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Semi-empirical material removal rate distribution model for SiO₂ chemical mechanical polishing (CMP) processes

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A B S T R A C T
A novel semi-empirical model was developed for predicting the material removal rate (MRR) during chemical mechanical polishing (CMP) based on the following assumptions: plastic contact at the wafer–particle interface, elastic contact at the pad–particle interface, a particle size distribution, and a randomly distributed surface roughness of the polishing pad. The proposed model incorporates the effects of particle size, concentration, and distribution, as well as the slurry flow rate, pad surface topography, material properties, and chemical reactions during the silicon dioxide (SiO₂) CMP. To obtain the unknown parameters and ensure the validity of the model, a SiO₂ CMP experiment was conducted by using various-sized CMP slurries. The spatial distribution of the MRRs is expressed with respect to the normal contact stress distribution and the relative velocity distribution. The proposed MRR model can be used for the development of a CMP simulator, the optimization of CMP process parameters, and the design of next-generation CMP machines.

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1. Introduction

Chemical mechanical polishing (CMP) is a process of smoothing and planarizing wafer surfaces by using a combination of chemical reactions and mechanical forces [1]. Numerous parameters are involved in the material removal process, such as the type of abrasive, pressure on the wafer, relative velocity between the polishing pad and the wafer, slurry chemistry, polishing pad, and substrate characteristics [2–5]. The modeling of the material removal rate (MRR) is crucial to understand the complexity of the CMP process, and considerable research efforts have been concentrated on this topic. The fundamentals of silicon dioxide (SiO₂) CMP are understood via studies of glass polishing. The predominant mechanism responsible for SiO₂ removal is the mechanical abrasion followed by the hydration of the SiO₂ surface in the presence of an alkaline slurry [6,7]. The hydrated layer is rapidly formed on the SiO₂ surface by the indentation of the silica particles against the SiO₂ film in the slurry [8].

Early models of CMP were based on glass polishing technology and the MRR was described by Preston’s equation [9], which indicates that the product of the pressure and the relative velocity between the wafer and the polishing pad contributes significantly toward the MRR. Alternatively, Runnels and Eyman [10] replaced the applied pressure and the relative velocity with normal and tangential stresses at the wafer–pad interface in Preston’s equation. In addition, Liu et al. [11] developed a CMP model based on elastic theory and the kinematics of an abrasive particle moving in the gap of a pair of surfaces in rolling contact. Fu et al. [12] assumed that perfect plastic deformation occurred when particles abraded the softer hydrated layer on the SiO₂ surface. Luo and Dornfeld [13] investigated the material removal model under the following assumptions: plastic contact between the wafer–abrasive and the pad–abrasive interfaces, a periodic roughness of the polishing pad, and a normal distribution of particle size. The synergistic effect of chemical and mechanical forces was represented by a dynamic hardness of the wafer surface. Zhao and Chang [14] proposed a CMP model for silicon wafer based on contact mechanics. In their model, plastic contact at the wafer–particle interface and elastic contact at the particle–pad interface were assumed for calculating the indentation depth of the particle in the wafer surface. The line density of uniformly dispersed particles in the slurry and the real contact area between the wafer and the polishing pad were used to calculate the number of active particles. Qin et al. [15] took into account the chemical and mechanical interactions involved in a typical CMP process, using the thickness of the thin chemically modified layer and the indentation depth of the particle into the wafer surface to understand the nonlinear behavior of the MRR. Lin [16] described the relationship between the polishing parameters and the MRR with an analytical model on the basis of elastic and elastic–plastic deformations during a polishing process. Jiang et al. [17] modified...
Zhao and Chang’s model to understand the removal of the amorphous layer on the wafer surface by a single particle based on the viscous flow of the amorphous layer.

The MRR distribution in SiO₂ CMP is determined by the distributions of relative velocity and normal stress between the wafer and the polishing pad [18]. Hocheng et al. [19] proposed a model for material removal using abrasive cutting, which provided a part of the analytical background for the empirical Preston’s equation. The uniformity of the relative velocity between the wafer and the pad at any point was determined by a kinematic analysis. Kim and Jeong [20] calculated the velocity distribution, sliding distance of the wafer, and sliding distance of the polishing pad in order to verify the effect of the process conditions on the velocity uniformity and the wear distance of the pad and the wafer.

Researchers studying the MRR distribution in CMP have focused on the stress distribution caused by the applied pressure of the carrier by using a finite element analysis (FEA) method or a mathematical analysis. Wang et al. [21] introduced the concept of a Von Mises stress in the analysis of the MRR distribution by using commercial FEA software. Subsequently, many researchers began applying a Von Mises stress in the analysis of CMP processes. Srinivasa-Murthy et al. [22] investigated the variations in the Von Mises stress on the wafer surface using a 3D model in rectangular Cartesian coordinates. Chen et al. [23] utilized the normal contact stress as a stress indicator in CMP and concluded that the Von Mises stress and normal contact stresses are not equivalent, which is a significant finding. The normal contact stress is an appropriate stress index because the frictional force is proportional to the normal contact stress. Lee and Jeong [24] integrated the effects of the normal contact stress, relative velocity, and chemical reaction rate distributions of Cu CMP by an empirically obtained spatial parameter.

However, there is still room for a better theoretical understanding of the removal mechanisms for modeling the CMP process, because the MRR models and the MRR distribution models have been studied independently. In this paper, we propose an integrated MRR distribution model that incorporates the effects of the material properties of the particles, wafer, and polishing pad, and process conditions such as pressure, relative velocity, and slurry flow rate.

2. Model development

2.1. Real contact area and contact pressure

Fig. 1 illustrates the wafer surface topology in contact with the chemically modified layer on the wafer surface and the distribution of the pad asperity heights. The polishing pad is made of porous urethane. The distribution of the pad asperity height follows the normal distribution function. The roughness of the wafer surface is small; compared to the pad, the wafer surface is assumed to be a smooth plane.

Based on the Greenwood–Williamson model [25] and contact mechanics [26], Qin et al. [15] reported that the real contact area $(A_r)$ for CMP between a smooth, flat wafer and a randomly rough pad under a normal force $(F)$ can be expressed as

$$A_r = \left( \frac{f_s}{\zeta} \right) \left( \frac{R_p}{\sigma_p} \right)^{1/2} P A_m \frac{E_{pw}}{E_{wv}},$$

where $\sigma_p$ is the standard deviation of the pad asperity height $(z)$ distribution; $f_s$ is the area density of the up-features divided by the area of a flat pad; $R_p$ is the average radius of curvature of the pad asperity; and $\varphi$ is the normal distribution function.

2.2. Number of active particles

Previous research on calculating the number of active particles in CMP has not considered the slurry flow rate because the active particles were only calculated from the volume concentration of the particles in the slurry [14–17]. If we consider the previously reported line density of particles given by Ref. [14], we see that the MRR becomes independent of the size of the particles. In order to overcome these analytical shortcomings, we obtained a line density from an imaginary slurry volume on the apparent wafer–pad sliding area $(A_{ps})$, which was calculated from the total contact area between the rotating wafer and the polishing pad during the process.

Earlier studies indicate that the size distribution of the particles satisfies a probability density function $(\Phi(D))$ [14]. All of the particles are spherical in shape and estimated to be uniformly dispersed in the slurry. We assumed that the particles are rearranged in the imaginary slurry volume in the apparent wafer–pad sliding area as they participate in the polishing and that the particles embedded in the polishing pad participate in the material removal process.

The weight of a single particle $(\omega(D))$ can be calculated as

$$\omega(D) = \frac{1}{6} \pi D^2 \rho_a,$$

where $D$ is the diameter of a particle and $\rho_a$ is its density.

The total number of particles in the slurry container can be written as

$$N_p = \frac{\int_{0}^{\infty} X \rho_s C_a \Phi(D) \omega(D) dD}{\Phi(D) \omega(D) dD},$$

where $\rho_s$ is the density of the slurry; $C_a$ is the weight concentration of the particle; $\Phi(D)$ is the probability density function; and $X$ is the total slurry volume during CMP.
The apparent wafer–pad sliding area is calculated as

\[ A_w^T = \pi n_p [(r_c + 2r_w)^2 - r_w^2] \]  

(5)

where \( n_p \) is the number revolutions of the polishing pad; \( r_c \) is the length between the center of the polishing pad and the inner boundary of the wafer sliding area; and \( r_w \) is the radius of the wafer, as shown in Fig. 2.

The imaginary thickness \( t_b \) in the apparent wafer–pad sliding area can be obtained from Eq. (6).

\[ t_b = \frac{X}{A_w} \]  

(6)

The distance \( l \) between rearranged particles in the hypothetical slurry volume that contains \( N_p \) particles can be obtained by solving

\[ l^3 - \left( \frac{2\sqrt{A_w t_b}}{N_p - 1} \right) \cdot l^2 - \left( \frac{2\sqrt{A_w t_b} + A_w^T}{N_p - 1} \right) \cdot l - \left( \frac{A_w t_b}{N_p - 1} \right) = 0. \]  

(7)

The area density of particles \( q \) can be obtained from the distance between particles:

\[ q = \left( \frac{\sqrt{A_w} / l + 1}{A_w} \right)^2. \]  

(8)

The particles in the CMP slurry are statistically distributed and have a mean diameter with a standard deviation. Because some of the particle sizes are much smaller than the nano-scale roughness of the polishing pad, not all of the particles participate in the material removal process. In this paper, the abrasive particles that are involved in the removal process are called active particles. They have a diameter that is greater than the critical particle diameter \( (D_{c\alpha}) \), as shown in Fig. 3 [28]. Therefore, the total number of active particles \( (n_a) \) that participate in material removal during CMP is expressed as

\[ n_a = qA_w \int_{D_{c\alpha}}^{+\infty} \Phi(D)dD = \frac{\left( \sqrt{\frac{A_w}{l + 1}} \right)^2}{A_w} \]

\[ \times \left( \frac{f_1}{E} \right) \left( \frac{R_p}{\sigma_p} \right) \]  

\[ \frac{1}{2} PA_w \int_{D_{c\alpha}}^{+\infty} \Phi(D)dD, \]  

(9)

where \( D_{c\alpha} \) is the critical particle diameter of particles that can participate in the material removal process.

### 2.3. Calculation of average MRR

Because the pad material is much softer than the wafer material, the particles at the wafer–pad interface are located on the contact asperities of the pad surface after the wafer presses on the polishing pad. The down-force is sustained by the contact asperities and embedded particles in the pad surface. With respect to particle indentation, the polishing pad and the wafer experience different modes of deformation because they have different mechanical properties. Zhao and Chang [14] reported that the particle indentation deformation associated with the pad is elastic and the deformation associated with the wafer is fully plastic. Wang et al. [29] proposed an equation for the indentation depth of a single particle into the pad surface by using a parabolic approximation for the profile of a sphere. In this study, we adopted Wang’s nonlinear and micro-contact model for a single particle and incorporated large elastic pad deformation from the particle–pad contact. Additionally, according to Zhao and Chang’s research, we assumed that there is plastic deformation at the wafer–particle interface and elastic deformation at the pad–particle interface.

The indentation depth of the particle in the wafer–particle–pad system is determined based on the force equilibrium of the particle participating in the wear process. Fig. 4 shows the wafer–particle–pad micro-contact. The parabolic approximation of the profile of the spherical particle (diameter, \( D \)) [29] is

\[ f(x) = \frac{D}{2} - \sqrt{\left( \frac{D}{2} \right)^2 - (ax)^2} \quad \text{and} \quad x = \frac{r}{a}. \]  

(10)
from the comparison of the model and the experimental data. \( S(D) \) is expressed as

\[
S(D) = k \Delta S(D) = \frac{4}{3} k \delta_w(D) \sqrt{\delta_w(D) D}.
\] (14)

Based on the number of active particles and the particle indentation, the average MRR \( \langle MRR_{\text{avg}} \rangle \) is expressed as follows:

\[
MRR_{\text{avg}} = \left( \frac{4}{3} k \left( \frac{\sqrt{\Delta \sigma_p^2 / \eta_1}}{\eta_0} \right)^2 \left( \frac{\eta_0}{\sigma_p} \right)^{\frac{1}{2}} \frac{\rho_{\text{REavg}}}{E_{\text{p}}} \left( 1 - \frac{\zeta}{2} \right)^{\frac{3}{2}} \right) \left( \int_{\delta_0}^{\infty} \Phi(D) D^2 dD \right),
\] (15)

where \( k \) is a constant obtained from the experimental data and \( V_{\text{REavg}} \) is the average relative velocity of the wafer.

The equivalent indentation depth of a single particle can be calculated from the experimentally obtained \( k \) value, as shown below:

\[
\delta_w(D) = k^{2/3} \delta_w(D) = \left( 1 - \frac{\zeta}{2} \right) k^{2/3} D.
\] (16)

Therefore, the average MRR in Eq. (15) is rewritten with the equivalent indentation depth as follows:

\[
MRR_{\text{avg}} = \left( \frac{4}{3} k \left( \frac{\sqrt{\Delta \sigma_p^2 / \eta_1}}{\eta_0} \right)^2 \left( \frac{\eta_0}{\sigma_p} \right)^{\frac{1}{2}} \frac{\rho_{\text{REavg}}}{E_{\text{p}}} \left( 1 - \frac{\zeta}{2} \right)^{\frac{3}{2}} \right) \left( \int_{\delta_0}^{\infty} \Phi(D) D^2 dD \right),
\] (17)

where

\[
\zeta = 2 - k^{2/3} (2 - \zeta).
\]

2.4. MRR distribution model

The spatial distribution of the MRR can be expressed by using a spatial parameter consisting of the normalized normal contact stress and the normalized average relative velocity distribution, as shown below: [24]

\[
MRR(x, y) = MRR_{\text{avg}} \cdot \left\{ \left( \frac{\sigma_n(x, y)}{\sigma_n_{\text{avg}}} \right)^{\alpha} \left( \frac{V_{\text{REavg}}(x, y)}{V_{\text{REavg}}} \right)^{\beta} \right\},
\] (18)

where \( \sigma_n(x, y) \) is the normal contact stress at an arbitrary position on the wafer; \( \sigma_n_{\text{avg}} \) is the average normal contact stress; \( V_{\text{REavg}}(x, y) \) is the average relative velocity at an arbitrary position on the wafer; and \( V_{\text{REavg}} \) is the average relative velocity of the wafer. The normal contact stress distribution can be obtained from an FEA simulation and the relative velocity distribution can be calculated using a kinematic analysis that accounts for the operating conditions. However, it is inappropriate to compare the influence of each parameter on the MRR distribution because the units and magnitudes of the normal contact stress and the relative velocity are different. All of the parameters are normalized with respect to their average values to represent their deviations; \( \alpha \) and \( \beta \) are constants that represent the influence of each normalized parameter. When the angular velocity of the carrier equals that of the platen, the value of \( V_{\text{REavg}}(x, y) / V_{\text{REavg}} \) is “1” and the MRR distribution depends only on the normalized normal contact stress. In this study, we only considered the normal contact stress distribution by setting the angular velocities of the carrier and the platen equal to each other.
3. Experimental conditions

An IC1000/SubaIV stacked pad (Nitta Haas Inc., Japan) was used as the stacked form, composed of an IC1000 (polyurethane pad) as the top pad and a SubaIV (felt-type pad) as the base, and it was designed for easy use and for improving the performance consistency. A plasma-enhanced chemical vapor deposition (PECVD) was used to deposit a silicon dioxide (SiO₂) film (1.5 μm thick) on an 8-in. (200 mm) silicon wafer. The CMP process was performed using a rotary CMP polisher (GnP POLIS500, GnP Technology, Korea). The distance from the center of the platen to the center of the carrier was 130 mm. The carrier was estimated to be devoid of oscillations during the CMP process. The operating pressures were 27.58 kPa for the wafer and 34.47 kPa for the retaining ring. The relative velocity was 65.312 m/min, and the slurry flow rate was 150 ml/min. Four types of CMP slurries were prepared for the experiments, as shown in Table 1. The particle diameter was measured with a particle-size analyzer (ELS-8000, OTSUKA Electronics Co.). The mean particle diameters for the four slurries were 13.3 nm (D13), 22.4 nm (D22), 60.9 nm (D61), and 117.7 nm (D118). The concentration of particles was fixed at 12.5 wt%. During CMP, the conditioning process was ex situ at a pressure of 5.88 kPa and rotational velocities of 40 rpm for the conditioner disk and 60 rpm for the platen. After polishing for 1 min, the thickness of the SiO₂ film was measured using a reflectometer (K-Mac ST5030-SL). The MRRs of the SiO₂ films were measured at 41 points on each wafer, and the edge exclusion was 3 mm.

4. Experimental verification and discussion

Park and Jeong [30] reported the real contact area ratio (real contact area/nominal contact area) without considering the grooves of the polishing pad before and after conditioning. When the applied pressure was 34.47 kPa, the real contact area ratio of the as-received polishing pad was 0.0027, and the real contact area ratios after a conditioning process with a random diamond disk (RDD) and a uniform diamond disk (UDD) were 0.0089 and 0.0145, respectively. Considering the area density of the up-features divided by the area of a flat pad \( \pi \) (0.83), the real contact area ratios at 5 psi were calculated to be 0.0074 and 0.0120 for the RDD and the UDD, respectively. These values of the real contact area are similar to the experimentally reported range. According to Eq. (1) and the material properties in Table 2, the real contact area ratio in this study at 34.47 kPa is 0.0086. For a pressure of 27.58 kPa, the real contact area ratio is calculated to be 0.0052.

For the model, \( D_C \) is assumed to be 22 nm. The MRR at a particle diameter of 118 nm was used to calculate the value of \( k \), and \( k \) was obtained from the comparison between the model and the experimental data to be 1.21. The size distribution of the particles is measured as a discrete probability density distribution, as shown in Fig. 5. The discrete probability density function is used to calculate the total number of particles.

The value of \( k \) indicates that the SiO₂ surface is softened by the chemical reaction with the slurry because the chemicals in a CMP slurry change the mechanical properties of the wafer surface. This chemically reacted surface layer is then removed by the abrasive mechanical action of the sliding particles in the slurry. If the chemically reacted surface layer is thick enough, the indentation of the particles into the wafer causes plastic deformation of the reacted layer. According to Sorooshian et al. [31], the etch rate of SiO₂ in the oxide slurry is approximately zero. The predominant phenomenon responsible for the removal of SiO₂ is a combination of chemical and mechanical interactions that first hydrate the SiO₂ surface owing to the presence of the alkaline slurry and then mechanically abrade the surface with the particles present in the slurry. In SiO₂ CMP, material removal by chemical etching is negligible for the modeling of MRR.

Fig. 6 shows the experimentally obtained average MRRs and the calculated average MRRs as a function of particle diameter, with the

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### Table 1

<table>
<thead>
<tr>
<th>Slurry</th>
<th>Mean (nm)</th>
<th>Standard deviation (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D13</td>
<td>13.3</td>
<td>3.7</td>
</tr>
<tr>
<td>D22</td>
<td>22.4</td>
<td>4.4</td>
</tr>
<tr>
<td>D61</td>
<td>60.9</td>
<td>12.5</td>
</tr>
<tr>
<td>D118</td>
<td>117.7</td>
<td>26.4</td>
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### Table 2

<table>
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<th>Variable</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( \sigma_p )</td>
<td>Standard deviation of pad asperity</td>
<td>30</td>
<td>μm</td>
</tr>
<tr>
<td>( R_p )</td>
<td>Average radius of pad asperity</td>
<td>25</td>
<td>μm</td>
</tr>
<tr>
<td>( E_p )</td>
<td>Young’s modulus of pad material</td>
<td>10</td>
<td>GPa</td>
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<tr>
<td>( \nu_p )</td>
<td>Poisson ratio of pad material</td>
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<tr>
<td>( E_s )</td>
<td>Young’s modulus of silica particle</td>
<td>94</td>
<td>GPa</td>
</tr>
<tr>
<td>( \nu_s )</td>
<td>Poisson ratio of silica particle</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>( \rho_p )</td>
<td>Density of silica particle</td>
<td>2270</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Density of slurry</td>
<td>1040</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( E_w )</td>
<td>Young’s modulus of silicon dioxide</td>
<td>66</td>
<td>GPa</td>
</tr>
<tr>
<td>( \nu_w )</td>
<td>Poisson ratio of silicon dioxide</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>( H_w )</td>
<td>Hardness of silicon dioxide</td>
<td>18</td>
<td>GPa</td>
</tr>
</tbody>
</table>
particle concentration fixed at 12.5 wt%. The MRR increases from D13 to D61, and decreases slightly from D61 to D118. Zhou et al. [32] obtained similar results in the CMP of a SiO₂ film using six kinds of colloidal silica slurries with different mean particle diameters of 10, 20, 50, 80, 110, and 140 nm. They found that the 80 nm silica particle exhibited the highest MRR and best surface finish. Zhang et al. [33] also reported a similar experimental result on the effect of the mean particle size on the MRR. As is seen in Fig. 6, the MRRs predicted by the model are in agreement with the experimentally measured MRRs under the same CMP conditions.

Fig. 7 shows the experimentally measured average MRRs and the predicted average MRRs from Eq. (15) as a function of particle concentration for the D118 slurry. The particle concentration was varied from 5 wt% to 17.5 wt%. Mahajan’s experiment [34] showed a similar trend for SiO₂ CMP with 0.2 μm silica particles. The MRR increases with the particle concentration, indicating that the presence of more active particles increases the material removal of SiO₂. However, Choi et al. [35] showed that the increase in particle concentration leads to an increased MRR for low particle concentrations; conversely, for high particle concentrations, the MRR decreases with increasing particle concentration. However, they used 0.2, 0.5, 1.0, and 1.5 μm particles, which are larger than the particles used for this study. They explained their experimental results via the dynamic motion of silica particles: sliding motion for low particle concentrations and rolling motion for high particle concentrations. Only the CMP results using 0.2 μm particles show a similar trend to our experimental data and modeling results. Our model cannot predict the effects of rolling motion because we assumed that the SiO₂ film is removed by a two-body abrasion caused by the sliding motion of the imbedded particles in the pad surface. However, the typical particle size in CMP is less than 200 nm [2,36], and the size distribution is tightly controlled to prevent particle agglomeration that results in scratches. Zhou et al. [32] concluded that for SiO₂ CMP, the MRR increases with the increase in particle concentration for the nano-scale abrasives, which is different than the trend for micro-scale abrasives. Therefore, the proposed model is plausible for explaining the MRR for SiO₂ CMP processes involving nano-scale abrasives.

Normal contact stress uniformity is a key parameter in wafer-level CMP performance because it relates to the frictional force. In this study, the normal contact stress distribution in the CMP process is considered with a 2D axisymmetric model. The CMP finite element model consists of a polishing pad, wafer, and carrier film. The pressure on the back of the carrier is assumed to be uniformly distributed. The following assumptions are also made: all the materials are isotropic and homogeneous; the surfaces of the backing film, wafer, retainer ring, PC film, and pad are smooth; the wafer and the polishing pad are in contact at every point of the interface at which small sliding occurs; and the relative velocity between the wafer and the polishing pad is constant at all positions. For the model, a quadrilateral mesh was used, and the numbers of nodes and elements were 115,496 and 34,780, respectively. Because the rotational velocity of the carrier is equivalent to that of the platen, the relative velocity distribution does not influence the theoretical MRR distribution.

Figs. 8 and 9 show the distributions of the measured and predicted MRRs. Specifically, Fig. 8 shows the measured and predicted results of the model using various particle diameters with a concentration of 12.5 wt%. Fig. 9 shows the experimental and calculated MRR distributions of the D118 slurry for various particle concentrations. α was calculated to be 3.77 from the comparison between the experimental data and the proposed model. The constant in the regression is negligible. The average normalized MRRs of each measuring point in the experiments on particle size effect were compared with the normalized stress distribution because the particle concentration may largely impacts MRRs near the edge of the wafer. Both outermost measuring points were ignored because of the irregularity. The correlation coefficient was 0.818 and the stress distribution positively correlated with the MRR distribution. Table 3 shows the normalized stress distribution and the average normalized MRR for regression analysis. The distribution of the MRRs follows the distribution of the normal contact stress. The results show that the MRRs are distributed uniformly at the center.
of the wafer; however, the MRRs near the edge of the wafer reduce and then increase at the outermost radius, according to the normal contact stress distribution. Some errors near the wafer edge may be caused by the slurry flow, which was not considered in the model. Nevertheless, the predicted results and measured results show good agreement.

5. Conclusions

Based on contact mechanics, this paper proposes a MRR model for SiO₂ CMP, incorporating the effects of particle size, particle concentration, slurry flow rate, area density of the pad surface, and chemical reactions. It is assumed that the polishing pad has a randomly rough surface, plastic contact occurs at the wafer–particle interface, and the polishing pad deforms elastically via particle indentation. The proposed model includes the line density of particles from an imaginary slurry volume in the wafer–pad sliding area, which has not been included in previous models. The predicted results show good agreement with the experimentally obtained results. The proposed MRR model can be used for the development of a CMP simulator, the optimization of process parameters, and the design of the next-generation of CMP machines.

Acknowledgments

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Table 3

<table>
<thead>
<tr>
<th>Position</th>
<th>Normalized stress</th>
<th>Avg. normalized MRR</th>
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</thead>
<tbody>
<tr>
<td>-95</td>
<td>0.9268</td>
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<td>-90</td>
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