Effects of the reciprocating parameters of the carrier on material removal rate and non-uniformity in CMP*

Wang Cailing(王彩玲)†, Kang Renke(康仁科), Jin Zhuji(金洙吉), and Guo Dongming(郭东明)

(Key Laboratory for Precision & Non-Traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian 116024, China)

Abstract: Based on the Preston equation, the mathematical model of the material removal rate (MRR), aiming at a line-orbit chemical mechanical polisher, is established. The MRR and the material removal non-uniformity (MRNU) are numerically calculated by MATLAB, and the effects of the reciprocating parameters on the MRR and the MRNU are discussed. It is shown that the smaller the inclination angle and the larger the amplitude, the higher the MRR and the lower the MRNU. The reciprocating speed of the carrier plays a minor role to improve the MRR and decrease the MRNU. The results provide a guide for the design of a polisher and the determination of a process in line-orbit chemical mechanical polishing.

Key words: chemical mechanical polishing; reciprocating parameters; material removal rate; material removal non-uniformity

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1. Introduction

Chemical mechanical polishing (CMP) is the effective technology to provide global planarization of topography in IC manufacturing. The material removal rate (MRR) and the material removal non-uniformity (MRNU) indicate the machining efficiency and the surface quality of the wafer in the CMP process, respectively, so they are highlighted in research into the mechanism of CMP.

Hocheng[1] investigated the effects of the kinematic variables on MRNU in line-orbit CMP, such as the rotational and translational speeds, carrier eccentricity and wafer diameter. However, the effects of the reciprocating parameters on the MRR were not considered and discussed. Su[2, 3] researched the MRNU of silicon wafer in CMP by analyzing the abrasive tracks, but the effects of the reciprocating parameters were not mentioned. Forsberg[4], Cho[5] and Stavreva[6] carried out experiments of CMP on Al, Si (110) and copper to study the effects of the process parameters, especially the polishing pressure, the rotation speed of the polishing plate, the rotation speed of the carrier and the slurry flow rate, on MRR. In addition, the trajectory model of the MRR for a double sided polisher was also established by Kasai and Tso[7, 8]. The effects of the process parameters, such as the speeds of the sun gear and the ring gear, and the speeds of the top plate and the bottom plate, on MRR were discussed. Most of the above mentioned research focused on the effects of the rotational speed and the pressure on the MRR theoretically or experimentally. The effects of the reciprocating parameters were not studied systematically in line-obit chemical mechanical polishing.

The relative velocity is the kinematic factor to affect the MRR and the MRNU in CMP, and reciprocating parameters of the carrier are the important kinematic factors besides the rotational speeds of the plate and the carrier. At present, the line-orbit polisher, the carrier tracking along the line orbit, is widely used, but little research is carried out on the influence of the reciprocating parameters on the MRR and the MRNU. It is important to know the influence of the reciprocating parameters on the MRR and the MRNU in line-orbit CMP. In this paper, a model of MRR is established on the basis of the Preston equation, and the effects of the reciprocating variables on the MRR and the MRNU are analyzed numerically.

2. Mathematical model of the MRR in CMP

2.1. Preston equation

Preston conducted experiments in glass polishing and established the material removal rate equation[9],

$$\frac{\mathrm{d}R}{\mathrm{d}t} = kPV, \tag{1}$$

where $\mathrm{d}R/\mathrm{d}t$ is the material removal rate, P is the applied pressure, V is the velocity of any point on the wafer relative to the pad, and k is the Preston coefficient depending on the processing conditions, such as the slurry, the pad and the process environment.

The Preston equation is widely accepted to simulate or predict the polishing behaviour. It reveals the relation between the MRR and the relative velocity and the pressure. From the existing models of MRR for other materials' CMP[10−13], it is stated that the MRR is proportional to the relative velocity between the pad and the wafer surface to the power[1]. Stressed on the relationship between the reciprocating parameters of the carrier and the MRR, the pressure P is supposed to be a constant in the polishing process. So the material removal R of any

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† Corresponding author. Email: w_cailing@163.com

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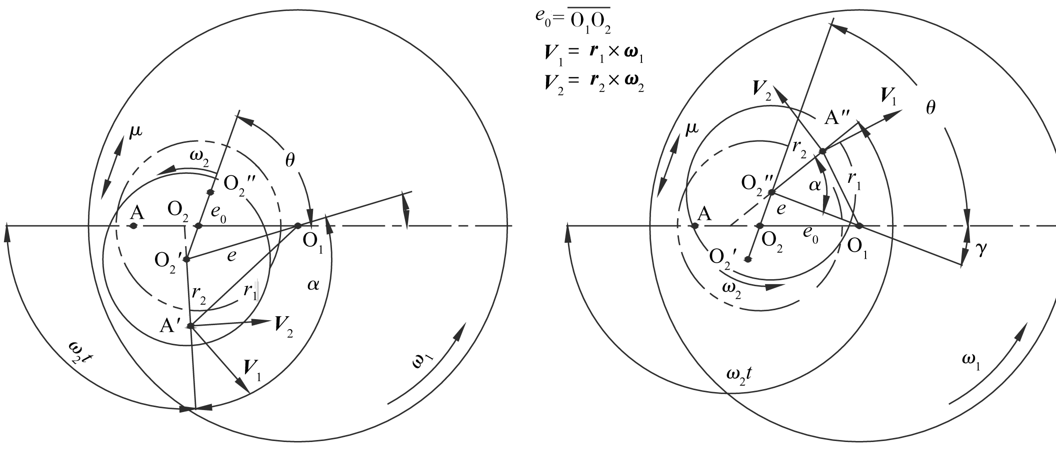

(a) Wafer centre under the initial position. (b) Wafer centre over the initial position

Fig. 1. Kinematic relations of line-orbit CMP in the situations (a) and (b).

point A in a polishing period T can be expressed as

$$R = kP \int_0^T \boldsymbol{V}(x, y, t)\mathrm{d}t, \tag{2}$$

and the non-uniformity N can be expressed as

$$N = \frac{S_\mathrm{R}}{\overline{R}} \times 100\%, \tag{3}$$

where S_R is the standard deviation of the MRR, and $\overline{R}$ is the average of the MRR.

2.2. Material removal model

The calculations follow the assumption that all of the points on the bottom surface of the wafer, the surface in contact with the upper surface of the pad, touch the pad at any moment.

In line-orbit CMP, the carrier reciprocates along a straight line while the carrier and the plate rotate around their axis, respectively. Figure 1 shows the kinematic relations between the wafer and the pad under the conditions that the carrier center locates in different positions on the pad in the line-orbit CMP process. In the sketch, the center of the wafer reciprocates from the initial middle position O_2 to the upper instantaneous position O_2' and the lower instantaneous position O_2'' at the same time the center of the plate O_1 is fixed. Any point A on the wafer moves to A' and A'' correspondingly when the wafer center is located in O_2' and O_2''.

The velocity of any point A on the wafer relative to the coincident point on the pad can be expressed as

$$\boldsymbol{V} = \boldsymbol{V}_2 + \boldsymbol{\mu} - \boldsymbol{V}_1 = \boldsymbol{r}_2 \times \boldsymbol{\omega}_2 + \boldsymbol{\mu} - \boldsymbol{r}_1 \times \boldsymbol{\omega}_1, \tag{4}$$

where $\boldsymbol{V}_2$ is the rotation velocity of point A on the wafer, $\boldsymbol{V}_1$ is the velocity of the coincident point on the pad, r_2 is the radius of point A on the wafer, r_1 is the radius of coincident point on the plate, ω_1 is the angular velocity of the pad, and ω_2 is the angular velocity of the carrier.

Substituting Eq. (4) into Eq. (2), we have

$$R = kP \left(\int_0^T \boldsymbol{r}_2 \times \boldsymbol{\omega}_2 - \boldsymbol{r}_1 \times \boldsymbol{\omega}_1 \mathrm{d}t + \int_0^T \boldsymbol{\mu} \mathrm{d}t \right). \tag{5}$$

Assume that the carrier reciprocates with an amplitude L at a constant speed of μ, the oscillating velocity $\boldsymbol{\mu}$ in the machining process is an odd function with a period of $T_1 = 4L/\mu$. The machining period T can be expressed as $T = mT_1$ (m is a positive integer), therefore, $\int_0^T \boldsymbol{\mu}\mathrm{d}t = 0$, then Equation (5) can be simplified as

$$R = kP \int_0^T (\boldsymbol{r}_2 \times \boldsymbol{\omega}_2 - \boldsymbol{r}_1 \times \boldsymbol{\omega}_1)\, \mathrm{d}t. \tag{6}$$

Suppose that L_μ is the reciprocating displacement of the wafer centre at any time, and it can be expressed as

$$L_\mu = \begin{cases} \mu(t - nT_1), & t \in \left(nT_1, nT_1 + \dfrac{1}{4}T_1\right), \\ \mu\left[\dfrac{T_1}{2} - (t - nT_1)\right], & t \in \left(nT_1 + \dfrac{1}{4}T_1, nT_1 + \dfrac{1}{2}T_1\right), \\ \mu\left[t - nT_1) - \dfrac{T_1}{2}\right], & t \in \left(nT_1 + \dfrac{1}{2}T_1, nT_1 + \dfrac{3}{4}T_1\right), \\ \mu\left[T_1 - (t - nT_1)\right], & t \in \left(nT_1 + \dfrac{3}{4}T_1, (n+1)T_1\right), \end{cases}$$
$$n = 0, 1, \cdots, m - 1. \tag{7}$$

Let $\boldsymbol{v} = \boldsymbol{r}_2 \times \boldsymbol{\omega}_2 - \boldsymbol{r}_1 \times \boldsymbol{\omega}_1$, from the geometric relationships shown in Fig. 1, we obtain

$$v = \left[r_2^2(\omega_1 - \omega_2)^2 - 2r_2 e\omega_1(\omega_1 - \omega_2)\cos\alpha + \omega_1^2 e^2\right]^{1/2}, \tag{8}$$

$$e = \left(e_0^2 + 2e_0 L_\mu \cos\theta + L_\mu^2\right)^{1/2}, \tag{9}$$

$$\cos\alpha = \begin{cases} -\cos(\omega_2 t - \gamma), & t \in \left(nT_1, nT_1 + \dfrac{1}{2}T_1\right), \\ -\cos(\omega_2 t + \gamma), & t \in \left(nT_1 + \dfrac{1}{2}T_1, (n+1)T_1\right), \end{cases}$$
$$n = 0, 1, \cdots, m - 1, \tag{10}$$

where e is the instantaneous eccentricity of the wafer, e_0 is the initial eccentricity of the wafer, θ is the inclination angle of the

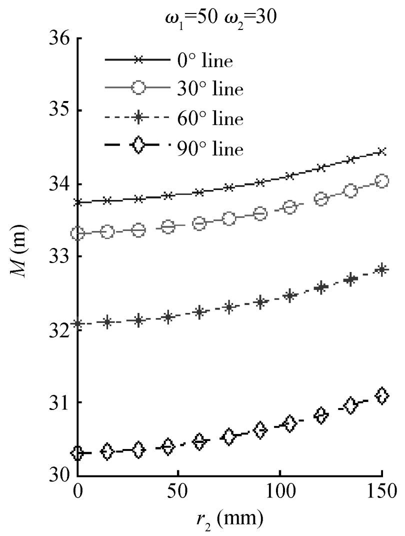

Fig. 2. Relationship between M and r_2 at inclination angles of 0°, 30°, 60°, 90° (μ = 400 mm/min, L = 50 mm).

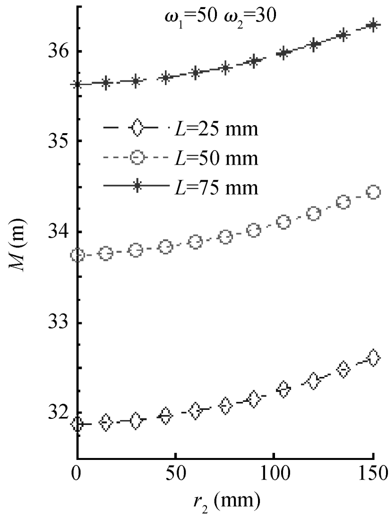

Fig. 3. Relationship between M and r_2 in reciprocating scope of 25 mm, 50 mm,75 mm (μ = 400 mm/min, θ = 0°).

locus of the wafer centre, α is the angle between $\boldsymbol{e}$ and $\boldsymbol{r}_2$, and γ is the angle between $\boldsymbol{e}$ and $\boldsymbol{e}_0$, as shown in Fig. 1. The angle γ can be expressed as a function of L_μ, e and θ,

$$\sin\gamma = \frac{L_\mu}{e}\sin\theta. \tag{11}$$

From Eqs. (6) to (11), the material removal in line-orbit polisher can be deduced as

$$R = kP\int_0^T \Bigg\{ r_2^2(\omega_1-\omega_2)^2 + 2r_2e\omega_1(\omega_1-\omega_2) \times \cos\left[\omega_2 t \mp \arcsin\left(\frac{L_\mu}{e}\sin\theta\right)\right] + e^2\omega_1^2 \Bigg\}^{1/2} \mathrm{d}t, \tag{12}$$

where the symbols "−" and "+" are adopted when $t \in (nT_1, nT_1 + \frac{1}{2}T_1)$, and $t \in (nT_1 + \frac{1}{2}T_1, (n+1)T_1)$, respectively.

3. Numerical calculation and analysis

3.1. Calculation results of the MRR

Under the same polishing conditions and polishing pressure, k and P are all constant. Suppose that $M = \int_0^T V(x,y,t)\mathrm{d}t$, then $R = kPM$, the variation law of R is the same as that of M.

The numerical values of M at different radii on the wafer are calculated by MATLAB, and the computing results for the wafer with a diameter of 300 mm are shown in Figs. 2–4. The radius r_2 is sampled by increments 15 mm from the wafer centre to the edge. The angular velocity of the polishing pad and the carrier are exampled as ω_1 = 50 min^{-1} and ω_2 = 30 min^{-1}.

Figure 2 shows that M decreases with increasing inclination angle θ, and the value of M is greatest at the inclination angle of 0°. The reciprocating amplitude is the important factor to affect the MRR, as shown in Fig. 3 for the greater M in the larger translational scope. The reciprocating speed has little effect on the MRR, as illustrated in Fig. 4.

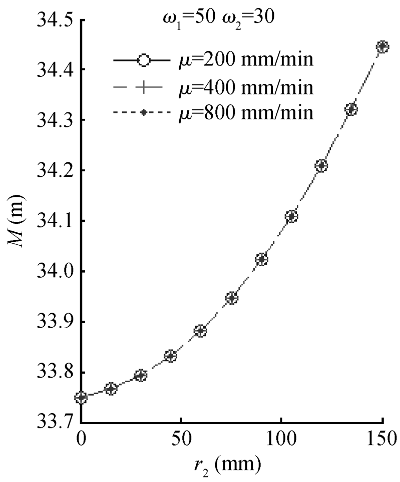

Fig. 4. Material removal rate at the reciprocating speed of 200, 400 and 800 mm/min (L = 50 mm, θ = 0°).

3.2. Calculated results of the MRNU

The MRNU is obtained from Eq. (3).

$$N = \frac{S_\mathrm{R}}{\overline{R}} \times 100\% = \frac{M_\mathrm{R}}{\overline{M}} \times 100\%, \tag{13}$$

where $M_\mathrm{R} = \sqrt{\frac{\sum_{i=1}^{n}(M_i-\overline{M})^2}{n-1}}\,(n=9)$, $\overline{M} = \frac{\sum_{i=1}^{n} M_i}{n}\,(n=9)$ and M_i refers to the value of the M at which r_2 varies from 0 to 150 mm with an increment of 15 mm. The calculated values of the MRNU at inclination angles of 0°, 30°, 60° and 90° are illustrated in Table 1, where the speeds of the carrier and the pad are sampled respectively as 30, 50 and 70 min^{-1}. The MRNU at a small inclination angle is less than that at the larger angle without regard to the change of the plate and carrier speed.

The values of the MRNU in different reciprocating scopes are calculated when ω_1 = 50 min^{-1}, ω_2 = 30min^{-1}, μ = 400 mm/min and θ = 0°, and the results are listed in Table 2. The larger the reciprocating amplitude, the smaller the MRNU.

Table 1. Calculated values of the MRNU at different inclination angles.

ω_1, ω_2 (min^{-1})	N (μ = 400 mm/min, L = 50 mm, e_0 = 200 mm, T = 3 min)			
	$\theta = 0°$	$\theta = 30°$	$\theta = 60°$	$\theta = 90°$
ω_1 = 50, ω_2 = 30	0.6985	0.7205	0.7774	0.8674
ω_1 = 30, ω_2 = 50	1.7697	1.8164	1.9581	2.1906
ω_1 = 50, ω_2 = 70	0.5967	0.6109	0.6571	0.7369
ω_1 = 70, ω_2 = 50	0.28560	0.29210	0.31220	0.34760

Table 2. Calculated values of the MRNU at different reciprocating amplitudes.

L (mm)	0	25	50	75
N	0.8680	0.7765	0.6985	0.6341

Table 3. Calculated values of the MRNU at different reciprocating speeds.

μ (mm/min)	0	200	400	800
N	0.8680	0.6988	0.6985	0.6994

The values of the MRNU at different reciprocating speeds, under the conditions ω_1 = 50 min^{-1}, ω_2 = 30 min^{-1}, L = 50 mm and θ = 0°, are shown in Table 3. The value of the MRNU under the condition μ = 0 is obviously larger than that at the speeds of 200, 400, and 800 mm/min, but the values of MRNU at the three speeds exhibit little difference. It shows that the change in the kinematic forms of carrier has great influence on the MRNU, but the reciprocating speed has little effect on it.

It can be seen from Tables 1–3 that the inclination angle and translational amplitude are the major reciprocating factors to affect the MRNU in the CMP process, while the reciprocating speed plays a minor role in it.

As mentioned above, the inclination angle and the reciprocating speed of the carrier are the important factors to influence the MRR and the MRNU in line-orbit CMP. In the polisher design, the inclination angle at zero is expected to maximize the MRR and minimize the MRNU. Although the great reciprocating amplitude is also expected, the small footprint of the polisher is also to be considered.

4. Conclusions

A numerical model of the MRR in line-orbit CMP is presented, and the effects of the reciprocating parameters of the carrier, the important kinematic factors except for the speeds of the polishing plate and the carrier, on the MRR and the MRNU are discussed. The results show that the inclination angle and reciprocating amplitude are the major reciprocating factors to affect the MRR and the MRNU. The best inclination angle of the track line is zero for high MRR and low non-uniformity. The increase in the reciprocating amplitude contributes to the increase in the MRR and the decrease in the MRNU in the CMP process. The translational speed of the carrier has little effect on the MRR and the MRNU without a consideration of the effects of the kinematic forms.

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