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Considering Different Temperatures and Volume Concentrations of Slurry to Esitablish Simulation and Regression Analysis Model of Abrasive Removal Depth of Silicon Wafer for Chemical Mechanical Polishing

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Keywords: abrasive removal depth, regression model, temperatures, volume concentrations, pattern-free polishing pad

ABSTRACT

The paper firstly soaks silicon wafer in slurry at different temperatures and different volume concentrations for 30 minutes, and then performs atomic force microscopic (AFM) experiment to calculate the specific down force energy $SDFE_{reaction}$ values of silicon wafer soaked in slurry at different temperatures and different volume concentrations. These $SDFE_{reaction}$ values are substituted into an innovatively established theoretical simulation model of abrasive removal depth of silicon wafer under chemical mechanical polishing (CMP) by a pattern-free polishing pad soaked in slurry at different temperatures and different volume concentrations. First of all, the paper conducts CMP of silicon wafer by a pattern-free polishing pad with slurry at different volume concentrations at room temperature, and then compares the experimental results with the simulation results. After that, the paper makes a comparison between the simulation result and experimental result of abrasive removal depth per minute and finds the average difference ratio. After applying the modification concept of average difference ratio, the simulated abrasive removal depth per minute being close to the experimental value after compensation and modification can serve as a parameter value being similar to experimental value for regression analysis. Finally, the paper establishes a compensatory regression equations with consideration of different temperatures and different volume concentrations.

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INTRODUCTION

A slurry at different temperatures and different volume concentrations would affect the softening feature of the chemical reaction layer of silicon wafer, and would further affect the abrasive removal depth of silicon wafer being ground by abrasive particles, thus leading to affect the abrasive removal depth per unit time of silicon wafer under chemical mechanical polishing (CMP). Preston (1927) proposed in 1927 the first theoretical model of CMP wear, which was expressed as MRR = KPV, where MRR denotes the material removal rate; P denotes the pressure applied; V denotes the relative velocity of wafer to polishing pad; and K denotes the Preston constant. After that, Yu et al. (1993) firstly proposed that the contact between the asperity of polishing pad and wafer surface should be considered, and explored the relationship between static contact and removal rate. Besides, Yu et al. (1994) also proposed combining the effects of both the polishing pad with asperity and the fluid dynamics of slurry on the CMP process. The contacts explored above were all under the suppositions that the asperity distribution on polishing pad surface was of Gaussian distribution; the peak of its asperity was circular; and the polishing pad did not have a pattern groove.

Chekina and Keer (1998), employing the concept of contact mechanics, analyzed the relationship between wafer surface morphology and contact pressure in the CMP wearing process under steady conditions, and determined that the effect of planarization is related to geometric unevenness on the surface and different surface materials. Xie and Bhushan (1996) intended to know the wear model of removal rate in mechanical polishing process, proposed how the size of abrasive particles, polishing pad and contact stress were related to removal rate, and proved their theoretical model by experiments. Jiang et al. (1998) suggested giving consideration to two-body wear model under the condition of asperous surface contact, and defined the wear energy of material. They supposed that the asperity peak of asperous surface was conic, and the asperity distribution was of Gaussian distribution. Besides, Jongwon et al. (2003) further discussed about a contact deformation effect model for abrasive particles, and derived a volumetric removal model for individual abrasive particle. Lin and Chen (2005) developed a binary image pixel numerical analysis method to calculate polishing frequency and polishing times for CMP of wafer. Lin and Huang (2012) studied the use of CMP of sapphire wafer as well as removal of wafer caused by chemical reaction during the contact of slurry containing SiO_2 with the substrate to observe the change in the removal amount and surface morphology of wafer when there are different down forces, different rotational velocities, use of polishing pads with different morphologies, such as hole-pattern polishing pad and pattern-free polishing pad, different abrasive particle sizes and different volumetric concentrations of slurry. They were also matched with the regression analysis theory. Focusing on the equation proposed by Preston for polishing of glass, improvement was made. Kim and Jeong (2004) studied and analyzed the relative velocity of wafer to polishing pad, and derived the relative abrasive length of each position on wafer to polishing pad.

Atomic force microscopy (AFM), invented by Bining et al. in 1986 (1986), is a kind of scanning probe microscopy generally used for measurement and observation of the surface morphology of conductor and non-conductor, so the related scholars explored the measurement and application of AFM. It was proved by the related scholars that applying AFM probe as a machining tool to perform mechanical cutting was a quite useful technique in machining of nanostructures, such as semiconductor, optoelectronic component and metallic surface (2008).

In the above literature, there is no in-depth exploration for establishment of a theoretical model, experiment, regression analysis equation and average difference ratio model of the abrasive removal depth of silicon wafer being affected by the chemical reaction of slurry at different temperatures and different volume concentrations during CMP of silicon wafer by a pattern-free polishing pad.

THEORETICAL MODEL AND EXPERIMENTAL METHOD FOR $SDFE_{reaction}$ OF SILICON WAFER WITH SLURRY AT DIFFERENT TEMPERATURES AND DIFFERENT VOLUME CONCENTRATIONS

First of all, the paper soaks silicon wafer in slurry at different temperatures and different volume concentrations for 30 minutes to make silicon wafer produce a chemical reaction layer. This paper can uses a smaller down force to make the cutting depth of the AFM-machined V-shaped groove smaller than 0.09nm, which then can be used to calculate the $SDFE_{reaction}$ value inside the chemical reaction layer of silicon wafer soaked in slurry at different temperatures and different volume concentrations.

The slurry used in this paper for conducting experiments is SiO_2 slurry provided by San Chuin Scientific Co., Ltd., with the abrasive particle size in slurry being 0.05μm. As to adjustment of concentration, deionized water is added to slurry, and then they are mixed well by a stirrer in order to make the abrasive particles evenly distributed. In this paper, the mixing proportion is that the volume concentration of the slurry without deionized water added is 50%, and the volume concentrations of the slurry with deionized water added are 20%, 30%, 40% and 50%. Comparison is made for these 4 kinds of slurry at different volume concentrations.

As to control of soaking temperature of slurry, the slurry is poured to a beaker, which is then placed on a heating plate. Turn the knob on the heating device to different numerical values in order to achieve the slurry temperatures of 50℃, 40℃ and 30℃ respectively. In the heating process of slurry, a thermometer is used to monitor its temperature. Once the slurry is heated to the specified temperature, pour it to another beaker, and soak the single-crystal silicon substrate in the heated slurry for 30 minutes. Therefore, during the soaking period, it should not simply monitor the slurry temperature using a thermometer. If the slurry temperature starts to fall, use another beaker to hold the slurry that is on the heating plate, and then pour the slurry to the beaker with the single-crystal silicon substrate soaked in. Meanwhile, use a thermometer to monitor the slurry temperature. The thermometer measures the temperature of the slurry being poured in and heated, ensuring that during the 30 minutes that the single-crystal silicon substrate is being soaked, the slurry temperature is controlled at the required temperature of ± 1℃, so as to meet the required experimental parameter of temperature.

After the single-crystal silicon substrate has been soaked in the various slurry aforesaid under different conditions, place the single-crystal silicon substrate on the AFM. Use a diamond-coated probe as a cutting tool, and employ contact mode to do the experiment of cutting and machining a straight-line nanogroove. The paper's $SDFE_{reaction}$ inside the chemical reaction layer of silicon wafer soaked in slurry at different temperatures and different volume concentrations is defined as that the downward force multiplying the cutting depth applied on the silicon wafer workpiece being soaked in slurry at different temperatures and different volume concentrations, and dividing by the volume of the workpiece removed by the downward force of the cutting tool, as shown in equation (1):

$$SDFE_{reaction}\text{(specific downward force energy)} = \frac{F_d \times \Delta d}{\Delta V} \quad (1)$$

Here, F_d denotes the downward force applied by cutting tool onto the workpiece; Δd denotes the cutting depth; and ΔV denotes the volume removed from the workpiece by the cutting tool.

Since the AFM probe tip is like a semispherical cutting tool, the volume removed from the workpiece by cutting tool can be obtained by the geometric equation of sphere. From moving of cutting tool to machining of groove, the depth in the middle area gradually inclines to be at a fixed cutting depth. As to the volume removed by downward force after moving of cutting tool, the volume of the distance of the radius R behind the cap of the workpiece being cutted by the probe in advancing direction has been removed. Therefore, at this moment, the removed volume is half of the cap volume under the cutting depth, and the removed volume is shown as follows equation (2):

$$V_i = \frac{1}{2}\pi {d_i}^2 (R - \frac{d_i}{3}) \quad (2)$$

where R denotes the tip radius of the cutting tool of probe; and $\triangle d$ denotes the cutting depth.

In times of CMP machining, when the abrasive particles in slurry are polishing the wafer, the machining via polishing and cutting is similar to making of an abrasive depth by each spherical abrasive particle, and is also similar to the foregoing AFM probe's machining behavior on silicon wafer. Therefore, if the paper firstly uses scanning electron microscope (SEM) to measure the diameter of the semi-sphere of the AFM probe, and the diameter of the probe tip of AFM is 150nm. Then applies the abovementioned AFM machining experiment, with the soaked silicon wafer affected by the slurry at different temperatures and different volume concentrations, the paper should firstly set the downward force, perform cutting, and then measure the obtained cutting depth. After that, the paper uses equation (2) to calculate the removed volume, and then calculate the $SDFE_{reaction}$ value of the chemical reaction layer of silicon wafer soaked in slurry at different temperatures and different volume concentrations.

MODEL OF ABRASIVE REMOVAL DEPTH OF SILICON WAFER SOAKED IN SLURRY AT DIFFERENT TEMPERATURES AND DIFFERENT VOLUME CONCENTRATIONS UNDER CMP BY A PATTERN-FREE POLISHING PAD

For the experiment focusing on each of the same experimental parameter, the paper conducts CMP experiment for 5 times. In each experiment, polishing is carried out for 20 minutes, and then the experimental average value of the abrasive removal depth per minute is obtained.

Calculation Method of The Contact Area Between Asperity Peak of Polishing Pad and Wafer

The paper supposes that the asperity peak of pattern-free polishing pad was supposed to be of Gaussian distribution, and the wafer was supposed to be a flat surface. As to the derived contact area between polishing pad and wafer as well as the load, it supposed that abrasive particles were embedded on the polishing pad only on the contact area between the asperity peak of polishing pad and wafer, to perform polishing of wafer. Under this model, in order to use pattern-free polishing pad, the paper divides the silicon wafer into multiple single elements, with each element in the size of 1mm x1mm, as shown in Figure 1. Thus, the contact area between each element of wafer and polishing pad is Gaussion distribution. When the silicon wafer is rotating, each element would have continuous relative turning contacts with the pattern-free polishing pad.

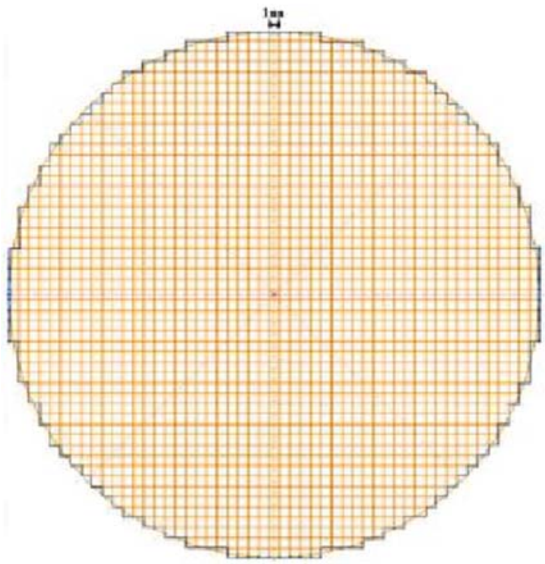

Figure 1 Schematic diagram of division of silicon wafer elements

According to the equations of contact area and contact load in Qing et al. (2004), the paper further modifies the equations, and proposes the effective contact area (A_{rs}) equation and contact load (F) equation, as shown below, for the contact between the asperity peak of polishing pad and each element of silicon wafer. It is supposed that abrasive particles on the polishing pad are embedded only on the effective contact area (A_{rs}) between the asperity peak of polishing pad and wafer, and these abrasive particles are used to polish the wafer.

$$A_{rs} = \eta A_0 \pi \beta \int_h^{\infty} (z-h)\emptyset(z)dz \quad (3)$$

$$\frac{A_{rs}}{F} = \frac{3\pi\beta^{\frac{1}{2}}}{4E^*} \frac{\int_h^{\infty}(z-h)\varphi(z)dz}{\int_h^{\infty}(z-h)^{\frac{3}{2}}\varphi(z)dz} \quad (4)$$

Johnson (1985) used numerical integration to perform integration of equation (4). But for h/σ within a range, the ratio of two integrals is approximately a constant, so that equation (5) can be obtained:

$$A_{rs} = C^{-1}(\frac{\beta}{\sigma})^{\frac{1}{2}}\frac{F}{E^*} \quad (5)$$

$$E^* = \frac{1-\nu_p{}^2}{E_p} + \frac{1-\nu_w{}^2}{E_w}$$

where E^* denotes the equivalent Young's modulus; ν_p denotes Poisson's ratio of polishing pad; ν_w denotes Poisson's ratio of silicon wafer; E_p denotes Young's modulus of polishing pad; and E_w denotes Young's modulus of silicon wafer.

In equation (5), C is a constant. In Yu et al. (1993) of the paper, the constant was derived and calculated. From Johnson (1985), it is known that the ratio h/σ of polishing pad is generally between 0.5 and 3.0. When h/σ is between 0.5 and 3.0, C value is approximately 0.35. The polishing pad used in this paper and the polishing pad used in Johnson (1985) are made by the same company, and of similar model number. Therefore, for the variables of equation (6), the paper refers to the β and σ values in Johnson (1985).

Theoretical Method for Calculation of Abrasive Removal Depth of Single Element of Silicon Wafer

In Kim and Jeong (2004) of the paper, a pattern-free polishing pad was used to polish wafer. It mentioned that at any point, being position P, on silicon wafer, the relative velocity $v_{w/p}$ of polishing pad is expressed as the following equation:

$$V_{w/p} = \omega_p D_{wp}\sqrt{(\rho\zeta)^2 + 2\rho\zeta cos\phi + 1} \quad (6)$$

In this paper, it set the central position of each element of silicon wafer to be at the abovementioned position P on the wafer surface. Therefore, the actual relative abrasive length per minute at the central position of each element on silicon wafer is $\omega_p D_{wp}$. Dividing $\omega_p D_{wp}$ by each element's length of L_e can achieve the relative number of polishing times FF per unit time for the contact between each element and polishing pad. Therefore, $\mathrm{FF} = \frac{\omega_p D_{wp}}{L_e}$.

The paper lets the size of each element of silicon wafer be 1mm × 1mm; therefore, L=1mm. Right now, the wafer's surface volume (Vol) that can be removed by abrasive particle and expressed as the following equation:

$$\mathrm{Vol} = A_p * \ell \quad (7)$$

where

Vol: volume of wafer removed by a single abrasive particle per unit number of polishing times

A_p : cross-sectional area of abrasive depth δ_{aw} of a single abrasive particle

ℓ : moving length of abrasive particles per unit time

The paper supposes that the abrasive particles on the effective contact area in each of the divided element of silicon wafer are distributed evenly. Therefore, the moving length ℓ per unit time of a single abrasive particle within each of the divided elements of silicon wafer is expressed as the following equation:

$$\ell = \omega_p D_{wp} \quad (8)$$

where

$$A_p \approx \frac{1}{2}\cdot\delta_{aw}\cdot 2r_a \approx \delta_{aw}\sqrt{\delta_{aw}D} \quad (9)$$

Besides, if N_e denotes the number of effective abrasive particles of each element of wafer, and the unit volume concentration of the number of particles in slurry is supposed to be χ, and the average diameter of abrasive particles is D, then $(\frac{6\chi}{\pi D^3})^{2/3}$ is the number of particles per unit volume in slurry. Since the length of each element of wafer is 1mm, the number of effective abrasive particles of effective contact area of a single element is (Zhao and Chang, 2002):

$$N_e = A_{rs}\cdot\left(\frac{6\chi}{\pi D^3}\right)^{2/3} = C^{-1}(\frac{\beta}{\alpha})^{\frac{1}{2}}\frac{F}{E^*}(\frac{6\chi}{\pi D^3})^{2/3} \quad (10)$$

where A_{rs} denotes the effective contact area between the asperity peak of polishing pad, which is for the interface between single element's position and polishing pad, and each element of wafer surface. In this paper, the contact between the asperity peak of polishing pad and wafer is of Gaussian distribution, which derives equation (5) of A_{rs} to be used for calculation.

The paper proposes a supposition that the downward force borne by each element of wafer is: $F=F_{total}/n$. Here, F_{total} denotes the total down force of CMP machine for polishing pad to press down to wafer; n denotes the number of the divided elements of wafer on the contact between wafer and polishing pad. Furthermore, the paper derives a new equation of down force F_{aw} of a single abrasive particle in polishing the wafer:

$$F_{aw} = \frac{F_{total}}{n\times N_e} \quad (11)$$

where N_e denotes the number of effective abrasive particles of each element on the effective contact area. The total downward force F_{total} of polishing pad in pressing down to wafer can be measured and known by the experimental CMP machine. Besides, the number *n* of elements of wafer on the contact between wafer and polishing pad is the number of the divided elements of wafer. From the catalog provided by the manufacturer, the volume concentration (χ) of abrasive particles in slurry can be known. Equation (10) can be used to obtain N_e, and hence, F_{aw} can also be subsequently obtained. After substituting the contact force F_{aw} between a single abrasive particle and wafer surface into the $SDFE_{reaction}$ equation (1) of silicon wafer soaked in slurry at different temperatures and different volume concentrations, the abrasive removal depth Δd on wafer surface by a single abrasive particle can be achieved:

$$\Delta d = \frac{\Delta V \times SDFE_{reaction}}{F_{aw}} \quad (12)$$

$$\Delta d = \frac{\frac{1}{2}\pi \times \Delta d^2 \times (R - \frac{\Delta d}{3}) \times SDFE_{reaction}}{F_{aw}} \quad (13)$$

where R denotes the radius of abrasive particle.

Using equation (13), the quadratic equation in one variable that takes Δd as a single variable can be solved.

$$\Delta d = \frac{3R - \sqrt{9R^2 - \frac{24F_{aw}}{\pi \times SDFE_{reaction}}}}{2} = \delta_{aw} \quad (14)$$

The paper further substitutes equation (11) into equation (14) to find the polishing depth δ_{aw} of a single abrasive particle on wafer surface:

$$\Delta d = \frac{3R - (9R^2 - \frac{24 \times \frac{F_{total}}{n \times N_e}}{\pi \times SDFE_{reaction}})^{\frac{1}{2}}}{2} = \delta_{aw} \quad (15)$$

Substitute the obtained δ_{aw} into equatio (9) and equation (7) to acquire the effective removal volume of a single abrasive particle of a single element on wafer surface per unit time: $\mathrm{Vol} = \delta_{aw}\sqrt{\delta_{aw}D} \times l$. Besides, based on equation (8), $\ell = \omega_p D_{wp}$, and hence $\mathrm{Vol} = \delta_{aw}\sqrt{\delta_{aw}D} \times \omega_p D_{wp}$.

Multiply Vol by the number N_e of effective abrasive particles of each element. Therefore, the effective abrasive removal volume $V_{\Delta t}$ of each element per unit time is expressed as the following equation:

$$V_{\Delta t} = Vol \times N_e \quad (16)$$

The paper proposes dividing $V_{\Delta t}$ by the area A_0 at the position of a single element of wafer, to obtain the average abrasive removal depth $\delta_{\Delta t}$ per unit time at the position of each element:

$$\delta_{\Delta t} = \frac{V_{\Delta t}}{A_0} \quad (17)$$

Theoretical Equation for Calculation of Abrasive Removal of Silicon Wafer Under CMP by a Pattern-Free Polishing Pad

Therefore, after multiplying the effective removal volume per unit time of a single element by the number n of the divided elements of wafer contacting the polishing pad, the effective removal volume of wafer per unit time can be obtained. After dividing the effective removal volume of wafer per unit time by the area A_w of wafer, the average abrasive removal depth of wafer per unit time can be obtained.

After rearranging the above equations, the following equation of abrasive removal depth d_{ab} of silicon wafer per unit time is obtained:

$$d_{ab} = \frac{\delta_{aw}\sqrt{\delta_{aw}D} \times \omega_p D_{wp} \times A_{rs} \cdot \left(\frac{6\chi}{\pi D^3}\right)^{2/3} \times n}{\pi R_w^2} \quad (18)$$

In equation (18), F_{total} can be known from measurement by CMP machine. The $SDFE_{reaction}$ value of the chemical reaction layer of silicon wafer soaked in slurry at different temperatures and different volume concentrations can be known from calculation in AFM experiment. The rotational velocity ω_p of polishing pad is a set value; and D_{wp} is known. By the time the slurry is purchased, the diameter D of abrasive particles is known to be 50nm, so that the radius R of abrasive particles is 25mm. The number n of the divided elements of silicon wafer can be known; and the volume concentration χ of slurry can be known as well. Therefore, the abrasive removal depth d_{ab} of silicon wafer per unit time of minute can be calculated and known. As seen from d_{ab} of equation (18), the paper can derive an innovative theoretical equation of abrasive removal depth per unit time of minute of silicon wafer under CMP by a pattern-free polishing pad and being affected by slurry at different temperatures and different volume concentrations, as shown in equation (18), which is of academic innovativeness.

In the experiment, CMP of silicon wafer is performed repeatedly for 5 times. The rotational velocity of both the polishing pad and wafer is 60rpm; and the downward force of CMP machine is 3psi (equivalent to a downward force of 42.026N onto a 2-inch wafer). For the experiment performed each time, silicon wafer is polished for 20 minutes, achieving the average abrasive removal depth of silicon wafer per minute of the experiments done for 5 times. Under the same conditions, and using the already derived theoretical equation of abrasive removal depth of silicon wafer per unit time of minute, the paper simulates calculation of the abrasive removal depth d_{ab} per minute.

AVERAGE ABRASIVE REMOVAL DEPTH PER MINUTE BEING CLOSE TO THE EXPERIMENTAL VALUE

Regarding the CMP equipment being currently used, in times of polishing, the slurry continuously flows out on the wafer and polishing pad, and the study can currently prepare slurry at different volume concentrations at room temperature to do the CMP experiment. However, in the CMP experiments with great flow rate of slurry, it is still difficult to control the slurry temperature. But, this paper is able to calculate the $SDFE_{reaction}$ values inside the chemical reaction layer of silicon wafer soaked in slurry at different temperatures and different volume concentrations by using AFM experiment. Therefore, the abrasive removal depth per minute calculated from the theoretical model has considered the effects of slurry at different temperatures and different volume concentrations on the CMP of silicon wafer. Therefore, it can apply the paper's concept of average difference ratio, use the simulated and calculated abrasive removal depth per minute of silicon wafer soaked in slurry at different temperatures and different volume concentrations for CMP, and then employ the average difference ratio value previously obtained in the paper, to compensate and modify the calculation of the numerical value of average abrasive removal depth per minute being close to the experimental value. After that, the obtained numerical value of this average abrasive removal depth per minute being close to the experimental value under different downward forces, different rotational velocities, and with slurry at different temperatures and different volume concentrations can serve as an input numerical value for regression analysis.

With the innovative concept aforesaid, it can save a lot of efforts on doing experiments, and can use a cost-saving theoretical model to calculate the abrasive removal depth value being close to the experimental value per minute of silicon wafer under CMP by a pattern-free polishing pad with slurry at different temperatures and different volume concentrations, and under different downward forces and different rotational velocities. Thus, this research is of academic innovativeness.

The $SDFE_{reaction}$ values of the chemical reaction layers of 4 silicon wafers soaked in slurry at different volume concentrations of 20%, 30%, 40% and 50% at room temperature can be substituted into equation (18) to find d_{ab}. Furthermore, from equation (18), 4 abrasive removal depths per minute d_{ab} of silicon wafer can be simulated and calculated. The paper makes a comparison between the abovementioned experimental result of silicon wafer under CMP by a pattern-free polishing pad with slurry at different volume concentrations, and the 4 simulated results of abrasive removal depth per minute of silicon wafer soaked in slurry at different volume concentrations at room temperature, achieving an equation of difference ratio between the experimental and simulation results, as shown in equation (19).

$$\text{Difference ratio} = \frac{\text{(Simulation calculated abrasive removal depth per minute} - \text{Experimental average abrasive removal depth per minute)}}{\text{Simulation calculated abrasive removal depth per minute}} \quad (19)$$

According to our past experience, such a difference ratio value is approximately within a certain range, and the change would not be too great. Therefore, using the result with slurry at volume concentration of 50% and at room temperature as well as the 4 difference ratio values of silicon wafer soaked in slurry at 4 different volume concentrations at room temperature, the average difference ratio value can be obtained. Thus, using this average difference ratio value, this study can make compensatory modification of the simulated and calculated abrasive removal depth per minute, thus achieving an average abrasive removal depth value per minute that is close to the experimental value. Therefore,

Average abrasive removal depth value per minute being close to the experimental value
= Simulated abrasive removal depth per minute − (Simulated abrasive removal depth per minute × Average difference ratio value) (20)

After that, using the calculation method of average difference ratio value, the paper finds the average abrasive removal depth per minute being close to the experimental result.

REGRESSION MODEL OF CMP OF SILICON WAFER SOAKED IN SLURRY AT DIFFERENT TEMPERATURES AND DIFFFERENT VOLUME CONCENTRATIONS

In general, Preston's volumetric material removal equation is commonly used in CMP, and is expressed as MRR = KPV, where K is a constant; P denotes the downward force; and V denotes the rotational velocity. However, in order to calculate the abrasive removal depth, a new regression equation is used. As mentioned above, the abrasive removal depth per minute being close to the experimental value and newly obtained from calculation based on the foregoing concept of difference ratio is MRR_e. Then the paper firstly makes regression calculation of the equation $\mathrm{MRR_e} = \mathrm{k_{p_e}} \mathrm{P}^{\alpha_e} \mathrm{V}^{\beta_e}$, where k_{pe} is a constant; P denotes the downward force; and V denotes the rotational velocity of both wafer and polishing pad. The values of $\mathrm{k_{p_e}}$, α_e and β_e can be acquired by the following method and equation:

$$\mathrm{MRR_e} = \mathrm{k_{p_e}} \mathrm{P}^{\alpha_e} \mathrm{V}^{\beta_e} \quad (21)$$

A natural logarithm (El-Kareh, 1995), so that equation (21) can be changed as

$$\ln \mathrm{MR}R_e = \ln \mathrm{k_{p_e}} + \alpha_e \ln P + \beta_e \ln V.$$

This equation is equivalent to

$$\mathrm{y} = \beta_0 + \beta_1 \chi_1 + \beta_2 \chi_2 \quad (22)$$

$\mathrm{y} = \ln MRR_e$, $\beta_0 = \ln \mathrm{k_{p_e}}$, $\chi_1 = lnP$, $\chi_2 = lnV$, $\beta_1 = \alpha_e$, $\beta_2 = \beta_e$;

Therefore, $\mathrm{Y} = \hat{\beta} X$.

Use the least square method, and then multiply it by X', achieving $X'Y = (X'X)\hat{\beta}$.

Therefore,

$$\hat{\beta} = (X'X)^{-1}(X'Y') \text{ and } \hat{\beta} = \begin{bmatrix}\beta_0\\ \beta_1\\ \beta_2\end{bmatrix} \quad (23)$$

From the matrix of equation (23) aforesaid, it can calculate $k_{p_e} = e^{\beta_0}$, $\alpha_e = \beta_1$, $\beta_e = \beta_2$, and further find the regression equation of $MRR_e = k_{p_e} \times P^{\alpha_e} \times V^{\beta_e}$.

Furthermore, this study tests whether the regression result obtained from MRR_e equation as well as the R-square value of the average abrasive removal depth per minute being close to the actual result are excessively less than 1, or whether the average residual is excessively greater than 0. If positive, the paper would consider adding to the MMR_e regression equation a compensatory regression equation of S_{vce} and S_{tme} with consideration of the effects of slurry at different temperatures and different volume concentrations, i.e. $MRR_e = k_{p_e} \times P^{\alpha_e} \times V^{\beta_e} + S_{vce} + S_{tme}$; For the compensatory regression equation of S_{vce} , $S_{vce} = MRR_e - (k_{p_e} \times P^{\alpha_e} \times V^{\beta_e})$. Here, the paper lets S_{vce} be a quadratic regression model; $S_{vce} = y_{vce}$; and the volume concentration of slurry be x_{vce}.

$$\therefore y_{vce} = \beta_{0vce} + \beta_{1vce}x_{vce} + \beta_{2vce}x_{vce}^2 \quad (24)$$

$$\therefore MRR_e = k_{pe}P^{\alpha_e}V^{\beta_e} + (\beta_{0vce} + \beta_{1vce}x_{vce} + \beta_{2vce}x_{vce}^2) = k_{pe}P^{\alpha_e}V^{\beta_e} + S_{vce} \quad (25)$$

This paper also simulates calculation of the experimental average abrasive removal depth per minute being close to the experimental value, with slurry at different volume concentrations under a different downward force, a different rotational velocity and at room temperature, and then calculate the MRR_e value of the abrasive removal depth per minute obtained from the regression equation under the same condition. The paper makes comparison between these two results, and proves that the regression equation is reasonable.

According to our past experience in doing researches, in general, the rise of slurry temperature would affect the abrasive removal depth per minute, and can achieve a greater abrasive removal depth per minute. Therefore, during regression analysis, the effects of different slurry temperatures should also be considered. In this study, it thus adds a compensatory regression equation of S_{tme} with consideration of the effects of slurry temperature: $S_{tme} = MRR_e - (k_{p_e}P^{\alpha_e}V^{\beta_e} + S_{vc_e})$. Let S_{tme} be a quadratic regression model, so $S_{tme} = y_{tme}$.

And in $y_{tm} = \beta_{0tme} + \beta_{1tme}x_{tme} + \beta_{2tme}x_{tme}^2$, x_{tme} denotes the slurry temperature.

Therefore,

$$MRR_e = k_P P^{\alpha_e}V^{\beta_e} + S_{vc_e} + S_{tme} = k_P P^{\alpha_e}V^{\beta_e} + \beta_{0vc_e} = + \beta_{1vc_e}x_{vce} + \beta_{2vc_e}x_{vce}^2 + \beta_{0tme} + \beta_{1tme}x_{tme} + \beta_{2tme}x_{tme}^2 \quad (26)$$

Then, this study compares the result of average abrasive removal depth per minute being close to the experimental value simulated and calculated by using a group of unused downward force, rotational velocity, different volume concentrations of slurry and different slurry temperatures during establishment of the regression equation aforesaid, with the result calculated by the regression equation, to prove the rationality of the regression equation.

RESULTS AND DISCUSSION

Simulation Result of The Theoretical Model of Silicon Wafer Under CMP by A Pattern-Free Polishing Pad

From the theoretical model-based simulation results of abrasive removal depth per minute, it finds that the abrasive removal depth per minute can be easily affected by the change of the temperature and volume concentration of slurry, downward force as well as rotational velocity. First of all, this study uses the slurry temperatures at 23°C, 30°C, 40°C and 50°C, downward force of 3 psi, rotational velocity of 60 rpm, as well as a fixed volume concentration of slurry at 20%, to do experiments. As seen from the AFM experimental results, the $SDFE_{reaction}$ values are $0.016772 \mu N \cdot nm / nm^3$, $0.016438 \mu N \cdot nm / nm^3$, $0.016352 \mu N \cdot nm / nm^3$ and $0.016208 \mu N \cdot nm / nm^3$ respectively. The paper analyzes the simulation results of abrasive removal depth per minute of the theoretical model. As seen from the simulation results, the obtained abrasive removal depths per minute are 23.0627nm/min., 23.3524nm/min., 24.2589nm/min. and 32.1839nm/min. respectively. It can also use a fixed slurry temperature of 30°C, 3 psi, 60 rpm, as well as the volume concentrations of slurry at 20%, 30%, 40% and 50% respectively to do AFM experiments and simulations. As seen from the AFM experimental results, the $SDFE_{reaction}$ values are $0.016633 \mu N \cdot nm / nm^3$, $0.016282 \mu N \cdot nm / nm^3$, $0.016102 \mu N \cdot nm / nm^3$ and $0.015943 \mu N \cdot nm / nm^3$ respectively. The paper also analyzes the simulation results of abrasive removal depth per minute of the theoretical model. From the simulation results, it can obtain the abrasive removal depths per minute, being 23.3524nm/min., 25.0534nm/min., 26.9911nm/min. and 29.1126nm/min. respectively. Therefore, it is known that under the same slurry volume concentration, the same downward force, the same rotational velocity, as well as the increased temperature of slurry, the abrasive removal depth per minute would be increased. This is because under the same volume concentration of slurry, the higher the slurry temperature, the more easily the chemical reaction layer of silicon wafer would be softened; and this would made the $SDFE_{reaction}$ value decreased, and hence, the abrasive removal depth value per minute would be greater. A greater volume concentration of slurry indicates that there is a great number of abrasives in slurry. Thus, when the surface of silicon wafer is being polished by a pattern-free polishing pad, the removed volume is greater. Therefore, after dividing the removed volume by the surface area of silicon wafer, the abrasive removal depth per minute would be relatively greater.

Regression Analysis of CMP Simulation Result of Silicon Wafer

Under the multiple conditions that a pattern-free polishing pad is used, the volume concentrations of slurry are 20%, 30%, 40% and 50%, the temperatures of slurry are 23°C, 30°C, 40°C and 50°C, all of which are matched with different downward forces of 1psi, 1.5psi, 2psi, 2.5psi and 3psi, as well as different rotational velocities at 20rpm, 30rpm, 40rpm, 50rpm and 60rpm, the paper uses the theoretical simulation result of the abrasive removal depth value per minute to serve as the input value, and employs the least square method to perform regression analysis, acquiring the regression result of $MRR = k_p P^{\alpha} V^{\beta}$. When the slurry is at different volume concentrations and temperatures, the values of α and β are all 1.0059 and 1 respectively, only that k_p value changes with different temperatures and different volume concentrations of slurry.

Analysis on The Difference Ratio of CMP Experimental Result of Silicon Wafer at Room Temperature

This paper makes the 6 groups of CMP experiments of silicon wafer polished by a pattern-free polishing pad at room temperature with different volume concentrations of slurry, under different downward forces and different rotational velocities: (1) 20%, 3psi, 60rpm; (2) 30%, 3psi, 60rpm; (3) 50%, 3psi, 60rpm; (4) 40%, 2psi, 40rpm; (5) 50%, 2psi, 40rpm; and (6) 50%, 1psi, 60rpm. Then the paper compares the theoretical simulation result of abrasive removal depth for CMP by a pattern-free polishing pad with slurry at different volume concentrations at room temperature, with the above 6 CMP experimental results of abrasive removal depth. The paper calculates the theoretical simulation values of individual abrasive removal depth per minute of the polished wafer soaked in slurry at different volume concentrations at room temperature, and obtains them in the above 6 experiments, as well as the average difference ratio values of the experimental average abrasive removal depths per minute, being 4.05%, 4.16%, 4.23%, 4.26%, 4.35% and 4.19% respectively. The paper also calculates the average difference ratio value, which is approximately 4.2%.

Although the average difference ratio of the theoretical simulation result to the experimental result of abrasive removal depth per minute is approximately 4.2%, it can still be proved that the paper's established theoretical model of abrasive removal depth of silicon wafer under CMP by a pattern-free polishing pad with consideration of the chemical reaction effects of slurry at different temperatures and different volume concentrations is still reasonable.

Result of Average Abrasive Removal Depth Per Minute Being Close to The Experimental Value At Different Temperatures and Different Vlume Concentrations Simulated From the Modified Theoretical Model

The paper uses the abovementioned average difference ratio value of 4.2% to calculate the new theoretical simulation result of the average abrasive removal depth per minute being close to the experimental result, with slurry at different temperatures and different volume concentrations. These theoretical simulation results of the average abrasive depth per minute being close to the experimental value serves as an input value of the new regression equation. The volume concentrations of slurry are 20%, 30%, 40% and 50%, and the temperatures of slurry are 23°C, 30°C, 40°C and 50°C, all of which are matched with different downward forces of 1psi, 1.5psi, 2psi, 2.5psi and 3psi, as well as different rotational velocities of 20rpm, 30rpm, 40rpm, 50rpm and 60rpm. The paper uses the least square method to perform regression analysis, obtaining $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e}$, which is the regression equation of the average abrasive removal depth per minute being close to the experimental result, with slurry at different temperatures and different volume concentrations. From the regression result, the values of α_e and β_e with slurry at different temperatures and different volume concentrations can be obtained, and are all 1.0059 and 1 respectively, only that k_{p_e} value changes with different temperatures and different volume concentrations of slurry. The paper finds the k_{p_e} values with slurry at different volume concentrations of 20%, 30%, 40% and 50% and different temperatures of 23°C, 30°C, 40°C and 50°C. Table 1 shows the equation of $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e}$ with slurry at the temperature of 30°C and different volume concentrations. In this equation, there are different k_{p_e} values.

Table 1 Regression equation $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e}$ with slurry at temperature 30°C and different volume concentrations

Volume concentration	Regression equation	
50%	MRR_e= 0.1541$P^{1.0059}$ V^1	k_{p_e}=0.1541, α_e=1.0059, β_e=1, R^2=0.999992 Average residual=0.00004
40%	MRR_e= 0.1429$P^{1.0059}$ V^1	k_{p_e}=0.1429, α_e=1.0059, β_e=1, R^2=0.999991 Average residual=-0.000002
30%	MRR_e= 0.1326$P^{1.0059}$ V^1	k_{p_e}=0.1326, α_e=1.0059, β_e=1, R^2=0.999992 Average residual=0.000004
20%	MRR_e= 0.1237^{0059} V^1	k_{p_e}=0.1327, α_e=1.0059, β_e=1, R^2=0.999992 Average residual=-0.000002

Finally, the paper calculates the results of average abrasive removal depth per minute being close to the experimental result, and the regression results of $MRR_e = k_{pe} P^{\alpha e} V^{\beta e}$. As known from the calculated results, the difference are all less than 0.26%, which is within an acceptable range since the difference in practical application is below 1%, and is also a result that can be conveniently used for calculation under a fixed volume concentration of slurry, different temperatures of slurry, different downward forces and different rotational velocities. From here, it is known that the equation $MRR_e = k_{pe} P^{\alpha e} V^{\beta e}$ with slurry at a fixed volume concentration is acceptable.

Compensatory Regression Result of Average Abrasive Removal Depth Per Minute Being Close to The Experimental Result with Slurry at Different Temperatures and Different Volume Concentrations After Modification of Compensatory Regression Equation by Average Difference Ratio Value

This paper uses the difference value with consideration for S_{vc_e} = (Simulation value of average abrasive removal depth per minute being close to the experimental value after modification $-k_{p_e} P^{\alpha_e} V^{\beta_e}$) as well as S_{tm_e} = Simulation value of average abrasive removal depth per minute being close to the experimental value after modification $-(k_{p_e} P^{\alpha_e} V^{\beta_e} + \mathbf{S_{vc_e}})$ to calculate the difference values of S_{vc_e} and S_{tm_e}, with slurry at different temperatures and different volume concentrations, under different downward forces and at different rotational velocities.

After regression analysis, these regression equations are acquired:

$MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e}$ and

$MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e} + S_{tm_e}$.

Furthermore, this paper can calculate the regression result of average abrasive removal depth per minute of the polished silicon wafer being close to the experimental value.

This paper compares the result of average abrasive removal depth per minute being close to the experimental value, simulated and calculated by using a group of unused downward force, rotational velocity, different volume concentrations of slurry and different slurry temperatures during establishment of the regression equations aforesaid, with the results calculated by regression equations. For example, Table 2 shows the equation of $MRR_e = k_{p_e}(x, y) P^{\alpha_e} V^{\beta_e} + S_{vc_e}$, which is the compensatory regression equation of average abrasive removal depth per minute, being close to the experimental value, with slurry at the temperature of 50°C and different volume concentrations after having considered the volume concentration and temperature of slurry. For example, Table 3 shows the equation of $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e} + S_{tm_e}$, which is the compensatory regression equation of average abrasive removal depth per minute, being close to the experimental value, with slurry at the temperature of 40°C and different volume concentrations after having considered the volume concentration and temperature of slurry.

Table 2 Compensatory regression equation $\mathbf{MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e}}$ of average abrasive removal depth per minute being close to the experimental value, with slurry at the temperature of 50°C and different volume concentrations, and different downward forces

Volume concentration	Downward force	Regression equation $\mathbf{MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e}}$
50%	1psi	MRR_e=0.1704 $P^{1.0059}$ V^1 + (-326.72668+1337.726x_{vc_e}-1368.5714$x_{vc_e}^2$)
	1.5psi	MRR_e=0.1704 $P^{1.0059}$ V^1 + (-203.36103+748.8907x_{vc_e}-684.28571$x_{vc_e}^2$)
	2psi	MRR_e=0.1704 $P^{1.0059}$ V^1 + (327.0473-1338.3679x_{vc_e}+1368.571$x_{vc_e}^2$)

	2.5psi	$MRR_e=0.1704\ P^{1.0059}\ V^1 + (6.914757-13.835048x_{vc_e}+0.0000000254x_{vc_e}{}^2)$
	3psi	$MRR_e=0.1704\ P^{1.0059}\ V^1 + (-312.41169+1309.085x_{vc_e}-1368.5714x_{vc_e}{}^2)$
40%	1psi	$MRR_e=0.1573\ P^{1.0059}\ V^1 + (120.8434-575.83689x_{vc_e}+684.2857x_{vc_e}{}^2)$
	1.5psi	$MRR_e=0.1573\ P^{1.0059}\ V^1 + (85.34917-487.05705x_{vc_e}+684.2857x_{vc_e}{}^2)$
	2psi	$MRR_e=0.1573\ P^{1.0059}\ V^1 + (-11.904663+29.77655x_{vc_e}+0.0000000508x_{vc_e}{}^2)$
	2.5psi	$MRR_e=0.1573\ P^{1.0059}\ V^1 + (-105.11354+536.4926x_{vc_e}-684.28571x_{vc_e}{}^2)$
	3psi	$MRR_e=0.1573\ P^{1.0059}\ V^1 + (130.909-601.01339x_{vc_e}+684.2857x_{vc_e}{}^2)$
30%	1psi	$MRR_e=0.1472\ P^{1.0059}\ V^1 + (69.91442-438.35214x_{vc_e}+684.2857x_{vc_e}{}^2)$
	1.5psi	$MRR_e=0.1472\ P^{1.0059}\ V^1 + (45.24264-356.05775x_{vc_e}+684.2857x_{vc_e}{}^2)$
	2psi	$MRR_e=0.1472\ P^{1.0059}\ V^1 + (115.6191-795.95151x_{vc_e}+1368.571x_{vc_e}{}^2)$
	2.5psi	$MRR_e=0.1472\ P^{1.0059}\ V^1 + (3.940307-13.143118x_{vc_e}-0.00000000002206x_{vc_e}{}^2)$
	3psi	$MRR_e=0.1472\ P^{1.0059}\ V^1 + (39.2855-2684.89187x_{vc_e}+1368.571x_{vc_e}{}^2)$
20%	1psi	$MRR_e=0.1355\ P^{1.0059}\ V^1 + (32.62772-300.0214x_{vc_e}+684.2857x_{vc_e}{}^2)$
	1.5psi	$MRR_e=0.1355\ P^{1.0059}\ V^1 + (17.45605-224.0876x_{vc_e}+684.2857x_{vc_e}{}^2)$
	2psi	$MRR_e=0.1355\ P^{1.0059}\ V^1 + (-59.362287+570.5482x_{vc_e}-1368.5714x_{vc_e}{}^2)$
	2.5psi	$MRR_e=0.1355\ P^{1.0059}\ V^1 + (30.10761-287.40846x_{vc_e}+684.2857x_{vc_e}{}^2)$
	3psi	$MRR_e=0.1355\ P^{1.0059}\ V^1 + (39.47979-334.31642x_{vc_e}+684.2857x_{vc_e}{}^2)$

Table 3 Compensatory regression equation $\mathbf{MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e} + S_{tm_e}}$ of average abrasive removal depth per minute being close to the experimental value, with slurry at the temperature of 40°C and different volume concentrations, and different downward forces

Volume concentration	Downward force	Regression equation $\mathbf{MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e} + S_{tm_e}}$
50%	1psi	$MRR_e=0.1603\ P^{1.0059}\ V^1 + (185.8847-713.92403x_{vc_e}+684.2857x_{vc_e}{}^2)+(63.54-0.239958x_{tm_e}-0.003784837x_{tm_e}{}^2)$
	1.5psi	$MRR_e=0.1603\ P^{1.0059}\ V^1 + (-372.88884+1430.088x_{vc_e}-1368.5714x_{vc_e}{}^2)+(-91.074135+7.245716329x_{tm_e}-0.14845103x_{tm_e}{}^2)$
	2psi	$MRR_e=0.1603\ P^{1.0059}\ V^1 + (327.7067-1339.6873x_{vc_e}+1368.571x_{vc_e}{}^2)+(-8.833532+0.3849781x_{tm_e}+0.00000351112646x_{tm_e}{}^2)$
	2.5psi	$MRR_e=0.1603\ P^{1.0059}\ V^1 + (-314.56414+1313.392x_{vc_e}-1368.5714x_{vc_e}{}^2) +(-37.7756996941518+0.522266x_{tm_e}-0.36438x_{tm_e}{}^2)$
	3psi	$MRR_e=0.1603\ P^{1.0059}\ V^1 + (-314.56414+1313.392x_{vc_e}-1368.5714x_{vc_e}{}^2) +(-66.436167+6.1740345x_{tm_e}-0.142857142847756x_{tm_e}{}^2)$
40%	1psi	$MRR_e=0.1484\ P^{1.0059}\ V^1 + (11.00649-27.53x_{vc_e}-0.000000006373x_{vc_e}{}^2) +(5.060004082-0.22504x_{tm_e}+0.\ 51277x_{tm_e}{}^2)$
	1.5psi	$MRR_e=0.1484\quad P^{1.0059}\ V^1 + (-131.97473+603.679x_{vc_e}-684.28571x_{vc_e}{}^2) +(-90.0676+7.2016974784x_{tm_e}-0.1428565171x_{tm_e}{}^2)$
	2psi	$MRR_e=0.1484\quad P^{1.0059}\ V^1 + (-120.25869+574.3742x_{vc_e}-684.28571x_{vc_e}{}^2)+(29.551677-2.92771245x_{tm_e}+0.0714285714261846x_{tm_e}{}^2)$
	2.5psi	$MRR_e=0.1484\ P^{1.0059}\ V^1 + (114.5788-560.16754x_{vc_e}+684.2857x_{vc_e}{}^2)+(-75.7831439194+6.588657x_{tm_e}-0.1428868651x_{tm_e}{}^2)$
	3psi	$MRR_e=0.1484\ P^{1.0059}\ V^1 + (-88.540498+495.0392x_{vc_e}-684.28571x_{vc_e}{}^2)+(-29.4013742+2.92116968362x_{tm_e}-0.071428536606x_{tm_e}{}^2)$
30%	1psi	$MRR_e=0.1392\ P^{1.0059}\ V^1 + (131.1753-847.83989x_{vc_e}+1368.571x_{vc_e}{}^2)+(6.67000054-0.28996614x_{tm_e}-0.00000007359469554x_{tm_e}{}^2)$
	1.5psi	$MRR_e=0.1392\ P^{1.0059}\ V^1 + (46.11015-358.95162x_{vc_e}+684.2857x_{vc_e}{}^2)+(-86.44556+7.04139508x_{tm_e}-0.14285786685x_{tm_e}{}^2)$
	2psi	$MRR_e=0.1392P^{1.0059}\ V^1 + (54.41474-386.65207x_{vc_e}+684.2857x_{vc_e}{}^2)+(3.999328+0.1738855256x_{tm_e}+0.017113126187x_{tm_e}{}^2)$

	2.5psi	$MRR_e=0.1392\ P^{1.0059}\ V^1 + (3.761308-12.546057x_{vc_e}-0.00000000001814x_{vc_e}^2)+(-33.13+3.17870871x_{tm_e}-0.0714285714140339x_{tm_e}^2)$
	3psi	$MRR_e=0.1392\ P^{1.0059}\ V^1 + (15.12779-50.459604x_{vc_e}+0.000000038x_{vc_e}^2)+(107.94666-92.64864x_{tm_e}+1.903462x_{tm_e}^2)$
20%	1psi	$MRR_e=0.1285\ P^{1.0059}\ V^1 + (59.8347-572.9124x_{vc_e}+1368.571x_{vc_e}^2)+(77.86312-6.53307x_{tm_e}+0.136857x_{tm_e}^2)$
	1.5psi	$MRR_e=0.1285\ P^{1.0059}\ V^1 + (18.08986-227.25953x_{vc_e}+684.2857x_{vc_e}^2)+(-48.1769939+3.73756366x_{tm_e}-0.092018x_{tm_e}^2)$
	2psi	$MRR_e=0.1285\ P^{1.0059}\ V^1 + (-4.1405506+20.72348x_{vc_e}+0.000000000278x_{vc_e}^2)+(150.0109462-131.31779317x_{tm_e}+5.5737948x_{tm_e}^2)$
	2.5psi	$MRR_e=0.1285\ P^{1.0059}\ V^1 + (57.5528-561.49149x_{vc_e}+1368.571x_{vc_e}^2)+(494.5966-6.73700842588655x_{tm_e}+0.2837107x_{tm_e}^2)$
	3psi	$MRR_e=0.1285\ P^{1.0059}\ V^1 + (-15.787833+215.7381x_{vc_e}-684.28571x_{vc_e}^2)+(8.68409455-7.186385x_{tm_e}+0.2833424x_{tm_e}^2)$

From the difference between the results of average abrasive removal depth per minute being close to the experimental value and the regression results of $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e}$, it is known that each of the difference is less than 0.26%. From the difference between the results of average abrasive removal depth per minute being close to the experimental value as simulated from the theoretical model and the regression results of $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e}$, it is known that each of the difference is less than 0.17%. From the difference ratios between the results of average abrasive removal depth per minute being close to the experimental value as simulated from the theoretical model and the regression result of $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e} + S_{tm_e}$, it is known that each of the difference is less than 0.09%.Therefore, it can be seen that after adding the compensatory regression equation of S_{vc_e}, its difference from the modified simulation result of average abrasive removal depth per minute being close to the experimental value is smaller. Besides, after compensation by S_{vc_e} and addition of the compensatory result of S_{tm_e}, its difference from the simulation result of average abrasive removal depth per minute being close to the experimental value is even smaller.

CONCLUSION

The paper establishes the theoretical simulation model of the removal depth of silicon wafer under CMP by a pattern-free polishing pad, employs regression analysis theory and analyzes the experimental results, achieving the following conclusions:

1. For the abrasive removal depth of silicon wafer with slurry at different temperatures and different volume concentrations, the higher the slurry temperature and the greater the slurry's volume concentration, the deeper the abrasive removal depth. This is because with the increase in the temperature of slurry, the $SDFE_{reaction}$ would be lower, and then the abrasive removal depth would be inversely proportional to the $SDFE_{reaction}$. Besides, as the volume concentration of slurry is greater, there would be more abrasive particles performing polishing, so that the overall average abrasive removal depth of silicon wafer would be greater. Regarding the abrasive removal depth of silicon wafer with slurry at different temperatures, the higher the temperatures of slurry, the deeper the abrasive removal depth. This is because the higher the slurry temperature, the more easily the surface material of silicon wafer would be softened, so that the abrasive removal depth would be greater.
2. Applying the concept of average difference ratio value, and for the silicon wafer soaked in slurry at different temperatures and different volume concentrations, the paper makes calculation and obtains the compensatory equations for the regression equations of average abrasive removal depth per minute being close to the experimental value:
   $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e}$,
   $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e}$ and
   $MRR_e = k_{p_e} P^{\alpha_e} V^{\beta_e} + S_{vc_e} + S_{tm_e}$.
   Besides, it can be seen that after adding the compensatory regression equation of S_{vc_e}, its difference from the simulation result of average abrasive removal depth per minute being close to the experimental value is smaller. And after compensation by $S_{vc_e} + S_{tm_e}$, if S_{tm_e} is added for compensation, the difference would be smaller.

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考慮不同溫度及不同體積濃度研磨液建立化學機械拋光矽晶圓研磨移除深度理論模擬模式及迴歸分析模式

林榮慶
國立台灣科技大學光機電技術研發中心

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摘要

本研究先將矽晶圓浸泡在不同溫度及不同體積濃度研磨液 30 分鐘後，再進行原子力顯微鏡實驗，計算得出浸泡不同體積濃度及不同溫度研磨液的矽晶圓比下能值，再將這些值代入創新建立的不同溫度及不同體積濃度研磨液之無花紋研磨墊化學機械拋光矽晶圓的研磨移除深度理論模式。本研究先用室溫下不同體積濃度的無花紋研磨墊化學機械拋光矽晶圓實驗結果與模擬結果相比較。再比較模擬結果與實驗結果的每分鐘研磨移除深度的平均差異比例。應用平均差異比例的修正觀念，使得補償修正後的模擬所得接近實驗之平均每分鐘研磨移除深度值作為迴歸分析的類似實驗參數值。最後本研究建立考慮不同溫度及不同體積濃度研磨液的補償迴歸公式。