Dielectric Materials
and Electronic Devices
Numerical Simulations of a Back Grinding Process for Silicon Wafers

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Abstract
The optimization of grinding parameters for silicon wafers is necessary in order to maximize the reliability of electronic packages. This paper describes the work performed to simulate a back grinding process for silicon wafers using the commercial finite element code ABAQUS. The silicon wafer analyzed had a thickness of 120 µm and was mounted on a backing tape. The wafer was thinned to a thickness of 96 µm, by simulating the grinding with a diamond particle cutting through successive silicon layers. The modeled residual stresses induced in the wafer were compared with experimental data, and they were shown to agree well. A shear band of intense plastic deformation with a certain orientation angle was generated in the specimen, and the value of this angle was compared with experimental data for similar materials. The numerical model developed can be used to better understand the local conditions in wafers during this back grinding process.

Introduction
The development of electronic packages is based on strict weight and size requirements. Smaller, lighter, and higher capacity devices at low cost are what consumers demand. In order to achieve this goal, electronic packaging plays a major role in this industry. The silicon wafer thickness affects the package size, thus, the thinner the wafer the lower the overall package height. The manufacturing process of wafers faces many challenges. One of these challenges is the thinning process, which is performed during the back grinding of the wafer. Significant research efforts have been devoted to the development and improvement of this process. Most of the studies have been experimental or analytical in nature, with few analyses considering numerical simulations that studied the wafer-wheel behavior14. In order to better understand the details of the wafer grinding process; a micron scale study is needed to clarify the internal stresses, strains, and deformations that take place into the wafer material while and after the grinding process.

In this paper, a numerical study is performed to simulate the grinding process at the micron level in order to understand the stresses and deformations developed in the wafer during...
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this process. The model developed showed good correlation with the experimental data measured using Raman spectroscopy for similar silicon wafers.

**NUMERICAL MODEL**

The goal of this study is to simulate the back grinding process of the silicon wafer in order to be able to measure the stress field at different locations in the wafer, and to achieve a good understanding of the grinding process. The numerical simulations involved varying operating parameters affecting this manufacturing process to determine the optimum operating conditions.

To simulate the grinding process the commercial finite element software ABAQUS, Explicit was used. In the literature, there are different finite element grinding models, which can be categorized by the scale of the modeling approach as macro-scale or micro-scale models. Macro-scale models consider the overall wheel–workpiece interaction, which captures the aggregate effects of the abrasive wheel on the workpiece with no attempts to study the effect of the individual abrasive grain on the workpiece. The micro-scale models focus on the individual grain–workpiece interactions, which can examine the actual material removal mechanism. Thus, micro-scale models have the potential to allow the estimation of the grinding forces directly without resorting to measurements or empirical modeling. This model simulates the micro-scale grinding process, which includes the effect of a single diamond crystal (abrasive grain) while it removes layers from the silicon wafer (workpiece) as shown in figure 1.

![Micro-scale grinding model](image)

**Figure 1. Micro-scale grinding model.**

A two-dimensional model was built to simulate a part of the silicon wafer and a small particle of diamond which moves and cuts through successive silicon layers. In the present simulations, the number of the cutting passes was chosen as 12. The cutting depth of each pass was set at 2 μm, where we found a realistic cutting depth for the grinding process. After the
completion of the 12 cutting passes the model was allowed a relaxation time. The model considers only a part of the silicon wafer which is completely attached to a plastic backing film Poly Ethylene Terephthalate (PET) as shown in figure 2.

![Figure 2. Finite element model used to simulate the micro-scale grinding.](image)

The back grinding process of the silicon wafers is performed in three steps. First is the coarse grinding, the second step is the intermediate grinding, which involves the thinning of the wafer to a thickness of approximately 85 μm. This step is the focus of our study. The third and final step is the fine grinding, when the wafer thickness is reduced to the desired value.

The boundary conditions shown in figure 2 were set as:

1) The bottom of the model is pinned to simulate the attachment to the vacuum chuck.
2) The sides of the model are symmetry boundary conditions along the X-axis to simulate the effect of the remaining parts of the wafer and the adhesive tape on each side which have not been included in the model.
3) The diamond crystal was displaced in the X direction to simulate the cutting action and returning back, and was displaced in the Y direction to simulate the cutting depth.

An initial mesh with a global element size of 5 μm was used for both the silicon and PET material. The mesh was further refined to a global element size of 1 μm. Finally, a more refined mesh of 0.5 μm global element size was used for the silicon wafer, and a mesh with a larger element size of 20 μm was used for the PET adhesive tape. This mesh size was used to extract the data presented in this paper.

The model consists of two materials, silicon as the wafer and PET as the backing tape materials. Silicon <100> single crystal at room temperature is a hard and brittle material. As the working temperature is kept at 23 °C by the effect of the coolant during the grinding process, the stress-strain curve for the silicon at 25 °C was used to model the material behavior as elastic-plastic with a damage criterion. A damage criterion and an element deletion scheme have been used to simulate the material removal during grinding.

ELASTIC-PLASTIC AND DAMAGE MODEL

Because of the crystalline nature of the silicon <100>, orthotropic elasticity was chosen to model the elasticity of the material. Linear elasticity in an orthotropic material can be defined by nine independent elastic stiffness parameters. These parameters can be functions of temperature and other predefined fields, such as the strain rate. In our model there is no effect of the temperature due to the cooling process that maintain the wafer at 23°C, and the model is not
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strain rate dependent. In this case the stress (σ)-strain (ε) relations take the form shown in equation 1, with the constants $D^{e}$ shown in table 1.

$$
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix} =
\begin{bmatrix}
D_{1111} & D_{1122} & D_{1133} & 0 & 0 & 0 \\
D_{1212} & D_{2222} & D_{2233} & 0 & 0 & 0 \\
D_{1313} & D_{2323} & D_{3333} & 0 & 0 & 0 \\
0 & 0 & 0 & D_{1222} & 0 & 0 \\
0 & 0 & 0 & 0 & D_{1313} & 0 \\
0 & 0 & 0 & 0 & 0 & D_{2323}
\end{bmatrix}
\begin{bmatrix}
\epsilon_{11} \\
\epsilon_{22} \\
\epsilon_{33} \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix}
$$

(1)

An isotropic plasticity model with a von-Mises hardening criterion was used to simulate the plasticity of the silicon material. Silicon does not deform significantly in the plastic region before damage onset and fracture. The plasticity of the silicon was modeled by building the effective stress-strain curve using the data from table 2.

<table>
<thead>
<tr>
<th>Table 1. $D^{e}$ matrix constants</th>
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<tbody>
<tr>
<td>$D_{1111}$</td>
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<tr>
<td>$D_{1212}$</td>
</tr>
<tr>
<td>$D_{2222}$</td>
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<tr>
<td>$D_{1313}$</td>
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<tr>
<td>$D_{2323}$</td>
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<tr>
<td>$D_{1222}$</td>
</tr>
<tr>
<td>$D_{1313}$</td>
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<tr>
<td>$D_{2323}$</td>
</tr>
</tbody>
</table>

A shear damage initiation criterion with an element deletion scheme was used to simulate the material removal that occurs due to the grinding process. The shear damage criterion predicts the onset of damage due to shear band localization, and it is used in conjunction with the von Mises plasticity model.

<table>
<thead>
<tr>
<th>Table II. Plasticity constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress MPa</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>1100</td>
</tr>
<tr>
<td>1200</td>
</tr>
</tbody>
</table>
The shear damage criteria model assumes that the equivalent plastic strain at the onset of damage $\varepsilon^p_s$ is a function of the shear stress ratio $\theta_s$, and strain rate $\dot{\varepsilon}^p$.

$$\theta_s = \frac{(q + k_p)\dot{\varepsilon}^p}{\tau_{max}}$$

(2)

where $\tau_{max}$ is the maximum shear stress, $k_p$ is a material parameter, which was set to 0.3, $q$ is the equivalent stress, and $\rho$ is the pressure stress. The criterion for damage initiation is met when the following condition is satisfied:

$$w_s = \frac{\int d\dot{\varepsilon}^p}{\dot{\varepsilon}^p \left( \theta_s, \dot{\varepsilon} \right)} = 1$$

(3)

where $w_s$ is a state variable that increases monotonically with the plastic deformation and is proportional to the incremental change in equivalent plastic strain. At each increment during the analysis the incremental increase in $w_s$ is computed as:

$$\Delta w_s = \frac{\Delta \dot{\varepsilon}^p}{\dot{\varepsilon}^p \left( \theta_s, \dot{\varepsilon} \right)} \geq 0$$

(4)

PET is a hyper-elastic polymeric material used as a thin layer to model the tape on which the wafer is mounted, before both wafer and tape are mounted on the vacuum chuck as one assembly. In order to simulate the behavior of this material, the Mooney-Rivlin model for hyperelastic materials was used:

$$U = C_{10} \left( I_1 - 3 \right) + C_{01} \left( I_2 - 3 \right) + \frac{1}{D_t} \left( J^0 - 1 \right)^2$$

(5)

where $U$ is the strain energy per unit of reference volume $C_{10}$, $C_{01}$, and $D_t$ are temperature-dependent material parameters; $I_1$ and $I_2$ are the first and second deviatoric strain invariants which are defined as:

$$I_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2$$

(6)

and

$$I_2 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2}$$

(7)

where $\bar{\lambda}_1$, $\bar{\lambda}_2$, and $\bar{\lambda}_3$ are the three principal stretches, and $J^0$ is the elastic volume ratio, which relates the total volume ratio to the thermal volume ratio. The constant $D_t$ was set to a large number to eliminate the effect of the thermal expansion because of the effect of the cooling process. The $C_{10}$, $C_{01}$, constants were chosen 0.3. These values were found from literature by curve
fitting experimental data with the Mooney-Rivlin strain energy potential model used by ABAQUS\textsuperscript{12}.

RESULTS
An intense shear deformation band was observed forming at an angle of $30^\circ$ with the surface of the specimen. A similar angle, called the shear angle ($\phi$), has been reported in the literature in reference to the machining of metals\textsuperscript{13}. Comparing the angle value that was observed in the model and the data from the literature, a similar behavior can be found as in the case of other brittle materials, as shown in figures 3 and 4. Figure 3 also shows surface elements that experienced damage on the surface after machining. The damage of the surface elements is due to intense stresses induced by the grinding operation on the surface of the specimen, which forms surface cracks and the usual surface roughness observed in real wafers. Surface cracks and roughness are removed in the fine grinding process. Figure 4 illustrates the stress distribution in the $x$-direction and the shear stress band in the model.

![Figure 3. Shear angle $\phi$ as observed in the simulation with a value of $30^\circ$.](image)

The residual stress induced in the model after grinding was investigated in two ways: first by comparing the stresses at the back of the wafer after grinding with literature data, and then by comparing the stress distribution through the depth of the wafer with experimental data.
The residual stress at the back of the wafer after grinding was found from the literature to be ranging between -100 MPa and -150 MPa \(^{14}\). This data was originally measured using Raman spectroscopy for grounded wafers. These residual stress values match the simulation results as observed in figure 5.

Figure 5. Simulated stress distribution at the back of the wafer after grinding.
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the same type of measurement, shows a good agreement between the simulation results and the Raman spectroscopy measurement as shown in figure 6.4.

The graph shows a good agreement between the model results and the measurements at the center of the wafer for depths greater than or equal to 4 μm. At depths less than 4 μm, there is a small discrepancy between the model and experimental results, which will be investigated in the future.

![Graph showing stress distribution comparisons between model output and Raman spectroscopy](image)

Figure 6. Stress distribution comparisons between model output and Raman spectroscopy

CONCLUSIONS

The continuing development of electronic devices leads to slim, cheap and high capacity packages. The development of such products increases the need of thinner wafers, which are achieved by optimized grinding processes. Experimental studies are expensive and can significantly increase the wafer price. In this paper, we built a model that simulates the back grinding processes of a silicon wafer. The accuracy of the model was verified by measuring the shear angle in the cutting operation and comparing it with literature data. Good agreement was observed between the model results and the literature data. The residual stresses induced in the back side of the wafer after the grinding process also agreed with Raman spectroscopy data, after releasing the wafer from the vacuum chuck and the adhesive backing tape. An additional verification showed a good agreement between the stress distributions in the cross-section of the wafer that was measured by Raman spectroscopy with the model output.

The model is able to accurately simulate the back grinding process of silicon wafers, and it can be used to develop a better understanding of the parameters affecting the grinding process.
ACKNOWLEDGMENT

The authors would like to thank the Micron Foundation for their financial support of this work.

REFERENCE


