Process study on large-size silicon wafer grinding by using a small-diameter wheel

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Abstract
Silicon (Si) is a fundamental material in the semiconductor industry. The advancement of semiconductor devices have offered convenience and comfort to our life. In order to raise productivity and economic efficiency, the semiconductor industry keeps looking for use of larger size Si wafers. The next generation wafer is expected to be sized as large as 450 mm in diameter. Many wafering processes including lapping, grinding and polishing have been studied and grinding technology stands out as the most promising process for large-size Si wafer manufacturing. In the current in-feed grinding scheme adopted for Si wafers, the wheel diameter used is generally equal to or larger than the wafer diameter. In turn, larger diameter wheels require larger size machine tools and production lines, which lead to increase in manufacturing costs. In this paper, both experiment and kinematical analysis have been carried out to investigate the feasibility of using small diameter grinding wheels to grind large size Si wafers, mainly focusing on the effects of wheel diameter on wafer geometry and surface roughness. The results show that both wheels generated a central convex profile on the wafer and the small wheel achieved a slightly better flatness than the large wheel. The surface roughness were similar one to another for most area of the wafer except the fringe around its edge. All these experimental results were predictable by the kinematic model established in this paper. Particularly, the kinematic analysis found that the cutting path made by small wheel with diameter equaling to the wafer radius was parallel each other at the fringe around wafer edge, which directly worsened the surface roughness.

Key words: Silicon wafer, In-feed grinding, Wheel diameter, Wafer geometry, Cutting path density, Surface roughness

1. Introduction

Si is a fundamental material in the semiconductor industry. In order to raise productivity and economic efficiency, the semiconductor industry keeps looking for use of larger Si wafers (Shiraishi, et al., 2001). The current mainstream is 300 mm wafer which has been manufactured since 2001. Grinding by use of fixed diamond abrasive stands out as the most promising process technology for large size Si wafering (Okahata, et al., 2014). Currently, the in-feed grinding scheme as shown in Fig. 1 (a) has been widely adopted in the grinding of Si wafers. The diameter of grinding wheel used is generally equal to or larger than the wafer diameter (Zhang, et al., 2011, Huo, et al., 2013, Okahata, et al., 2014). Consequently, larger diameter grinding wheels require larger size machine tools and production lines, which lead to increase in manufacturing costs. However, very few report concerned the influence of wheel diameter on the grinding performance.

In this paper, both experiment and kinematical analysis have been carried out to investigate the feasibility of using small diameter grinding wheels to grind large size Si wafers as shown in Fig. 1 (b), and the effects of wheel diameter on wafer geometry and surface roughness have particularly been studied.
2. Experimental description and results

The grinding experiments were carried out on a horizontal type ultra-precision grinding machine as shown in Fig. 2 (a) (Eda, et al., 2001). The grinding machine was equipped with two aerostatic spindles for work and wheel rotation, and had two degrees of freedom along X- and Z-axis directions. In addition, the work spindle was able to be precisely tilted around both X- and Y-axis at the resolution of 10 ppm over the range of ±1.5 degrees. Two SD5000C75V grinding wheels with different diameters but the same specifications were purposely prepared for grinding of φ300 mm Si wafers as shown in Fig. 2 (b), one was the same in size of Si wafer (φ300 mm), while another was one-half in diameter (φ150 mm) which was minimally required to fully cover the wafer surface under the in-feed grinding scheme.

Most wafer grinding systems utilize the rotational in-feed grinding method to keep the contact area unchanged and thereby deliver a stable grinding performance throughout the grinding process (Zhou, et al., 2002). During grinding, the Si wafer was mounted on a porous ceramic vacuum chuck, and sufficient purified water was applied to the grinding zone as coolant. The wheel and the wafer were offset by a distance of wheel radius and rotated at the revolution velocity \( n_1 \) and \( n_2 \) around their rotational axes simultaneously, while the diamond wheel was moved towards the wafer at the down-feed rate of \( f \).

In the actual experiments, the revolution velocity of the φ150 mm wheel was as twice high as that of the φ300 mm wheel, in order to keep their wheel speeds same as 1400 m/min. The down-feed was carried out in two steps; feed of 33 µm at the down-feed rate of 5 µm/min in the first step, and feed of 2 µm at the down-feed rate of 2 µm/min in the second step. The detailed wheel specifications and selected grinding parameters were listed in Table 1.

Fig. 3 showed the external view of wafer surfaces ground by two different wheels. Both wafers were mirror finished with the roughness approximately Ra = 2 nm. Through a detailed examination, it was found that different wheels left different patterns of cutting paths on the wafer surfaces which were emphasized by solid lines in the photos. As shown in the top-left panel in Fig. 3 (b), in particular, concentric cutting paths were observed at the fringe of wafer when it was ground by the φ150 mm wheel.
The wafer geometry was measured on machine by use of a laser interferometer (Zhou, et al., 2010). Fig. 4 showed the wafer geometries obtained when the tilt angle $\alpha$ was set to be $1/15 \times 10^{-3}$ and $\beta$ was set to be 0. The tilt angles and their effects on wafer geometry and surface roughness were detailed in the subsequent section. It was observed that the wafer became thick inward its center. As the result, the wafer profile became central convex for both large and small grinding wheels. However, the $\phi$150 mm wheel achieved a slightly better flatness in terms of TTV (total thickness variation) than the $\phi$300 mm wheel.

Shown in Fig. 5 were the surface roughness variations with the wafer radius. The surface roughness obtained by the $\phi$300 mm wheel slightly increased with the wafer radius, but was stably below $Ra = 2 \, \text{nm}$. The surface roughness achieved by the $\phi$150 mm wheel, on the other hand, was equivalent or slightly larger for most wafer surface area, but showed a sharp increase at the wafer fringe.

### 3. Kinematical analyses

#### 3.1 3D cutting path and resultant wafer geometry

Use of such precision grinding system has made it possible to precisely control the cutting path of each cutting edge. A kinematical analysis is useful to address the behavior of each grain in wafer surface generation (Zhou, et al., 2002, 2003, Chen and Hsu, 2006, 2008). The 3D model of rotational in-feed grinding method is shown in Fig. 1 (a). The axis of the wafer is often inclined minutely against the wheel in order to reduce the contact area. The tilt angles are defined as $\alpha$ and $\beta$, respectively around X- and Y-axis. The projection in X-Y plane is given in Fig. 6, where the initial

| Table 1 Grinding conditions |
|--------------------------------|
| Grinding wheel | SD5000C75V |
| Wheel revolution $n_1$ | $\phi$150 | $\phi$300 |
| Wheel revolution $n_2$ | 3000 | 1500 |
| Wheel speed $V$ | 50 |
| Wheel speed $V$ | 1400 | 1200 |
| Wheel speed $V$ | m/min |
| Step 1 | Feed rate $f_1$ | 5 |
| Step 1 | Feed $A_1$ | 33 |
| Step 2 | Feed rate $f_2$ | 2 |
| Step 2 | Feed $A_2$ | 2 |
| Spark-out | 30 sec |

(a) Ground by large wheel  
(b) Ground by small wheel

Fig. 3 External view of ground wafer surfaces
position components of a grain are represented as \([x_g \ y_g \ z_g]\). The rest parameters used for analysis are listed in Table 2.

In a coordinate system that the origin is fixed at the center of the wafer, the position of the grain after \(t\) seconds \([x(t) \ y(t) \ z(t)]\) is described as follows (Zhou, et al., 2003):

\[
\begin{bmatrix}
x(t) \\
y(t) \\
z(t) \\
1
\end{bmatrix} = A \cdot B \cdot C \cdot D \cdot E \cdot F
\begin{bmatrix}
x_g \\
y_g \\
z_g \\
1
\end{bmatrix}
\]  

(1)

where the matrix \(A\) and \(E\) shown below represent the rotations of wafer and wheel respectively;

\[
A = \begin{bmatrix}
\cos \omega_2 t & \sin \omega_2 t & 0 & 0 \\
-\sin \omega_2 t & \cos \omega_2 t & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad E = \begin{bmatrix}
\cos \omega_1 t & -\sin \omega_1 t & 0 & 0 \\
\sin \omega_1 t & \cos \omega_1 t & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(2)

while the matrix \(B\) and \(C\), respectively express the tilts of wafer around the X- and Y-axis, and are given as;

\[
B = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \alpha & -\sin \alpha & 0 \\
0 & \sin \alpha & \cos \alpha & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad C = \begin{bmatrix}
\cos \beta & 0 & \sin \beta & 0 \\
0 & 1 & 0 & 0 \\
-\sin \beta & 0 & \cos \beta & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(3)
The matrix $D$ and $F$, respectively describe the offset between the wafer and the wheel centers, and are given as:

$$D = \begin{bmatrix} 1 & 0 & 0 & L \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad F = \begin{bmatrix} 1 & 0 & 0 & -L \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

The above kinematical description is able to precisely predict the cutting path of each grain of a specified diamond wheel on a specified wafer surface, in a 3D manner. A series of samples is shown in Fig. 7, where the cutting paths are calculated for a combination of the $\phi 300$ mm Si wafer and the $\phi 300$ mm wheel, by varying the tilt angles of $\alpha$ and $\beta$ from $-3/150 \times 10^{-3}$ to $3/150 \times 10^{-3}$. Shown in the bottom panel in the cross-sectional views which in fact present the wafer profile obtainable at the corresponding tilt angles.

According to the results in Fig. 7, in the case of $\alpha \neq 0$, the wafer profile becomes a central convex, and unidirectional cutting paths are formed either inwards or outwards on the wafer surface. When $\alpha = 0$, contrarily, the cutting paths are intersected one to another. A positive $\beta$ makes a profile convex, while a negative $\beta$ leads to a concave profile. The effect of $\beta$ on the global flatness of the wafer is about half that of $\alpha$. Furthermore, a combination of $\alpha$ and $\beta$ is able to generate a variety of wafer geometry including “hat” like- and “gull wing” like-shape. Mathematically, it is possible to create a desirable axisymmetric profile on the wafer surface by properly aligning the tilt angles. Particularly, if the

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Table 2 Parameter list

| Parameter | Description |
|-----------|-------------|
| $R_1$     | Wheel radius [mm] |
| $w_1$     | Wheel segment width [mm] |
| $R_2$     | Wafer radius [mm] |
| $r$       | Distance from wafer center [mm] |
| $L$       | Offset between wheel and wafer axis [mm] |
| $n_1$     | Wheel revolution [rpm] |
| $n_2$     | Wafer revolution [rpm] |
| $\omega_1$ | Wheel angular speed ($=2\pi n_1$) [rad/min] |
| $\omega_2$ | Wafer angular speed ($=2\pi n_2$) [rad/min] |
| $f$       | In-feed rate [$\mu$m/min] |
| $\alpha$  | Wheel axis tilt around X-axis [rad] |
| $\beta$   | Wheel axis tilt around Y-axis [rad] |
| $a$       | Average width of cutting path [mm] |
| $m_0$     | Effective cutting edge density [particles/mm$^2$] |
wheel axis is parallel to the wafer axis \((\alpha = \beta = 0)\), the interaction between the wheel and the wafer is made in the X-Y plane and the wafer surface is ideally flat \((\text{TTV} = 0)\). However, wafer grinding at \(\alpha = 0\) is not favored from the viewpoints of reducing the grinding resistance and improving the surface roughness. Therefore, actual grinding is often carried out by presetting \(\alpha \neq 0\).

3.2 Cutting path density

Fig. 7 also suggested a fact that the cutting path in each case becomes denser inward the wafer center. It is known that denser cutting path delivers a better surface roughness (Zhou et al., 2002). Therefore, it is important to quantitatively understand the variation of the cutting path density at different wafer radius. When considering a concentric zone at radius \(r\) with a minute range of \(dr\), as illustrated in Fig. 8 (a), the area of declared zone is given as \(2\pi r \cdot dr\). If the length of the cutting path across the zone is given as \(d_s = \sqrt{dx^2 + dy^2 + dz^2}\) using Eq. (1), then the area that the diamond grains pass through is the product of the cutting length \(d_s\), the cutting width \(a\) and the number of grains \(m\) involved in the material removal. Here, the cutting path density is defined as the area ratio of cumulated cutting paths over the correspondent wafer surface and expressed as follows.

\[
D = \frac{d_s \times a \times m}{2\pi r \cdot dr}
\]

where, \(m\) is the number of grains involved in the material removal during one rotation of wafer, thereby given as \(m = 2\pi m_0 R_1 w_1 \cdot n_1 / n_2\). Having the parameters listed in Table 2 substituted into Eq. (5), then the cutting path density \(D\) can be rewritten as Eq. (6);

\[
D = a m_0 R_1 w_1 \cdot \frac{n_1}{n_2} \cdot \frac{d_s}{r \cdot dr}
\]

where, \(a m_0 R_1 w_1\) is determined by wheel specifications and \(n_1/n_2\) is determined by grinding conditions. Also, it is
worthy to note that $D$ is in fact a dimensionless factor representing the coverage of cutting path over the wafer surface, suggesting the number of cutting that the corresponding area of wafer is undertaken. As shown in Fig. 8 (b), therefore, the outward region satisfying $D < 1$ is undercut area, while the inward region where $D > 1$ is overcut area. In the overcut area ($D > 1$), the wafer is cut more than once. On the contrary, uncut wafer surface remains in the undercut area ($D < 1$). The white circle in Fig. 8 (b) expressing the critical value of $D = 1$ is dependent on the wheel specifications and grinding conditions as described below.

The calculated examples of the cutting path density are given in Fig. 9, where (a) shows the effects of change in the wheel radius while (b) is the effects of speed ratio $n_1/n_2$. Regardless of changes in wheel specifications and grinding conditions, the cutting path density sharply increases at the wafer center since the center is a mathematical singularity where the wafer radius $r$ takes 0. Because the wafer is always overcut at its center, in case that the tilt angles are preset to $\alpha = \beta = 0$, a center concave wafer geometry is often formed (Zhang, et al., 2006, Sun, et al., 2006) if the loop stiffness of the grinding system is not high enough.

On the other hand, the cutting path density gradually becomes lower with distance from the wafer center, and eventually less than 1 if the wafer diameter is large enough. Because the region where $D < 1$ is not fully ground, a particular attention needs to be paid to selection of grinding conditions for large size wafers. According to Eq. (6) and results shown in Fig. 9 (b), increase in rotational speed ratio $n_1/n_2$ is preferable to compensate the effect of reduction in the wheel radius.
Simulation and discussion

In order to investigate the effect of wheel diameter on wafer geometry and surface roughness, kinematical analysis was performed for both $\phi_{150}$ mm and $\phi_{300}$ mm wheels. The obtained cutting paths were projected in X-Y plane and shown in Fig. 10. Here, the same grinding conditions used for experiment were applied in the simulation. The patterns of cutting path were exactly the same as what were observed in the experiment as shown in Fig. 3. Two wheels generated cutting paths with almost same density all over the wafer surface, because they run at the same wheel speed (the $\phi_{150}$ mm wheel had one-half diameter but run at twice rotation velocity as compared to the $\phi_{300}$ mm wheel). As shown in Fig. 10 (b), in addition, concentric zone was also confirmed around the wafer edge when the $\phi_{150}$ mm wheel is used, where the cutting paths were found to be parallel each other.

Fig. 11 was the 3D views of cutting path made by a single grain, where the red circles represented the position of the wheels. Here, the number of cutting path was purposely decremented for a good impression of wafer geometry generated in the wafer grinding. Axisymmetric convex profiles were able to be clearly recognized for both large and small grinding wheels. Their cross sections were given in Fig. 12 for detailed examination. It is expected that the $\phi_{300}$ mm wheel generated a “hat” like shape with TTV about 4.5 $\mu$m while $\phi_{150}$ mm wheel generated a “gull wing” like shape with TTV approximately 2.5 $\mu$m. These simulation results well agreed quantitatively with the experimental results shown in Fig. 4. However, a “gull wing” shaped wafer profile (become a slightly thick at the wafer edge) was not able to be observed in the actual grinding by the $\phi_{150}$ mm wheel as expected.
Shown in Fig. 13 were the cutting path density variation along the radical direction of wafer. For both large and small wheels, the defined density was kept as $D > 1$ across the entire wafer. Therefore, no region on the wafer surface was undercut in these cases. Regardless of the difference in wheel diameter, both wheels created a very similar cutting path density for most region of the wafer except its fringe. This fact gave the reason to the experiment results shown in Fig. 5 in which the surface roughness were very close one to another. On the other hand, the density showed a sudden rise at the wafer edge in grinding by the $\phi 150$ mm wheel. Normally, a better surface roughness was expectable under denser cutting path. However, the experiment result in Fig. 5 showed the roughness was getting worse for this situation. As mentioned above, the diamond grains runs in parallel and thus do not overlap each other in the concentric zone around the wafer edge. In this case, the surface roughness no longer depends on the cutting path density, but on the number of effective cutting edge on the working surface of grinding wheel. It is an obvious drawback of using a small diameter grinding wheel because the working surface is direct proportional to the wheel diameter.

To avoid such undesired event, it was strongly recommended to use a wheel with diameter slightly larger than the wafer radius. For example, the simulation results obtained by $\phi 160$ mm wheel were added in the Fig. 12 (b) and Fig. 13 (b), where both TTV and cutting path density no longer show sharp increases at the wafer fringe.

5. Conclusions

In order to investigate the feasibility of using small diameter grinding wheels to grind large size Si wafers, this research first employed two SD5000C75V diamond wheels with different diameters of $\phi 150$ mm and $\phi 300$ mm, to conducted a grinding experiment on $\phi 300$ mm wafers. The effects of wheel diameter on wafer geometry and surface roughness were summarized as follows:
1) Both wheels generated central convex wafer profile when the tilt angle $\alpha = 1/15 \times 10^{-3}$. The $\phi$150 mm wheel achieved a slightly better flatness in terms of TTV than the $\phi$300 mm wheel.

2) The surface roughness achieved by the $\phi$150 mm wheel was equivalent to or slightly larger than that of the $\phi$300 mm for most wafer surface area, but showed a sharp increase at the wafer fringe.

This research also developed a mathematical model which was able to precisely describe kinematic movements of each grain of a specified diamond wheel on a specified wafer surface in a 3D manner, and a new index of cutting path density which was able to estimate the undercut/overcut area and the roughness on wafer surface. The achieved results can be summarized as follows:

3) The kinematic analysis was able to address the each effects including wheel specifications and grinding conditions on the generated wafer geometry, and provide a useful guidance for selection of grinding conditions.

4) These simulation results well agreed with wafer geometry obtained in experiments, except a “gull wing” shaped profile was not observed in the actual grinding by the $\phi$150 mm wheel as expected.

5) A particular attention needs to be paid to selection of grinding conditions for large size wafers because the wafer risks undercut due to reduction in cutting path density with increase in wafer radius. Increase in rotational speed ratio $n_1/n_2$ is preferable to compensate the effect of reduction in the wheel radius.

6) A concentric zone was formed around the wafer edge when the wheel diameter is equal to the wafer radius, where the cutting paths were found to be parallel one to another. This fact gave the reason to the sudden increase in surface roughness at the wafer fringe after grinding by the $\phi$150 mm wheel. It is recommended to use a grinding wheel with diameter slightly larger than the wafer radius to avoid such undesirable event.

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