Simultaneous double side grinding of silicon wafers: a review and analysis of experimental investigations

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Abstract

Simultaneous double side grinding (SDSG) has become an important flattening process for manufacturing of 300 mm silicon wafers. However, the literature contains only a small number of papers on SDSG. In contrast, there are a large number of patents pertinent to this process. There is no review paper summarizing all these reported experimental results. This paper reviews the literature on experimental investigations on SDSG of silicon wafers. It first describes input variables in SDSG, and then presents their effects on output variables, covering warp, flatness, surface roughness, nanotopography, wafer-thickness variation, rotational asymmetry, grinding marks, subsurface damage, wheel wear, and process cycle time. It also discusses the definition,

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significance, and measurement of each of these output variables. Finally, it tabulates reported experiments to show what has and has not been reported in the literature.

Keywords: Flatness; Grinding; Nanotopography; Silicon wafer; Simultaneous double side grinding; Warp.

1. Introduction

Silicon wafers are used as the substrates to build majority of semiconductor devices [Van Zant 2000]. In 2007, global semiconductor revenue was $273.9 billion [Gartner 2008], and the worldwide revenue generated by silicon wafers was $12.5 billion [Mutschler 2008]. Manufacturing of silicon wafers starts with growth of single crystal silicon ingots. A sequence of processes is used to turn a silicon ingot into wafers. It typically consists of the following processes [Bawa et al., 1995; Fukami et al., 1997; Pei et al., 1999; Tonshoff et al., 1990; Vandamme et al., 2000]: slicing, edge profiling or chamfering, flattening (lapping or grinding), etching, and polishing. Simultaneous double side grinding (SDSG) has become an important flattening process for manufacturing of 300 mm silicon wafers [Pei et al. 2008].

There are only a small number of published papers on SDSG. Pietsch and Kerstan published three papers on SDSG [Kerstan and Pietsch 2000, Pietsch and Kerstan 2001, 2005], evaluating designs and process kinematics of existing SDSG machines. A review paper on SDSG [Li et al. 2006] summarized the literature on SDSG of silicon wafers, including a comparison to other flattening processes (lapping and single-side grinding), history, and machine development. Later, two

papers were published on theoretical modeling of SDSG: one on wafer shape [Li et al. 2008] and the other on grinding marks [Li et al. 2009]. In contrast, there are many patents related to SDSG [Ikeda et al. 2003, Kulkarni and Desai 2001, Pietsch and Kerstan 2005, Pietsch et al. 2006, Bhagavat et al. 2007, Vandamme and Bhagavat 2007, Kuroki and Maeda 2000, Kato et al. 2002, Kato et al. 2001, Hashii et al. 2002]. Reports on experimental investigations on SDSG scatter in both papers and patents. There are no review papers that summarize all the experimental investigations in the literature. Such review papers would be helpful to both researchers and industrial practitioners.

This paper reviews the literature pertinent to experimental investigations on SDSG of silicon wafers. It is organized into eight sections. Following this introduction section, section 2 provides background information on SDSG and its input variables. Sections 3 to 6 present experimental investigations on four SDSG output variables related to wafer quality (warp, flatness, surface roughness, and nanotopography), respectively. Section 7 covers experimental investigations on other output variables, including wafer-thickness variation, rotational asymmetry, grinding marks, subsurface damage, wheel wear, and process cycle time. Section 8 contains concluding remarks.

2. Simultaneous double side grinding (SDSG) and its input variables

SDSG is also called double-disk grinding (DDG) [Pietsch and Kerstan 2005]. Fig. 1 illustrates SDSG. A silicon wafer is held by a pair of hydrostatic pads. These hydrostatic pads produce a water cushion between the respective pad and wafer surface to hold the wafer without physical

contacts between the pads and the wafer during grinding. Two diamond cup wheels are located on the opposite sides of the wafer. Both sides of the rotating wafer are ground simultaneously by the two rotating wheels that are synchronously fed towards the wafer. It is noted that the wheel diameter is about half of the wafer diameter in this illustration. Grinding wheels of other sizes have also been used [Ikeda et al. 2003]. Both two-step SDSG (first by coarse or rough grinding, and then by fine or finish grinding) [Pietsch et al. 2005] and one-step SDSG [Pietsch et al. 2006] have been reported.

Important input variables in SDSG can be classified into four categories:

- Variables related to grinding wheels: abrasive type and grain size, bond type, porosity, and wheel diameter;

- Variables related to process: wheel rotational speed, wafer rotational speed, and feedrate (of wheels toward the wafer);

- Variables related to relative position between wheels and wafer: wheel spindle tilt, and wheel shift;

- Variables related to hydrostatic pads: design of hydrostatic pads, and hydrostatic pressure.

2.1 Abrasive type and grain size

For silicon grinding, diamond abrasives are used almost exclusively [Liu et al. 2007]. They possess certain outstanding properties, such as superior hardness, high heat conductivity, high wear resistance, and low coefficient of friction [Braun et al. 2005, Liu and Tso 2003, Andersson et al. 2001, Golabczak and Koziarski 2002]. A major weakness of diamond abrasives is that they

are easily transformed into graphite when the temperature becomes too high [Tanaka et al. 2004].

The grain size of the diamond abrasives in the grinding wheels is usually expressed by mesh size. It corresponds to the number of openings per linear inch in the wire gauze used to "size" abrasive grains. But this wire gauze is employed primarily for sizes from #4 to #240 [Salmon 1992]. For much smaller grains, the diameter of the abrasive grains is used to express the abrasive grain size.

Different diamond grain sizes were reported for grinding wheels used in SDSG. For example, diamond grains with mesh sizes of #300 - #2000 (approximately 50 - 6 μm) were used in coarse grinding, and diamond grains with mesh sizes of #2000 - #10000 (approximately 6 - 1.3 μm) were used in fine grinding [Kuroki and Maeda 2000, Kato et al. 2001, Pietsch and Kerstan 2005]. It is important to note that, despite that smaller grain sizes were reported in some experiments, the smallest diamond abrasive grain size used in resin or vitrified bond wheels commercially offered by major wheel manufacturers was #2000 (or #4000) [Liu et al. 2007]. Although smaller diamond grain sizes can produce smoother surfaces and reduce subsurface damage [Lundt et al. 1994, Pei et al. 1999, Ohmori and Nakagawa 1990], it is very difficult to maintain wheel's self-dressing ability when diamond grains become too small [Carlisle and Stocker 1997].

2.2 Wheel bond type, porosity, and wheel diameter

Bond material in a grinding wheel holds abrasive grains in place, and plays an important role in determining the wheel's performance [Jackson 2002 , Stoica et al. 2003]. Wheel bond materials could be metal, resin, or vitrified ceramics [Kato et al. 2002, Hashii et al. 2002, Pietsch et al.

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2006]. For SDSG of silicon wafers, relatively rigid bond materials (metal or vitrified ceramics) were used for coarse grinding, and relatively soft bond materials (resin or softer vitrified ceramics) were used for fine grinding [Kato et al. 2001].

Open voids (pores) were created in grinding wheels to carry swarf and grinding fluids during grinding [Abrasive Engineering Society 2004]. Pores tend to promote more efficient cutting, minimize damage to ground surfaces, and improve tool life [Ramanath et al. 2003]. Besides, the porosity could affect the surface roughness of ground silicon wafers. Another benefit of porous wheels is the significant improvement of the wheels' self-dressing ability [Bright and Wu 2004].

The wheel geometry, such as wheel diameter, will affect the quality of ground wafers [Liu et al. 2007]. Effects of wheel diameter on grinding mark curvature were studied by Chidambaram et al. [2002] for single-side grinding and by Li et al. [2009] for SDSG. The diameter of the grinding wheel also indirectly affected the depth of grinding marks in single-side grinding [Pei and Strasbaugh 2002].

2.3 Wheel rotational speed

Wheel rotational speed refers to the rotational speed (rpm, or revolution per minute) of the two grinding wheels. They can rotate in the same direction [Ikeda et al. 2003] or in opposite directions [Pietsch and Kerstan 2005].

2.4 Wafer rotational speed

The silicon wafer rotates around its axis of symmetry at a certain speed during SDSG. Its rotation is typically driven by a notch finger that engages the orientation notch in the wafer [Pietsch et al. 2005]. However, other driving means have also been reported [Ikeda et al. 2003].

2.5 Feedrate

Feedrate refers to the rate at which the two grinding wheels are synchronously fed toward the wafer. In fine grinding (with smaller diamond grains), slow federate is usually required. Otherwise, the grinding force might become too high, causing an overload at the notch finger [Pietsch et al. 2005].

2.6 Grinding wheel spindle tilt

Grinding wheel spindles can be tilted relative to the silicon wafer vertically, or horizontally, or obliquely, as shown in Fig. 2. Theoretically, these tilts should be measured in the unit of either radian or degree. In practice, they sometimes were measured by δ, the distance by which the edge of a grinding wheel has moved, as illustrated in Fig. 3 [Ikeda et al. 2003]. The tilts of two wheels could be in opposite directions, as shown in Fig. 2, or in the same direction, as shown in Fig. 3.

2.7 Wheel shift

As shown in Fig. 4, wheel shift, p, is the distance between two centers, m and n. Center m is the center of wafer thickness determined by the wafer holding devices (hydrostatic pads) before

grinding wheels make any contact with the wafer. Center n is the center between the two grinding wheels [Ikeda et al. 2003].

2.8 Hydrostatic pad design

Hydrostatic pads produce water cushions between the respective pad and wafer to hold the wafer without direct contact between the pads and the wafer. This reduces damage to the wafer that may be caused by physical clamping and allows the wafer to rotate with less friction [Bhagavat et al. 2008b]. Hydrostatic pads can also provide efficient rinsing to grinding wheels and hence increase wheel life [Pietsch and Kerstan 2001, Kerstan and Pietsch 2000]. Important variables related to water cushions include their arrangement, shape, thickness, pressure, and flow rate [Pietsch et al. 2005, Pietsch and Kerstan 2001, Kerstan and Pietsch 2000]. The design of hydrostatic pads can significantly affect these variables.

Two designs of hydrostatic pads are illustrated in Fig. 5. Hydrostatic pockets formed into the pads were used to spray water during grinding [Vandamme and Bhagavat 2007]. Positions and orientations of these pockets could affect hydrostatic bending moments in the wafer when the grinding wheels had any shift or tilt relative to the hydrostatic pads, hence affecting nanotopography [Bhagavat et al. 2008b]. Several hydrostatic pockets were positioned about the grinding wheel opening on the pad. They were arcuate in shape and elongate around the pad [Bhagavat et al. 2008a]. The vertical sidewalls of the pockets were relatively flat and corners were rounded [Bhagavat et al. 2008a]. The ratio between the pocket surface area and the total surface area of the pad, the orientation of pockets, and the radial distance between each pocket

and the wheel center could influence the nanotopography [Bhagavat et al. 2008a].

2.9 Hydrostatic pressure

Hydrostatic pressure refers to the water pressure fed through the hydrostatic pads to form water cushions. If the pressure on both sides of the wafer was not balanced, the wafer might bend and produce regions of localized high stress in the wafer, affecting wafer quality (especially nanotopography) [Vandamme and Bhagavat 2007].

3. Warp

3.1 Definition, significance, and measurement of warp

Warp is the difference between the maximum and minimum deviations of the median surface of a free, unclamped wafer from a reference place [ASTM 1997]. High wafer warp can adversely influence handling and processing of silicon wafers, significantly affecting device yield [ASTM 1997].

Warp is typically measured with a noncontact, nondestructive, five-step procedure [ASTM 1997]. A calibration step was firstly performed to determine the mechanical signature of an instrument and gravitational effects of the wafer and to set the instrument's scale factor and other constants.

Secondly, the wafer was supported by a small-area chuck and scanned along a prescribed pattern by a pair of non-contact probes (capacitive sensors) located at both sides of the wafer. Thirdly, the paired distance values (measured by the two probes) were used to construct a median surface of the wafer with mathematical correction for mechanical signature of the instrument and gravitational effects of the wafer. Fourthly, a least-squares reference plane was constructed from the median surface and deviation of the median surface from the reference plane (RPD) was calculated at each measured point. Lastly, warp was represented as the algebraic difference between the most positive deviation from the reference plane (RPD_{max}) and the most negative deviation from the reference plane (RPD_{min}) [ASTM 1997] .

Fig. 6 is an example of warp calculation. In this example, the most positive deviation of the median surface from the reference plane, shown as RPD_{max}, is 2; and the most negative deviation of the median surface from the reference plane, shown as RPD_{min}, is -2. Warp = RPD_{max} - RPD_{min} = 2 - (-2) = 4. Note that warp is always a positive value [MTI instruments].

Typical instruments used to measure wafer warp include ADE Ultra Gage (model 9500, 9700, and 9900) (KLA-Tencor, Milpitas, California, USA) [KLA-Tencor website], Kuroda Precision Industries' Nanometro series (Kawasaki, Japan) [Kuroda Precision Industries website], and E+H MX 7012 gage (Karlsruhe, Germany) [E+H Metrology web site].

3.2 Effects of grinding wheel spindle tilt on warp

Ikeda et al. [2003] conducted experiments to study influences of wheel spindle tilt and wheel shift on warp. Their experimental conditions are shown in Table 1.

Fig. 7 shows effects of wheel spindle tilt on warp. Note that, in this figure, the wheel spindle tilt was measured by δ, the distance the wheel edge was moved away from the wafer, as illustrated in Fig. 3. The vertical axis of the graph in Fig. 7 is the absolute value of warp variation (|warp after grinding – warp before grinding|). It can be seen that, when the wheel spindle tilt δ was 2 μm to the right, the warp variation was minimized. Their explanation was that, when δ = 2 μm, the surfaces of the grinding wheels would be parallel to the wafer surfaces.

3.3 Effects of wheel shift on warp

Fig. 8 shows effects of wheel shift on warp reported by Ikeda et al. [2003]. The left grinding wheel (regarded as the reference side) was shifted from its original position to right by 0, 5, 10, 15, 20, 25, and 30 μm, respectively. It can be seen that there was an optimum position (19 μm to right from the original position) of the left wheel where the warp variation was nearly zero. Also, when the left wheel was shifted away from this optimum position, warp variation (defined as warp after grinding – warp before grinding) would increase. For example, when the left wheel was shifted from the optimum position to right by 11 μm, wafer warp increased by 6 μm. When the left wheel was shifted from the optimum position to left by 19 μm (back to its original position), wafer warp decreased by 5 μm. Therefore, with wheel shift, the direction and degree of the warp could be controlled arbitrarily.

Ikeda et al. [2003] also conducted a comparison test using two groups of wafers. One group were ground with wheel shift < 3 μm, the other group with wheel shift > 10 μm. The grinding conditions were the same as those in Table 1, except that wheel mesh size was #2000 and bond

type was vitrified. Note that wheel shift in this test was the shift amount of left wheel away from its optimum position. Their results are shown in Fig. 9. It is clearly seen that warp variation was much smaller when wheel shift was kept less than 3 μm.

3.4 Effects of wheel conditions on warp

Ikeda et al. [2003] reported that warp could be improved by dressing of grinding wheels. When the grinding force became large due to loading of grinding wheels, the force applied on the wafer by the grinding wheels would become large, causing deformation of the wafer. Dressing of the grinding wheels would make the grinding force smaller, suppressing wafer deformation and improving wafer warp [Ikeda et al. 2003].

4. Flatness

4.1 Definition, significance, and measurement of flatness

Wafer flatness measures how flat a wafer surface is. It directly impacts device line-width capability, process latitude, yield, and throughput [Kulkarni and Desai 2001; Oh and Lee 2001]. As feature sizes of semiconductor devices shrink, requirements on wafer flatness have become more stringent. Fig. 10 shows how wafer flatness specifications have changed over the years [ITRS].

Unlike warp measurements which are based on the median surface of the wafer, flatness measurements are based on the front surface of the wafer relative to a specified reference plane. There is another difference. For warp, a wafer is assumed to be in an unclamped state; while for flatness, a wafer is assumed to be clamped down so that the back side of the wafer is flat. The first two measurement steps for flatness are the same as those for warp, but other steps are different. The paired distance values measured by two probes were used to construct a thickness data array representing the front surface of the wafer when the back surface of the wafer was ideally flat. The last step was to report the flatness by an acronym defining the type of the flatness measurement (Global or Site), the reference plane used (Backside or Frontside), and the reporting method (Ideal Focal Plane Range, 3 Point Focal Plane Range, or Least Squares Focal Plane Deviation) [ASTM F 1530- 02].

An example of such acronyms is GBIR: (G)lobal, (B)ackside, (I)deal, Focal Plane, and (R)ange [SEMI M1]. In this case, the reading of flatness is equal to total thickness variation (TTV). TTV is defined as the difference between the maximum and minimum values of the wafer thickness [ASTM F 657-92], and can be calculated using the following formula:

$$TTV = (a + b)_{max} - (a + b)_{min} \tag{1}$$

where a is the distance between wafer top surface and upper probe, b the distance between wafer bottom surface and lower probe, max denotes the largest value of the sum $(a + b)$, and min the smallest value of the sum. An example of calculating TTV is shown in Fig. 11.

Another example of flatness acronym is SFQR: (S)ite, (F)rontside, Least S(Q)uares, Focal Plane,

and (R)ange [SEMI M1]. For site flatness, the size of the site has to be specified.

Standard tools for warp measurement can also be used for flatness measurement, including ADE Ultra Gage (model 9500, 9700, and 9900) [KLA-Tencor website], Kuroda Precision Industries' Nanometro series [Kuroda Precision Industries website], and E+H MX 7012 gage [E+H Metrology web site].

4.2 Experimental data on TTV, edge roll-off, and center "navel"

Using #2000 vitrified grinding wheels, Kerstan and Pietsch [2000] ground 45 pieces of 300 mm wafers in a continuous run without interim adjusting. They later ground 104 pieces of 300 mm wafers and 200 pieces of 200 mm wafers. They found that wafer TTV after SDSG could be comparable to those obtained from established single-side grinding processes. Their TTV data are shown in Fig. 12.

Kerstan and Pietsch [2000] reported edge roll-off (thickness decrease in the edge region) and center "navel" (a hole or center depression) on some wafers ground by SDSG (as shown in Fig. 13 and 14). On wafers ground with #2000 vitrified grinding wheels, they observed that roll-off occurred around the wafer notch. They also observed a center "navel" at the wafer center. Radial adjustment of the grinding wheels would determine the shape of the center "navel". If the wheel abrasive segment directly cut through the wafer center, a deep but small "hole" would be obtained. If the wheel abrasive segment just touched the wafer center, a shallow but wide "ring" would be obtained. It was possible that the navel "dominated the thickness profile of the wafer ground with well-aligned spindles and thus determined the achievable minimum TTV" [Pietsch

and Kerstan 2005].

4.3 Effects of grinding wheel spindle tilt on flatness

Pietsch and Kerstan [2005] investigated influences of vertical, horizontal and oblique tilts of grinding wheel spindles on wafer thickness radial profile. Their results are shown in Fig. 15. They found that a vertical downwards tilt would yield a stronger tapering-off on the wafer towards its edge, slightly decreasing the center "navel" and slightly improving TTV. A vertical upwards tilt would yield a deeper navel, leading to degraded TTV. A horizontal spindle tilt would reduce the center "navel" and improve TTV. An oblique spindle tilt (weaker vertical and stronger horizontal tilt), would produce a profile close to the best TTV (around 0.5 µm) practically achievable by SDSG tools. However, details of experimental conditions were not provided in their paper.

4.4 Effects of wheel shift on flatness

Ikeda et al. [2003] stated that ground wafers could have better flatness if the wheel shift could be controlled within 3 µm. Flatness data were not provided in their report.

4.5 Effects of diamond grain size on flatness

Pietsch et al. [2005] studied influences of diamond grain size in the grinding wheels on wafer

TTV. Their experimental conditions are shown in Table 2. In rough grinding, a TTV of 0.7 to 3 μm could be achieved with diamond grain size of 4 to 50 μm. In finish grinding, a TTV of less than 1 μm could be achieved with diamond grain size of 0.1 to 5 μm. They also achieved a site flatness of less than 16 nm in a measurement window of 2 mm x 2 mm (and less than 40 nm in a measurement window of 10 mm x 10 mm).

5. Surface roughness

5.1 Definition, significance, and measurement of surface roughness

Surface roughness consists of fine irregularities resulting from production processes [Drozda and Wick 1983]. Surface roughness parameters include amplitude parameters, spacing parameters, and hybrid parameters [Gadelmawla and Koura 2002]. For the purpose of quantitative comparison and analysis it is desirable to be able to express the surface roughness of machined surfaces in terms of a single factor or index. RMS (Root Mean Square) is used to describe fluctuations of surface heights and is defined as (this definition was presented in many papers such as [Elsholz and Scholl 2004]):

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h(x_i) - \bar{h})^2}$$

(2)

where n is the number of lattice points, $h(x_i)$ the height at lattice site x_i, and $\bar{h}$ the average height of the profile.

$$\bar{h} = \frac{1}{n}\sum_{i=1}^{n}h(x_i)$$

(3)

Surface roughness can be measured with a variety of instruments. These instruments include Daktak stylus profilers and Wyko optical profilers from Veeco (Plainview, NY, USA) [Veeco web site], Surfanalyzer 5600 from Mahr Federal Inc. (Providence, RI, USA) [Mahr Federal website], P-6 stylus profiler from KLA-Tencor, and Z3D-720 metrology system from Zygo (Middlefield, CT, USA) [Zygo website], as well as atomic force microscopes (AFM).

5.2 Effects of wheel condition on surface roughness

According to Pietsch et al. [2001], surface roughness after SDSG was determined by diamond grain size, bond type, and bond hardness. They investigated influences of wheel bond hardness on surface roughness. Their experimental conditions and results are shown in Fig. 16. Grinding wheels with #2000 diamond grain size were used for all the tests. L, K, JL and JF were used to represent the bond hardness level. It can be seen that the harder the wheel bond, the lower the surface roughness.

Pietsch et al. [2006] also studied influences of diamond grain size on surface roughness after SDSG. After SDSG with #2000 ceramic-bonded grinding wheels (and after polishing), around 400 Å RMS could be achieved with 4 - 6 μm diamond grain size, 100 Å RMS could be achieved with 1.5 μm diamond grain size, and 50 Å RMS could be achieved with a prototype grinding wheel.

5.3 Effects of process method on surface roughness

Pietsch et al. [2005] described a SDSG process where the wafer was ground first by rough

grinding, and then by finish grinding. During transition from rough grinding to finish grinding, the wafer remained on the grinder and a constant load was applied. Table 2 shows the experimental conditions. Surface roughness (RMS) was 250 - 3000 Å after rough grinding, and 5 - 200 Å after finish grinding.

6. Nanotopography

6.1 Definition, significance, and measurement of nanotopography

Nanotopography is defined as the deviation of the wafer front surface within a spatial wavelength range of approximately 0.2 to 20 mm [SEMI M43 2001]. Nanotopography is also called nanotopology [Pietsch and Kerstan 2005]. It bridges the gap between surface roughness and flatness in the topography map of wafer surface irregularities in spatial frequency, as shown in Fig. 17. Its wavelength (~mm) is between those of surface roughness (~μm) and flatness ($\geq$cm).

Nanotopography differs from flatness (SFQR). For nanotopography, the wafer is measured in a free state; for flatness, the wafer is assumed to be held to a perfectly-flat chuck by vacuum. If the front and back surfaces of a wafer are parallel (but the wafer has surface irregularities on front and back surfaces), this wafer will be considered perfectly flat (SFQR = 0). However, this wafer will exhibit nanotopography, as illustrated in Fig. 18. In recent years, as the integration level of semiconductor devices increased and more and more layers were lithographically etched or deposited onto the wafer surface, nanotopography has become very important [Pei et al. 2008]. Nanotopography determines the uniformity of chemo-mechanical planarization used in

processing sub-micron microelectronic multi-layer devices [Kerstan and Pietsch 2000]. Fig. 19 shows how wafer nanotopography specifications from the semiconductor industry have become more stringent over the years.

Measurements of nanotopography have been reported with scanning probe [Pietsch et al. 2006], scanning laser triangulation (SQM system) [Kerstan and Pietsch 2000], NanoMapper (KLA-Tencor, California, USA) [Bhagavat et al. 2007; Phase-shift website], and interferometry [Bhagavat et al. 2008].

6.2 Effects of grinding wheel spindle tilt and wheel shift on nanotopography

Pietsch and Kerstan [2005] stated that a wheel spindle horizontal tilt could bear "the risk of unbalancing the wafer's perfectly parallel and centered alignment between the hydro-pads", deteriorating the nanotopography due to additional bending forces. However, no experimental details were provided.

According to Bhagavat et al. [2008], nanotopography degradation could be reduced by adjusting wheel spindle tilt and wheel shift. They described two phenomena for nanotopography, central marks and B-ring, as shown in Fig. 20. B-ring was the wafer region whose radius was between 100 mm and 150 mm. B-ring value was the maximum peak-to-valley value in the B-ring region. They claimed that the shift direction could be determined by the nanotopography profile in the B-ring region. If the profile had a peak followed by a valley, the shift direction of the grinding wheels was left. Contrarily, if the profile had a valley followed by a peak, the shift direction of the grinding wheels was right. The shift magnitude could be determined by the B-ring value. If

the B-ring value was greater than 18 nm, the shift magnitude was 15 μm. If the B-ring value was greater than 8 nm but less than or equal to 18 nm, the shift magnitude was 10 μm. If the B-ring value was greater than or equal to 5 nm but less than or equal to 8 nm, the shift magnitude was 1 μm. If the B-ring value was less than 5 nm, the shift magnitude was negligible and no adjustment was necessary. These are summarized in Table 3.

Misalignment of the hydrostatic pads clamping planes could cause nanotopography defects. It was generally caused by a combination of wheel shift and wheel spindle vertical tilt and by a combination of wheel shift and wheel spindle horizontal tilt [Bhagavat et al. 2008].

6.3 Effects of grinding wheel cutting ability on nanotopography

Pietsch et al. [2005] studied effects of grinding wheel's cutting ability on wafer nanotopography. Their experimental conditions are shown in Tables 2 and 4, and results are shown in Fig. 21. The SDSG grinder was DXSG 320 or 300A from Koyo Machine Industries Co. Ltd, the metal hydrostatic pads had a diameter of 365 mm, and silicon wafers had a diameter of 300 mm. Three grinding wheels of different levels of coarseness (and therefore different cutting abilities) were used. It can be seen that the more aggressive the grinding wheels (and hence the rougher the ground surface would be, the higher the maximum feedrate would be), the better the wafer nanotopography.

6.4 Effects of hydrostatic pad designs on nanotopography

Bhagavat et al. [2008a] conducted experiments to study effects of hydrostatic pad designs on

nanotopography. They used SDSG grinders (models DXSG 320 and 300A) from Koyo Machine Industries Co. Ltd, and metal hydrostatic pads with 365 mm diameter, to grind 300 mm silicon wafers.

Two designs of hydrostatic pads used in their experiments are illustrated in Fig. 5. The pocket area on hydrostatic pad B was smaller and, therefore, these pockets would receive less water. In addition, the pocket area below the wafer center was reduced, and the clamping forces at the left and right sides of the grinding wheel opening was lower. Consequently, the overall clamping force applied by the pads on the wafer was reduced. This would cause the wafer to be held less rigidly by the hydrostatic pads. Therefore, the wafer could conform more easily to shift or/and tilt movements of grinding wheels. With hydrostatic pad B, the wafer would not bend as sharply as with hydrostatic pad A. Therefore, hydrostatic pad B promoted more uniform grinding and the nanotopography degradation was reduced or eliminated. The wafer ground with pad B was substantially free of B-rings and center-marks, as shown in Fig. 20(b). The wafer nanotopography value with hydrostatic pad B was lower than that with hydrostatic pad A, as shown in Fig. 22.

7. Others

7.1 Wafer-thickness variation (ΔTHK)

Wafer-thickness variation (ΔTHK) represents the variation of wafer thickness (THK) among the wafers in a batch. Wafer-thickness variation (ΔTHK) after SDSG is important to polishing, one of its subsequent processes. Polishing (especially double side polishing) is usually run in batches (i.e., many wafers are processed at a time [Pietsch and Kerstan 2001]). These batch processes

require incoming wafers to have relatively uniform thickness. A small wafer-to-wafer thickness variation within a batch is more important than where the average thickness (THK$_{ave}$) lies (as long as it is inside the thickness specification range) [Kerstan and Pietsch 2000]. For example, ΔTHK after SDSG should be less than 1 μm [Pietsch and Kerstan 2001].

Using SDSG, Kerstan and Pietsch [2000], ground 45 pieces of 300 mm wafers with vitrified bond #2000 grinding wheel without interim adjusting. They later ground 104 pieces of 300 mm wafers and 200 pieces of 200 mm wafers. Thickness distributions of these ground wafers are shown in Fig. 23 and Table 5. They claimed that these values of wafer-thickness variation were comparable to those obtained from established single-side grinding processes.

7.2 Rotational asymmetry (ΔROT)

ΔROT measures the degree of rotational asymmetry of a silicon wafer. By definition, ΔROT must not be larger than TTV [Pietsch et al. 2006]. Usually, ΔROT of a wafer after SDSG is much smaller than TTV of the wafer. TTV of ground wafers is almost completely determined by a radial symmetrical cross-sectional profile. Pietsch et al. [2006] measured wafers after SDSG and found that ΔROT ≤ 0.5 μm.

7.3 Grinding marks

Grinding marks are cutting trajectories swept by diamond grains bonded on grinding wheels [Li et al. 2006], as illustrated in Fig. 24. Grinding marks can be observed with a Magic Mirror (Hologenix, Huntington Beach, CA, USA) [Hologenix website]. Pietsch and Kerstan [2000]

reported that a "criss-cross" grinding marks were visible on wafer surfaces processed by SDSG, different from radial grinding marks on the wafer surfaces processed by single-side grinding. However, they did not report any systematic studies about effects of input variables on grinding marks.

7.4 Subsurface damage

Kerstan and Pietsch [2000] reported subsurface damage of 3 – 4 μm deep on wafers ground by SDSG with #2000 vitrified wheels. They observed that subsurface damage was consisted of (a) a topmost layer (150-200 nm thick) of amorphous silicon, (b) a subsequent layer (200 - 400 nm thick) of heavily strained crystal lattice (micro-cracks and mosaics), and (c) a layer of "spikes" of "hot spots" which extended 2 - 6 μm deep into the bulk silicon. They did not give details on what these "hot spots" were.

Numerous methods have been used by various investigators to measure surface damage in silicon wafers [Lu et al. 2007]. These methods include cross-sectional microscopy, scanning electron microscopy, ultrasonic measurement, optical scattering method, X-ray topography, and scanning infrared depolarization (SIRD).

Abrasive grain sizes have great influences on subsurface damage of silicon wafers. Pietsch et al. [2005] measured the change of subsurface damage (light-scattering surface defects) with grinding wheels of different diamond grain sizes. Experimental conditions were the same as those in Table 2. Fig. 25 shows the means of subsurface damage (light-scattering surface defects) of three groups of wafers using grinding wheels of different cutting abilities. It can be seen that, grinding

wheels that were more aggressive (and hence would produce a rougher ground surface, and could be used with a higher maximum feedrate) produced more severe surface damage.

7.5 Wheel wear

The wear of grinding wheels has significant impacts on manufacturing cost of silicon wafers and quality of ground wafers.

Pietsch and Kerstan [2005] stated that a wheel spindle horizontal tilt could possibly stall wheels' self-dressing. This could disturb balanced wear on the two wheels, since the inward-cutting wheel would wear faster than the opposite outward-cutting wheel. Any departure from a balanced leading-edge to trailing-edge removal would cause the inward-cutting wheel to wear even faster and the opposite outward-cutting wheel to wear slower. The latter wheel then would have a higher risk to clog and lose its ability of continuous self-dressing. However, they did not provide details of their experiments.

7.6 Cycle time

Cycle time is the time it takes to complete the grinding operation for a wafer. It directly affects the throughput (i.e. the number of wafers processed with a certain period of time, such as a day, a shift, or an hour) of a grinder. Pietsch and Kerstan [2001] found that cycle time of below 2 min (average) could be achieved easily for both 200 mm and 300 mm wafers (with 2 x 30 μm = 60 μm removal) on SDSG. Fig. 26 shows their experiment data. Their experiment conditions were

not provided.

8. Concluding remarks

Simultaneous double side grinding (SDSG) has become an important flattening method for 300 mm silicon wafers. However, there are few reports on experimental investigations on relationships between input variables and output variables. Table 6 summarizes experimental investigations reported in the literature. It is clear that there are many blanks that need to be filled.

It is noted that all experimental investigations on SDSG were reported from industry. This probably is due to the fact that no academic institutions have SDSG machines in their facility and access to SDSG machines in production lines by academic researchers is very limited.

Another reason for the scarcity of reported experimental studies on SDSG might be that it is very expensive to conduct SDSG experiments. SDSG experiments would necessitate a certain number of 300 mm silicon wafers and a long period of machine time for SDSG grinders.

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