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Grinding wheels for manufacturing of silicon wafers: A literature review

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Abstract

Grinding is an important process for manufacturing of silicon wafers. The demand for silicon wafers with better quality and lower price presents tremendous challenges for the grinding wheels used in the silicon wafer industry. The stringent requirements for these grinding wheels include low damage on ground surfaces, self-dressing ability, consistent performance, long wheel lives, and low prices. This paper presents a literature review on grinding wheels for manufacturing of silicon wafers. It discusses recent development in abrasives, bond materials, porosity formation, and geometry design of the grinding wheels to meet the stringent requirements.

Keywords: Abrasive; Grinding wheel; Machining; Semiconductor material; Silicon wafer

Contents

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1. Introduction

Silicon-based semiconductors are found in applications such as computer systems, telecommunications, automobiles, consumer electronics, industrial automation and control systems, and defense systems. In 2004, the worldwide revenues generated by silicon wafers and semiconductor devices were \$7.3 billion [1] and \$213 billion [2], respectively.

Manufacturing of high-quality silicon wafers starts with growth of silicon ingots. A sequence of processes is required to turn an ingot into wafers. Some typical processes are listed below [3–5].

(1) Slicing—slice silicon ingots into wafers of thin disk shape;
(2) Flattening (lapping or grinding)—achieve higher degree of flatness on the wafers;
(3) Etching—chemically remove the damage induced by slicing and flattening;
(4) Polishing—to obtain smooth wafer surfaces;
(5) Cleaning—to remove the polishing agent or dust particles from wafer surfaces.

In addition to being a major flattening process for wire-sawn wafers, grinding can also be used to fine-grind etched wafers [6,7]. The purpose of fine-grinding of etched wafers is to improve the flatness of the feedstock wafers to polishing and to reduce the polishing removal amount, hence to achieve a higher throughput for polishing and better flatness for polished wafers.

Another application of grinding is to thin the completed device wafers before dicing them into individual dies (chips) [8,9]. The expanding market of thin and flexible silicon chips such as those in smart cards and smart labels (RFID) demands more advanced back-grinding processes [10].

The grinding process referred in this paper is the vertical spindle surface grinding (a.k.a. wafer grinding) using a cup wheel. A typical cup wheel is illustrated in Fig. 1. Fig. 2 illustrates the wafer grinding process. 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 rotation axis for the grinding wheel is offset by a distance of the wheel radius relative to the rotation axis for the wafer.

This paper is organized into nine sections. Following this introduction section, Section 2 describes the stringent requirements for grinding wheels used in the silicon industry. In Section 3, the structure of grinding wheels will be introduced. The abrasive types and grain size will be discussed in Sections 4 and 5, respectively. Then, Section 6 will discuss the bond systems for wheels used in silicon grinding. After that, the porosity of grinding wheels will be presented in Section 7. Section 8 addresses the wheel geometry. Section 9 contains concluding remarks.

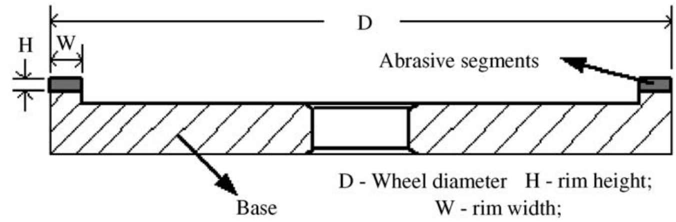


Fig. 1. A typical grinding wheel for silicon wafers.

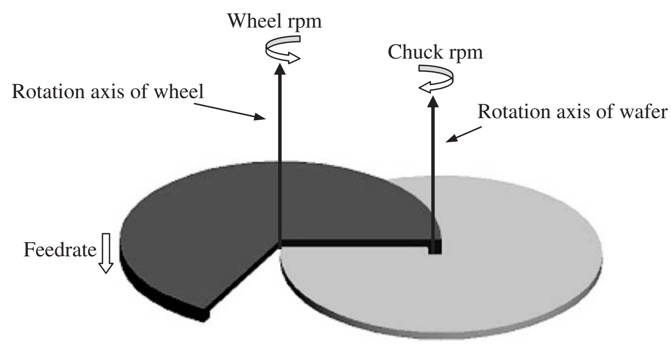


Fig. 2. Illustration of wafer grinding.

2. Stringent requirements for grinding wheels in the silicon industry

2.1. Low damage and roughness on ground surfaces

Lundt et al. [11] stated that grinding of silicon wafers would cause unavoidable subsurface damage (SSD). Six different configurations of subsurface cracks (median, lateral, "umbrella", "chevron", "branch", and "fork") were observed in ground silicon wafers [12]. The grinding-induced SSD must be removed by subsequent processes (such as etching and polishing). Deeper SSD will require a thicker layer of silicon to be removed from the ground surfaces, resulting in higher manufacturing costs. Therefore, it is highly desirable that grinding wheels generate only very low damage to ground wafers.

Since it is the post-polishing processes (such as polishing), not the grinding process, that produce the final surface roughness on silicon wafers, the surface roughness on ground wafers generally is not considered as a critical parameter. However, higher roughness can be an indication of deeper damage, since workpiece roughness can sometimes be correlated with sub-surface damage (SSD) and is more amenable to routine measurement [13,14]. Therefore, it is desirable that the surface roughness on ground wafers is low.

2.2. Consistent performance

For silicon wafer manufacturing, the performance variations within a wheel (throughout the wheel life) and between wheels have to be very low. For example, the wheel wear rate needs to be consistent in order to obtain

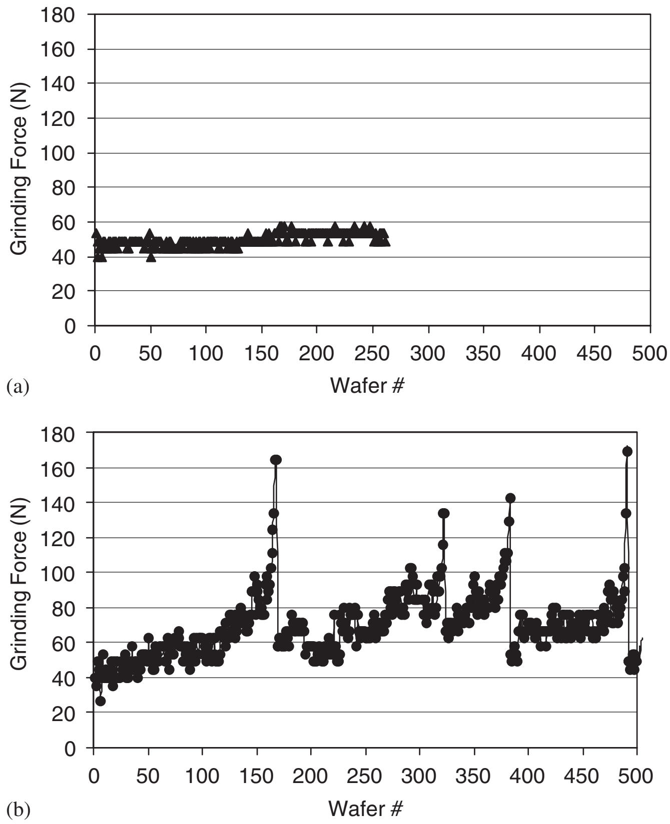


Fig. 3. Consistent versus fluctuating force when grinding silicon wafers [6]. (a) Relatively Consistent grinding force, (b) fluctuating grinding force.

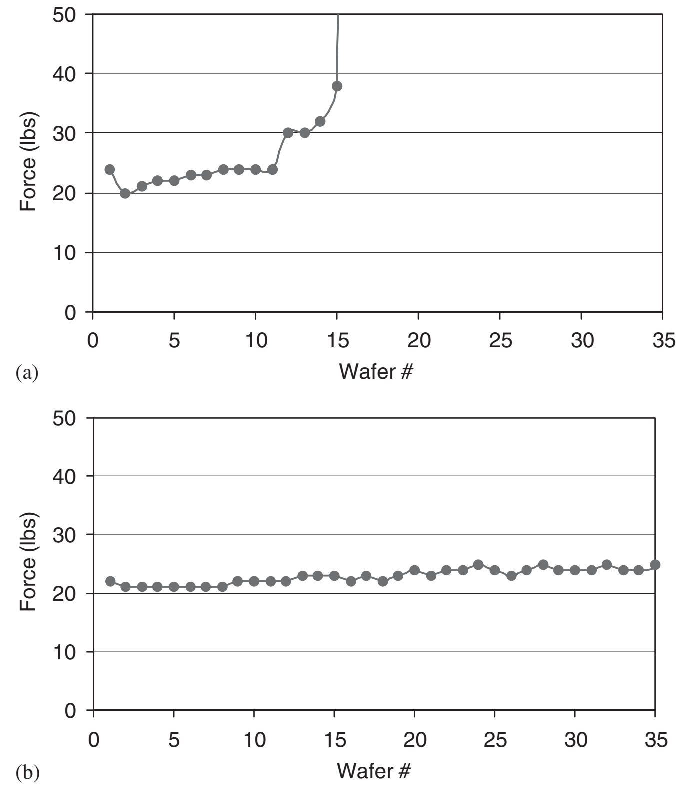


Fig. 4. Self-dressing ability indicated by grinding force curves [6]. (a) Grinding force curve of a wheel without self-dressing ability, (b) grinding force curve of a wheel with self-dressing ability.

the predictability of wheel lives for better scheduling of wheel changes.

Furthermore, the grinding force must be consistent in order to maintain a desired shape for ground wafers. In practice, on any commercially available wafer grinders, spindle angle adjustments (to change the angle between the wheel rotation axis and the wafer rotation axis) based on the wafer shape ground is almost inevitable in order to achieve flat wafers [15–17]. Fluctuations in the grinding force will not only make such adjustments very difficult but also result in changes in the wafer shape. Fig. 3(a) shows a case with relatively consistent grinding force, and Fig. 3(b) a case with fluctuating grinding force. (The detailed information about these two cases was reported by Pei and Strasbaugh [6].)

2.3. Self-dressing ability

The requirement of performance consistency will demand the grinding wheel to possess the self-dressing ability. This means that, after initial truing, the wheel should not need any periodic dressing by external means. Pei and Strasbaugh [6] tested the self-dressing ability of more than 10 different wheels. Some wheels could grind hundreds of wafers with relatively constant grinding force, without any dressing procedure performed in between. For some other wheels, the grinding force kept increasing until reaching a threshold value when a dressing procedure became necessary. Fig. 4(a) shows a case where the grinding wheel was not self-dressing, and Fig. 4(b) a case where the wheel possessed the self-dressing ability. (Grinding conditions for these two cases can be found elsewhere [6].)

2.4. Long wheel lives and low prices

The life and price of the grinding wheels directly affect the manufacturing cost of silicon wafers. In many cases, requirements of long wheel lives and low prices (as well as some other performance requirements) are contradicting, and compromises have to be made. However, the demands from customers and the pressure from competitors will, to a certain extent, drive the wheel price lower while the same or better grinding performances are maintained.

3. Wheel structure

A grinding wheel (more specifically, the rim, or the abrasive segments, of the grinding wheel) consists of abrasive grains (a.k.a. abrasive grits), bond material, and pores, as shown in Fig. 5 [18]. Grinding wheels can be manufactured in a variety of grades or structures determined by the relative volume percentage of abrasive grains, bond, and porosity [19].

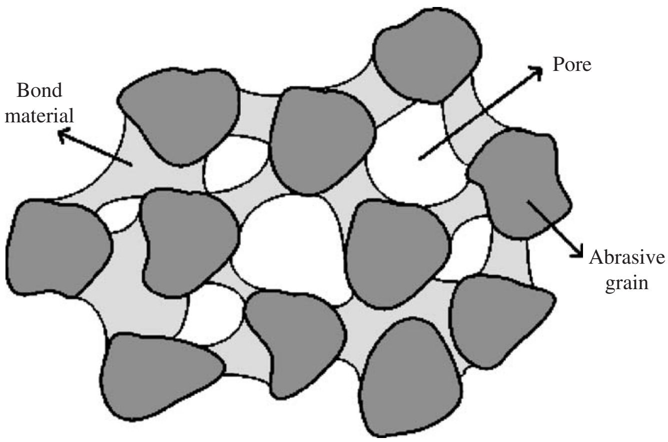


Fig. 5. Compositions of a grinding wheel (after [20]).

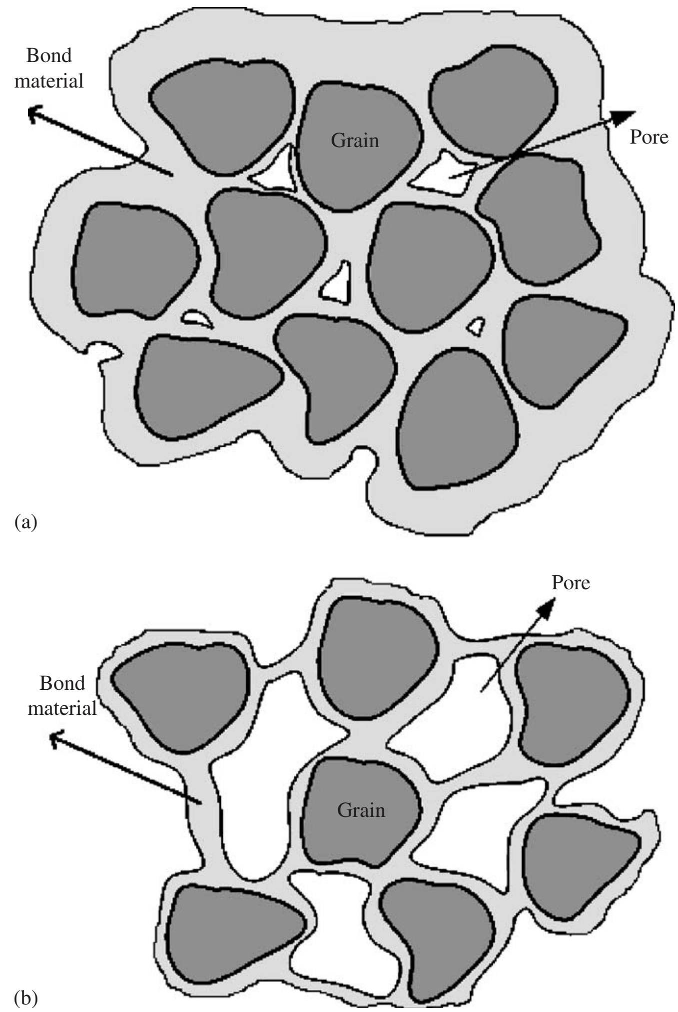


Fig. 6. Illustration of wheel structure (after [20]). (a) Closed structure, (b) open structure.

Fig. 6 illustrates the open/closed structures of grinding wheels. When a great deal of abrasive grains are mixed with very strong bond material and pressed under high pressure, a dense, low porosity grinding wheel will result. This closed-structure wheel is typically used for holding the form. When a small amount of grains are mixed with a small amount of bond material and pore inducers, a very open, highly porous structure grinding wheel will result once the pore inducers are removed. This open structure wheel is used to remove a great amount of materials from workpieces when chip clearance is a limiting factor [20].

The wheel grade, frequently referred as the wheel hardness, indicates the resistance of the abrasive grains from breaking out of the wheel's bonding system [21,22]. It indicates the bond strength—the holding power of the bond to hold the abrasive grains in position under grinding forces [21]. With hard wheels, relatively more fracture occurs within the grain than at the bond [23,24]. With soft wheels, the wheels wear faster [24].

For silicon wafers, harder wheels are generally used in coarse grinding to obtain a longer wheel life. Softer wheels are usually used in fine grinding to ensure the self-dressing ability.

4. Abrasive types

There are mainly four types of abrasives for grinding wheels, namely silicon carbide, aluminum oxide, cubic boron nitride (CBN), and diamond [20]. For silicon grinding, diamond is used almost exclusively.

4.1. Diamond

Diamonds possess certain outstanding properties, such as superior hardness, high heat conductivity, high wear resistance, and low coefficient of friction, making them preferable for silicon grinding [22,25–27].

There are two types of diamonds: natural and synthetic. Both can be used as the abrasives in the grinding wheels for silicon wafers. Studies about the effects of diamond type (natural versus synthetic) on silicon grinding performance could not be found in the available literature.

One major weakness of diamond abrasives is that they are easily transformed into graphite during sintering if the temperature is too high [28]. Similar problems exist when the grinding temperature becomes too high.

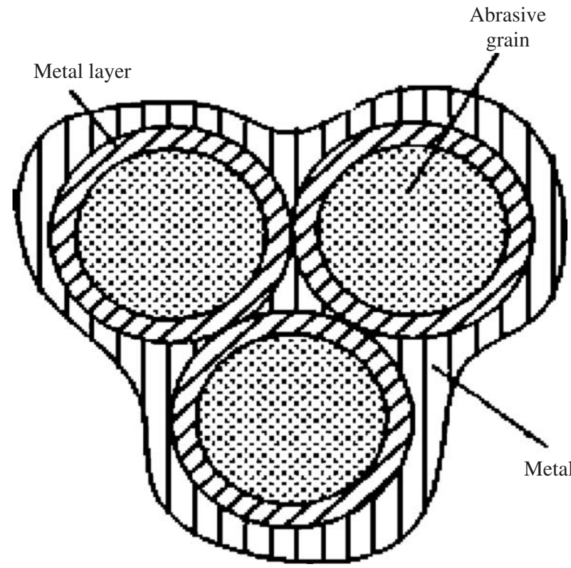
4.2. Coated diamond

In order to prevent the oxidation or other damage to diamond grains, most bonding processes must be restricted to a certain temperature, resulting in a weak adhesion between diamond grains and bond [29]. Furthermore, the difference of thermal expansion coefficient between the bond and the diamond grains will also adversely affect the adhesion between them [30]. A typical result of the insufficient adhesion between the bond and the diamond grains is the significant pull-out of the diamond grains [29].

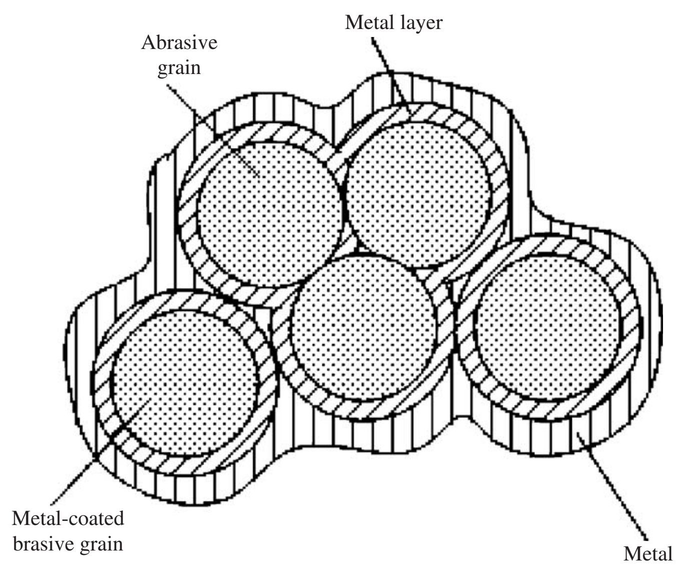
An effective method to improve the adhesion between diamond grains and bond materials is to coat diamond grains with suitable materials [31]. This coating can reduce the falling off of the diamond grains during grinding and improve the grinding ratio (defined as the ratio of the volume of material removed from the workpiece to the volume of grinding wheel that has lost during the process) [32].

When the grain size becomes very small, it is difficult to attain sufficient retention force between the coated diamond grains and the bond [32]. Especially for the resin bond with weaker bond strength, as the grain size decreases, smaller irregularities are formed on the coated surface. As a result, the contact area between the coated surface and the bond layer decreases, and the retention force to retain the abrasive in the bond becomes insufficient [32]. Aiming to solve this problem, Ihara [32] developed a method to attain a sufficient retention force in a resin-bond wheel even for small grains (0.5 to 300 μm). As shown in Fig. 7(a), each abrasive grain was coated with a metal layer. Then multiple coated abrasive grains (in the figure, three grains are shown) were bonded together by another metal layer to form a single agglomerate. These agglomerates were bonded by the resin bond to form a grinding wheel. Fig. 7(b) shows another example where multiple abrasive grains (three are shown in the figure) were coated with a metal layer and were bonded with other metal-coated abrasive grains to form the agglomerate. The retention force in the resin bond was increased compared to the conventional single-grain metal-coated abrasive, and thus it was possible to suppress falling-off of the abrasive during grinding and to remarkably improve the grinding ratio. Experiments with wheels using such coated CBN abrasives to grind a high-speed steel workpiece showed that the grinding ratio was improved. No information is available about if this method can be applied to silicon grinding.

Another problem with coated diamond grains is that the thick metal coating will lower the grain friability, since the friable grains are necessary for the self-dressing ability of diamond wheels [31]. To prevent lowering the self-dressing ability, Wang et al. [31] developed corundum-coated diamonds for resin bond wheels. As shown in Fig. 8, diamond grains are coated with the corundum micron powders bonded by a vitreous layer. The size of the diamond grains ranged from 150 to 850 μm in diameter and the size of the corundum particles ranged from 40 to 126 μm in diameter. The thickness of the vitreous bond layer was in the range of 10–150 μm. It was declared that, on one hand, the corundum-coated diamond exhibited good retention in the resin bond and prolonged the wheel life. On the other hand, the brittleness of the coating could maintain the friability of diamond grains, therefore the self-dressing ability of the wheel was not lowered. Furthermore, the oxidation resistance of diamond grains was improved due to the protection of the coating. Grinding tests on cemented carbide with a resin-bond wheel made of corundum-coated diamond grains showed that the grinding efficiency increased by more than 30% and the wheel life increased by 30–35% [31].



(a)



(b)

Fig. 7. Metal-coated abrasive (after [32]). (a) Abrasive grains are individually coated before forming the agglomerate, (b) plural grains are coated together before forming the agglomerate.

4.3. Other abrasives

Silica EPD (electrophoretic deposition) grinding wheels were developed for mirror grinding of silicon wafers [33–36]. The EPD pellets consisted of fine silica powder as the abrasives, and sodium alginate as the bonding agent. Fig. 9 shows a cup-type grinding wheel with silica EPD pellets. The pellets were about 7 mm in diameter and 10 mm in height. 16 pellets were bonded on a brass disk with a diameter of 80 mm. Grinding tests using the silica

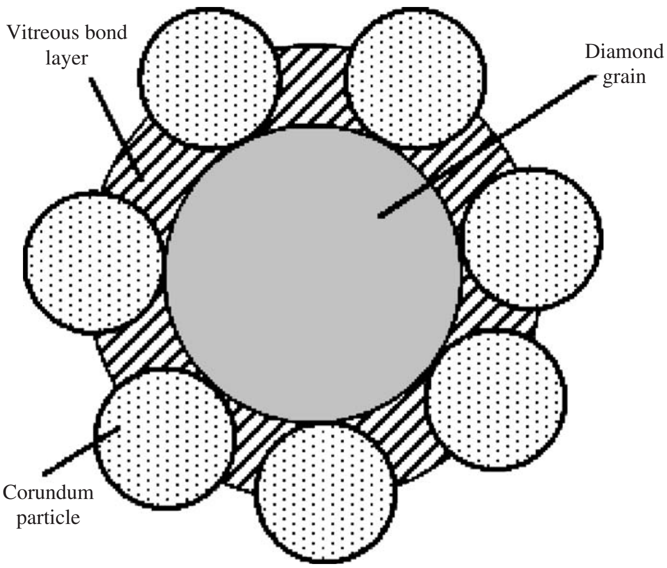


Fig. 8. Illustration of coating structure (after [31]).

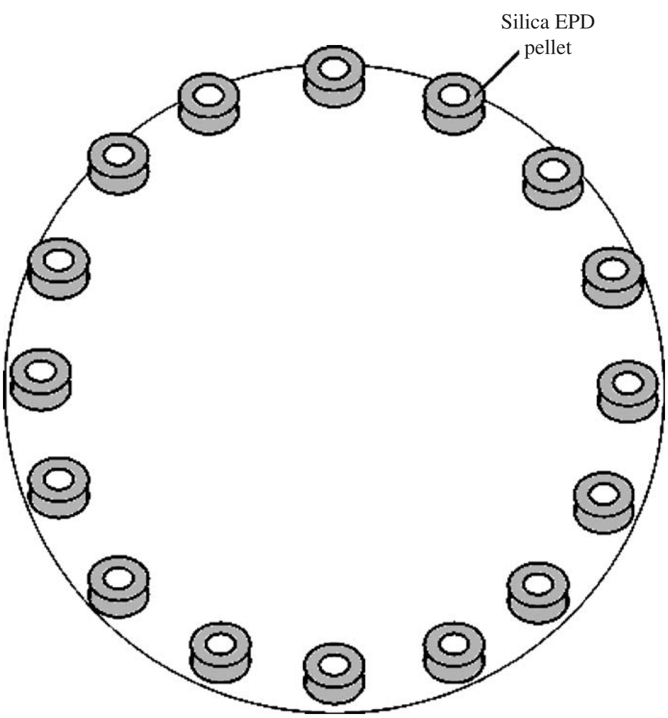


Fig. 9. Grinding wheel with silica EPD pellets (after [36]).

EPD pellets produced a mirror surface of approximately 3.4 nm in R_a on a silicon wafer, and the grinding ratio was as high as 3.5.

5. Grain size

Traditionally, the grain size of abrasive particles is expressed in term of mesh sizes. The mesh size corresponds to the number of openings per linear inch in the wire gauze. This method is carried out for sizes from ♯4 to ♯240 [20].

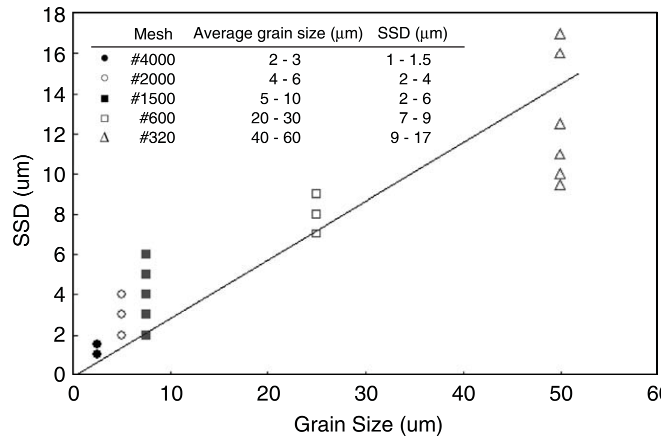


Fig. 10. Grain size versus subsurface damage (SSD) in ground wafers (after [11]).

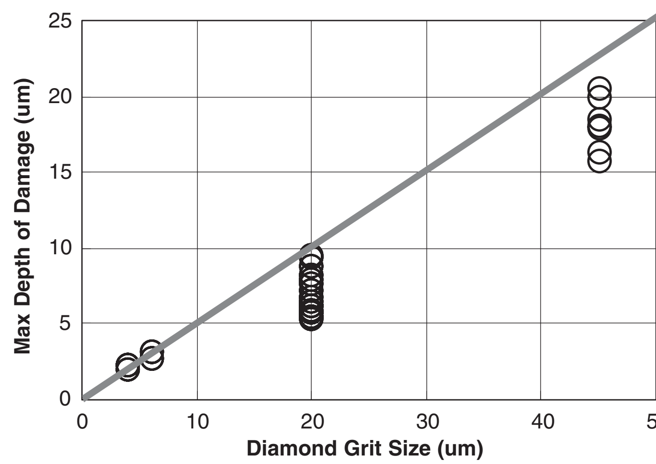


Fig. 11. Relation between grit size and maximum depth of cracks [12].

For much finer grains (possibly, as fine as ♯4000 on the mesh scale), it is difficult to segregate them by gauzes. In this case, the diameter of the abrasive particles is used to express the grain size.

Generally, small grain sizes can produce better finishes on ground surfaces, while larger grain sizes allow higher material removal rates. According to Matsumoto et al. [37], finer grain sizes were preferred for silicon back-grinding. A grain size ranging from 0/1 to 60 μm was suitable, 0/1 to 20/40 μm was preferred, and 3/6 μm was most preferred. It has been reported that wheels with smaller grain sizes produce less subsurface damage (SSD) on ground wafers [11,12,38,]. Fig. 10 shows the experimental relationship between SSD and the grain size in the wheel. Fig. 11 is the experimentally determined relation between the subsurface crack depth and the grain size in the wheel [12]. It can be seen that the depth of subsurface crack in ground silicon wafers is approximately equal to half of the diamond grain size in the wheel.

Furthermore, wheels with smaller grain sizes generally produce smoother surfaces. As shown in Fig. 12, as the

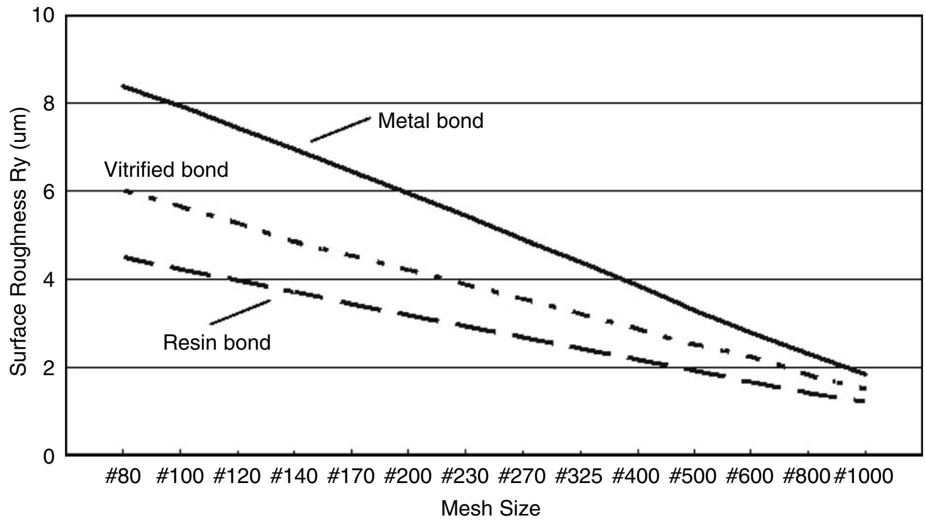


Fig. 12. Relationship between grain size and surface roughness when grinding ceramics (after [39]).

grain size becomes smaller, the roughness of the ground surfaces decreases [39].

A brief surfing of the Web sites of major wheel manufacturers [40–44] has indicated that the smallest diamond grain size used in resin- or vitrified-bond grinding wheels for silicon wafers is ♯2000 (or ♯4000). Finer diamond grain sizes are desirable to further reduce the subsurface damage and surface roughness, but it is very difficult to maintain grinding wheels to be self-dressing when grain sizes are very small (for example, 1 μm) [45].

Metal-bond wheels with much finer diamond grains (♯120,000) have been reported in ELID (electrolytic in-process dressing) grinding of silicon wafers [38]. In ELID grinding, the wheel surface is electrolytically dressed [46]. When ELID grinding of silicon wafers with ♯120,000 metal-bond wheels, the average surface roughness (R_a) could be as low as 2 nm and the maximum surface roughness (R_{max}) could be as low as 10 nm [38]. However, there has been no report on applications of ELID grinding in silicon wafer manufacturing.

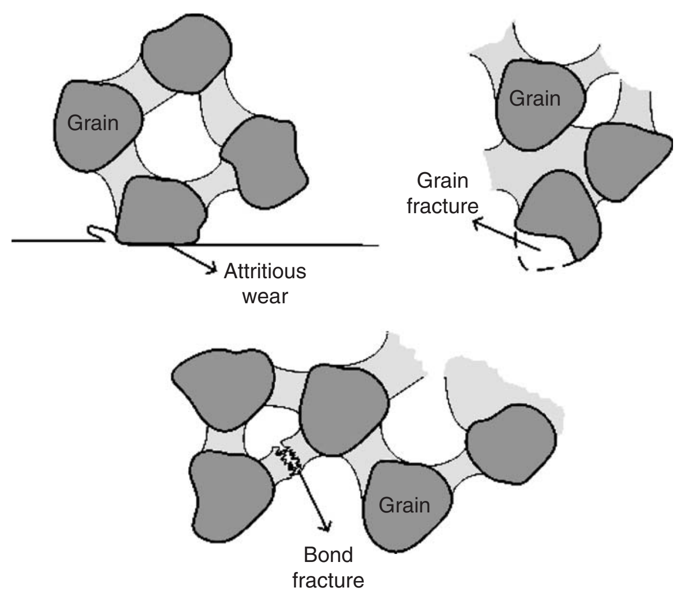


Fig. 13. Wheel wear mechanisms (after [23,47]).

6. Bonds

6.1. Importance of bond materials

The bond in a grinding wheel cements the abrasive grains together [21]. Among other factors, the bond plays a predominant part in the diamond wheel performances and on the quality of grinding results [47,48].

As shown in Fig. 13, there are mainly three distinct wheel wear mechanisms, namely attritious wear, grain fracture, and bond fracture [47]. To optimize wheel life and grinding performance, the bond wear rate should be equal to or slightly higher than the wear rate of the abrasive grain during grinding operations [49]. The bond material must allow the diamond grains to fracture or pull out after they become worn to expose new cutting surfaces [29].

6.2. Bond types and their properties

There are mainly three different bond systems, namely, metal, resin, and vitrified, as shown in Fig. 14. The metal bond system has been used for thin wheels intended for cutting (slicing) silicon wafers [26]. However, for silicon wafer surface grinding, resin bond and vitrified bond systems are used.

The resin bond is usually made with heat-cured resin (mainly phenolic resin) [39]. For synthetic resins such as an epoxy, the bonding strength tends to decrease with an

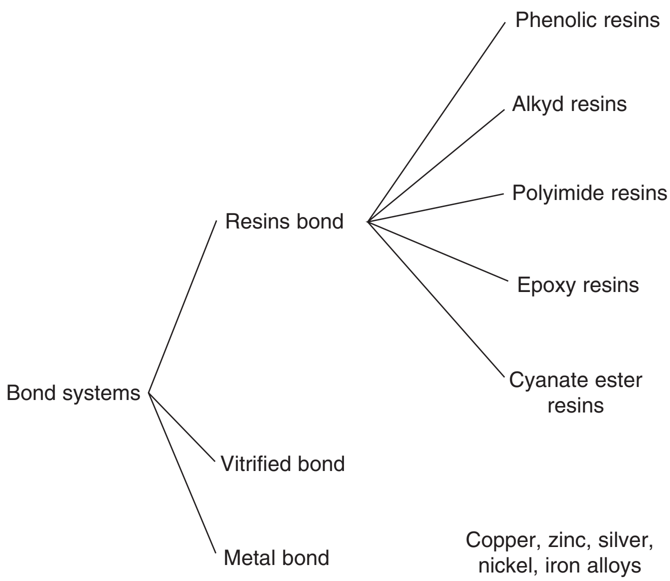


Fig. 14. Bond systems for grinding wheels (after [26,37]).

increase in the temperature of the grinding wheel [50]. One way to assure a sufficiently high bonding strength for a synthetic resin bond is to harden or cure the synthetic resin bond at a temperature as high as possible.

The vitrified bond has a glass-like structure. This structure is made by firing clays, ground glass frits, mineral fluxes such as feldspars, and chemical fluxes at a high temperature [51]. The elastic modulus of a vitrified bond is approximately 4 times that of the resin bond [28]. The vitrified bond has a relatively higher strength to hold the abrasive grains together, and a relatively easier dressing operation [52].

Zhou et al. [53] believed that ''In vitrified wheels wear can occur through brittle fracture of the bond materials, allowing rapid emergence of new abrasives for continued grinding. Vitrified bonds are also of interest because the porosity level of the bond can be tailored to control bond facture, so that self-sharpening is facilitated and continuous grinding established.''

Smith et al. [54] discussed resin (including copper-resin bond) and vitrified bonds for grinding of sapphire. Normal resin bonds would begin to deteriorate as temperatures approached 200 °C. For copper–resin bonds, copper particles were dispersed throughout the bond to conduct heat away from the diamonds so that the resin would not melt and reject diamonds prematurely. Vitrified bonds showed promise of offering free cutting and self-sharpening; however, wheel manufacturers claimed that it was one of the most difficult bond systems to produce with consistent results. Measurement of ultrasonic velocity showed variations in the ultrasonic images across the wheel surface.

The effects of the bond type on the roughness of ground surfaces are illustrated in Fig. 12. For the same grain size, the surface roughness is the lowest for the resin bond and highest for the metal bond.

It was reported that, when grinding silicon wafer, by switching from a vitrified bond wheel to a resin bond wheel, edge chipping was reduced and various other quality issues were mitigated or eliminated [42].

6.3. Special bond systems

Aiming to achieve sufficient abrasive-bond adhesion while avoid the oxidation or other damage to the diamond grains, Sherwood [29] developed a bond system using a ceramic-forming polymer. The ceramic-forming polymer could be heated to convert it to a ceramic material at a low enough temperature to prevent damage to the diamond grains. Tanaka et al. [28] developed a vitrified bond that could easily melt by heating at low temperatures. In this way, it was possible to prevent the graphitization of diamond grains [28].

Electrolytic in-process dressing (ELID) is an effective method to dress the grinding wheel during grinding. However, the problem with using metal bond wheels in the ELID grinding is that there is workpiece ''chipping'' during the grinding and ''scratches'' on the workpiece by the chips [55]. Accordingly, ground surface merely had an $R_{\max}$ of about 18 to 20 nm, and better quality ground surface could not be obtained. To solve this problem, Ohmori et al. [55] invented a conductive metal-resin bond for the ELID grinding. With this bond, it was possible to obtain a high-quality mirror surface by ELID grinding.

7. Porosity

Open voids (pores) are intentionally created in grinding wheels to carry swarf and grinding fluids during grinding [56]. The clearance of chips or swarf is important especially when the workpiece being ground is relatively soft or when surface finish requirements are demanding (e.g., when backgrinding silicon wafers) [57]. Pores tend to promote more efficient cutting, minimize damage to ground surfaces, and improve tool life [57]. Besides, the porosity also has great effect on the roughness of ground silicon wafers. As shown in Fig. 15, as the pore volume percentage in the electrodeposited wheels increases, the surface roughness of the ground silicon wafers decreases. Another benefit of porous wheels is the significant improvement of the wheel's self-dressing ability [19].

7.1. Pore formation

The natural porosity arising from packing of the abrasive grains and bond materials is insufficient to achieve the porosity level desirable for certain grinding operations [19]. One technique to increase the porosity in grinding wheels is to use pore inducers of two categories [58].

For the first category, the pore inducers are added to the mix (along with the bond, abrasives, and temporary binder) and removed after the wheel is formed, leaving a porous structure [58]. The pore inducers are conventionally

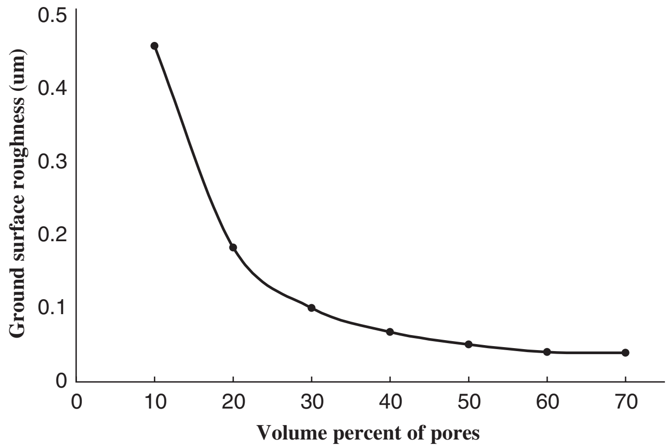


Fig. 15. Relation between the pore volume percentage in the wheel and the surface roughness of the ground wafers (after [61]).

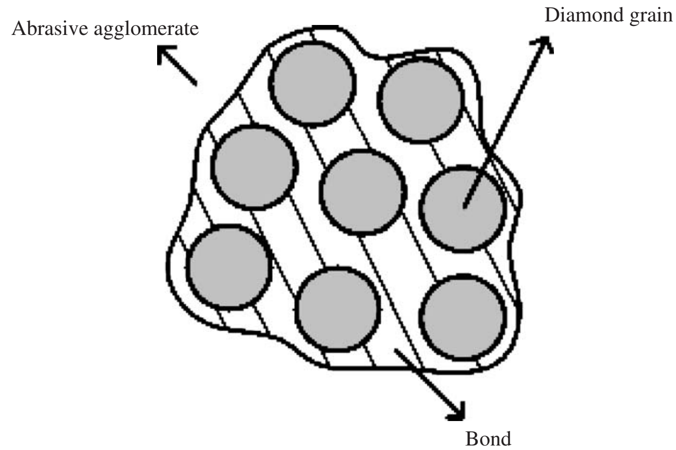


Fig. 16. Abrasive agglomerate.

removed by thermal methods. Typical pore inducers include nut shells and other carbon-based materials [58]. Another example of the pore inducers is naphthalene, which is burned off to leave pores prior to the firing cycle of the wheel [59]. One advantage of naphthalene as pore inducers is that it does not expand when heated and burned off. Additionally, since it does not expand under heat, there is no introduction of heat-related stresses into the grinding wheel. For some grinding applications (such as silicon wafers and other electronics components), it may be desirable to use non-ionic (i.e., non-salt) pore inducers, such as sugar, dextrin, and polysaccharide oligomers [57]. Butyl carbamate has been used as the pore inducer to produce highly porous vitrified-bond wheels [58].

For the second category, closed cell, hollow pore inducers (such as bubble alumina, hollow glass, and ceramic spheres) [57] are added to the abrasive composite mixtures to obtain the adequate volume percent porosity in the wheel [19]. Note that the pore inducers in this category will not be removed from the wheels.

There are two main problems with the technique of using pore inducers. One is that interconnected porosity could not be achieved (although pore inducers added to the wheel structure could generate high porosity percentages). The volume percent of open channels or interconnected porosity has been found to be a more significant determinant of the grinding performance than mere volume percent of porosity [19]. Moreover, the pore inducers (in the first category) must be burnt out of the abrasive matrix, giving rise to various manufacturing difficulties. In order to address these problems, a technique to use agglomerates was developed to generate porosity in diamond wheels [19]. As shown in Fig. 16, the agglomerate was formed by bonding a certain number of individual grains together [60]. Bright et al. [19] invented grinding wheels using agglomerated diamond grains and bond materials to control the percentage and characteristics of the porosity. The permeable and interconnected porosity was created without the addition of pore inducers.

For conventional electrodeposited grinding wheels, the volume percentage of pores in the electrodeposited abrasive layer is substantially zero, or extremely low, and the interstices among the abrasive grains are filled with metal [61]. Wheels with this structure scarcely develop their self-dressing ability. In order to address this problem, Kajiyama [61] invented a method for making an electro-deposited grinding wheel in which the pores were dispersed in a volume percentage of 10% to 70%.

7.2. *Applications of porous wheels*

Tanaka et al. [28] developed a porous vitrified-bond wheel with ultra-fine diamond grains (~0.125 μm). As shown in Fig. 17, pores were fabricated by evaporating the pore inducers mixed in a vitrified-bond diamond wheel [28]. This wheel provided a high elastic modulus and high exhaust ability of the chips due to the presence of a great number of pores [28].

Ramanath et al. [57] invented porous resin-bond wheels with an interconnected pore structure. These wheels were claimed to be "potentially advantageous for mirror finish grinding of hard and brittle materials, such as silicon wafers". The average size of the diamond grains ranged from 0.5 to 75 μm.

Matsumoto et al. [37] invented resin-bond diamond wheels containing high concentrations of hollow fillers for grinding of silicon wafers. The hollow fillers were preferably in the form of friable hollow spheres such as silica spheres or microspheres. The hollow spheres were preferably larger than the diamond grains, and might range from 4 to 130 μm in diameter. The wheel comprised 2 to 15 volume percent diamond grains (preferably 4 to 11 volume percent), 5 to 20 volume percent resin bond (preferably 6 to 10 volume percent), and 40 to 75 volume percent hollow filler material (preferably 50 to 65 volume percent). The grain to bond ratio might range from 1.5:1.0 to 0.3:1.0 (preferably from 1.2:1.0 to 0.6:1.0). The wheel could grind silicon wafers at commercially acceptable material removal

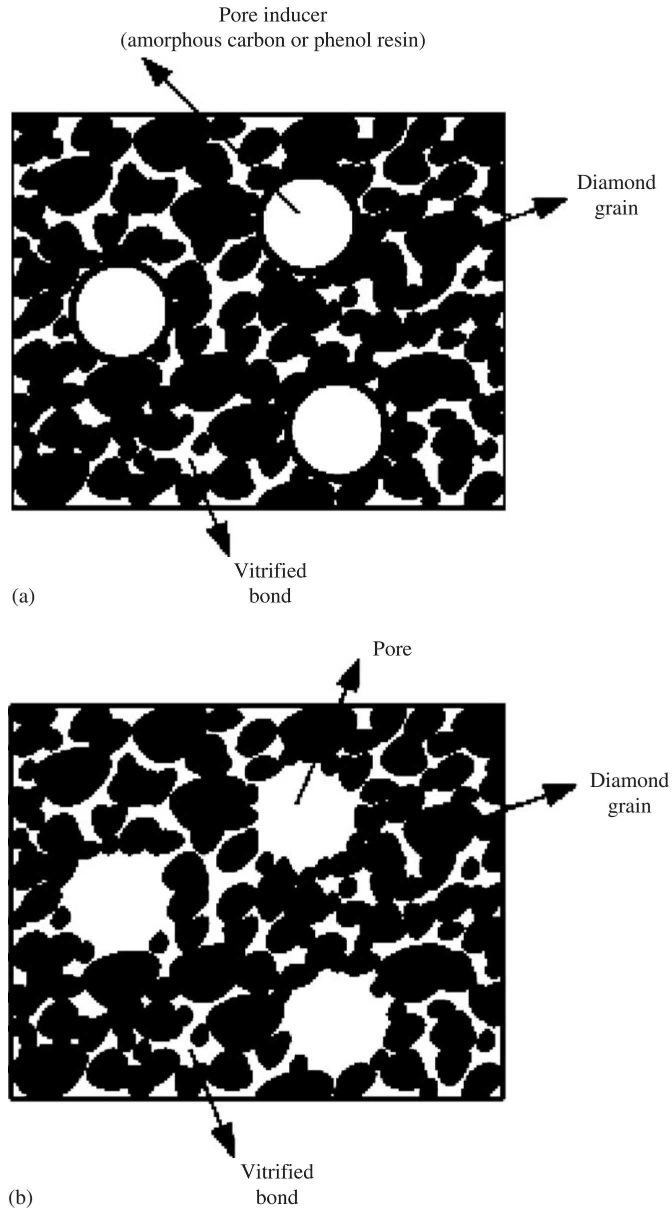


Fig. 17. Pore formation in a vitrified-bond wheel (after [28]). (a) Before sintering, (b) after sintering.

rates and wheel wear rates with less workpiece damage than conventional diamond wheels.

Itoh [52] invented a vitrified-bond wheel in which the bond was reinforced by impregnation with a cured composition including a thermosetting synthetic resin and a surfactant (surface active agent). The invented wheel had a network of pores filled with the thermosetting synthetic resin. This could prevent an excessive rise in the temperature on the workpiece surface due to the excessive friction heat generated between the workpiece surface and the diamond grains that remained dull. On the other hand, the diamond grains which were only loosely held together by the vitrified bond could be tightly held together with an additional bonding force provided by the thermosetting synthetic resin, assuring a high grinding ratio.

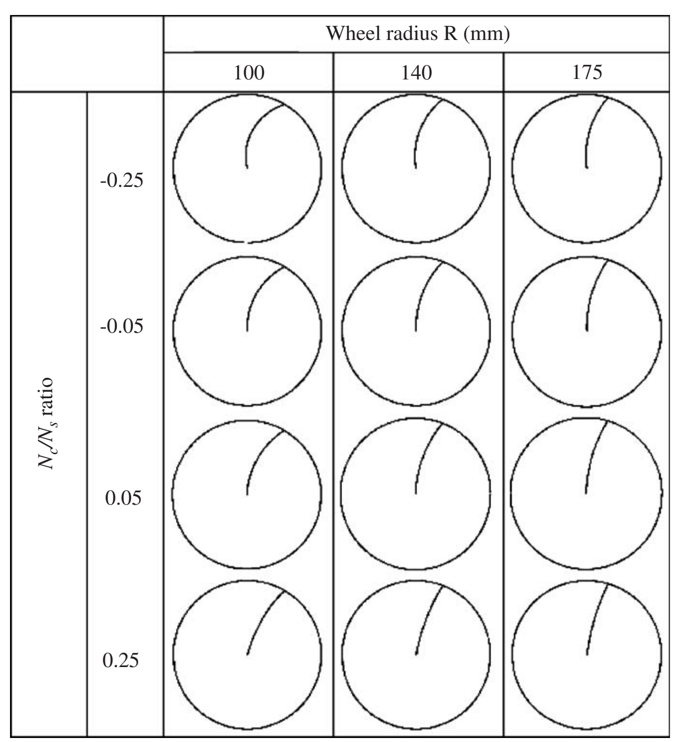
8. Design of wheel geometry

In addition to abrasive type, grain size, etc., the thickness of the abrasive layer (height of the wheel segments) also plays an important role in determining the aggressiveness and longevity of a grinding wheel [24]. The wheel life is proportional to the thickness of the layer [24].

For ordinary electrodeposited grinding wheels, the presence of only one abrasive layer naturally makes their service lives short [61]. In order to solve this problem, Kajiyama invented an electrodeposited grinding wheel and tested it on silicon wafers. In this wheel, the abrasive layer was formed by electrodepositing abrasive grains to a thickness at least three times as large as the diameter of the diamond grains.

The wheel geometry will also affect the quality of the ground wafers. The effects of wheel diameter on grinding mark curvature were studied by Chidambaram et al. [8]. As shown in Fig. 18, the grinding line tends to be less curved as wheel diameter increases.

The diameter of the grinding wheel may also indirectly affect the depth of grinding marks [62]. When the wheel spindle exhibits tilt motion errors, a wheel with a larger diameter will have more severe unevenness measured at the grinding segment. Therefore, a smaller wheel should cause less severe grinding marks if all the other conditions are kept the same. This is illustrated in Fig. 19, where α is the tilt motion error measured as an angle, D_1 and D_2 are the diameters of two wheels, and δ_1 and δ_2 are the



(Nc - rotational speed of chuck,
Ns - rotational speed of wafer)

Fig. 18. Effects of wheel diameter on grinding mark curvature [8].

unevenness measured at the outer diameter of the wheels. As can be seen, the wheel with larger diameter D_1 has larger unevenness δ_1.

One phenomenon associated with silicon wafer grinding is the central dimples on the ground wafers. Fig. 20 shows two ground wafers with one having a center dimple and the other not. The central dimples are the main reasons for the poor site flatness near the wafer center. A study by Zhang et al. [63] showed that the size of the central dimples would increase as the wheel's segment height increased or the segment width decreased.

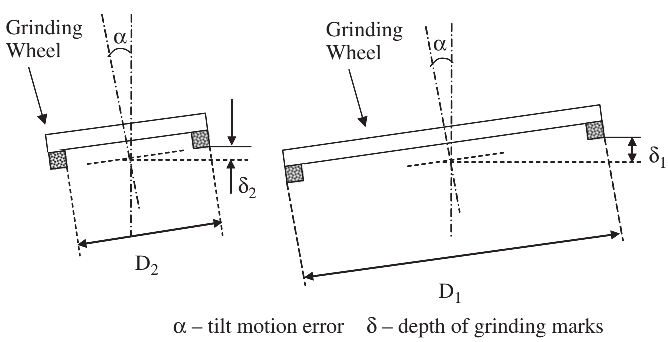


Fig. 19. Effects of wheel diameter on grinding mark depth [62].

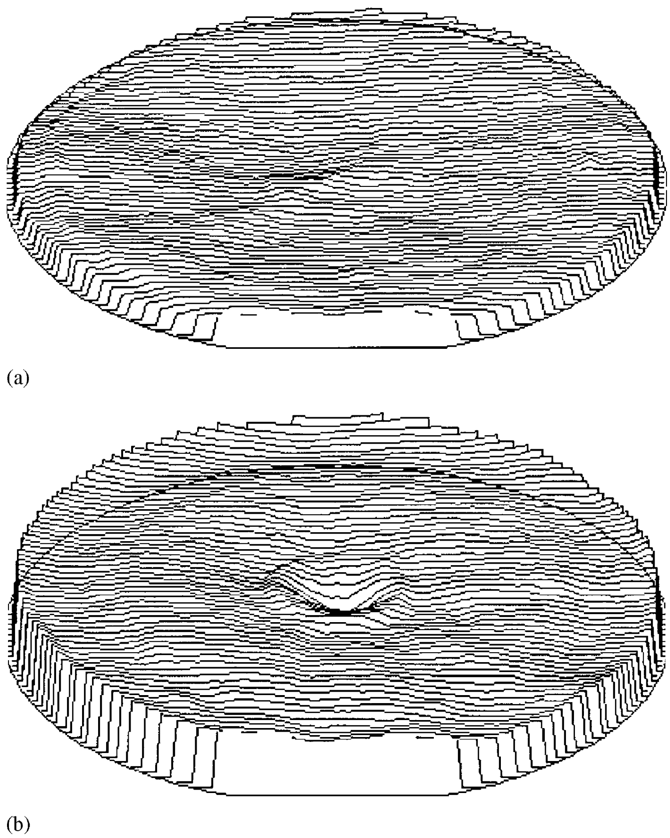


Fig. 20. Illustration of center dimples on ground wafers (after [63]). (a) A ground wafer without central dimple, (b) a ground wafer with central dimple.

9. Concluding remarks

The ideal grinding wheels (that meet all the requirements discussed in Section 2) for manufacturing of silicon wafers do not exist yet. For example, in commercially available grinding wheels, the smallest diamond grain size is ♯3000 or ♯4000 mesh (for resin or vitrified bond). Removal of the damage induced by these grinding wheels requires unsatisfactorily high polishing amount. Utilization of even finer diamond grains has been suggested as an effective approach to reduce the grinding-induced damage on ground wafers. However, finer diamond grains in resin or vitrified bond wheels bring about tremendous challenges to fabricate wheels with the self-dressing ability.

Metal-bond wheels with much finer diamond grains (♯120,000) have been reported in ELID grinding of silicon wafers. However, the silicon industry has not accepted ELID grinding as a practical manufacturing process.

Lack of fundamental understanding about silicon wafer grinding has added more difficulties for the wheel manufacturers. For example, what causes the deepest cracks in silicon grinding? Are they caused by the largest diamond grains embedded in the grinding wheel? Are they caused by the largest loose grains that have already fallen off the wheel but are trapped between the wafer and the wheel? Are they caused by a cluster of grains that has fallen off but is trapped between the wafer and the wheel? Answers to these questions are critical to wheel development for fine grinding of silicon wafers. For example, if it is individual diamond grain that have caused the deepest cracks, then it makes sense to further reduce the grain size. However, if it is a cluster of diamond grain that has caused the deepest cracks, only reducing the grain size will not necessarily reduce the depth of deepest cracks. Efforts to prohibit diamond grains from falling off in clusters will be more fruitful.

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