Fine grinding of silicon wafers: a mathematical model for the chuck shape

S. Chidambaram a, Z.J. Pei a,*, S. Kassir b

a Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA
b Strasbaugh, Inc., 825 Buckley Road, San Luis Obispo, CA 93401, USA

Received 15 November 2002; accepted 15 January 2003

Abstract

Fine grinding of silicon wafers is a patented technology to manufacture super flat semiconductor wafers cost-effectively. Two papers on fine grinding were previously published in this journal, one discussed its uniqueness and special requirements, and the other presented the results of a designed experimental investigation. As a follow up, this paper presents a study aiming at overcoming one of the technical barriers that have hindered the widespread application of this technology, namely, the difficulty and uncertainty in chuck preparation. Although the chuck shape is critically important in fine grinding, there are no standard procedures for its preparation. Furthermore, the information on the relation between the set-up parameters and the resulting chuck shape is not readily available. In this paper, a mathematical model for the chuck shape is first developed. Then the model is used to predict the relations between the chuck shape and the set-up parameters. Finally, the results of the pilot experiments to verify the model are discussed.

Keywords: Chuck; Grinding; Machining; Modeling; Semiconductor materials; Silicon wafers

1. Introduction

Feature sizes on integrated circuits have continuously shrunk since the beginning of semiconductor fabrication. They started at about 125 µm in the early 1950s [1] and reached 0.13 µm recently [2]. In order to ensure high quality chips with high yield, the base material, semiconductor wafers (over 90% are silicon), must have superior quality. Flatness of the wafer surface directly impacts device feature size capability, process yield and throughput. The continuing reduction in feature size and increasingly stringent device fabrication specifications are forcing wafer manufacturers to prepare increasingly flatter wafers. It is critically important to develop new manufacturing processes that allow silicon wafer manufacturers to produce flatter wafers at a reasonably low cost.

One such process is a patented technology—fine grinding of etched silicon wafers [3]. Wafer grinding is illustrated in Fig. 1. The grinding wheel is a diamond cup wheel. The workpiece (wafer) is held onto a porous ceramic chuck by means of vacuum. The rotational axis of the grinding wheel is offset by a distance of the wheel radius relative to the rotational axis of the wafer. During grinding, the grinding wheel and the wafer rotate about their own rotational axes simultaneously, and the wheel is fed towards the wafer along its axis. The ceramic chuck is typically dressed to a conic shape with a very small slope (see Fig. 2). When the wafer is held onto the chuck, it elastically deforms 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 Grinding Zone” in Fig. 1. By adjusting β, the angle between the wheel rotational axis and wafer rotational axis, the wafer shape can be controlled. With larger β, the wafer tends to be convex. With smaller β, the wafer tends to be concave.

Fine grinding of silicon wafers first appeared in the public domain through a US patent [3]. Pei and Strasbaugh [4] reported preliminary experimental work on the effects of grinding wheels, process parameters, and grinding coolant. In a follow-up paper, Pei and Stras-
Fine grinding has been implemented in production, but the scale of its application is very limited. Several technical barriers have hindered its widespread application. One such barrier is related to preparation of the chuck shape used in fine grinding.

The chuck shape is very critical in wafer grinding. Certain shapes produce better results than others do. However, in practice, there are no sufficient guidelines for chuck preparation. Different people use different set-up parameters to grind the chuck and obtain different shapes. The relation between set-up parameters and chuck shape is not available in the literature. Lack of such knowledge has caused the difficulty and uncertainty in chuck preparation. This is one of the obstacles to further advancement of fine grinding technology.

This paper is to address this technical barrier. It develops a mathematical model to predict the chuck shape from the set-up parameters. The results of this study are also useful to two other wafer-grinding applications. One is to flatten sliced wafers after wire sawing or ID (internal diameter) sawing. The other is to thin (or back-grind) the completed wafers after integrated circuits are built on the front sides. More information on grinding of sliced wafers and back grinding of completed wafers can be found in [7–16].

Among the literature relevant to the chuck preparation are analyses on vertical-spindle surface grinding using conventional wheels [17], diamond cup wheel grinding of parabolic and toroidal surface on ceramics for mirrors [18,19], and precision cylindrical face grinding using a narrow-ring superabrasive wheel [20]. These analyses are instrumental to the model development for silicon wafer fine grinding but cannot be applied directly.

This paper is organized into five sections. Following this introduction section, Section 2 develops the mathematical model. In Section 3, the model is used to predict the relations between the chuck shape and the set-up parameters. Section 4 discusses the pilot experiments performed to verify the model. Conclusions are drawn up in Section 5.

### 2. Development of the mathematical model

Though there are several different configurations for wafer grinders, they all use the same principle for chuck set-up. The common set-up parameters are the distances between the wheel-segment surface and the chuck plane at three different locations, $M$, $O$ and $N$, as shown in Fig. 3. The chuck plane is a plane perpendicular to the chuck rotational axis.

In Fig. 3, the small circle with radius $R_c$ represents the chuck with its rotational axis perpendicular to this paper surface. The big circle with radius $R$ represents the wheel with its rotational axis forming a small angle to the chuck rotational axis. Strictly speaking, the big
circle should not be a perfect circle on this paper surface. However, the distortion is hardly visible because the inclination angle is very small. The origin of the XYZ coordinate system is at point O, the center of the chuck. The XOY plane coincides with the chuck plane. The Z-axis points out of this paper surface. Points M(x_M, y_M, z_M), O(0, 0, 0), and N(x_N, y_N, z_N) are fixed on the wheel where z_M and z_N are the vertical distances between the wheel-segment surface and the chuck plane. Note that if z_M = z_N, the case becomes similar to Shih and Lee’s calculation [20]. For the UVW coordinate system, its origin is also at O, but its three axes are to be determined from set-up parameters. The W axis is parallel to the rotational axis of the wheel. The direction of the W axis relative to the XYZ system is the same as the following vector:

\[
\vec{n} = \vec{ON} \times \vec{OM} = 
\begin{bmatrix}
\hat{i} & \hat{j} & \hat{k} \\
 x_N & y_N & z_N \\
 x_M & y_M & z_M 
\end{bmatrix}.
\] (1)

Or

\[
\vec{n} = (y_Nz_M - y_Mz_N)\hat{i} + (x_Mz_N - x_Nz_M)\hat{j} + (x_Ny_M - x_My_N)\hat{k}. \] (2)

The direction cosines of the W axis are

\[
l_3 = \frac{y_Nz_M - y_Mz_N}{\sqrt{(y_Nz_M - y_Mz_N)^2 + (x_Mz_N - x_Nz_M)^2 + (x_Ny_M - x_My_N)^2}}. \] (3)

\[
m_3 = \frac{x_Mz_N - x_Nz_M}{\sqrt{(y_Nz_M - y_Mz_N)^2 + (x_Mz_N - x_Nz_M)^2 + (x_Ny_M - x_My_N)^2}} \]

\[
n_3 = \frac{x_Ny_M - x_My_N}{\sqrt{(y_Nz_M - y_Mz_N)^2 + (x_Mz_N - x_Nz_M)^2 + (x_Ny_M - x_My_N)^2}}. \]

The V axis is parallel to the vector below:

\[
\vec{MN} = (x_N - x_M)\hat{i} + (y_N - y_M)\hat{j} + (z_N - z_M)\hat{k}, \] (4)

so the direction cosines of the V axis, l_2, m_2, n_2, can be found. The direction cosines, l_1, m_1, n_1, of the U axis can be found by the fact that \(\vec{U} = \vec{V} \times \vec{W}\).

For any point along the arc MO, a relation between its coordinates (u, v, w) in the UVW system and its coordinates (x, y, z) in the XYZ system can be derived as:

\[
\begin{bmatrix}
x \\
y \\
z \\
1 
\end{bmatrix} = 
\begin{bmatrix}
l_1 & l_2 & l_3 & 0 \\
m_1 & m_2 & m_3 & 0 \\
n_1 & n_2 & n_3 & 0 \\
0 & 0 & 0 & 1 
\end{bmatrix} 
\begin{bmatrix}
u \\
v \\
w \\
1 
\end{bmatrix}. \] (5)

In the UVW system, the arc MO is expressed as

\[
u = R \cos \phi - R \]

\[
v = R \sin \phi \]

\[
w = 0 - 2 \arcsin \left(\frac{R}{2R}\right) \leq \phi \leq 0 \] (6)

From Eqs (5) and (6), the arc MO can be expressed in the XYZ system in the form of

\[
x = f(\phi) \]

\[
y = g(\phi) \]

\[
z = h(\phi) - 2 \arcsin \left(\frac{R}{2R}\right) \leq \phi \leq 0 \] (7)

For every value of \(\phi\), r can be calculated by \(r^2 = x^2 + y^2\). Combining \(r\) and \(z\) will give the chuck line profile. The chuck line profile refers to the surface contour on a cross-section along a chuck diameter.

The above mathematical equations are used to develop a program using a commercial software package Matlab (The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760, USA). This program will accept set-up parameters as input variables and plot the chuck profile as output.

3. Effects of set-up parameters on chuck shape

In the preceding section, a mathematical model has been developed to predict the chuck shape when the set-up parameters (i.e., the z-coordinates of points M, O and N) are known. Next, this model will be used to investigate the effects of set-up parameters on the chuck shape. If \(z_O\) is assumed to be zero, then the z-coordinates of points M and N, \(z_M\) and \(z_N\), will determine the inclination angle between the rotational axis of the grinding wheel relative to the rotational axis of the chuck. In order to systematically investigate the effects of \(z_M\) and \(z_N\) on the
chuck shape, the values of $z_M$ and $z_N$ will be assigned in a manner that they will cause the wheel to either "roll" or "pitch". The "roll" motion of the wheel is the rotation of the grinding wheel about the X-axis with point $O$ on the grinding wheel as the pivot. The "pitch" motion of the wheel is the rotation of the grinding wheel about the Y-axis with point $O$ on the grinding wheel as the pivot.

The variation of the chuck shape with the "roll" motion of the grinding wheel can be understood by increasing $z_M$ and decreasing $z_N$ simultaneously, or decreasing $z_M$ and increasing $z_N$ simultaneously. The variation of the chuck shape with the "pitch" motion of the grinding wheel can be appreciated by increasing $z_M$ and $z_N$ simultaneously, or decreasing $z_M$ and $z_N$ simultaneously.

3.1. The effects of "roll"

Fig. 4 shows various chuck shapes as the grinding wheel "rolls" to different orientations. As the difference ($z_N - z_M$) decreases, the slope of the chuck decreases. But the convexity or concavity remains the same (for values of $z_M$ and $z_N$ used here, the chuck shape remains relatively straight from edge to center).

The practical use of this knowledge can be illustrated as follows. After grinding the chuck with a set of parameters ($z_M$ and $z_N$), the slope of the chuck shape can be measured. If a smaller (or larger) slope is desired, the wheel should be "rolled" in such a way that the difference ($z_N - z_M$) will be decreased (or increased).

3.2. The effects of "pitch"

Fig. 5 shows several chuck shapes as the grinding wheel "pitches" to different orientations. As $z_M$ and $z_N$ decrease simultaneously, the chuck shape from the edge to the center (note that the chuck shape discussed here does not go across the entire chuck diameter) changes from concave to straight, and then to convex.

This knowledge can be useful for chuck preparation. The following example can be used to illustrate the use of this knowledge. Assume that a straight profile (from edge to center) of chuck shape is desirable. After a chuck is ground and measured, one can use the knowledge to decide how to adjust the wheel orientation to reach the desirable profile. If the ground chuck has convex shape (or concave shape) from edge to center, then the wheel should be "pitched" in a way that both $z_M$ and $z_N$ should be increased (or decreased) simultaneously.

4. Pilot experimental verification

4.1. Experimental procedure

The pilot experiments consisted of two parts: (a) chuck grinding, and (b) chuck shape measurement.

![Fig. 4. Variation of line profile along the chuck diameter due to the "roll" of wheel.](image-url)
was a diamond cup wheel with the grit size of mesh #320. The diameter of the wheel was 280 mm. During chuck grinding, deionized (purified) water was used to cool the grinding wheel and the chuck surface. The coolant was supplied to the inner side of the cup wheel, at a flow rate of 3 gallons per minute. Wheel rotational speed was 34.84 rev s\(^{-1}\) (2125 rpm), chuck rotational speed was 0.97 rev s\(^{-1}\) (60 rpm), and feedrate was 0.6 \(\mu m\) s\(^{-1}\).

Measurement of chuck shape was conducted with two different instruments: dial indicators and a CMM (coordinate measuring machine). Three dial indicators were used. The Mahr dial indicator has divisions of 0.5 \(\mu m\), the Mikrokator dial indicator 0.25 \(\mu m\) and the Starrett dial indicator 0.5 \(\mu m\). Each dial indicator was mounted on a base as shown in Fig. 6. Each base has three supports evenly distributed on a circle. The diameter of the circle is 3 inches, 6 inches and 8 inches for the three bases, respectively. Each base with the dial indicator installed is put on the chuck in such a way that the probe of the dial indicator is on the center of the chuck. The reading on the dial indicator indicates the height of the chuck center relative to the circle where the tips of the supports rest.

The DEA Swift coordinate measuring machine (CMM) used for the measurement is located in the Manufacturing Laboratory at California Polytechnic State University (San Luis Obispo, CA). It is shown in Fig. 7. It has the resolution of 1 \(\mu m\). It is used to measure the heights of the points on the chuck surface along a diameter by moving along only one axis at a time. Data are collected along two directions: AB (X axis) and CD (Y axis), as shown in Fig. 8.

Fig. 5. Variation of line profile along the chuck diameter due to the "pitch" of wheel.

![Variation of line profile along the chuck diameter](image)

Table 1

<table>
<thead>
<tr>
<th>Chuck identification</th>
<th>Height of point N, Z(_N) ((\mu m))</th>
<th>Height of point O, Z(_O) ((\mu m))</th>
<th>Height of point M, Z(_M) ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chuck 1</td>
<td>4.5</td>
<td>0</td>
<td>−4.5</td>
</tr>
<tr>
<td>Chuck 2</td>
<td>1.0</td>
<td>0</td>
<td>−0.7</td>
</tr>
</tbody>
</table>

Fig. 6. The set-up of dial indicator to measure the height of the chuck center relative to the supports.

![Set-up of dial indicator](image)
4.2. Experimental results

Both chuck 1 and chuck 2 were measured by the dial indicators. The measured data are presented in Tables 2 and 3. Comparisons with the model predictions are provided in Fig. 9. Only chuck 1 was measured by CMM and the results are included in Tables 4 and 5. Again, the experimental data are compared with the model predictions, as shown in Fig. 10.

It can be seen that there is some scattering for the measured data points. However, the trends of model predictions and experimental data are consistent. The experimental results are fairly good considering the resolutions of the instruments used.

Further experimental verification will be undertaken when more advanced measuring instrumentation becomes available.

5. Conclusion

A mathematical model has been developed to predict the chuck shape for fine grinding. Given the set-up para-
Table 4
Experimental data for chuck 1 measured with CMM along direction AB (X axis)

<table>
<thead>
<tr>
<th>X coordinate (mm)</th>
<th>Measured Z (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−100</td>
<td>−3.9795</td>
</tr>
<tr>
<td>−93</td>
<td>−3.3361</td>
</tr>
<tr>
<td>−82</td>
<td>−4.2679</td>
</tr>
<tr>
<td>−71</td>
<td>−3.1997</td>
</tr>
<tr>
<td>−63</td>
<td>−3.4501</td>
</tr>
<tr>
<td>−44</td>
<td>−2.4323</td>
</tr>
<tr>
<td>−34</td>
<td>−1.2703</td>
</tr>
<tr>
<td>−28</td>
<td>−1.5331</td>
</tr>
<tr>
<td>−16</td>
<td>−1.2587</td>
</tr>
<tr>
<td>−3</td>
<td>−1.7781</td>
</tr>
<tr>
<td>1</td>
<td>−1.2533</td>
</tr>
<tr>
<td>9</td>
<td>−0.4037</td>
</tr>
<tr>
<td>10</td>
<td>−0.2975</td>
</tr>
<tr>
<td>28</td>
<td>−1.1859</td>
</tr>
<tr>
<td>40</td>
<td>−1.8115</td>
</tr>
<tr>
<td>47</td>
<td>−4.0681</td>
</tr>
<tr>
<td>54</td>
<td>−3.2247</td>
</tr>
<tr>
<td>65</td>
<td>−3.0565</td>
</tr>
<tr>
<td>73</td>
<td>−4.1069</td>
</tr>
<tr>
<td>81</td>
<td>−3.1573</td>
</tr>
<tr>
<td>89</td>
<td>−4.3077</td>
</tr>
<tr>
<td>95</td>
<td>−2.4705</td>
</tr>
</tbody>
</table>

Table 5
Experimental data for chuck 1 measured with CMM along direction CD (Y axis)

<table>
<thead>
<tr>
<th>Y coordinate (mm)</th>
<th>Measured Z (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−100</td>
<td>−2.7479</td>
</tr>
<tr>
<td>−90</td>
<td>−2.8869</td>
</tr>
<tr>
<td>−84</td>
<td>−2.2503</td>
</tr>
<tr>
<td>−74</td>
<td>−4.3893</td>
</tr>
<tr>
<td>−61</td>
<td>−2.1100</td>
</tr>
<tr>
<td>−50</td>
<td>−1.8429</td>
</tr>
<tr>
<td>−44</td>
<td>−3.1063</td>
</tr>
<tr>
<td>−42</td>
<td>−1.8941</td>
</tr>
<tr>
<td>−36</td>
<td>−2.2575</td>
</tr>
<tr>
<td>−25</td>
<td>−0.9004</td>
</tr>
<tr>
<td>−17</td>
<td>−1.0416</td>
</tr>
<tr>
<td>−3</td>
<td>−0.4562</td>
</tr>
<tr>
<td>8</td>
<td>−0.1891</td>
</tr>
<tr>
<td>18</td>
<td>−1.1281</td>
</tr>
<tr>
<td>31</td>
<td>−2.6488</td>
</tr>
<tr>
<td>39</td>
<td>−1.7000</td>
</tr>
<tr>
<td>48</td>
<td>−1.7451</td>
</tr>
<tr>
<td>56</td>
<td>−3.7963</td>
</tr>
<tr>
<td>68</td>
<td>−2.4231</td>
</tr>
<tr>
<td>76</td>
<td>−2.4743</td>
</tr>
<tr>
<td>83</td>
<td>−2.7316</td>
</tr>
<tr>
<td>90</td>
<td>−2.8889</td>
</tr>
<tr>
<td>97</td>
<td>−2.8462</td>
</tr>
</tbody>
</table>

Fig. 10. Comparison of the predicted chuck shape for chuck 1 with experimental results by CMM.

meters (the height of three points on the wheel relative to the chuck surface), the model will be able to plot the line profile of the chuck shape. The relationships between the chuck shape and set-up parameters derived from the model are useful in the preparation of chuck shape. Pilot experiments have shown that the model predictions match with the experimental data fairly well.

Acknowledgements

Financial support for this work was provided by the Advanced Manufacturing Institute at Kansas State University. The authors would like to thank Professor Daniel J. Waldorf at California Polytechnic State University for his arrangement to allow the use of the CMM at the manufacturing laboratory.

References