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# Soft-pad grinding of 300 mm wire-sawn silicon wafers: finite element analysis with designed experiments

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**Abstract:** Silicon wafers are the primary semiconductor substrates used to fabricate Integrated Circuits (ICs). Recently, the industry is making a transition from 200 to 300 mm wafers. To attain very flat 300 mm silicon wafers, grinding has been used to flatten the wire-sawn wafers. However, it is challenging for grinding to remove the waviness induced in wire sawing. To enhance the waviness removal ability of grinding process, several approaches have been explored including soft-pad grinding. This paper presents a study on soft-pad grinding of 300 mm wire-sawn silicon wafers through Finite Element Analysis (FEA) with designed experiments. A $2^5$ (five factors, two levels) full factorial design is employed to reveal the main effects as well as the interaction effects of five factors (elastic modulus, Poisson's ratio and thickness of the soft pad; waviness wavelength and waviness height of silicon wafers) on the effectiveness of waviness removal. FEA simulation results are compared with relevant experimental results. Implications of this study to manufacturing are also discussed.

**Keywords:** factorial design; finite element analysis; FEA; grinding; semiconductor material; silicon wafer.

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**Biographical notes:** Jian (Jessie) Wu received her BS from Beijing Institute of Technology in 2000 and an MS in Industrial Engineering from Kansas State University in 2003. Her Master's thesis is entitled 'Soft-pad grinding of wire-sawn silicon wafers: finite element analysis with designed experiments'. She has authored/co-authored five papers.

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Kelli Simmelink received a BS in Industrial Engineering from Kansas State University in 2004 and currently works at General Mills, Inc. While she was an undergraduate student in the Department of Industrial and Manufacturing Systems Engineering at Kansas State University, she conducted research on soft-pad grinding of wire-sawn silicon wafers. She was supported by the National Science Foundation through an Research Experiences for Undergraduates (REU) supplement.

## 1 Introduction

### 1.1 Transition from 200 to 300 mm silicon wafers

Silicon wafers are widely used as the substrates upon which the majority of Integrated Circuit (IC) chips are built (Van Zant, 2000). In 2002, worldwide silicon wafer revenue totalled $5.7 billion (Wafer Revenue Up, 2002). Wafer diameter has increased steadily from less than 50 mm in the 1970s (Tricard et al., 1998) to 200 and 300 mm today. Currently, 300 mm wafers constitute only a small percentage of all wafers produced. However, this percentage will increase rapidly. In 2002, global monthly demand for 300 mm wafers was about 200,000. The monthly demand in 2004 is projected to reach the level of 500,000–600,000 wafers.[1]

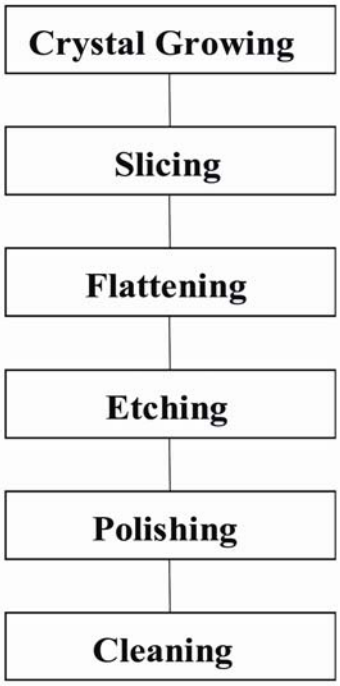
The most important motivation for the increase in wafer diameter is cost. In the semiconductor industry, there exists a constant demand for faster, more powerful ICs at lower prices. Using wafers with a larger diameter means that ICs can be manufactured more cost-effectively. The number of dies that can be produced on a 300 mm wafer is roughly 2.5 times that on a 200 mm wafer and the cost per die saving is estimated to be about 30–40% (Ristelhueber, 1999).

## *1.2 Manufacturing processes for 300 mm silicon wafers*

To manufacture 300 mm silicon wafers, a sequence of processes is required (Bawa et al., 1995; Fukami et al., 1997; Pei, 2002; Pei and Strasbaugh, 2001; Tonshoff et al., 1990; Vandamme et al., 2000; Yamagishi et al., 1999). Figure 1 illustrates the major processes:

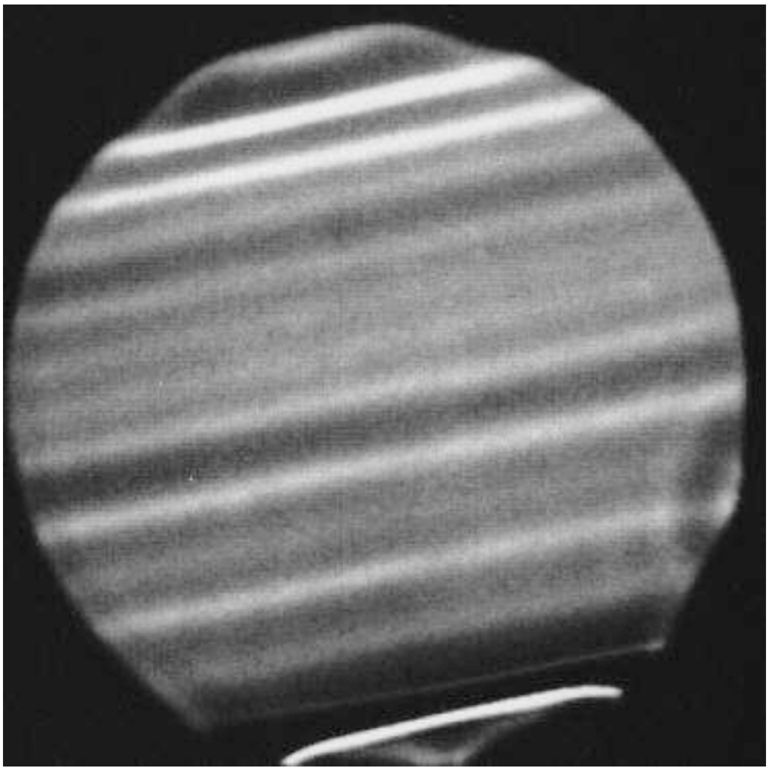
1. *Crystal growing*: to produce single crystal silicon ingot.
2. *Slicing (wire sawing)*: to slice the silicon ingot into wafers of thin disk shape.
3. *Flattening (lapping or grinding)*: to flatten the wafer surface.
4. *Etching*: to chemically remove processing-induced damage without introducing further mechanical damage.
5. *Polishing*: to obtain a mirror surface on the wafer.
6. *Cleaning*: to remove the polishing agent or dust particles from the wafer surface.

**Figure 1** Major processes for 300 mm silicon wafer manufacturing



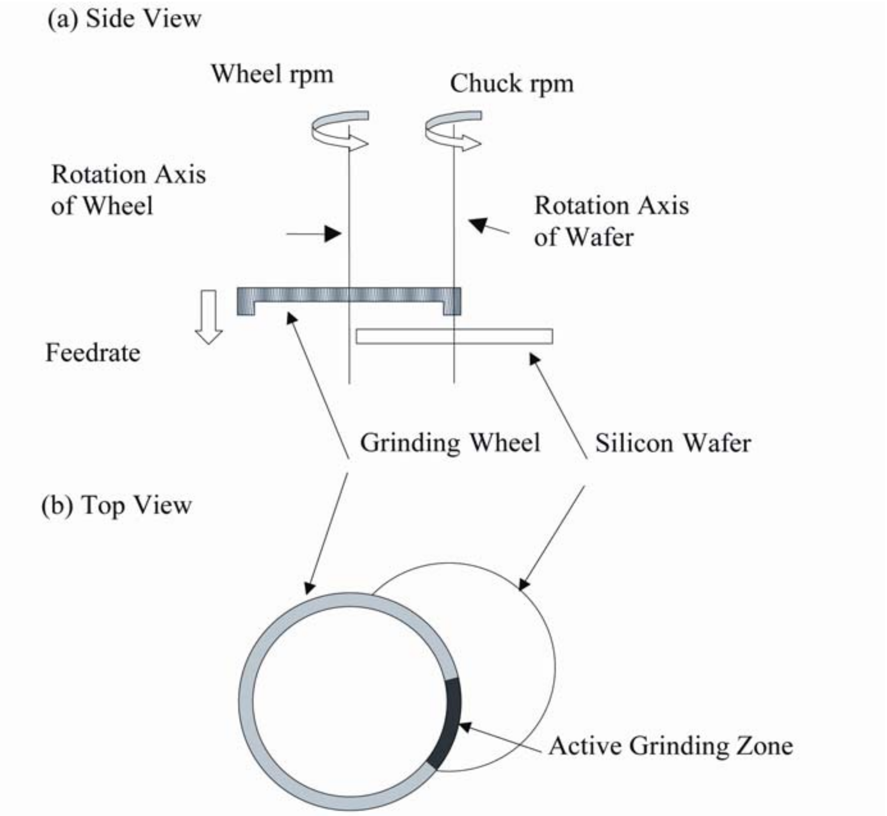
Recently, wire sawing has been fully established as the preferred method of slicing large diameter ingots. It cuts an entire ingot into many wafers simultaneously while minimising kerf loss (Kao et al., 1997). A major drawback of wire sawing is the waviness. The waviness is also called long cycle swelling or unevenness or wavy stripes (Yasunaga et al., 1997). It has wavelength of 0.5–30 mm (Kato et al., 1997). Figure 2 shows a magic mirror picture of a wafer exhibiting waviness. Information on magic mirrors can be found in Hahn et al. (1990, 1992), Shiue et al. (1992) and at the website (http://www.hologenix.com). Since the generation mechanism of this waviness is not fully understood yet, it is very difficult to prevent waviness during wire-sawing process. Lapping, grinding or other processes are required to effectively remove the waviness in order to achieve desirable wafer flatness.

**Figure 2** Wire-sawing induced waviness on a silicon wafer



Lapping and grinding are the two flattening processes for wire-sawn wafers. Lapping is very effective in removing the waviness while conventional grinding with a rigid chunk is not (Kato et al., 1997; Pei and Fisher, 2001; Pietsch and Kerstan, 2001; Yasunaga et al., 1997). Figure 3 illustrates the conventional wafer grinding process. Grinding wheels are diamond cup wheels. The wafer is held on a porous ceramic chuck by means of vacuum. The axis of rotation for the grinding wheel is offset by the distance of the wheel radius relative to the axis of rotation for the wafer. During grinding, the grinding wheel and the wafer rotate about their own axes of rotation simultaneously and the wheel is fed towards the wafer along its axis.

**Figure 3** Illustration of wafer grinding



If grinding can be made more effective in removing waviness, it will be the preferred method due to its following advantages over lapping:

1 the process is fully automatic with cassette-to-cassette operation

2 it uses a fixed-abrasive grinding wheel rather than loose abrasive slurry so the cost of consumables per wafer is lower and it is more benign to the environment and

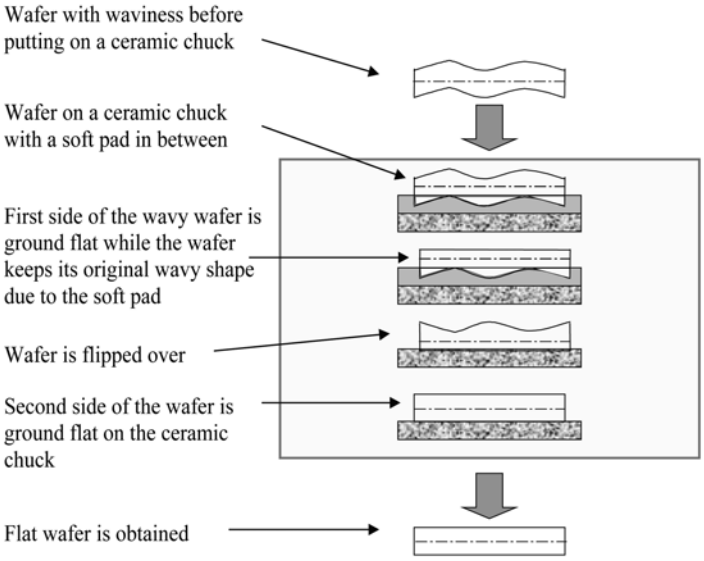
3 it has higher throughput.

### *1.3 Waviness removal in wafer grinding*

Several approaches have been proposed to improve the effectiveness of waviness removal in grinding, including wafer grinding followed by lapping (Vandamme et al., 2000), reduced chuck vacuum (Shinetsu, 1997), use of a ‘soft-pad’ (Kassir and Walsh, 1999) and wax mounting (Kato et al., 1997). These approaches have been summarised and discussed in Pei and Fisher (2001). It has been shown that soft-pad grinding is effective in reducing the waviness and its implementation is easy (Xin et al., 2002).

The root cause of the inability of grinding to remove waviness is elastic deformation of the wafer during grinding. If, during grinding, a wavy wafer deforms elastically and conforms to the shape of the ceramic chuck, after the grinding operation, it will spring back to its original shape thus preserving the waviness. Soft-pad grinding, a newly patented approach (Kassir and Walsh, 1999), is illustrated in Figure 4. When grinding the first side of a wire-sawn wafer, a perforated soft 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 undeformed 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.

**Figure 4** Illustration of soft-pad grinding



## 1.4 Significance and outline of this paper

The authors have published their previous work on soft-pad grinding of 200 mm wire-sawn silicon wafers. A Two-Dimensional (2D) Finite Element Analysis (FEA) study (Xin et al., 2004) has shown that soft-pad grinding is effective in removing waviness because use of a soft pad in between the chuck and the wafer significantly reduces the elastic deformation of the wafer in comparison with grinding on a rigid chuck. The advantages of this 2D model include shorter computing time and less complexity in modelling. Although the 2D model has produced insightful understanding, it could not capture the 3D nature of wafer grinding process. A Three-Dimensional (3D) FEA model on soft-pad grinding of 200 mm wire-sawn wafers has been developed and the results of a designed experiment study using this 3D model were reported (Sun et al., 2004). In that investigation, a $2^4$ (four factors, two levels) full factorial design was employed to reveal the main effects and interaction effects of four important factors: elastic modulus, Poisson's ratio and thickness of the soft pad and waviness wavelength of the wafer. An experimental investigation into soft-pad grinding of 200 mm wire-sawn wafers has also been reported (Pei et al., 2004). The experimental results have substantiated the FEA simulation results.

This paper reports the first attempt to systematically study soft-pad grinding of 300 mm wire-sawn wafers. The $2^5$ (five factors, two levels) full factorial design was employed to study the main and interaction effects of five factors (elastic modulus, Poisson's ratio and thickness of the soft pad; waviness wavelength and waviness height of silicon wafers) on waviness removal. Several of these effects were not studied at all in the previously reported FEA work (Sun et al., 2004; Xin et al., 2004).

For this study, 2D instead of 3D FEA modelling was used, in order to avoid extremely long computing time and not to exceed the element number allowed by the ANSYS version available to this research. In the 3D model for the 200 mm wafers, the number of finite elements was about 85,000 and each simulation took about 10 hours on a computer with 1.8 GHz Pentium 4 processor and 1 GB SDRAM. Please note that the number of test conditions is doubled from the $2^4$ full factorial design to the $2^5$ full factorial design and that the surface area of a 300 mm wafer is 125% larger than that of a 200 mm wafer.

There are four sections in this paper. Following this introduction section, Section 2 describes the FEA model and the design of experiments. In Section 3, the results of the FEA will be presented. These results are compared with relevant experimental results. Implications of these results to manufacturing are also discussed. Finally, conclusions are drawn in Section 4.

## 2 FEA model and design of experiments

### *2.1 FEA model*

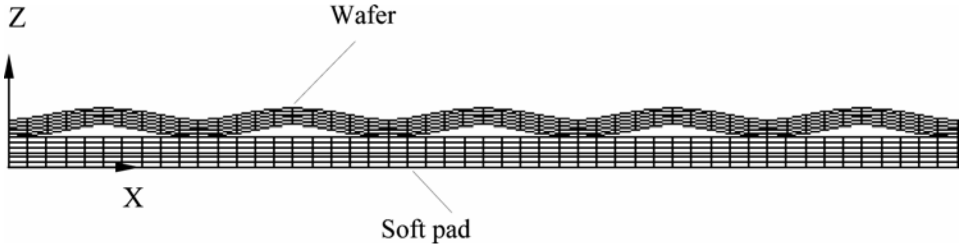
Grinding in actual production is a dynamic process that involves material removal under the action of a grinding wheel. However, since the focus of this study was the effectiveness of waviness removal, in which the elastic deformation of the wafer under the impressing grinding wheel is presumably the most important controlling parameter, the grinding process was simulated as a static process. This approach simplifies the computation significantly while still capturing the essential features of wafer deformation during grinding.

The orientation of waviness strips observed in the manufacturing process are approximately identical but the wavelength and height change irregularly. In this paper, the waviness profile is simplified as sinusoids with uniform wavelength and height.

Commercial FEA software package, ANSYS, was used for this study. To create the FEA model, a sinusoidal wave for a full period was created with the spline function in ANSYS passing 12 predefined key points. The sinusoidal spline was then swept (using the sweep function in ANSYS) along the wafer thickness direction to generate a representative area. Next, this representative area was copied $N$ times with appropriate offset distances to create $N + 1$ areas. These areas were then glued together (using the Boolean glue operation in ANSYS) to create one wafer with $N + 1$ peaks and valleys of waviness. The grinding wheel and soft pad were modelled as rectangular areas.

Because the thickness of the wafer is very small (in the order of 1 mm) compared with its diameter (300 mm), care must be taken during meshing, especially near grinding wheel-wafer and wafer-soft pad contacts. The wafer was meshed with four layers of elements along its thickness direction and soft pad with six layers. Four-node Plane-42 bi-linear elements with plain strain condition were used for both the wafer and soft pad and the total number of Plane-42 elements was 5200. Higher order elements were not used because linear element performs better for contact calculation. A typical mesh is shown in Figure 5. In the figure, the magnitude of the waviness is exaggerated for illustration purpose.

**Figure 5** The FEA mesh for the wafer and soft-pad (waviness is exaggerated for illustration purpose)



In the FEA model, the grinding wheel was treated as a rigid body, and the grinding wheel-wafer contact was modelled by rigid-flexible contact elements. For wafer-soft pad contact, flexible-flexible contact pair was used. The contact stiffness affects the convergence of the contact calculation. In most cases, the contact stiffness was set to be equal to the elastic modulus of the soft pad. When the elastic modulus of soft pad was greater than 0.001 of the elastic modulus of silicon wafer, the contact stiffness had to be lowered to 0.1–0.01 of the modulus of the soft pad. A total of 3000 contact elements were generated.

Grinding force was applied directly on the rigid grinding wheel, while the soft pad was held rigidly at its bottom surface with bottom nodes constrained from moving in any direction. Because of symmetry, a half model was used and symmetrical conditions were applied on the left edges of both the wafer and soft pad.

Iterative solver with large deformation option was selected to simulate the wafer grinding process. For good contact performance, very small initial loading step, in increment of 1% of the total loading force, was specified initially during the solution process. After the wheel-wafer contact and wafer-soft pad contact were established, larger loading step, in increment of 20% of the total loading force, was used to speed up the computation.

## *2.2 Design of experiments*

A $2^5$ (five factors, two levels, 32 tests) full factorial design was used for the FEA simulations. Detailed description of factorial design can be found in many textbooks such as the one by DeVor et al. (1992). The factor levels are listed in Table 1 and the experiment matrix is shown in Table 2. Table 3 shows the values of other parameters that were kept constant in this study. Please note that the total grinding force was 2.5 N and the force on the half model was 1.25 N.

Two output variables were investigated:

1 Relative Peak Displacement (RPD) and

2 Valley Displacement (VD).

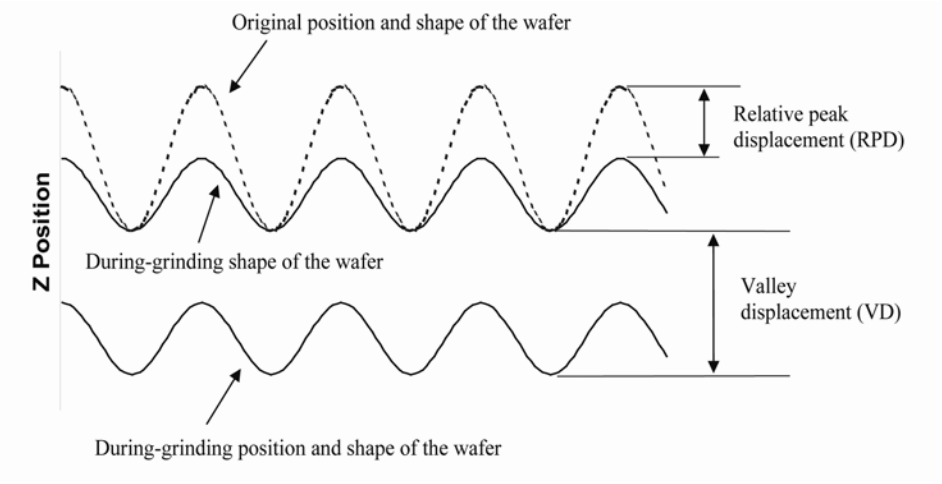
**Table 1** Factor levels

| *Factor* | *Unit* | *Low level (−)* | *High level (+)* |
|---|---|---|---|
| Pad elastic modulus (*A*) | MPa | 1 | 5 |
| Pad Poisson's ratio (*B*) | | 0.2 | 0.45 |
| Pad thickness (*C*) | mm | 0.5 | 1 |
| Waviness wavelength (*D*) | mm | 20 | 30 |
| Waviness height (*E*) | µm | 15 | 30 |

RPD is the average displacement of the waviness peaks relative to the waviness valleys, along the grinding force direction (the *Z*-direction); while VD is the average displacement of the waviness valleys, also along the grinding force direction.

Figure 6 illustrates both RPD and VD. It is clear that the smaller the RPD is, the better the top wafer surface will retain its original wavy shape and therefore the more effective the waviness removal process will be. In principle, VD has no effect on waviness removal, but a large VD will make it difficult to control the position of the wafer, causing trouble for the grinding operation.

**Figure 6** Illustration of RPD and VD



## 3 Results and discussion

The simulation results of RPD and VD are given in Table 2. The software called Design-Expert (Version 5, Stat-Ease Corporation, Minneapolis, MN) was used to process the data. Tables 4 and 5 are ANOVA (analysis of variance) tables for RPD and VD, respectively, where significant factors are identified. Information about ANOVA and *p*-value is available in many statistics books such as the one by Montgomery and Runger (2003).

In the following, only the significant effects (those with *p*-values less than 0.017) will be represented geometrically and discussed.

**Table 2** Test matrix and results

| *Test* | *Pad elastic modulus* | *Pad Poisson's ratio* | *Pad thickness* | *Waviness wavelength* | *Waviness height* | *RPD ($\mu$m)* | *VD ($\mu$m)* |
|---|---|---|---|---|---|---|---|
| 1 | – | – | – | – | – | 1.44 | 10.90 |
| 2 | + | – | – | – | – | 1.70 | 3.79 |
| 3 | – | + | – | – | – | 1.64 | 5.35 |
| 4 | + | + | – | – | – | 1.78 | 1.71 |
| 5 | – | – | + | – | – | 1.18 | 15.96 |
| 6 | + | – | + | – | – | 1.63 | 5.87 |
| 7 | – | + | + | – | – | 1.50 | 8.19 |
| 8 | + | + | + | – | – | 1.72 | 2.79 |
| 9 | – | – | – | + | – | 6.46 | 9.03 |
| 10 | + | – | – | + | – | 8.44 | 3.03 |
| 11 | – | + | – | + | – | 8.02 | 4.24 |
| 12 | + | + | – | + | – | 8.99 | 1.27 |
| 13 | – | – | + | + | – | 5.45 | 13.98 |
| 14 | + | – | + | + | – | 7.91 | 4.76 |
| 15 | – | + | + | + | – | 7.26 | 6.52 |
| 16 | + | + | + | + | – | 8.68 | 1.89 |
| 17 | – | – | – | – | + | 1.67 | 14.44 |
| 18 | + | – | – | – | + | 1.83 | 4.97 |
| 19 | – | + | – | – | + | 1.78 | 7.11 |
| 20 | + | + | – | – | + | 1.87 | 2.40 |
| 21 | – | – | + | – | + | 1.53 | 21.98 |
| 22 | + | – | + | – | + | 1.78 | 7.72 |
| 23 | – | + | + | – | + | 1.69 | 3.93 |
| 24 | + | + | + | – | + | 1.83 | 11.09 |
| 25 | – | – | – | + | + | 8.39 | 13.34 |
| 26 | + | – | – | + | + | 9.50 | 4.59 |
| 27 | – | + | – | + | + | 9.24 | 6.35 |
| 28 | + | + | – | + | + | 9.80 | 2.11 |
| 29 | – | – | + | + | + | 7.51 | 20.29 |
| 30 | + | – | + | + | + | 9.20 | 7.13 |
| 31 | – | + | + | + | + | 8.76 | 9.81 |
| 32 | + | + | + | + | + | 9.59 | 3.30 |

*Note*: '–' indicates low level and '+' indicates high level.

**Table 3** Values of other parameters that were kept constant

| *Parameter* | *Unit* | *Value* |
|---|---|---|
| Wafer diameter | mm | 300 |
| Wafer thickness | mm | 0.8 |
| Pad diameter | mm | 300 |
| Total grinding force | N | 2.5 |

**Table 4** ANOVA table for RPD

| *Source of variance* | *Sum of squares* | *DOF* | *Mean square* | *F-ratio* | *p-Value* |
|---|---|---|---|---|---|
| Pad elastic modulus (A) | 5.06 | 1 | 5.06 | 126.50 | <0.0001 |
| Pad Poisson's ratio (B) | 2.27 | 1 | 2.27 | 56.75 | <0.0001 |
| Pad thickness (C) | 0.89 | 1 | 0.89 | 22.25 | 0.0001 |
| Waviness wavelength (D) | 355.31 | 1 | 355.31 | 8882.75 | <0.0001 |
| Waviness height (E) | 4.63 | 1 | 4.63 | 115.75 | <0.0001 |
| AB | 0.50 | 1 | 0.50 | 12.50 | 0.002 |
| AD | 2.71 | 1 | 2.71 | 67.75 | <0.0001 |
| AE | 0.29 | 1 | 0.29 | 7.25 | 0.0124 |
| BD | 1.29 | 1 | 1.29 | 32.25 | <0.0001 |
| CD | 0.41 | 1 | 0.41 | 10.25 | 0.0041 |
| DE | 2.76 | 1 | 2.76 | 69.00 | <0.0001 |
| ABD | 0.27 | 1 | 0.27 | 6.75 | 0.0163 |
| Error | 0.73 | 19 | 0.04 | | |
| Total | 377.13 | 31 | | | |

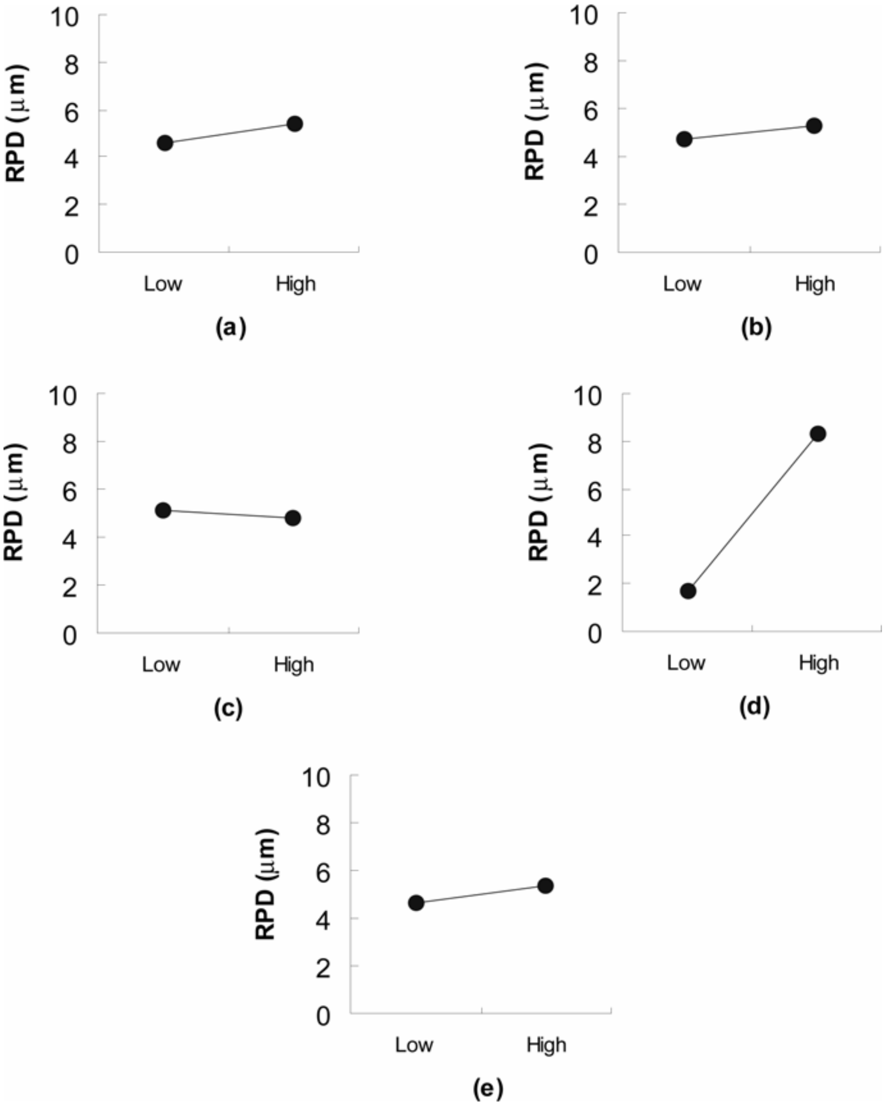
**Table 5** ANOVA table for VD

| *Source of variance* | *Sum of squares* | *DOF* | *Mean square* | *F-ratio* | *p-Value* |
|---|---|---|---|---|---|
| Pad elastic modulus (A) | 331.53 | 1 | 331.53 | 52.29 | <0.0001 |
| Pad Poisson's ratio (B) | 219.03 | 1 | 219.03 | 34.55 | <0.0001 |
| Pad thickness (C) | 79.95 | 1 | 79.95 | 12.61 | 0.0014 |
| AB | 88.18 | 1 | 88.18 | 13.91 | 0.0009 |
| Error | 171.08 | 27 | 6.34 | | |
| Total | 889.78 | 31 | | | |

### *3.1 Main effects on RPD*

Figure 7 shows the main effects on RPD.

**Figure 7** Main effects on RPD: (a) pad elastic modulus; (b) pad Poisson's ratio; (c) pad thickness; (d) waviness wavelength and (e) waviness height



It can be seen in Figure 7(a) that when the pad elastic modulus increases, RPD will increase. In other words, it is easier to remove the wire-sawing induced waviness when the pad elastic modulus is smaller. This result is consistent with that obtained from the 3D FEA study on soft-pad grinding of 200 mm wire-sawn wafers (Sun et al., 2004) where a smaller full factorial design (four factors instead of five factors) was used.

Figure 7(b) shows that with the augmentation of pad Poisson's ratio, RPD will increase. This result is also consistent with the 3D FEA result for soft-pad grinding of 200 mm wafers (Sun et al., 2004).

Figure 7(c) illustrates that, when the pad becomes thicker, RPD will decrease. Based on this result, the waviness is easier to remove when a thicker pad is used. This result is consistent with that obtained from the 3D FEA study on soft-pad grinding of 200 mm wafers (Sun et al., 2004).

From Figure 7(d), it can be seen that RPD increases rapidly as waviness wavelength increases. In other words, it becomes more difficult to remove waviness with longer wavelength. This result is consistent with that obtained from the 3D FEA study on soft-pad grinding of 200 mm wafers (Sun et al., 2004), as well as that from a 2D FEA study on rigid-chuck grinding of 200 mm wire-sawn wafers (Pei et al., 2003). This simulation result has also been substantiated by an experimental observation (Pei et al., 2004). The practical implication of this finding to manufacturing is that wire-sawing should produce wafers with shorter waviness wavelength if possible. Although the current knowledge and 'know-how' are not sufficient to eliminate waviness by wire-sawing, waviness wavelength can be altered to a certain degree.

Figure 7(e) shows that when the wafer waviness height increases, RPD will increase. It is interesting to compare this result with the result from the 2D FEA study on rigid-chuck grinding of 200 mm wire-sawn wafers (Pei et al., 2003). It was shown that, for rigid-chuck grinding, none of the main effects and interaction effects of waviness height was significant.

### *3.2 Interaction effects on RPD*

Significant two-factor interactions on RPD are shown in Figure 8.

The interactions of pad elastic modulus with three other factors (pad Poisson's ratio, waviness wavelength and waviness height) are significant. From Figure 8(a)–(c), it can be seen that at the low level of Poisson's ratio, high level of waviness wavelength and low level of waviness height, the change in pad elastic modulus will cause a larger change in RPD.

The interactions of waviness wavelength with each of other four factors are significant. As shown in Figure 8(b) and (d)–(f), at the high level of waviness wavelength, the change in pad elastic modulus, in pad Poisson's ratio, in pad thickness and in waviness height will cause a larger change in RPD than at the low level of waviness wavelength. In other words, longer wavelength gives less tolerance to the changes in pad elastic modulus, in pad Poisson's ratio, in pad thickness and in waviness height; and therefore, allows less freedom to choose properties of the pad material to compensate other issues. This observation further substantiates the finding discussed in the preceding paragraph: waviness with longer wavelength is more difficult to remove.

The three-factor interaction on RPD of pad elastic modulus, pad Poisson's ratio and waviness wavelength is significant. It is illustrated in Figure 9 that the best scenario for removing waviness is the combination of smaller pad elastic modulus, smaller pad Poisson's ratio and shorter waviness wavelength. The worst case occurs with the larger pad elastic modulus, larger pad Poisson's ratio and larger waviness wavelength.

**Figure 8** Two-factor interaction effects on RPD: (a) pad elastic modulus; (b) pad elastic modulus; (c) pad elastic modulus; (d) pad Poisson's ratio; (e) pad thickness and (f) waviness wavelength

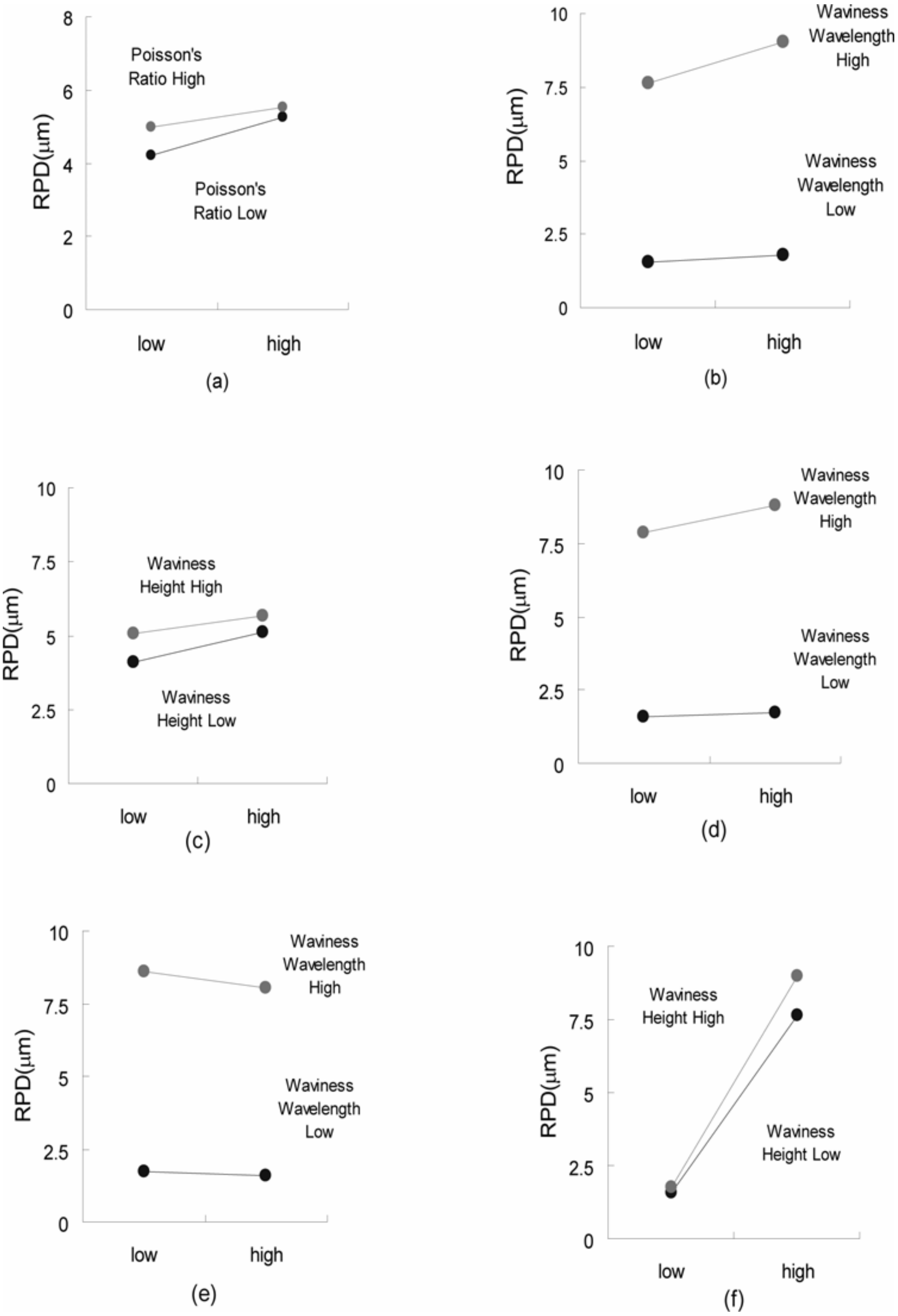
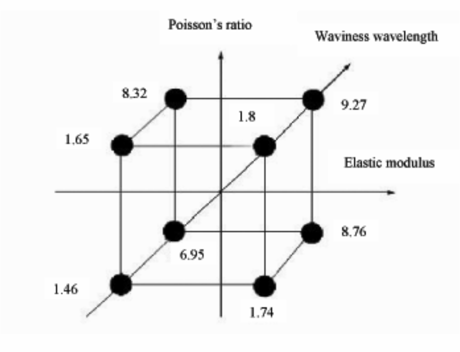


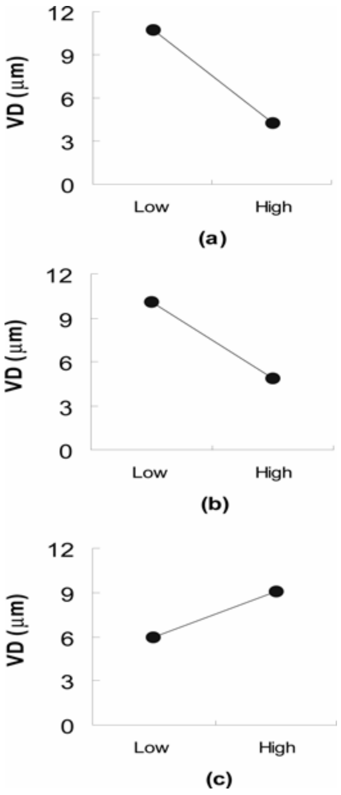
**Figure 9** Three-factor interaction effect on RPD



### 3.3 *Main effects on VD*

Figure 10 shows the three significant main effects on VD: pad elastic modulus, pad Poisson's ratio and pad thickness. It can be seen that, when pad elastic modulus or pad Poisson's ratio increases or when pad thickness decreases, VD will decrease. These simulation trends are consistent with those obtained from the 3D FEA study on soft-pad grinding of 200 mm wafers.

**Figure 10** Main effects on VD: (a) elastic modulus; (b) pad Poisson's ratio and (c) pad thickness

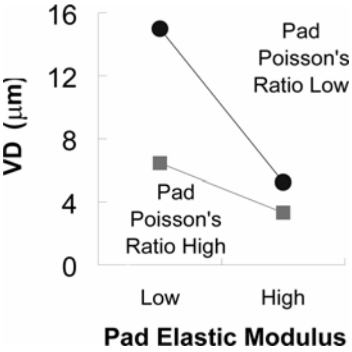


It is important to note that these factors have the opposite effects on RPD and VD. Smaller pad elastic modulus, smaller pad Poisson's ratio and larger pad thickness lead to smaller RPD, hence more effective waviness removal, but result in larger VD, which may cause difficulties in wafer position control during grinding. A compromise is therefore needed in the selection of appropriate pad parameters.

### *3.4 Interaction effects on VD*

Figure 11 illustrates the interaction effect of pad elastic modulus and pad Poisson's ratio on VD. At the low level of pad Poisson's ratio, the effect of pad elastic modulus is enhanced compared with that at the high level of pad Poisson's ratio. This result is consistent with that obtained from the 3D FEA study on soft-pad grinding of 200 mm wafers.

**Figure 11** Two-factor interaction effect on VD



## 4 Conclusions

This study is the first attempt to systematically investigate the effects of five important factors in soft-pad grinding of 300 mm wire-sawn silicon wafers: elastic modulus, Poisson's ratio and thickness of the soft pad; waviness wavelength and waviness height of silicon wafers. The following conclusions can be drawn from this study:

1. To remove the waviness more efficiently, it is better to use a thicker pad with smaller pad elastic modulus and smaller pad Poisson's ratio. Waviness with shorter wavelength and smaller waviness height is easier to remove.
2. The effect of pad elastic modulus on RPD is enhanced at the low level of pad Poisson's ratio, high level of waviness wavelength and low level of waviness height. Furthermore, at the high level of waviness wavelength, a change in pad elastic modulus, in pad Poisson's ratio and in pad thickness will cause a greater change in RPD than at the low level of waviness wavelength.
3. The three-factor interaction of pad elastic modulus, pad Poisson's ratio and waviness wavelength is significant. The best combination for removing waviness is smaller pad elastic modulus, smaller pad Poisson's ratio and shorter waviness wavelength.

4 VD is smaller at the high level of pad elastic modulus, high level of pad Poisson's ratio and low level of pad thickness.

5 The interaction effect of pad elastic modulus and pad Poisson's ratio on VD is significant. At the low level of pad Poisson's ratio, a change in pad elastic modulus will cause a larger change in VD.

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## Note

[1] Shin-Etsu Handotai to increase its 300 mm silicon wafer production capacity to 300,000 monthly, retrieved from: http://www.shinetsu.co.jp/e/news/s20030305.shtml.