# Implicit and Explicit Finite Element Simulation of Soft-Pad Grinding of Silicon Wafers

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## Abstract

*Silicon wafers are used to fabricate more than 90% of all integrated circuits. Surface grinding is the preferred technique used to flatten wire-sawn wafers. While conventional grinding is not effective in removing the waviness induced by wire-sawing process, experiments and finite element analysis indicated that soft-pad grinding is a promising method to remove waviness effectively. This paper presents the simulations of the process of the waviness removal of wire-sawn wafers by both implicit and explicit finite element methods using ANSYS and LS-DYNA respectively. Contact algorithms are important in the simulation of wafer grinding. Since the wafer thickness and pad thickness are in the range of millimeters which is thin in comparison with the wafer diameter (in the range of hundreds of millimeters), and the waviness height is usually in the range of tens of micrometers, selecting suitable penetration values in the contact algorithm is challenging. This paper is focused on the selection of contact model, element type, and other solution control parameters in both implicit and explicit methods. The study will be helpful for finding a generalized methodology in similar simulations of contact analysis.*

## 1. Introduction

Manufacture of silicon wafers includes the following processes [1-2]: (1) Crystal growing; (2) Slicing (wire sawing); (3) Flattening (lapping or grinding); (4) Etching; (5) Polishing; and (6) Cleaning. For 300 mm wafers, wire sawing has been chosen to slice ingots, primarily due to its lower kerf loss compared with ID (internal diameter) sawing [3]. A phenomenon associated with wire sawing is the waviness. The wire-sawing induced waviness is also called long cycle swelling or unevenness, or wavy stripes [4]. It has wavelength typically in the range of 0.5 mm to 30 mm [5]. Fig. 1 shows localization of wafer deformation in wafer grinding illustrated, which is greatly exaggerated for illustration purpose, by FEA simulation. The generation mechanism of this waviness is not fully understood yet. This has been the main reason why it is very difficult to eliminate waviness at wire-sawing process. If subsequent processes do not remove this waviness, it will adversely affect wafer flatness, especially site flatness.

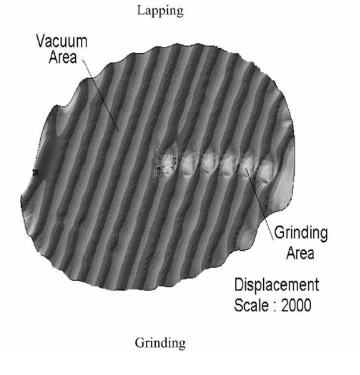

*Fig. 1.* Localization of wafer deformation in wafer grinding illustrated by FEA simulation.

Soft-pad grinding is a newly patented approach that involves the use of a “soft pad” or a resilient pad. When grinding the first side of a wire-sawn wafer, a perforated resilient pad is inserted in between the wafer and the ceramic chuck. The soft pad accommodates and supports the wavy surface of the wafer and holds the wafer in an un-deformed or less deformed condition. As a result, the waviness of the top surface is removed effectively by grinding. This ground surface will be the flat reference plane for grinding the other side of the wafer on a conventional ceramic chuck. Fig.2 illustrates the wafer grinding process. The process is illustrated in Fig. 3.

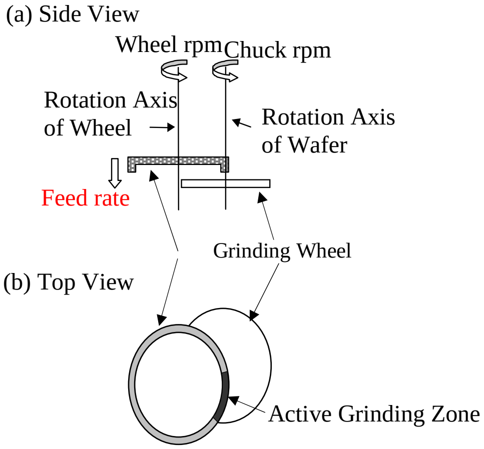

Fig. 2. Illustration of wafer grinding.

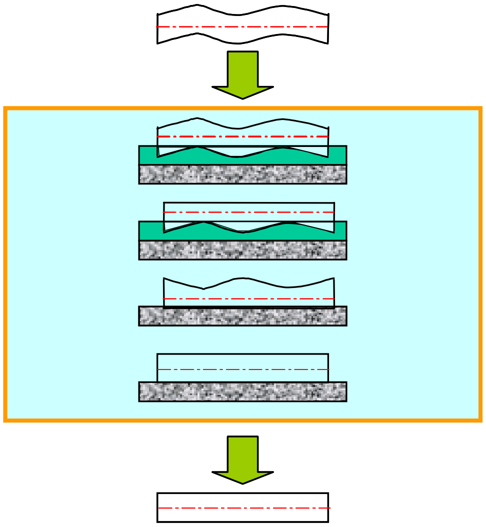

*Fig. 3. Illustration of soft-pad*

This paper presents a study of finite element analysis on soft-pad grinding of 300 mm wire-sawn silicon wafers. The present study focuses on the selection of contact model, element type, and other solution control parameters in both implicit and explicit methods. There are four sections in this paper. Following this introduction section, section 2 describes the FEM model. In section 3, the results of the implicit and explicit FEM simulations are presented and discussed. Finally, conclusions are drawn in section 4.

## 2. Finite Analysis Model

### 2.1 Model descriptions

In this study the simulation is assumed to be a quasi-static analysis. Grinding in actual production is a dynamic process that involves material removal under the action of a grinding wheel. However, since the focus of this study is the effectiveness of waviness removal, in which the elastic deformation of the wafer under the impressing grinding wheel is presumably the most important controlling factor, the grinding process is modeled as a static problem. This approach simplifies the computation significantly while still capturing the essential features of the deformation process.

For simplicity, the wafer grinding is simulated using two-dimensional (2D) finite element analysis. The plane strain condition is assumed in the grinding region. Each component, the rigid chuck, the wafer and the soft pad, is created systematically using 2D FEM model. The waviness profile is simplified as sinusoids with uniform wavelength and height. The typical parameters are selected as listed in Table 1. The parameters of Table 1 are default values in the simulations described in Section 3 unless specified otherwise.

Table 1. Default values of geometric dimensions and material properties used in simulation

| Part | Default values |
|---|---|
| Wafer | diameter = 300 mm; thickness ($T_w$) = 0.8 mm; waviness height ($H_w$) = 20 μm; waviness wavelength ($L_w$) = 30 mm; Young's modulus = 135 GPa; Poisson's ratio = 0.3 |
| Pad | diameter = 300 mm; thickness = 1.0 mm; Young's modulus = 2.0 MPa; Poisson's ratio = 0.2 |
| Wheel | diameter = 300 mm; thickness = 1 mm; Young's modulus = 300 GPa; Poisson's ratio = 0.2 |
| Total grinding force = 2.5 N | |

Grinding force is applied directly on the rigid grinding wheel, while the bottom nodes of the soft pad were constrained from moving in any direction. A half model is used and symmetrical conditions are applied on the left edges of both the wafer and the soft pad.

### 2.2 The FEA model by implicit algorithm using ANSYS

#### 2.2.1 Element type

In order to obtain the results with good accuracy, fine meshes representing local regions of the wafer and the pad are used. The size of mesh is selected as 0.2 mm. The wafer is meshed with 4 layers of elements along its thickness, and soft pad with 5 layers. The 4- nodes linear element with 2×2 integrate points (Plane42) and the 8-node quadratic elements with 2×2 integrate points (Plane80), with plane strain condition, are selected separately for both the wafer and the soft pad. There are a total of 3000 elements in wafer, and 3745 in the pad. Although the linear element generally performs better for contact, the higher order element is also used for the comparison purpose due to the fact that the stress and strain in the local regions need to be considered. A typical mesh is shown in Fig. 4. In the figure, the magnitude of the waviness is exaggerated for easy recognition.

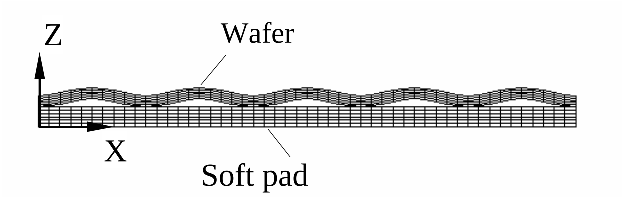

*Fig. 4. The FEM mesh for the wafer and soft-pad. (Waviness is exaggerated for illustration purpose.)*

### 2.2.2 Contact interface definitions

The grinding wheel was treated as a rigid body, and the grinding wheel-wafer contact is modeled by rigid-flexible contact elements (contact pair type Target 169/Contact 172 in ANSYS) with pilot node. For wafer-soft pad contact, flexible-flexible contact pair is used (Target 169/Contact 172 in ANSYS).

Since the wafer thickness and pad thickness are in the range of millimeters which is thin in comparison with the wafer diameter (which is in the range of hundreds of millimeters), and the waviness height is usually in the range of tens of micrometers, selecting suitable penetration values in the contact algorithm is challenging. Contact algorithms in FEM generally allow some penetration between contact and target surfaces that depends on the normal stiffness, as well as slip in sticking contact that depends on the tangential stiffness. Higher stiffness values decrease the amount of penetration/slip, but can lead to ill-conditioning of the global stiffness matrix and to convergence difficulties. Lower stiffness values can lead to a certain amount of penetration/slip and produce an inaccurate solution. If too much initial penetration between target and contact surfaces occurs, the contact elements may overestimate the contact forces, resulting in no convergence or in breaking-away of the components in contact. In our simulations, the contact stiffness is selected to be the same as that of the wafer. The factor of stiffness, 1.0, is selected properly. The factor of penetration tolerance is chosen as 0.1. While the augmented Lagrangian method is chosen, the normal and tangential contact stiffness are updated in each load step during the course of an analysis automatically. Friction coefficient is assumed to be 0.2. The automatic contact adjustment is set, that is, the small gap and penetration are allowed to be adjusted automatically. In the following section, the results with different values of contact parameters are compared.

### 2.2.3 Time step:

Iterative solver with large deformation option is selected to simulate the wafer grinding process. For good contact performance, time control should be initially specified. The number of load step is set to be 200. Automatic time stepping is used. Number of sub-steps is set to be 50. The minimum number of sub-steps is taken as 50.

## 2.3 Explicit analysis using LS-DYNA

In this section, the model for the explicit method is described.

2.3.1 Element size

Although the mesh size affects the minimum time step in the explicit method, the size of mesh for both the wafer and the pad has to be as small as possible due to the fact that the thickness of both of the wafer and the pad are much smaller than the diameter of the wafer. Shell elements with plane strain condition were chosen for both of the wafer and the soft pad, resulting in a total of 3000 elements in the wafer, and 3745 elements in the pad. In order to avoid the principal inertia of rigid body in the explicit method, the thickness of the wheel need to be small. Since the excessively coarse discretization of rigid target surface can affect the contact calculation based on penalty-based approach, the wheel is meshed as reasonable size as 1mm. For contact stability between the wafer and the pad, the target surfaces are created larger than the contact surfaces.

2.3.2 Load step

There are two methods for speeding up running time in the explicit method. One is the velocity of the loading method, and the other is mass scaling method. The speed of calculation is proportional to the speed of loading, while the speed of calculation is proportional to square root of mass scaling. Therefore choosing a reasonable loading velocity is important. The loading time is chosen as 1 sec for the grinding process.

Time-step control is very important. Since the mesh size of both the wafer and the pad has to sufficiently fine, the mass scaling is used in the simulation. Here time step size for mass scaled solution is chosen as 10E-6 s.

Through observation of the global kinetic energy in the post-processing, the proper loading time and mass scaling are determined.

2.3.3 Contact interface

The initial contact region should be kept in “touch” condition very well. Otherwise, unstable results will occur when the structure is subjected to quasi-static loading. For example, we can use *Contact_2D with tied sliding to tie the peak of wafer to the pad (deformable part), and use *constraint_extra_node to tie the peak of wafer to the wheel (rigid material). Penalty-based approach (soft=0 in Option Card ‘A’ in *contact) cannot used in the contact of wafer and pad since the difference of both elastic modulus is so big that the contact algorithm breaks down. The control card for contact is also adopted to specify the penalty stiffness.

## 3. Results and discussion

### 3.1 The verification of both implicit and explicit model:

The contour of displacement in Y direction calculated by LS-DYNA is shown in Fig.5.

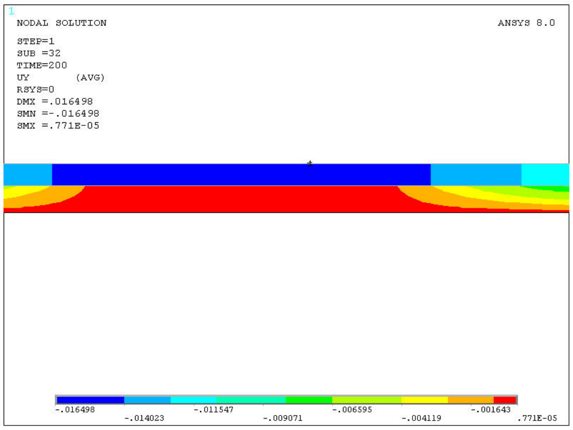

*Figure 5 Displacement by the implicit method using ANSYS*

Figure 6 illustrate the peak and valley displacement of the wafer for pad elastic modulus of 50MPa.

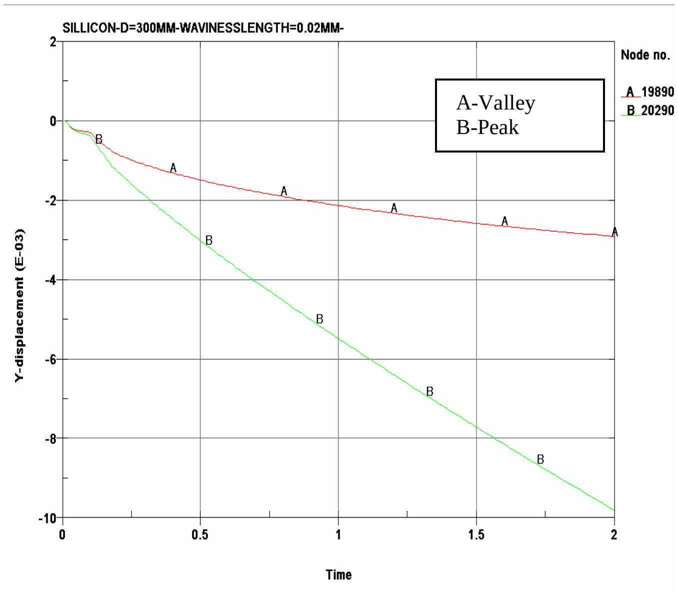

*Figure 6 Displacement*
*by the explicit method using LS-DYNA*

These figures indicate that the results are reasonable. The variations of peak displacement, valley displacement, and relative peak displacement of the wafer with the elastic modulus and the Poisson ratio of the pad are listed in Table 2.

Table 2 Comparisons of displacements of the wafer with the pad material parameters.

| Pad Material | Peak Displacement ($\mu m$) | Valley Displacement ($\mu m$) | Relative Displacement ($\mu m$) |
|---|---|---|---|
| Elastic Modulus =50MPa Poisson Ratio =0.2 | -7.88 | -1.36 | 6.520 |
| Elastic Modulus =2MPa Poisson Ratio =0.2 | -16.49 | -11.24 | 5.246 |
| Elastic Modulus=2MPa Poisson Ratio=0.4 | -15.768 | -10.427 | 5.341 |

Table 2 indicates that softer pad is more effective in reducing the relative displacement of the wafer. Poisson's ratio of the pad also influences the displacement of the wafer.

### 3.2 Comparisons of different model

#### 3.2.1 Element type

Table 3 shows that the higher order elements increase the accuracy of results, as expected. However, the table 3 indicates that the results of low order elements are close to those of high order ones. Therefore the results of lower order elements are acceptable.

Table 3 Comparisons of displacements of the wafer with the element type.

| Element type | Peak Displacement ($\mu m$) | Valley Displacement ($\mu m$) | Relative Displacement ($\mu m$) | Cumulative iterative number |
|---|---|---|---|---|
| 8-node | -16.38 | -11.28 | 5.100 | 130 |
| 4-node | -16.49 | -11.24 | 5.246 | 168 |

#### 3.2.2 Contact stiffness

Two values of contact stiffness, 1.0 and 0.1, are tested in the simulation. Table 4 shows that the contact stiffness greatly affects the results. This table indicates that the wafer penetrates the pad too much and the relative displacement drops from 5.1 µm to 4.4 µm if the contact stiffness factor is changed from 1.0 to 0.1. Since the primary concern in the wafer grinding simulation is the relative displacement, low contact stiffness factor such as 0.1 should be avoided in the simulation.

Table 4 Comparisons of displacements of the wafer with the contact stiffness factor.

| Contact stiffness factor | Peak Displacement ($\mu m$) | Valley Displacement ($\mu m$) | Relative Displacement ($\mu m$) | Cumulative iterative number |
|---|---|---|---|---|
| 1.0 | -16.38 | -11.28 | 5.100 | 130 |
| 0.1 | -20.636 | -16.208 | 4.428 | 40 |

Table 4 also reveals that the cumulative iterative number is reduced with decrease in contact stiffness. For computational efficiency, low contact stiffness may be used if the amount of penetration is within the acceptable range.

The effects of penetration factor on contact for Plane42 are also investigated. Two penetration factors, 0.1 and 0.01, are used. The results show very similar trend. Therefore penetration factor can be set up as 0.1, which is the default value in ANSYS.

### 3.2.3 Comparisons between the explicit method and the implicit method

The displacements from both the explicit and the implicit method are listed in Table 5. The results by the implicit method are slight smaller than those by the explicit method. The difference may come from two different algorithms. However, the simulation by the explicit method takes much more time than one by implicit method. The former is about 4 hrs, while the latter is only 0.5 hours.

Table 5 Comparisons of displacements of the wafer by both of the explicit and the implicit method.

| Method | Software | Peak displacement ($\mu m$) | Valley Displacement ($\mu m$) | Relative Displacement ($\mu m$) |
|---|---|---|---|---|
| Explicit | LS-DYNA | -8.5 | -2.7 | 5.8 |
| Implicit | ANSYS | -7.8 | -1.36 | 6.44 |

## 4. Conclusions and Discussion

1) A higher contact stiffness (around 1.0) should be used in order to reduce the contact penetration.
2) Linear plane element can be used in the simulation of the silicon grinding process.
3) To simulate wafer grading, the implicit method takes much less CPU time than the explicit method for the quasi-static simulation.
4) The explicit method can be used in the simulation of the soft-pad grinding of silicon wafers under assumed quasi static loading. It is better suited for the complex contact problem under high impact load. Since the wafer grinding is a dynamic process, the explicit method may be a better simulation tool if dynamic simulation is desired. The explicit method can be used to analyze silicon under assumed static loading, but the following aspects must be handled properly:

a) Load step: Selecting a reasonable loading speed and using proper mass scaling are necessary.
b) The energy: It must be ensured that the global kinetic energy of whole model is much smaller that internal energy in order to avoid inertia effect. Generally the kinetic energy should not exceed 5%-10% of the internal energy.
c) Contact interface: The initial contact region should be kept in "touch" condition very well. Otherwise, loading of the structure will cause unstable results. For example, we can use the method stated in section 2 to tie the peak of wafer to the pad (deformable part) and the chuck (rigid). Penalty-based approach (soft=0 in Option Card 'A' in *contact) cannot be used in the contact of wafer and pad since the difference of both elastic modulus is so big that the contact algorithm breaks down.

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