafers. In the third paper, a model will be developed to predict the shape of the work chuck from the set-up information.

This paper is organized into five sections. Following this introduction section, Section 2 describes the experimental conditions. In Section 3, the effects of the grinding wheels will be examined. The test results about the effects of process parameters and the effects of grinding

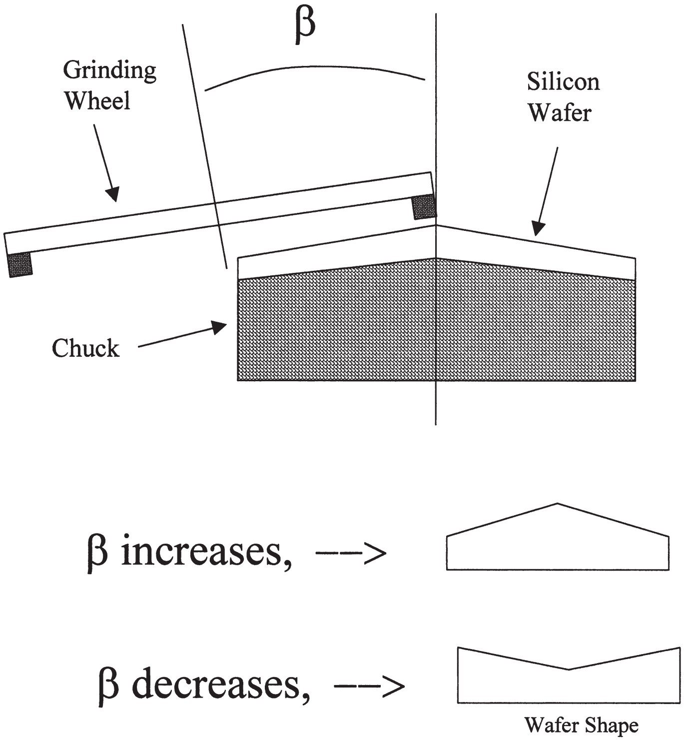
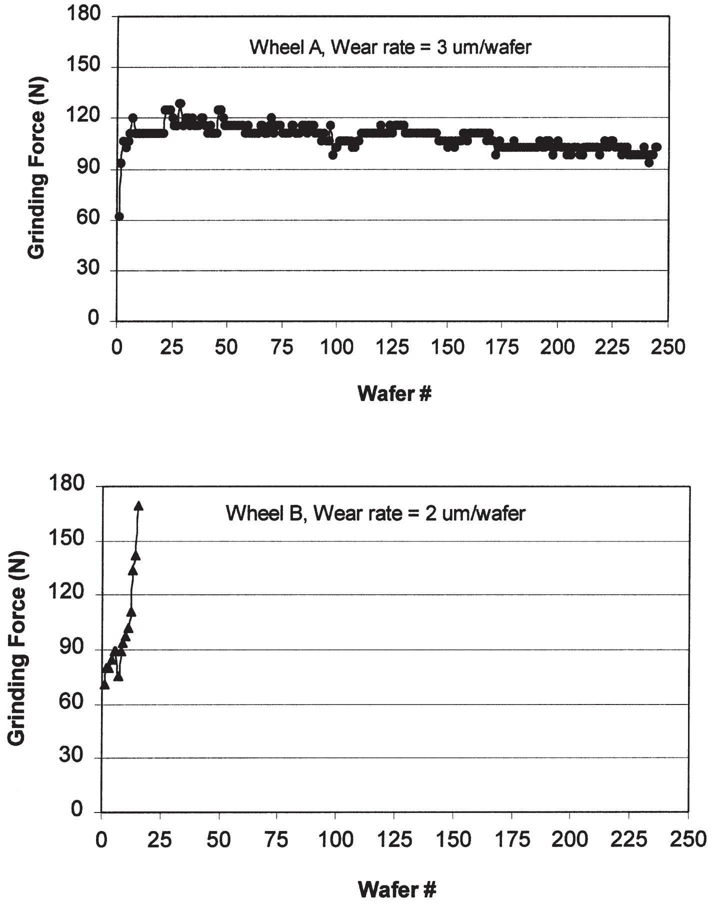


Fig. 3. Wafer shape controlling in wafer surface grinding.

coolant will be discussed in Sections 4 and 5, respectively. Section 6 draws conclusions of this study.

2. Experimental conditions

Fig. 2 illustrates the surface grinding process. Grinding wheels are diamond cup wheels. The workpiece (wafer) is held on the porous ceramic chuck by means of a vacuum. The axis of rotation for the grinding wheel is offset by a distance of the wheel radius relative to the axis of



Grinder: Model 7AF.
Wheel diameter: 280 mm.
Test wafer diameter: 200 mm.
Removal amount: 6 μm.
Wheel speed = 36.25 rev s^{-1} (2175 rpm).
Chuck speed = 0.67 rev s^{-1} (40 rpm).
Feedrate = 0.3 μm s^{-1}.
Coolant flow rate: 3.2 gallon/minute.

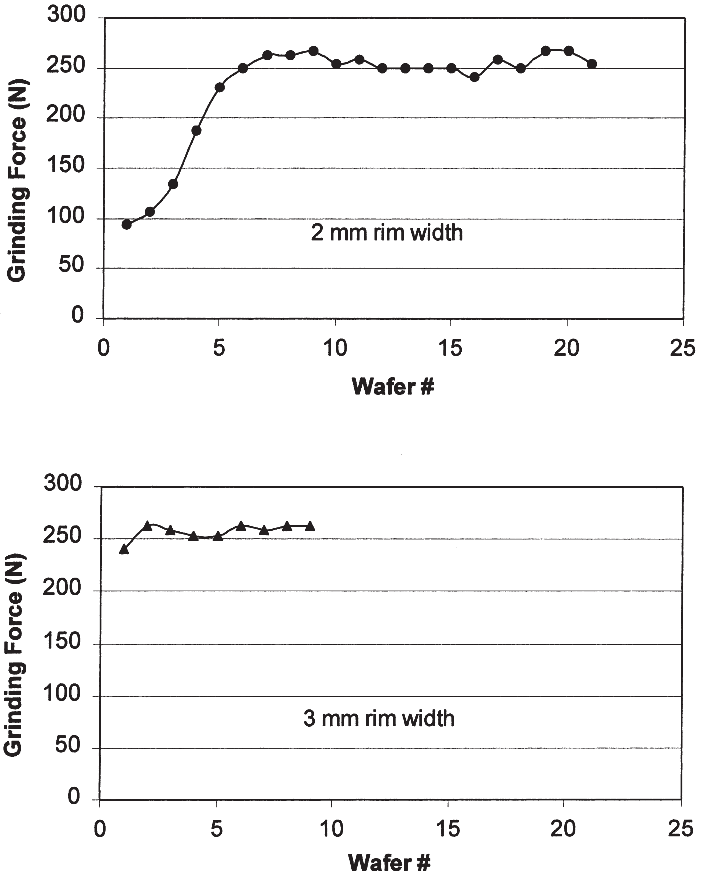
Fig. 4. Effect of wheel on grinding force and wheel wear rate.

rotation of the wafer. During grinding, the grinding wheel and the wafer rotate about their own axes of rotation simultaneously, and the wheel is fed towards the wafer along its axis.

The shape of the ceramic chuck can be dressed to a conic shape with a very small angle (see Fig. 3). When the wafer is held on the chuck, it elastically deforms to the chuck's conic shape, thus ensuring that the grinding wheel only contacts half of the wafer at any given instant.

By adjusting the angle between the wheel axis of rotation and the wafer axis of rotation, the shape of the ground wafer can be controlled. With a larger angle, the wafer tends to have a convex shape. With a smaller angle, the wafer tends to have a concave shape. This is also illustrated in Fig. 3.

Single-crystal silicon wafers of 125 and 200 mm in diameter with the (100) plane as the major



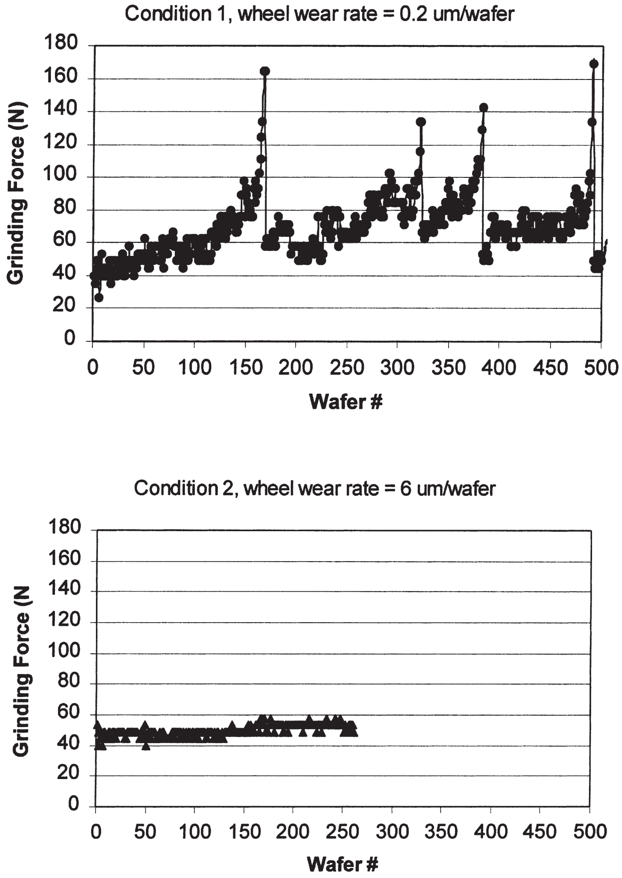
Grinder: Model 7AF.
Wheel diameter: 280 mm.
Test wafer diameter: 200 mm.
Removal amount: 6 μm.
Wheel speed = 72.50 rev s^{-1} (4350 rpm).
Chuck speed = 9.83 rev s^{-1} (590 rpm).
Feedrate = 0.3 μm s^{-1}.
Coolant flow rate: 3.2 gallon/minute.

Fig. 5. Effect of wheel rim width on grinding force.

surface are used for this investigation. Diamond grinding wheels with different grit sizes (mesh #2000 and #4000) and different tooth segment designs are used. These wheels are made by several different manufacturers and have different bond materials. The surface grinders used include Strasbaugh surface grinders, models 7AA and 7AF (Strasbaugh, Inc., San Luis Obispo, CA).

For every test, an identical dressing procedure is used for each wheel prior to grinding the first wafer. No further dressing is performed once the test starts.

During grinding, deionized (purified) water is used to cool the grinding wheel and the wafer surface. For most of the tests in this study, the coolant is supplied to the inner side of the cup



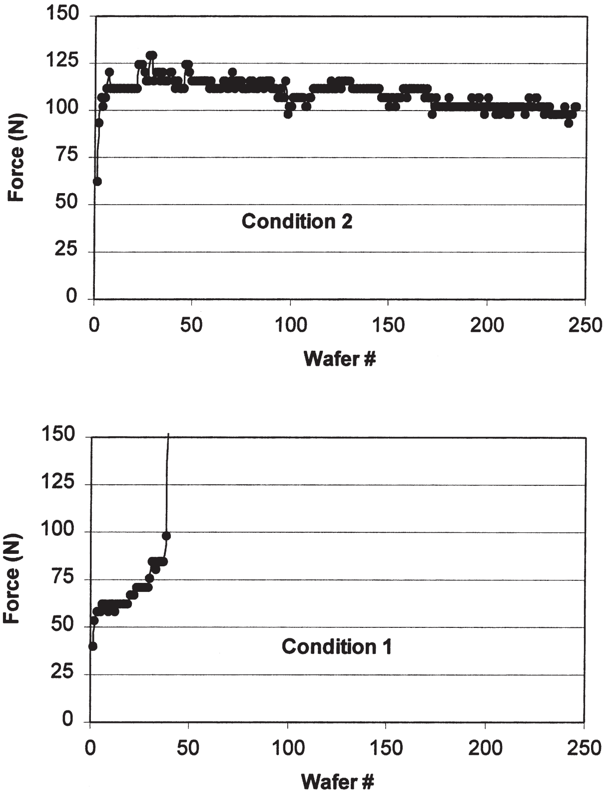
Grinder: Model 7AF. Wheel diameter: 280 mm.
Test wafer diameter: 200 mm. Removal amount: 6 μm.
Feedrate = 0.3 $\mu m\ s^{-1}$. Coolant flow rate: 3.2 gallon/minute.
Condition 1:
Wheel speed = 72.50 rev s^{-1} (4350 rpm). Chuck speed = 9.83 rev s^{-1} (590 rpm).
Condition 2:
Wheel speed = 36.25 rev s^{-1} (2175 rpm). Chuck speed = 0.67 rev s^{-1} (40 rpm).

Fig. 6. Effect of wheel speed and chuck speed (wheel C).

wheel. This will be the default setting unless otherwise specified. The coolant is also supplied to the outer side of the cup wheel to investigate the effects on the grinding process. Section 5 is devoted to discussing this issue.

3. Effects of grinding wheels

Grinding wheels have significant effects on the grinding performance in fine grinding of silicon wafers. Diamond abrasives are the only abrasives used in this application. To ensure minimum



Grinder: Model 7AF.
Wheel diameter: 278 mm.
Test wafer diameter: 200 mm.
Removal amount: 6 μm.
Feedrate = 0.3 μm s^{-1}.
Coolant flow rate: 3 gallon/minute.
Condition 1:
Wheel speed = 72.50 rev s^{-1} (4350 rpm).
Chuck speed = 9.83 rev s^{-1} (590 rpm).
Condition 2:
Wheel speed = 36.25 rev s^{-1} (2175 rpm).
Chuck speed = 0.67 rev s^{-1} (40 rpm).

Fig. 7. Effect of wheel speed and chuck speed (wheel A).

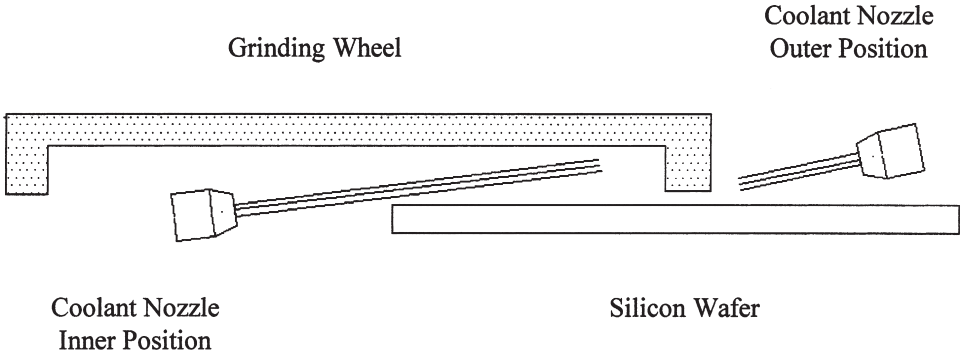


Fig. 8. Illustration of coolant nozzle positions.

subsurface damage to the silicon wafers and to achieve the desired surface roughness, the grit size of diamond abrasives should be as small as possible. The type of the bond materials, the hardness of the wheel, and the concentration play significant roles in determining the self-dressing ability and the wheel wear rate. The geometrical design of the tooth segments is also critical.

More than 10 different wheels have been tested for fine grinding of silicon wafers. Some wheels could grind hundreds of wafers with constant grinding force, without any dressing procedure performed in between. Some wheels could hardly grind several wafers before “overloading”. “Overloading” refers to the phenomenon when the wheel basically stops cutting and the grinding force increases to very high values, and the ground wafer exhibits some kind of “burning” appearance.

Fig. 4 shows the fine grinding performance (namely, grinding force and wheel wear rate) of two different wheels. Both wheels are resin bonded, with diamond grain size of 3~6 μm. They differ in wheel hardness and tooth segment geometry. The other process parameters are also listed under the graph in the figure.

It can been seen that the grinding force of wheel A was relatively stable over grinding more than 250 wafers. In the case of wheel B, the grinding force increased rapidly and overloaded after grinding only 15 wafers. On the other hand, wheel A had a higher wheel wear rate (3 μm per wafer) compared with wheel B (2 μm per wafer). It is apparent that wheel A is “softer” than wheel B.

The two wheels in Fig. 5 are identical except for the rim width. Both are resin-bonded with

Table 1
Test result of coolant nozzle position on 7AA grinder (wheel E)[a]

Nozzle position	Number of wafers ground before wheel overloading
Inner position	50
Outer position	107

[a] Grinder: Strasbaugh surface grinder model 7AF; wheel: #2000 mesh resin bond diamond wheel, 280 mm diameter; test wafers: 125 mm silicon wafers; removal amount: 10 μm; wheel speed: 72.50 rev s^{-1} (4350 rpm); chuck speed: 0.67 rev s^{-1} (40 rpm); feedrate: 0.3 μm s^{-1}; coolant flow rate: 3 gallon per min.

Table 2
Test result of coolant nozzle position on 7AF grinder (wheel E)[a]

Removal (μm)	Wheel speed (rev s^{-1})	Chuck speed (rev s^{-1})	Feedrate (μm s^{-1})	Number of wafers ground before wheel overloading	
				Coolant nozzle position 1 (inner)	Coolant nozzle position 2 (outer)
6	36.25	0.67	0.3	0	2
6	36.25	5.00	0.6	0	2
6	72.50	9.83	0.3	5	>9

[a] Grinder: Strasbaugh surface grinder model 7AF; wheel: #2000 mesh resin bond diamond wheel, 280 mm diameter; test wafers: 200 mm silicon wafers; coolant flow rate: 3.2 gallon per min.

Table 3
Test result of coolant nozzle position on 7AF grinder (wheel F)[a]

Removal (μm)	Wheel speed (rev s^{-1})	Chuck speed (rev s^{-1})	Feedrate (μm s^{-1})	Number of wafers ground before wheel overloading		
				Coolant nozzle position 1 (inner)	Coolant nozzle position 2 (outer)	Coolant nozzle position 3 (inner and outer)
10	36.67	5.00	0.6	6	7	>20
6	72.50	9.83	0.3	21	26	74

[a] Grinder: Strasbaugh surface grinder model 7AF; wheel: #2000 mesh resin bond diamond wheel, 280 mm diameter; test wafers: 200 mm silicon wafers; coolant flow rate: 3.2 gallon per min for positions 1 and 2, 6.3 gallon per min for position 3.

3~6 μm diamond grain size. It is obvious that the narrower wheel demonstrated a better grinding performance: it could grind twice as many wafers than the wheel with a wider rim. However, if the rim is too narrow, the tooth segments become very fragile and could break even while handling. A wheel with a rim width of 1.25 mm was tested and several segments were broken while the wheel was placed on the spindle, in spite of the wheel being handled very carefully.

Table 4
Test result of coolant flow rate on 7AF grinder (wheel F)[a]

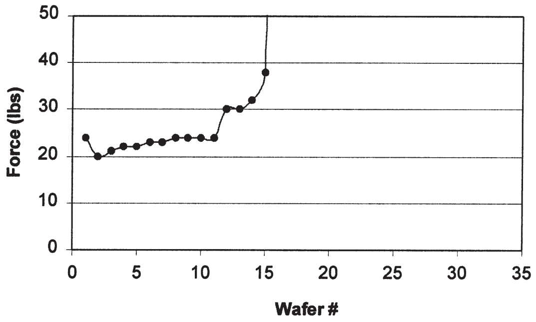
Coolant flow rate (gallon per min)	Number of wafers ground before wheel overloading
2.5	1
3.2	4
4.6	8
6.3	>20

[a] Grinder: Strasbaugh surface grinder model 7AF; wheel: #2000 mesh resin bond diamond wheel, 280 mm diameter; test wafers: 200 mm silicon wafers; removal amount: 10 μm; wheel speed: 36.67 rev s^{-1} (2200 rpm); chuck speed: 5 rev s^{-1} (300 rpm); feedrate: 0.6 μm s^{-1}.

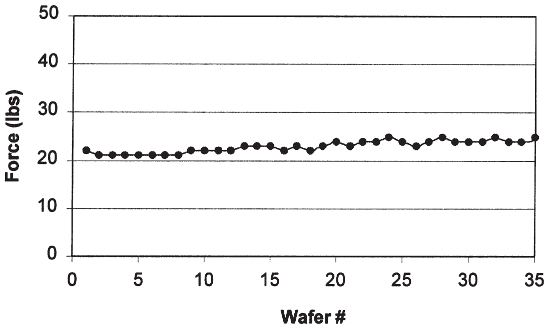
The mechanism of how the wheels affect the fine grinding of silicon wafers is not fully understood yet. It is one the topics for future investigation.

4. Effects of process parameters

Process parameters have significant effects on the wheel performance. One specific wheel may work well under one set of process parameters, but it may not work properly under a different set of process parameters. This is well illustrated in Fig. 6. Under condition 1 (high wheel speed and chuck speed), the grinding force was gradually increased as more and more wafers were ground. After the force reached a peak (between 140 and 180 N), it returned to relatively low



Coolant flow rate = 2.4 gallon per minute



Coolant flow rate = 3.5 gallon per minute

Grinder: Model 7AF.
Wheel diameter: 278 mm.
Test wafer diameter: 200 mm.
Removal amount: 6 μm.
Wheel speed = 36.25 rev s^{-1} (2175 rpm).
Chuck speed = 0.67 rev s^{-1} (40 rpm).
Feedrate = 0.3 μm s^{-1}.

Fig. 9. Effect of coolant flow rate (wheel G).

values. This cycle continued. Under condition 2 (low wheel speed and chuck speed), the grinding force stayed relatively constant at low levels. However, the wheel wear rate under condition 2 was very high (6 μm per wafer) compared with condition 1 (0.2 μm per wafer).

Under both conditions 1 and 2, this wheel exhibited "self-dressing" ability. However, under condition 1, the wheel gradually became duller and duller and broke down itself when the grinding force reached a certain level. While under condition 2, the wheel seemed to be breaking down itself at a much lower grinding force level, resulting in a constant grinding force and a high wheel wear rate.

A different wheel was used to run the same conditions as those in Fig. 7. Under condition 1, the wheel overloaded after grinding 38 wafers. However, under condition 2, the same wheel could grind 245 wafers with the grinding force level keeping relatively constant. See Fig. 7 for details.

5. Effects of grinding coolant

During all the grinding tests, deionized water (D.I. water) was used as the grinding coolant. It has been found that both coolant nozzle position and coolant flow rate affect the fine grinding process.

Two configurations of coolant nozzle positions (inner position and outer position), as shown in Fig. 8, have been tested. The outer position allows the coolant to shoot at the interface between the tooth segments and the wafer surface, while the inner position delivers the coolant to the metal base above the tooth segments.

The test results on the coolant nozzle position are summarized in Tables 1–3. Two different wheels were tested on two grinder models and similar results were obtained. With the coolant nozzle in the inner position, the wheel could grind more wafers before getting overloaded than when the nozzle was placed in the outer position. The best result was obtained by using both inner and outer positions simultaneously.

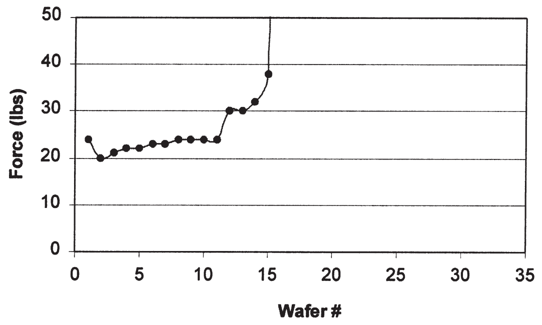
Table 4 summarizes the test results on the coolant flow rate. It was found that, for the wheel and the grinding condition tested, the higher the flow rate, the more wafers the wheel could grind before overloading. Similar results were obtained with a different wheel and are plotted in Fig. 9.

6. Conclusions

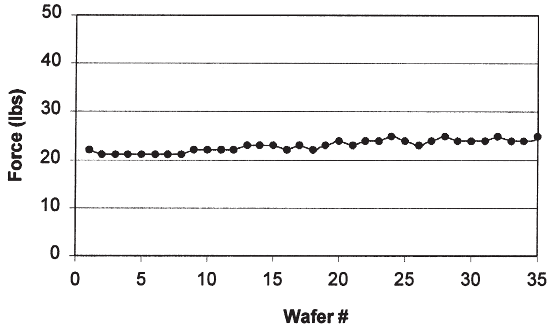
Fine grinding of silicon wafers has some unique requirements regarding the grinding wheels, the grinder design, and the process parameter optimization. Experiments have been conducted to explore the effects of the grinding wheel, the process parameters, and the grinding coolant in fine grinding of silicon wafers.

The following conclusions can be drawn from this study:

1. The grinding wheel has significant effects on the fine grinding process. "Softer" wheels tend to have a better self-dressing ability but a higher wheel wear rate and hence a lower wheel life.
2. Proper selection of process parameters is crucial to fine grinding of silicon wafers, as a grinding wheel that works satisfactorily under one set of grinding parameters may not work well under



Coolant flow rate = 2.4 gallon per minute



Coolant flow rate = 3.5 gallon per minute

Grinder: Model 7AF.
Wheel diameter: 278 mm.
Test wafer diameter: 200 mm.
Removal amount: 6 μm.
Wheel speed = 36.25 rev s^{-1} (2175 rpm).
Chuck speed = 0.67 rev s^{-1} (40 rpm).
Feedrate = 0.3 μm s^{-1}.

Fig. 9. Effect of coolant flow rate (wheel G).

another set of process parameters. The grinding wheels tend to become “softer” under lower wheel speed and/or lower chuck speed.

3. Both the nozzle position and the flow rate of the grinding coolant affect the fine grinding process. With the particular wheels and grinding conditions tested, the higher coolant flow rates give a better performance.

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