Simultaneous double side grinding of silicon wafers:
a mathematical model for the wafer shape

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Abstract: Silicon wafers are the most widely used substrates for fabricating Integrated Circuits (ICs). The quality of ICs depends directly on the quality of silicon wafers. Simultaneous Double Side Grinding (SDSG) is one of the processes used to flatten the sliced wafers. The literature contains several mathematical models for the wafer shape in Single Side Grinding (SSG). However, no systematical study on the wafer shape in SDSG has been reported. The first part of this paper gives an overview of current mathematical models for the wafer shape in SSG (or SDSG) of silicon wafers. Then a mathematical model for the wafer shape in SDSG of silicon wafers is developed. This developed model is then used to systematically study the effects of several SDSG parameters on the wafer shape.

Keywords: grinding; machining; semiconductor material; silicon wafer; wafer shape.


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1 Introduction

Over 90% of semiconductor wafers on which Integrated Circuits (ICs) are built are silicon (Van Zant, 2000). In 2006, the worldwide revenues generated by silicon wafers grew to $10 billion from $7.9 billion in 2005 (Taylor, 2007). 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; Vandamme et al., 2000): slicing, edge profiling or chamfering, flattening (lapping or grinding), etching, polishing, and cleaning.

Lapping (Dudley, 1986; Marinescu et al., 2002), Single Side Grinding (SSG) (Chidambaram et al., 2003; Pei, 2002; Pei and Strasbaugh, 2001, 2002; Sun et al., 2004; Zhang et al., 2006), and Simultaneous Double Side Grinding (SDSG) (Kerstan and Peitsch, 2000; Pietsch and Kerstan, 2001, 2005) are the processes to flatten the sliced wafers. In a review paper on SDSG (Li et al., 2006), these three processes were compared in five aspects: ability to remove wire-sawing induced waviness; throughput (number of wafers processed within the unit of time); consumable cost per wafer; level of automation; and environmental benignity. It was shown that SDSG is better in almost every aspect. The same review paper also summarised several process flows involving SDSG for manufacturing of silicon wafers (Hashii and Watanabe, 2004; Hashii et al., 2002; Watanabe, 2003).

Figure 1 illustrates the SDSG process. A pair of cup wheels are located on the opposite sides of a silicon wafer. The two grinding wheels rotate in the opposite directions and are synchronously fed towards the wafer. They simultaneously grind both sides of the rotating silicon wafer.

The wafer shape in this paper is the shape of the wafer surface. The wafer shape has significant effects on the wafer flatness. Generally, a perfectly flat wafer shape is desired after grinding in order to achieve superior flatness. Therefore, it is important to understand and control the wafer shape generated by the SDSG process.

Mathematical models have been reported for the part surface profile in cylindrical surface grinding of steel parts (Shih and Lee, 1999) and for the wafer shape in SSG of silicon wafers (Sun et al., 2004; Tso and Teng, 2001; Zhou et al., 2003). These models can potentially be used to study the wafer shape in SDSG but no such study has ever been published. Pietsch and Kerstan (2005) presented a mathematical model for the wafer shape in SDSG, but did not report any systematical study on the effects of SDSG parameters on the wafer shape.

This paper is organised as follows. Following the introductory section, Section 2 briefly reviews the available models for the part surface profile in cylindrical surface grinding and for the wafer shape in SSG and SDSG of silicon wafers. A mathematical
model for the wafer shape in SDSG is developed in Section 3. Then, in Section 4, this developed model is used to systematically study the effects of several SDSG parameters on the wafer shape. Conclusions are drawn up in Section 5.

![Illustration of SDSG](image)

**Figure 1** Illustration of SDSG


## 2 Overview of available models for the wafer shape

### 2.1 The model for the part face profile in cylindrical face grinding of metal parts by Shih and Lee (1999)

Shih and Lee (1999) developed a mathematical model to calculate the face profile of steel parts in cylindrical face grinding. An illustration of the cylindrical face grinding is shown in Figure 2. The part has the shape of a hollow cylinder and its inner and outer radii are designated by \( r_i \) and \( r_o \), respectively. The grinding wheel (with a radius of \( r_g \)) was modelled as a ring of rotating abrasives and the ring was offset by a distance from the rotation axis of the part. Both the part and grinding wheel rotate about their own axes.

The Z-axis coincided with the rotation axis of the part. The part material was removed by the ring of rotating abrasives and a convex or concave surface was generated by tilting the wheel spindle a small angle (\( \alpha \)) relative to the Z-axis. A series of equations were developed to present the part face profile. Several grinding experiments were conducted to validate the model and the experimental results agreed well with those predicted by the mathematical model.

In Shih and Lee’s model, the grinding wheel only has a ‘pitch’ angle (defined and discussed in Section 3) relative to the part. For grinding of silicon wafers, the grinding wheels typically have both ‘roll’ (defined and discussed in Section 3) and ‘pitch’ angles
relative to the wafer. Furthermore, Shih and Lee did not report any systematical study about the effects of those parameters (the ‘roll’ angle and the ‘pitch’ angle) on the part surface profile.

Figure 2 Illustration of cylindrical face grinding

Source: After Shih and Lee (1999).

2.2 The model for the wafer shape in SSG of silicon wafers by Sun et al. (2004)

For SSG of silicon wafers, as shown in Figure 3, the grinding wheel is a diamond cup wheel. The wafer is held on a porous ceramic chuck by means of vacuum. The rotation axis for the grinding wheel is offset by a distance of the wheel radius relative to the rotation axis for the wafer. During grinding, the grinding wheel and the wafer rotate about their own rotation axes simultaneously and the wheel is fed towards the wafer along its axis. The ceramic chuck is typically ground to a conic shape with a very small slope. When the wafer is held onto the chuck, it elastically deforms to conform to the chuck’s conic shape, thus ensuring that the grinding wheel only contacts half of the wafer. This contact area is marked as ‘Active contact zone’ in Figure 3.

Sun et al. (2004) developed a model to predict the wafer shape in SSG of silicon wafers. Using the model developed, they studied the relationship between the wafer shape and the setup parameters, and discussed the practical applications of the model. Both two-dimensional (2D) and three-dimensional (3D) wafer shapes based upon different setup parameters were presented.
2.3 The model for the wafer shape in SSG of silicon wafers by Tso and Teng (2001)

Figure 4 illustrates the geometry for developing Tso and Teng’s model for the wafer shape in SSG. By tilting the wheel rotation axis around the vector $O_T$, different profiles of the ground surface (or the wafer shape) could be obtained. Tso and Teng presented several cross-sectional profiles of the wafer (200 mm in diameter) along its diameter for different tilt angles.

2.4 The model for the wafer shape in SSG of silicon wafers by Zhou et al. (2003)

Zhou et al. (2003) presented an equation in matrix forms for the grinding marks in SSG of silicon wafers. Those grinding marks generated in 3D coordinates could possibly be used to represent the wafer shape. They presented eight basic wafer shapes by means of grinding marks in 3D coordinates. But, a systematical study of the effects of the process parameters on the wafer shape was not reported.
They also claimed that higher cutting path density always led to removal of more material and resulted in a concave wafer shape. Then the cutting path density at a specific area of the wafer surface was used to investigate the effects of rotation speeds of the wheel and the wafer on the wafer shape. They reported that a more practical solution to offset the effect of the rotation speeds on the wafer shape was to tilt the wafer rotation axis slightly against the wheel rotation axis.

2.5 The model for the wafer shape in SDSG of silicon wafers by Pietsch and Kerstan (2005)

Pietsch and Kerstan (2005) developed a model for the wafer shape in SDSG of silicon wafers. Their assumption was that the wafer shape was determined by the wheel/wafer kinematics (i.e. the wheel rotation speed $\omega$, the wafer rotation speed $\Omega$, the wheel radius $r_0$, and the wafer radius $R_0$). The geometry for developing their model is shown in Figure 5. They claimed that the amount of material removed by the wheel at any point along the radial direction on the wafer surface during time $dt$ could be described as:

$$\text{removal} = \frac{(\text{path swept by wheel})(\text{wheel rim width})}{\text{wafer area swept by wheel}} dt \quad (1)$$

As shown in Figure 5, the path swept by the wheel was arc BC; the rim width $w$ of the wheel was set as unity 1; the wafer area swept by the wheel was the sector $ABDC$.

Their investigation has some conclusions about the wafer shape in SDSG:

1. There was always a dimple at the centre of the wafer.
2. The edge of the wafer always tapered off ("roll-off").
3. When the two grinding wheels rotated in different directions, the surface on one side of the wafer was different from the other side. This was a limitation of SDSG if identical wafer surfaces on both sides were required in production. But, the difference could be reduced when the wheels rotated at a high speed making $\omega/\Omega >> 1$.

Figure 5  Geometry for developing the wafer shape model in SDSG

Their model could predict the wafer shape fairly well for the outer portion. But, there always exist singular solutions around the centre of the wafer. It is interesting to note that their predicted wafer shapes were obtained using the stock material removal through Equation (1), but in their experiments, the wafer shapes were altered by tilting the wheels. They did not report the effects of the ‘roll’ angle and the ‘pitch’ angle on the wafer shape.

Table 1 summarises the aforementioned models for the wafer shape. It indicates that no systematical study has been reported about the effects of important parameters (such as the ‘roll’ angle, ‘pitch’ angle and wheel radius) on the wafer shape in SDSG of silicon wafers.

Table 1  Summary of reported work on wafer shape

<table>
<thead>
<tr>
<th>Authors [Ref]</th>
<th>Reported work</th>
<th>Effects of ‘roll’ angle</th>
<th>Effects of ‘pitch’ angle</th>
<th>Effects of wheel diameter</th>
<th>Effects of rotation speed</th>
</tr>
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<td>Cylindrical surface grinding of metal parts</td>
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<tr>
<td>Sun et al. (2004)</td>
<td>SSG of 200 mm silicon wafers</td>
<td>√</td>
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<tr>
<td>Tso and Teng (2001)</td>
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<tr>
<td>Zhou et al. (2003)</td>
<td>SSG of 300 mm silicon wafers</td>
<td>√</td>
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<td>Pietsch and Kerstan (2005)</td>
<td>SDSG of 300 mm silicon wafers</td>
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</table>

3  Development of the mathematical model for the wafer shape in SDSG of 300 mm silicon wafers

3.1 Assumptions for the mathematical model

For the model in this paper, each grinding wheel in the SDSG process is assumed as a ring of rotating abrasives and the ring of rotating abrasives always passes through the wafer centre. As shown in Figure 6, the ‘roll’ angle, $\alpha$, is defined as the tilt angle of the grinding wheel around the $OX$ axis. The ‘pitch’ angle, $\beta$, is defined as the tilt angle of the grinding wheel around the $OY$ axis. The $OX$ and $OY$ axes are perpendicular to each other and both are perpendicular to the wafer rotation axis (the $Z$-axis).

In this paper, the wafer shape studied is the shape of one surface of the wafer. It is determined by the ‘roll’ and ‘pitch’ angles of the grinding wheel that grinds this side of the wafer. The shape of the other surface of the wafer can be studied in the same manner.

As illustrated in Figure 7, the ring of rotating abrasives enters the wafer surface at point $A$ along arc $AOB$ and exits the wafer surface at point $B$. A coordinate system $XOY$ is used to define all the points on the wafer and the grinding wheel. The origin of the $XOY$ coordinate system is at the centre of the wafer. Mathematically, the envelope swept by arc $AOB$ when it is rotated around the $Z$-axis forms the wafer shape.
Figure 6  Illustration of the ‘roll’ angle (\(\alpha\)) and ‘pitch’ angle (\(\beta\))

Figure 7  Geometry for developing the wafer shape model
3.2 Derivations of the mathematical model

When the wheel surface is parallel to the XOY plane (\( \alpha = 0 \) and \( \beta = 0 \)), arc AOB can be described by the following equations:

\[
\begin{align*}
X(t) &= R_1 \cos(2\pi N_1 t) + R_i \\
Y(t) &= R_1 \sin(2\pi N_1 t) \\
Z(t) &= 0
\end{align*}
\]

where \( X(t), Y(t) \) and \( Z(t) \) are the coordinate components of every point on arc AOB; \( R_1 \) and \( R_i \) the wheel radius and wafer radius, respectively; \( N_1 \) the wheel rotation speed; \( t \) the time.

When the wheel is tilted around the X-axis by an angle of \( \alpha \) and around the Y-axis by an angle of \( \beta \), arc AOB will be represented as:

\[
\begin{align*}
X(t) &= R_1 \cos(2\pi N_1 t) + R_i \\
Y(t) &= R_1 \sin(2\pi N_1 t) + R_i \\
Z(t) &= R_i \sin(2\pi N_1 t)
\end{align*}
\]

or

\[
\begin{align*}
X(t) &= \cos \beta R_i \cos(2\pi N_1 t) + R_i \\
Y(t) &= \sin \alpha \sin R_i \cos(2\pi N_1 t) + R_i \\
Z(t) &= \cos \alpha \sin R_i \sin(2\pi N_1 t) + \sin \alpha R_i \sin(2\pi N_1 t)
\end{align*}
\]

The relation between the length in wafer radial direction and the height of the wafer surface can be obtained from the above equation. This relation will produce a line profile to describe the wafer shape (2D). The 3D wafer shape can be obtained by rotating the line profile around the Z-axis.

3.3 Computer programs for the mathematical model

The model developed above has been used to write programs with a commercial software package Matlab (The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760, USA). All programs accept SDSG parameters (i.e. the ‘roll’ angle \( \alpha \), the ‘pitch’ angle \( \beta \), the wheel radius \( R_1 \) and the wafer radius \( R_i \)) as input variables and plot the wafer shapes (2D or 3D) as output. In the following sections of this paper, unless specified otherwise, the wafer has a radius of 150 mm while the wheel has a radius of 80 mm.

4 Simulation results and discussion

4.1 Basic wafer shapes

Figure 8 shows the wafer shapes (3D) for different combinations of the ‘roll’ angle and ‘pitch’ angle. Note that the wafer shape is not affected by the tilt direction of the ‘roll’ angle, hence the wafer shapes shown in Figure 8 (a), (d) and (g) are the same as those in Figure 8(c), (f) and (i), respectively.
Figure 8  3D wafer shapes for different combinations of ‘roll’ and ‘pitch’ angles (a) $\alpha = +5$ $\mu$rad, $\beta = +5$ $\mu$rad, (b) $\alpha = 0$ $\mu$rad, $\beta = +5$ $\mu$rad, (c) $\alpha = -5$ $\mu$rad, $\beta = +5$ $\mu$rad, (d) $\alpha = +5$ $\mu$rad, $\beta = 0$ $\mu$rad, (e) $\alpha = 0$ $\mu$rad, $\beta = 0$ $\mu$rad, (f) $\alpha = -5$ $\mu$rad, $\beta = 0$ $\mu$rad, (g) $\alpha = +5$ $\mu$rad, $\beta = -5$ $\mu$rad, (h) $\alpha = 0$ $\mu$rad, $\beta = -5$ $\mu$rad and (i) $\alpha = -5$ $\mu$rad, $\beta = -5$ $\mu$rad
For further discussion, the wafer shape is resolved into two components, the across-diameter component and the across-radius component as shown in Figure 9. The across-diameter component characterises the wafer shape along the wafer diameter, and is measured by $\delta_1$, the distance from the wafer centre (point O) to the line (line $AB$) connecting two ends (on the diameter of the wafer surface) of the wafer surface. The across-radius component characterises the wafer shape along the wafer radius and is measured by $\delta_2$, the maximum distance from any point on the wafer surface to the line (line $OA$ or $OB$) connecting the centre and the edge of the wafer surface. $\delta_1$ and $\delta_2$ are assigned the ‘+’ or ‘–’ sign by the following rule: when a component (either $\delta_1$ or $\delta_2$) is convex, the corresponding distance (either $\delta_1$ or $\delta_2$) will bear a positive sign; when a component is concave, the distance will have a negative sign.

4.2 Effects of the ‘roll’ angle on the wafer shape

Figures 10–12 show various wafer shapes for different ‘roll’ angles when the ‘pitch’ angle $\beta = 0$ µrad, $\beta = +2$ µrad and $\beta = -2$ µrad, respectively. As the absolute value of the ‘roll’ angle increases, $\delta_1$ increases but $\delta_2$ decreases.

**Figure 9**  Two components of the wafer shape

**Source:** After Sun et al. (2005).

**Figure 10**  Wafer shape variation with different ‘roll’ angles (when ‘pitch’ angle $\beta = 0$ µrad)
4.3 Effects of the ‘pitch’ angle on the wafer shape

Figures 13 and 14 show various wafer shapes for different ‘pitch’ angles when the ‘roll’ angle \( \alpha = 0 \) µrad and \( \alpha = \pm 2 \) µrad, respectively. Wafer shapes are not only related to the absolute value but also to the sign of the ‘pitch’ angle. As the ‘pitch’ angle increases from \(-8\) µrad to \(+8\) µrad, both \( \delta_1 \) and \( \delta_2 \) increase (changing from negative values to positive values).

4.4 Effects of the wheel radius on the wafer shape

Figure 15 shows various wafer shapes as the wheel radius increases from 75 to 150 mm when \( \alpha = 0 \) µrad and \( \beta = +5 \) µrad. As the wheel radius increases, both \( \delta_1 \) and \( \delta_2 \) decrease. Figures 16 and 17 show various wafer shapes as the wheel radius increases from 75 to 150 mm when \( \alpha = 0 \) µrad and \( \beta = -5 \) µrad and when \( \alpha = \pm 5 \) µrad and \( \beta = 0 \) µrad, respectively. As the wheel radius increases, both \( \delta_1 \) and \( \delta_2 \) increase.
Figure 13  Wafer shape variation with different ‘pitch’ angles (when ‘roll’ angle $\alpha = 0$ µrad)

Figure 14  Wafer shape variation with different ‘pitch’ angles (when ‘roll’ angle $\alpha = \pm 2$ µrad)

Figure 15  Wafer shape variation with different wheel radii ($\alpha = 0$ µrad, $\beta = +5$ µrad)
5 Conclusion

In this paper, a mathematical model is developed for the wafer shape in SDSG of silicon wafers. The following conclusions can be drawn from this study:

1. The wafer shape is affected by the absolute value only (not the sign) of the ‘roll’ angle. With the increase of the absolute value of the ‘roll’ angle, $\delta_1$ increases but $\delta_2$ decreases.

2. The wafer shape is affected not only by the absolute value but also by the sign of the ‘pitch’ angle. As the ‘pitch’ angle increases (changing from negative angles to positive angles), both $\delta_1$ and $\delta_2$ increase.

3. The wafer shape is also affected by the wheel radius. As the wheel radius increases, both $\delta_1$ and $\delta_2$ will either decrease or increase, depending on the values of the ‘roll’ angle and ‘pitch’ angle.
This work has provided a foundation for future investigations of SDSG. For example, it was reported that the nanotopography of the wafer surfaces was affected by the shift and tilts of the grinding wheels in SDSG (Bhagavat et al., 2005). The model developed in this paper will be instrumental in the model development for the nanotopography of the wafer surfaces processed by SDSG.

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