Material removal rate in chemical-mechanical polishing of wafers based on particle trajectories*

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Abstract: Distribution forms of abrasives in the chemical mechanical polishing (CMP) process are analyzed based on experimental results. Then the relationships between the wafer, the abrasive and the polishing pad are analyzed based on kinematics and contact mechanics. According to the track length of abrasives on the wafer surface, the relationships between the material removal rate and the polishing velocity are obtained. The analysis results are in accord with the experimental results. The conclusion provides a theoretical guide for further understanding the material removal mechanism of wafers in CMP.

Key words: chemical mechanical polishing; material removal mechanism; abrasive; material removal rate
DOI: 10.1088/1674-4926/31/5/056002 **EEACC:** 2520

1. Introduction

With the development of ultra large scale IC (ULSI), chemical mechanical polishing (CMP) has already become a practical and major planarization technology because of its global and local planarization ability. It is not only the most effective method of achieving a nano-scale and ultra-smooth surface without damage in monocrystalline silicon wafer manufacturing, but also the irreplaceable planarization method for multi-level wiring on the chip interconnects in ULSI manufacturing. A schematic of the CMP system is shown in Fig. 1[1]. The system consists of a rotational wafer carrier, a table supporting the polishing pad, and a slurry feedway. In the CMP process, a rotating wafer is pressed facedown onto a rotating polishing pad at a proper pressure. The polishing slurry, containing submicron or nanometer abrasive particles and chemical reagents such as the oxidant, activator, etc., flows between the wafer and the pad. A chemical reaction between chemical reagents in the slurry and the material of the wafer surface is conducted. A chemical reactant film is formed on the wafer surface and then is removed from the wafer surface by the abrasive particles in the slurry. The new surface will emerge and the next CMP cycle begins. In this way, the surface material will be removed from the wafer surface by the combined action of chemical reagents and abrasive particles.

Since CMP was applied in ULSI manufacturing, many researchers have studied the material removal mechanism in chemistry, physics and control area[2]. In the material removal rate (MRR) of wafer CMP, many different MRR models have been built by applying different theories[3]. Preston[4] put forward the first phenomenological model based on CMP process results by polishing optics glasses. Preston's model of MRR is as follows:

$$\mathrm{MRR} = k_{\mathrm{p}} P v, \tag{1}$$

where K_{p} is Preston's coefficient, P is the down pressure, and v is the relative velocity between the pad and the wafer surface. Subsequently, Preston's equation has been widely used in control of the CMP process and development of CMP consumables for integrated circuit (IC) fabrication. A micro-contact and wear model built on elastic-plastic micro-contact mechanics and abrasive wear theory has been presented by Zhao *et al*.[5]. The MRR of the wafer is given by

$$\mathrm{MRR} = \alpha \frac{9.9}{\pi^{5/3}} v \frac{A_{\mathrm{t}}}{A_{\mathrm{n}}} \left(\frac{\delta_{\mathrm{W}}}{D}\right)^2 \chi^{2/3}, \tag{2}$$

where A_{t} and A_{n} are the total real area and the nominal area of

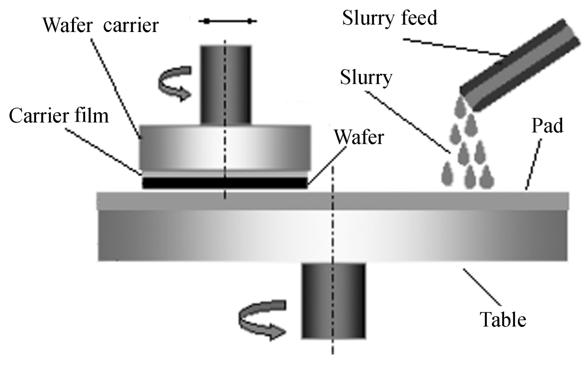

Fig. 1. Schematic of chemical mechanical polishing.

* Project supported by the Major Project of National Natural Science Foundation of China (No. 50390061), the Key Project of Science and Technology R & D Program of Henan Province, China (No. 102102210405), the Research Project Program of Natural Science of the Education Department of Henan Province, China (No. 2009A460004), the Scientific Research Foundation of Henan Institute of Science and Technology for High Level Scholar, and the Science and Technology Innovation Program of Henan Institute of Science and Technology.

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Received 21 October 2009, revised manuscript received 3 December 2009

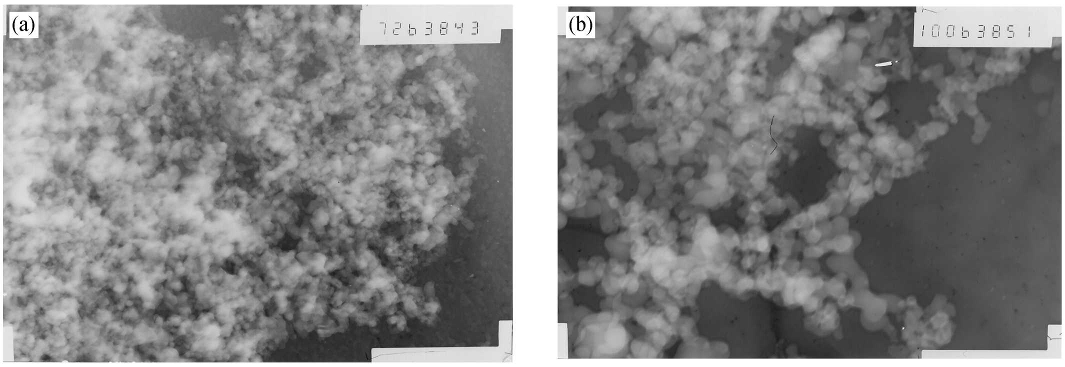

Fig. 2. TEM pictures of abrasives in slurry (×100 000). (a) TEM picture of Al_2O_3 abrasives in slurry iCue® 5001. (b) TEM picture of SiO_2 abrasives in slurry Semi-Sperse® 12 (SS12).

contact between the pad and the wafer, respectively, δ_W is the indentation depth of a particle in the wafer, α is the density ratio of the chemical film to the wafer, D is the average diameter of particles in slurry and χ is the particle volume concentration in the slurry. Shi *et al*.[6] have built a contact model of wafer CMP with a soft pad. The function of MRR in the model is as follows.

$$\mathrm{MRR} = K_{sz} P^{2/3} v, \tag{3}$$

where K_{sz} is the coefficient which is the function of other CMP variables, P and v are the same as in Eq. (1). Many other researchers using a different theory have also built MRR models, such as Refs. [7–9]. The results are that the MRR are proportional to the relative velocity v between the pad and the wafer.

According to these above-mentioned models, all MRR are proportional to the relative velocity v between the pad and the wafer. But the relative velocity v can not express the MRR directly, because wafer CMP is a process combining chemical action with mechanical action, and the chemical reaction layer on the wafer surface is mainly removed by the mechanical action of the abrasives in the slurry and the pad. Many experiments have showed that the MRR in the CMP process is very low if there are no abrasives or chemical ingredients[5, 6, 9]. It can be demonstrated that the friction or scratch produced by abrasives on the wafer surface in CMP process plays an important role in removing wafer material. So the material removal mechanism in wafer CMP can be studied by the scratch and friction produced by abrasives, which will show the practical situation and reveal the material removal mechanism of the CMP process directly. The scratch length produced by abrasives on the wafer surface has a direct influence on MRR. The longer the scratch length and the greater the numbers of abrasives participating in the CMP process under the same conditions, the larger the MRR. In this paper, the distribution forms of particles in the CMP process are analyzed based on experimental results. Then the relationships between the wafer, the abrasive particle and the polishing pad are analyzed based on kinematics and contact mechanics. According to the track length of abrasives on the wafer surface, the relationships between the MRR and the polishing velocity are obtained. The analysis results are in accord with the experimental results. The conclusion provides a theoretical guide to further understanding the material removal mechanism of the wafer in CMP. In regard to the MRR model based on motion tracks of abrasives on the wafer surface, a further study will be carried out in the nearest future.

2. Distribution forms of abrasives in the wafer CMP process

The wafer CMP is a process combining the chemical action of chemical reagents with the mechanical action of abrasives in slurry and the polishing pad, and the mechanical action of the abrasives has the main effects on material removal of the wafer surface. It is of great help to determine the distribution forms of abrasives for analysis of the action of abrasives and understanding the material removal mechanism in the CMP process.

2.1. Distribution forms of abrasives in slurry

In an ideal situation, the abrasive should be suspended and dispersed uniformly in the slurry with a single particle form. However, because the size of abrasive in the slurry on the market has currently reached about 15 nm in diameter, very fine abrasives in the slurry easily tend to intense agglomeration. A TEM was used to observe the distribution form of the abrasives in slurry. Before observation, the slurry was diluted with DI water in a container and churned for about 30 min by an ultrasonic cleaning machine. Figure 2 shows a TEM picture of abrasives in the slurry. From the TEM picture, the abrasives in the slurry have spherical shape and uniform size on the whole. By calculation, the size of Al_2O_3 abrasives in slurry iCue® 5001 is about 20 nm in diameter and the size of SiO_2 abrasives in slurry Semi-Sperse® 12 is about 25 nm in diameter. But the abrasives are still suspended in the slurry with an agglomeration form although the slurry is diluted and churned. So it can be concluded that the abrasives are suspended in the slurry in a larger agglomeration form.

2.2. Distribution forms of abrasives on the polishing pad in the CMP process

To analyze the distribution forms of abrasives between the pad and the wafer in the CMP process, a Cu wafer CMP experiment was conducted. In the Cu wafer CMP experiment, the polishing pad IC1000/SubIV produced by Rodel Corporation and the iCue® 5001 produced by Cabot Microelectronics Corporation were used. The polishing pad was not conditioned and washed after CMP, and was then dried. A piece of the pad, which was located in the polishing region, was cut

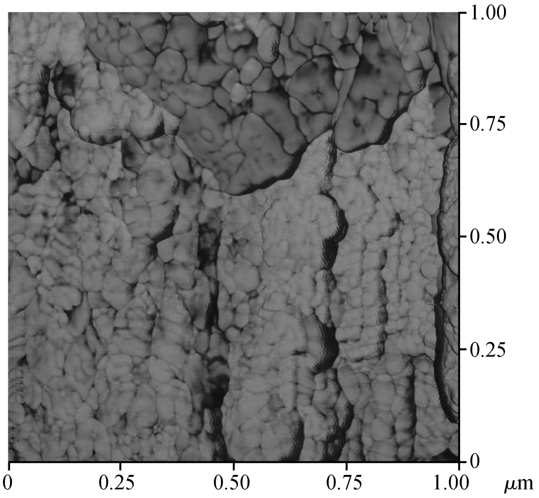

Fig. 3. AFM picture of Al_2O_3 abrasive distribution on the surface of pad IC1000 after CMP.

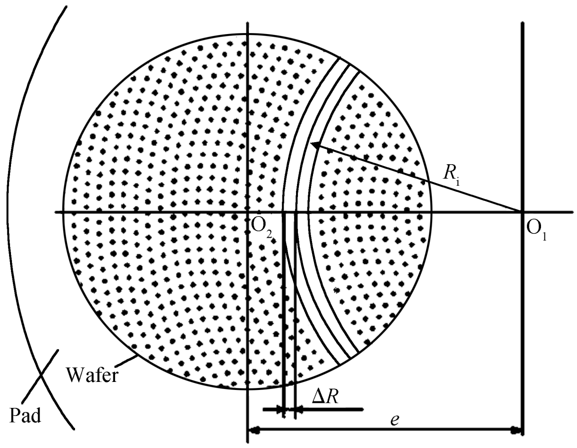

Fig. 4. Schematic of abrasive distribution on the wafer surface.

out and detected by using an AFM. Figure 3 is the AFM picture of the surface of pad IC1000 after polishing. According to Fig. 3, although the abrasives are suspended in the slurry with an agglomeration form, the abrasive agglomerations between the pad and the wafer are squeezed into an abrasive layer on the polishing pad under the polishing pressure. So it can be thought that the abrasives are distributed on the pad in a single layer. This result accords with the study results of Basim[10].

3. Track of abrasives on the wafer surface

In the traditional CMP system, the polishing pad is soft, porous and viscoelastic polymer. Most abrasives in the slurry are embedded in the pad under the polishing pressure and produce mechanical action on the wafer surface. So, according to the above analysis results, it is supposed that the abrasives are spherical for convenience of analysis, embedded in the pad, uniformly distributed on the pad in a single layer (distribution distance, ΔR) and moved along with the pad, as shown in Fig. 4. In Fig. 4, O_1 and O_2 are the center of the pad and the wafer respectively, e is the center distance between the wafer and the pad, R_i is the distance between an abrasive and the pad center O_1.

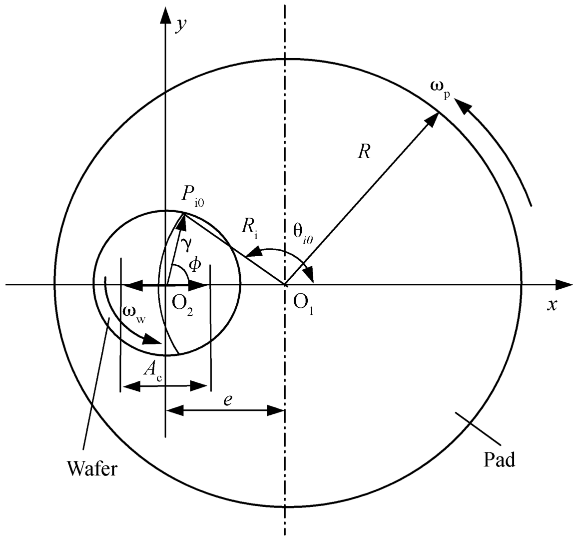

Fig. 5. Schematic of motion relationship between the wafer and the pad.

3.1. Track equation of abrasives on the wafer surface

Because there are many types of CMP machine, we will use the same motion form of CMP machine in the theoretical analysis and the test. In this paper, take the motion form of the CMP machine used in the experiment as an example for studying. Figure 5 presents the kinematical relationship between the wafer and the pad of the CMP machine used in the experiment. In Fig. 5, suppose that O_1 is the center of the pad, XO_2Y is the fixed coordinate system and the origin O_2 is in the midpoint of reciprocation. The polishing carrier with the wafer not only rotates around the wafer center at any rotation velocity, but also reciprocates at an approximate uniform speed centered in the origin O_2 along the x axis (neglect the change of speed). Also in Fig. 5, R, r denote the radius of the pad and the wafer respectively, e is the center distance between the wafer and the pad, n_p and n_w are the rotational speed of the pad and the wafer respectively, ω_p and ω_w are the angular velocity of the pad and the wafer respectively, v_r is the reciprocating motion speed of the carrier, T is the reciprocating period, and A_c is the stroke of reciprocating motion. Suppose that the wafer center lies in the coordinate origin at the beginning. When an abrasive, whose distance from O_1 is R_i, begins to contact with the wafer at point P_{i0}, the initiative angle θ_{i0} is as follows[11]:

$$\theta_{i0} = \pi - \arccos \frac{R_i^2 + e^2 - r^2}{2eR_i}, \tag{4}$$

and the movement equation of the abrasive following the pad is given by

$$\begin{cases} x_{ip} = R_i \cos(\theta_{i0} + \omega_p t) + e, \\ y_{ip} = R_i \sin(\theta_{i0} + \omega_p t). \end{cases} \tag{5}$$

The equation of the track of abrasives on the wafer surface when taking into account the reciprocation of the carrier is as follows:

$$\begin{cases} x_i = R_i \cos(\theta_{i0} + \omega_p t - \omega_w t) + e \cos(\omega_w t) \\ \qquad + vt \sin(2\pi t/T)/\left|\sin(2\pi t/T)\right|, \\ y_i = R_i \sin(\theta_{i0} + \omega_p t - \omega_w t) - e \sin(\omega_w t), \end{cases} \tag{6}$$

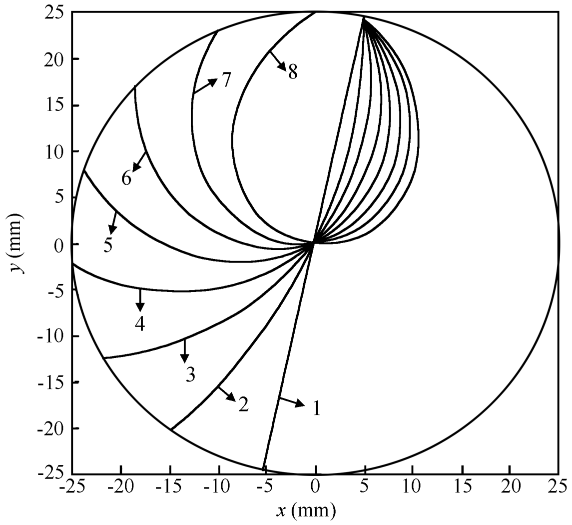

Fig. 6. Motion tracks of a single abrasive on the wafer surface under different motion variables, where n_p = 100 r/min, R_i = 60 mm, e = 60 mm, T = 8 s, v = 2.5 mm/min, line 1-n_w = 50 r/min, line 2-n_w = 100 r/min, line 3-n_w = 150 r/min, line 4-n_w = 200 r/min, line 5-n_w = 250 r/min, line 6-n_w = 300 r/min, line 7-n_w = 350 r/min, line 8-n_w = 400 r/min.

where $T = 2A_c/v_r$.

3.2. The track of a single abrasive on the wafer surface

Because the scratch length produced by abrasives on the wafer surface has a direct influence on MRR in the CMP process, the longer the scratch length of abrasives on the wafer surface and the greater the number of abrasives participating under the same conditions, the larger the MRR. A quantitative analysis of the relationships between the MRR and the CMP motion variables can be made by calculating the track of a single abrasive on the wafer surface using Eq. (6). Figure 6 shows the tracks of a single abrasive on the wafer surface with n_p = 100 r/min under different n_w at the same R_i. The wafer size in Fig. 6 is 50 mm in diameter. By Fig. 6, the track length of a single abrasive on the wafer surface increases with the increase of n_w at the same n_p and R_i. So the MRR increases with the increase of n_w at the same n_p and R_i. Figure 7 shows the tracks of a single abrasive on the wafer surface with $n_w = n_p$ = 50, 250 and 500 r/min, respectively, with the same other parameters. In Fig. 7, the wafer size also is 50 mm in diameter and the rotational speed ratio $\beta = n_p/n_w$ = 1. By Fig. 7, the track (line 1) of a single abrasive on the wafer surface at $n_w = n_p$ = 50 r/min is close to that of $n_w = n_p$ = 500 r/min and the track of a single abrasive on the wafer surface at $n_w = n_p$ = 250 r/min is coincident with that of $n_w = n_p$ = 500 r/min. It is concluded that the track length of a single abrasive on the wafer surface does not change with the increase of n_p at approximately the same rotational speed ratio, but the number of abrasives scratching on the wafer increases with the increase of the rotational speed n_p at the same β. So the MRR increases with the increase of n_p at the same β.

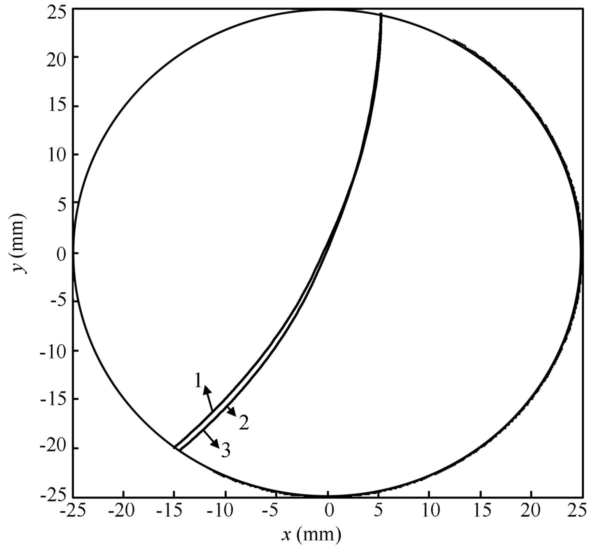

Fig. 7. Motion tracks of a single abrasive on wafer surface under different motion variables, where $\beta(= n_p/n_w)$ = 1, R_i = 60 mm, e = 60 mm, T = 8 s, v = 2.5 mm/min, line 1-n_p = 50 r/min, line 2-n_p = 250 r/min, line 3-n_p = 500 r/min.

4. Experiment

The CMP experiments were conducted on a CMP machine CP-4 made by CETR Inc. The friction force, the coefficient of friction (COF), the acoustic emission (AE) signal of the CMP system (including the wafer, the pad and the slurry) and the slurry temperature of the polishing region in the CMP process can be measured on the CMP machine. All the experiments are done in a clean room with Grade 1000 at a constant temperature of 22 ℃. Silicon wafers of 50 mm in diameter are used in the polishing experiments. The original surface roughness of the wafer is about Ra6 Å, which is tested by a ZYGO NewView 5022 3D surface profiler with the objective power 10×. In the CMP experiments, the Rodel IC1000/Sub IV pad is applied and conditioned for 15 min before every polishing experiment with a diamond conditioner; the slurry Semi-Sperse® 12 made by Cabot Inc is supplied at a flow rate of 100 mL/min. During the CMP process, the down force on the wafer is 6 psi, the carrier has a reciprocating motion with a stroke of 10 mm at the speed of 2.5 mm/s and the center distance between the pad and the wafer is set at 60 mm with the polishing time being 120 s. DI water with electrical resistivity 18.24 MΩ·cm is used for the cleaning of wafers.

5. Test results and analysis

There are many variables in wafer CMP. The input variables are mainly equipment and process variables, wafer variables, polishing pad variables and polishing slurry variables. The output variables concerned are the wafer surface quality, the MRR on the wafer surface and the nonuniformity of material removal on the wafer surface. Every input variable, such as the polishing pressure, the concentration and size of abrasive in the slurry, the chemical ingredient of the slurry and the hardness of the polishing pad, etc., has an important influence on the MRR of the wafer surface. In this paper, only the motion parameters influencing the MRR and related to the length of

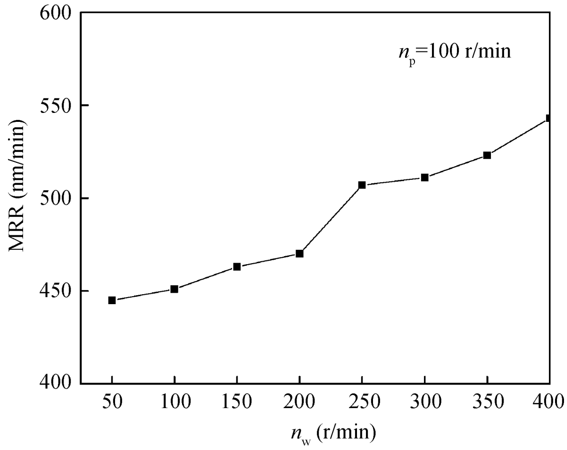

Fig. 8. Effect of the wafer rotational speed on MRR.

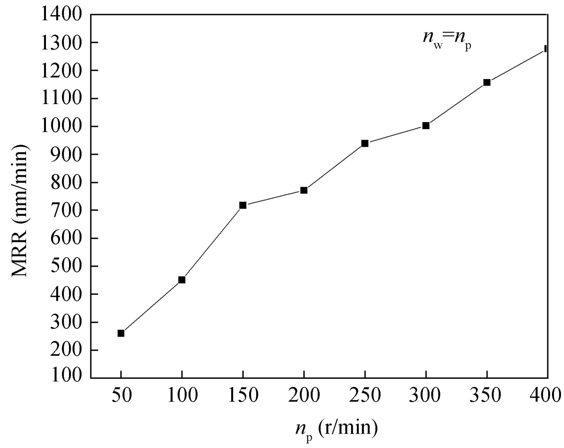

Fig. 9. MRR at $\beta = 1$ with different rotational speeds n_p.

motion tracks of abrasives on wafer surface, such as n_w and n_p, were studied. So, only the parameters n_w and n_p were changed while measuring the MRR of the wafer in the test.

Figure 8 shows the experimental results of MRR at $n_p = 100$ r/min with different n_w. From Fig. 8, the MRR increases with the increase of n_w at the same n_p, but the increasing degree of MRR is far less than that of increasing the rotational velocity n_p (see Fig. 9). This result is consistent with Fig. 6 simulated by Eq. (6) with the same variables as Fig. 9.

Figure 9 shows the experimental results of MRR at $\beta = 1$ with different rotational speeds n_p. By Fig. 9, the MRR increases with the increase of n_p at the same rotational velocity ratio ($\beta = 1$). The MRR is proportional to the rotational velocity n_p. This test result is consistent with the analysis results above.

The wafer CMP is a process of interaction between the mechanical action and the chemical action. The chemical action improves the mechanical action, and also the mechanical action improves the chemical action. The interaction between the mechanical action and the chemical action controls the MRR of wafer CMP. When the interaction between the mechanical action and the chemical action reaches a maximum and the mechanical action balances the chemical action, the maximum MRR can be obtained in wafer CMP. When the MRR reaches the maximum, the n_p and n_w can be taken as critical rotational velocities.

According to analysis above and below the test conditions of Fig. 9, when the rotational velocity is $n_p = n_w < 400$ r/min, the mechanical action does not balance the chemical action. When the rotational velocity is $n_p = n_w \geqslant 400$ r/min, there must be a critical rotational velocity at this polishing condition. So with the increase of rotational velocity, when above a critical rotational velocity, the MRR decreases with the increase of rotational velocity.

According to the research results above, it is concluded that the chemical reaction layer produced by slurry on the wafer surface is mainly removed by the mechanical action of abrasives in the slurry in the wafer CMP process and the scratches produced by abrasives on the wafer surface result from the mechanical action of abrasives. So the track form and length produced by abrasives have a direct influence on MRR. The longer the scratch length of abrasives produced on the wafer surface and the greater the numbers of abrasives participating in the CMP process under the same conditions, the larger the MRR.

By analyzing the simulation results of the track length of abrasives on the wafer surface and the test results of the MRR, it is considered that the mechanical action of the abrasive is dominant in CMP and material removal mainly results from the chemical mechanical interaction between the abrasives and the slurry. These results help to further understand the material removal mechanism in wafer CMP and in developing CMP slurry.

6. Summary

According to the experimental results and analysis above, some conclusions can be obtained as follows:

(1) Although abrasives suspend in slurry in an agglomeration form, they distribute on the polishing pad in a single layer form and produce a mechanical action on the wafer in the CMP process.

(2) The MRR increases with the increase of rotational velocity of the wafer n_w at the same rotational velocity of the pad n_p and the mechanical action does not balance the chemical action when the rotational velocity is $n_p = n_w < 400$ r/min under test conditions. When the rotational velocity is $n_p = n_w \geqslant 400$ r/min, with the increase of rotational velocity, because the mechanical action increases with the increase of rotational velocity, there must be a critical rotational velocity n'_p ($= n'_w$) at this polishing condition, making the mechanical action balance the chemical action and the MRR reaches a maximum at this polishing velocity. When above the critical rotational velocity n'_p ($= n'_w$), the MRR decreases with the increase of rotational velocity. It is concluded that there is an optimal polishing velocity in the CMP process, and at this polishing velocity, the mechanical action balances the chemical action in the wafer CMP process.

(3) In wafer CMP, mechanical action mainly results from the friction and scratch action on the wafer surface produced by abrasives between the wafer and the pad. The greater the scratch length of abrasives produced on the wafer surface and the greater the numbers of abrasives participating in the CMP process under the same conditions, the larger the MRR.

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