Material Removal Rate of Double-faced Mechanical Polishing of 4H-SiC Substrate

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Material removal rate of double-faced mechanical polishing of 4H-SiC substrate

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ABSTRACT: Silicon carbide (SiC) has been a promising the-third-generation semiconductor power device material for high-power, high-temperature, substrate applications. It aims to improve the material removal rate (*MRR*), on the premise of ensuring the surface roughness requirements of the double-faced mechanical polishing of 6-inch SiC substrate. To obtain the relationship between any point on SiC substrate and polishing pads, the model about double-faced mechanical polishing has been built and the kinematics equations were created. Best optimized material removal rate parameters were obtained. *MRR* reached the maximum when speed rate of the outside ring gear to the inside sun gear $m=-1$, speed rate of lower plate to the inside sun gear $n=5$, SiC substrate distribution radius $RB=75$. The primary and secondary order of *MRR* ($n>m>RB$) was obtained. An accurate mathematical model of orthogonal rotary regression test of Tri-factor quadratic of *MRR* was established and the regression model was significant. Surface quality of SiC substrate was observed and characterized with SEM and AFM. It greatly provides a key guarantee for the next process of CMP, confirmed the importance of *MRR* to ultra-smooth polishing, and provides a guarantee for its application in semiconductor equipment and technology.

Keywords: Material removal rate · Polishing · Orthogonal · Kinematic · Regression analysis

Introduction

Development of semiconductor industry has been closely related to the national defense, military, aerospace, energy and other important areas of science and technology.[1,2] As the representative of the semiconductor material, silicon carbide (SiC) single crystal was an important new wide band gap semiconductor material, which can be used as a substrate for the growth of gallium nitride (GaN) and grapheme.[3-5] At the same time, it can be widely used in the production of high temperature, high frequency and high power devices.[6,7]

Ultra-smooth polishing of the SiC substrate was required atomic surface roughness.[8-10] The biggest problem at present was that the processing efficiency was too low on the premise of ensuring the surface quality. However, the double-faced mechanical polishing (MP) process was the key to guarantee a certain surface roughness (*Ra*) and the high efficient material removal rate (*MRR*) of the SiC substrate. At the same time, it was the key to chemical mechanical polishing (CMP) which was the next procedures. Michio Uneda et al.[11]

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reported that when the ozone gas bubbles are applied to the conventional slurry, the reaction products of the surface can be generated to acquire a high *MRR* exceeding the dedicated slurry. Pan et al.[12] developed that the *MRR* could reach 45nm/h while polished by the slurry with H₂O₂ and silica. Meanwhile, *MRR* could increase to 105nm/h in CMP of SiC. Many researchers have analyzed the relationship between *MRR* and surface roughness.[13-15]

In this paper, kinematic equations of SiC substrate during double-faced polishing were analyzed. An accurate mathematical model of orthogonal rotary regression test of Tri-factor quadratic of *MRR* was established and the parameters affecting *MRR* were studied.

Materials and methods

Experimental materials were used 6 inch N type 4H-SiC. Structure model of double-faced MP was as shown in Fig. 1. The lower plate 1, the upper plate 4, the inside sun gear 5, and the outside ring gear 7 were respectively driven by four servo motors. SiC substrates 8 were distributed at the center of five middle planetary gears 6. The five middle planetary gears were caught between the lower pad 2 and the upper pad 3. The upper and the lower pads were respectively adhered to each surface of corresponding polishing disk. The five middle planetary gears were meshed with the inside sun gear 5 and the outside ring gear, driving the SiC substrates to realize the motion of revolution and rotation.[16,17]

Fig. 1. Model of double-faced MP of SiC single crystal substrate

Kinematic equations of any point *B* on SiC substrate relative to the lower pad during double-faced MP were analyzed. Theoretical model of *MRR* and the influence of various parameters on the processing efficiency were

studied.

Radius of five middle planetary gears represented as R_1 . Similarly, the inside sun gear radius was R_2 . Rotational speed of the inside sun gear, the outside ring gear and lower disk was ω_s , ω_r and ω_p respectively. Speed of the five middle planetary gears was ω_h . Furthermore, it was equivalent to that the five middle planetary gears only just revolved on its axis with an angular velocity ω_s when $-\omega_h$ added to the whole model. We selected certain point B (RB , φ) on the substrate in the coordinate system $X_1O_1Y_1$ and established kinematic equations of the point B relative to lower pad in $X_2O_2Y_2$. Among them, SiC substrate distribution radius $RB=|O_1B|$, $RB \in [0, R_M]$, R_M was the maximum radius of SiC substrate. Besides, φ was the angle between O_1B and O_1X_1 , $\varphi \in [0, 2\pi]$. $\theta_1 = \omega_s t$, $\theta_2 = \omega_h t$, $\theta_3 = \omega_p t$. Kinematic equations have been hold follows:

$$\begin{bmatrix} XB \\ YB \end{bmatrix} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 \\ \sin\theta_3 & \cos\theta_3 \end{bmatrix} \cdot \left(\begin{bmatrix} \cos(-\theta_2) & \sin(-\theta_2) \\ -\sin(-\theta_2) & \cos(-\theta_2) \end{bmatrix} \cdot \left(\begin{bmatrix} R+r \\ 0 \end{bmatrix} + \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 \\ \sin\theta_1 & \cos\theta_1 \end{bmatrix} \cdot \begin{bmatrix} RB\cos\varphi \\ RB\sin\varphi \end{bmatrix} \right) \right) \quad (1)$$

$$\begin{bmatrix} XB \\ YB \end{bmatrix} = \begin{bmatrix} RB\cos(\theta_1 + \theta_2 + \theta_3 + \varphi) + (R+r)\cos(\theta_2 + \theta_3) \\ RB\sin(\theta_1 + \theta_2 + \theta_3 + \varphi) + (R+r)\sin(\theta_2 + \theta_3) \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} XB \\ YB \end{bmatrix} = \begin{bmatrix} RB\cos[(\omega_c + \omega_h + \omega_p)t + \varphi] + (R+r)\cos[(\omega_h + \omega_p)t] \\ RB\sin[(\omega_c + \omega_h + \omega_p)t + \varphi] + (R+r)\sin[(\omega_h + \omega_p)t] \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} VXB \\ VYB \end{bmatrix} = \begin{bmatrix} -RB \cdot (\omega_c + \omega_h + \omega_p) \sin[(\omega_c + \omega_h + \omega_p)t + \varphi] - (R+r) \cdot (\omega_h + \omega_p) \sin(\omega_h + \omega_p)t \\ RB \cdot (\omega_c + \omega_h + \omega_p) \cos[(\omega_c + \omega_h + \omega_p)t + \varphi] + (R+r) \cdot (\omega_h + \omega_p) \cos(\omega_h + \omega_p)t \end{bmatrix} \quad (4)$$

$$VB = \sqrt{(VXB)^2 + (VYB)^2} = \left\{ \begin{bmatrix} [RB \cdot (\omega_c + \omega_h + \omega_p)]^2 + [(R+r) \cdot (\omega_h + \omega_p)]^2 \\ + 2RB \cdot (R+r) \cdot (\omega_c + \omega_h + \omega_p) \cdot (\omega_h + \omega_p) \cos(\omega_c t + \varphi) \end{bmatrix} \right\}^{\frac{1}{2}} \quad (5)$$

$$\begin{bmatrix} AXB \\ AYB \end{bmatrix} = \begin{bmatrix} -RB \cdot (\omega_c + \omega_h + \omega_p)^2 \cos[(\omega_c + \omega_h + \omega_p)t + \varphi] - (R+r) \cdot (\omega_h + \omega_p)^2 \cos(\omega_h + \omega_p)t \\ -RB \cdot (\omega_c + \omega_h + \omega_p)^2 \sin[(\omega_c + \omega_h + \omega_p)t + \varphi] - (R+r) \cdot (\omega_h + \omega_p)^2 \sin(\omega_h + \omega_p)t \end{bmatrix} \quad (6)$$

$$AB = \sqrt{(AXB)^2 + (AYB)^2} = \left\{ \begin{bmatrix} [RB \cdot (\omega_c + \omega_h + \omega_p)^2]^2 + [(R+r) \cdot (\omega_h + \omega_p)^2]^2 \\ + 2RB \cdot (R+r) \cdot (\omega_c + \omega_h + \omega_p)^2 \cdot (\omega_h + \omega_p)^2 \cos(\omega_c t + \varphi) \end{bmatrix} \right\}^{\frac{1}{2}} \quad (7)$$

The results expressed by equations (1)~(7) were shown the kinematics equations of point B on the surface of SiC relative to lower pad during double-faced MP. XB , VXB , and AXB were respectively the components of point B on X axis of the displacement, velocity, and the acceleration. YB , VYB , and AYB were respectively the components of point B on Y axis of the displacement, velocity, and the acceleration.

According to the equation Preston[18]:

$$MRR = K \cdot P \cdot V \quad (8)$$

During the polishing time t , the MRR of point B on the SiC substrate surface was as follows:

$$MRR = \frac{K \cdot P \cdot \int_0^t VB dt}{t} \quad (9)$$

Substituting equation (5) into equation (9), we got:

$$MRR = \frac{K \cdot P}{t} \cdot \int_0^t \left\{ \left[RB \cdot (\omega_c + \omega_h + \omega_p) \right]^2 + \left[(R+r) \cdot (\omega_h + \omega_p) \right]^2 + 2RB \cdot (R+r) \cdot (\omega_c + \omega_h + \omega_p) \cdot (\omega_h + \omega_p) \cdot \cos(\omega_c t + \varphi) \right\}^{\frac{1}{2}} dt \quad (10)$$

According to the transmission ratio relationship of the composite gear train:

$$i_{sr}^h = \frac{\omega_s^h}{\omega_r^h} = \frac{\omega_s - \omega_h}{\omega_r - \omega_h} = -\frac{Z_r}{Z_s} \quad (11)$$

$$i_{sc}^h = \frac{\omega_s^h}{\omega_c^h} = \frac{\omega_s - \omega_h}{\omega_c - \omega_h} = -\frac{Z_c}{Z_s} \quad (12)$$

$$\omega_h = \frac{Z_s \omega_s + Z_r \omega_r}{2(Z_s + Z_r)} \quad (13)$$

$$\omega_c = \frac{Z_r \omega_r - Z_s \omega_s}{(Z_r - Z_s)} \quad (14)$$

We set $m = \omega_r / \omega_s$, $n = \omega_p / \omega_s$, and substitute them into equation (10) to get the solution:

$$MRR = \frac{K \cdot P}{t} \cdot \int_0^t \left\{ \left[RB \cdot \left(\frac{Z_r \cdot m \cdot \omega_s - Z_s \omega_s}{(Z_r - Z_s)} + \frac{Z_s \omega_s + Z_r \cdot m \cdot \omega_s}{2(Z_s + Z_r)} + n \cdot \omega_s \right) \right]^2 + \left[(R+r) \cdot \left(\frac{Z_s \omega_s + Z_r \cdot m \cdot \omega_s}{2(Z_s + Z_r)} + n \cdot \omega_s \right) \right]^2 + 2RB \cdot (R+r) \cdot \left(\frac{Z_r \cdot m \cdot \omega_s - Z_s \omega_s}{(Z_r - Z_s)} + \frac{Z_s \omega_s + Z_r \cdot m \cdot \omega_s}{2(Z_s + Z_r)} + n \cdot \omega_s \right) \cdot \left(\frac{Z_s \omega_s + Z_r \cdot m \cdot \omega_s}{2(Z_s + Z_r)} + n \cdot \omega_s \right) \cdot \cos \left[\left(\frac{Z_r \cdot m \cdot \omega_s - Z_s \omega_s}{(Z_r - Z_s)} \right) \cdot t + \varphi \right] \right\}^{\frac{1}{2}} dt \quad (15)$$

Because polishing parameters K and polishing pressure P were constants and initial angle φ_0 has no effect on MRR , in order to facilitate normalization of simulation analysis, we set $K=1$, $P=1\text{Pa}$, initial angle $\varphi_0=0^\circ$, $\omega_s=-20\text{r/min}$, $t=1\text{s}$. Influence of the three parameters (speed rate of the outside ring gear to the inside sun gear m , speed rate of lower plate to the inside sun gear n , SiC substrate distribution radius RB) in formula (15) on MRR was studied.

MRR was calculated from equation (15) by setting $m=[-5,-4,-3,-2,-1]$, $n=[1,2,3,4,5]$, $RB=[15,30,45,60,75]$. MATLAB simulation was shown that the maximum $MRR=2.3066 \times 10^4$ occurs at $m=-1$, $n=5$, $RB=75$. That is to say, the closer the speed rate of the outside ring gear to the inside sun gear is to 0, and the greater speed rate of lower plate to the inside sun gear, the larger the SiC substrate distribution radius, the higher the MRR it is. The

slice figure of the influence of parameters on MRR was shown in Fig. 2.

Fig. 2. Slice of the influence of parameters on MRR

Results and discussion

Polishing disks were made of cast iron while polishing pads were grooved polyurethane polishing pad IC1400. At $T=25^{\circ}\text{C}$, $\omega_s=-20\text{r/min}$, $P=30\text{KPa}$, diamond powder W2.5. Orthogonal tests of three factors and five levels of L_{25} were carried out. Orthogonal test factors and levels were shown in Table 1 and orthogonal test results were shown in Table 2 as follows:

Table 1 Orthogonal test factors and levels of L_{25}

Levels	Factors		
	m	n	RB
	A	B	$C/(\text{mm})$
1	-5	1	15
2	-4	2	30
3	-3	3	45
4	-2	4	60
5	-1	5	75

Table 2 Orthogonal test results of L₂₅

No.	Factors			Index
	<i>m</i>	<i>n</i>	<i>RB</i>	<i>MRR</i>
	<i>A</i>	<i>B</i>	<i>C</i> /(mm)	<i>y</i> /(um/h)
1	-5	1	15	1.32
2	-5	2	30	1.51
3	-5	3	45	1.74
4	-5	4	60	1.90
5	-5	5	75	2.23
6	-4	1	30	1.39
7	-4	2	45	1.58
8	-4	3	60	1.86
9	-4	4	75	2.19
10	-4	5	15	2.22
11	-3	1	45	1.59
12	-3	2	60	1.75
13	-3	3	75	1.94
14	-3	4	15	2.18
15	-3	5	30	2.39
16	-2	1	60	1.79
17	-2	2	75	1.67
18	-2	3	15	2.12
19	-2	4	30	2.26
20	-2	5	45	2.44
21	-1	1	75	1.78
22	-1	2	15	1.81
23	-1	3	30	2.15
24	-1	4	45	2.40
25	-1	5	60	2.50

$$MRR = \frac{\Delta m}{\rho \cdot \pi r^2 \cdot t} \quad (16)$$

MRR was calculated by equation (16), among them, Δm means the difference of quality before and after double-faced mechanical polishing by electronic balance with an accuracy of 0.1mg, ρ means the SiC substrate density 3.2g/cm³, and *t* means polishing time.

Optimal level combination can be derived by calculating *K* value. Range *R* can be obtained by equation (17):

$$R = \max K_i - \min K_i (i = 1, 2, 3, 4, 5) \quad (17)$$

Table 3 Range analysis of L₂₅

Index	Projects	<i>A</i>	<i>B</i>	<i>C</i> /(mm)
<i>MRR</i> /(um/h)	<i>K</i> ₁	8.70	7.87	9.65
	<i>K</i> ₂	9.24	8.32	9.70
	<i>K</i> ₃	9.85	9.81	9.75

K_4	10.28	10.93	9.80
K_5	10.64	11.78	9.81
k_1	1.74	1.57	1.93
k_2	1.85	1.66	1.94
k_3	1.97	1.96	1.95
k_4	2.06	2.19	1.96
k_5	2.13	2.36	1.96
R	0.39	0.78	0.03
Primary and secondary order		$B>A>C$	
Optimal levels	A_5	B_5	C_5
Optimal combination	$A_5B_5C_5$		

Through range analysis shown in Table 3, the primary and secondary order of MRR was $B>A>C$, at the same time, the corresponding optimal combination was $A_5B_5C_5$. MRR reached the maximum when speed rate of the outside ring gear to the inside sun gear $m=-1$, speed rate of lower plate to the inside sun gear $n=5$, SiC substrate distribution radius $RB=75$. If only the influence of these three factors on MRR was considered, proportion of the influence of parameters was shown in Fig. 3.

Fig. 3. Proportion of the influence of parameters on MRR

Variance analysis[19] was used to study the significance of the influence of various factors on the index.

Analysis of variance was shown in Table 4.

Table 4 Variance analysis of L_{25}

Index	Source	SS	DF	F	Significance
MRR /($\mu m/h$)	A	0.489	4	7.562	**
	B	2.219	4	34.314	**
	C	0.004	4	0.062	
	Error	0.19	12		

Note: $F_{0.01}(4, 12)=5.410$, **means 0.01 levels significant

According to the table above, at 99% confidence, m and n have a significant effect on MRR while RB not. In

order to study the influence of factors on index, the trend chart in the intuitive analysis method was used as shown in Fig. 4. Horizontal axis was the five levels of each factor, and the vertical axis was the MRR .

Fig. 4. Influence trend of single factor on MRR

Fig. 4 shown that speed rate of lower plate to the inside sun gear n has the greatest influence on MRR , speed rate of the outside ring gear to the inside sun gear m has an effect on MRR while it was approximately linearly correlated, and SiC substrate distribution radius RB has little influence on MRR .

In order to build an accurate mathematical model and more accurately analyze the relationship between index and factors, orthogonal rotary regression test of Tri-factor quadratic was carried out based on orthogonal test of three factors and five levels of L_{25} . The number of central repeated tests was 9 and asterisk arm length γ was equal to 1.682. Orthogonal rotary regression test of factors and levels design and results were shown in Table 5 and Table 6.

Table 5 Orthogonal rotary regression test of factors and levels design of L_{23}

Levels	Factors		
	m	n	RB
	A	B	$C/(\text{mm})$
$+r$	-1.318	4.682	70.23
+1	-2	4	60
0	-3	3	45
-1	-4	2	30
$-r$	-4.682	1.318	19.77

Table 6 Orthogonal rotary regression test results of L_{23}

No.	Factors			Index
	m	n	RB	MRR
	x_1	x_2	$x_3/(mm)$	$y/(um/h)$
1	-2	4	60	2.32
2	-2	4	30	2.32
3	-2	2	60	1.71
4	-2	2	30	1.71
5	-4	4	60	2.10
6	-4	4	30	2.09
7	-4	2	60	1.55
8	-4	2	30	1.53
9	-1.318	3	45	2.09
10	-4.682	3	45	1.81
11	-3	4.682	45	2.42
12	-3	1.318	45	1.41
13	-3	3	70.23	1.93
14	-3	3	19.77	1.92
15	-3	3	45	1.93
16	-3	3	45	1.92
17	-3	3	45	1.93
18	-3	3	45	1.93
19	-3	3	45	1.93
20	-3	3	45	1.94
21	-3	3	45	1.92
22	-3	3	45	1.93
23	-3	3	45	1.93

It was used the STATISTICA 8.0 to analyze the variance of the test results[20,21], and the regression equation was obtained by fitting the ternary quadratic polynomial. Pareto Chart of t-Values for Coefficients was shown in Fig. 5. The variance analysis of MRR was shown in Table 7.

Fig. 5. Pareto Chart of t-Values for Coefficients

Table 7 Variance analysis of L_{23}

Source	SS	DF	MS	F	P	Significance
x_1	0.001761954	1	0.001761954	11.5726150	0.004725454	Yes
x_2 1	0.000336056	1	0.000336056	2.2072385	0.161207697	No
x_2 2	0.032578451	1	0.032578451	213.9771828	0.000000002	Yes
x_2 3	0.000960483	1	0.000960483	6.3085119	0.026009565	Yes
x_3	0.000099444	1	0.000099444	0.6531524	0.433528562	No
$x_1 \cdot x_2$	0.001512500	1	0.001512500	9.9341891	0.007644289	Yes
$x_1 \cdot x_3$	0.000112500	1	0.000112500	0.7389066	0.405584308	No
$x_2 \cdot x_3$	0.000012500	1	0.000012500	0.0821007	0.778986055	No
Regression	1.308194637	9	0.145354960	954.6999385	1.1E-16	
Lack of Fit	0.000288889	5	0.000057780	0.2734522		
Residual	0.001979276	13	0.000152252			
Error	0.001690387	8	0.000211298			
Total	1.310173913	22	0.059553360			

Among them, x_1 stands for speed rate of the outside ring gear to the inside sun gear, x_2 stands for speed rate of lower plate to the inside sun gear, x_3 stands for SiC substrate distribution radius. Coefficient of determination was $R^2=0.998$. Degree of regression and lack of fit must be tested according the following equation:

$$F_R = \frac{SS_R/df_R}{SS_{Re}/df_{Re}} = 954.69994 \quad (18)$$

$$F_L = \frac{SS_L/df_L}{SS_{Er}/df_{Er}} = 0.27345 \quad (19)$$

Table F shows that $F_{0.05}(5, 8)=3.69$, $F_{0.05}(9, 13)=2.71$, $F_R > F_{0.05}(9, 13)$, $F_L < F_{0.05}(5, 8)$. Therefore, the regression model was significant and the lack of fit model was not significant. So as that, the equation fit well. MRR equation was derived as (20). After removing the constant term and the insignificant term, the regression model can be simplified as (21). Surface response diagram of the coupling effect of three factors x_1 , x_2 and x_3 on MRR was shown in Fig. 6.

Fig. 6. Surface response diagram of MRR

$$MRR = 1.142972 + 0.08991x_1 + 0.004598x_1^2 + 0.386613x_2 - 0.007773x_2^2 + 0.001424x_3 - 0.000019x_3^2 + 0.01375x_1 \cdot x_2 - 0.00025x_1 \cdot x_3 - 0.000083x_2 \cdot x_3 \quad (20)$$

$$MRR = 0.08991x_1 + 0.386613x_2 - 0.007773x_2^2 + 0.013750x_1 \cdot x_2 \quad (21)$$

In order to verify the applicability of the model, three groups tested in Table 8 and add another three new groups were chosen by formula (20) in Table 8.

Table 8 Verification of test results

No.	x_1	x_2	x_3	$y(\text{test})$	$y(\text{model})$	Relative error
2	-2	4	30	2.32	2.324	0.0017
8	-4	2	30	1.53	1.540	0.0065

16	-3	3	45	1.92	1.929	0.0047
add1	-3	2	45	1.62	1.626	0.0037
add2	-2	4	60	2.33	2.321	0.0039
add3	-1	3	30	2.12	2.132	0.0056

In Table 8, it was shown that the test results were closed to the model, and the relative errors were less than 1%. It means that this model can well to respond the changes of the *MRR* of the SiC single crystal substrate.

At $m=-1$, $n=5$, $RB=75$, the maximum *MRR* was calculated 2.7um/h. Characterization parameters were calculated as shown in Fig. 7. The total thickness variation(TTV) was within 10um, bending of wafer(BOW) within 25um, Warp within 40um.

Fig. 7. Surface response diagram of *MRR*

At the same time, the micro-morphology of C-face and Si-face got by SEM (QUANTA FEC250) were shown in Fig. 8. Surface roughness (*Ra*) of C-face was in the range of -6.7nm to 7.8nm (10um×10um), while Si-face was in the range of -4.9nm to 4.4nm (10um×10um) through AFM (Dimension Fast Scan) as shown in Fig. 9.

(a) C-face after MP

(b) Si-face after MP

Fig. 8. Micro-morphology of C-face and Si-face after MP by SEM at 10000×

(a) C-face 3D (b) Si-face 3D (c) C-face 2D (d) Si-face 2D
Fig. 9. Surface roughness of C-face and Si-face after MP by AFM at 10um×10um

Conclusion

MRR of the double-faced MP of SiC substrate was researched. Based on the theory of coordinate transformation, the kinematic equations of SiC substrate relative to lower pad during double-faced MP were analyzed. *MRR* reached the maximum when speed rate of the outside ring gear to the inside sun gear $m=-1$, speed rate of lower plate to the inside sun gear $n=5$, SiC substrate distribution radius $RB=75$. Through range analysis of orthogonal test factors and levels of L_{25} , the primary and secondary order of *MRR* $n>m>RB$ was obtained. An accurate mathematical model of orthogonal rotary regression test of Tri-factor quadratic of *MRR* was established and the regression model was significant. At $m=-1$, $n=5$, $RB=75$, $TTV<10\mu m$, $BOW<25\mu m$, $Warp<40\mu m$, the maximum *MRR* was $2.7\mu m/h$, it really improves the processing efficiency. At the same time, *Ra* of C-face was in the range of $-6.7nm$ to $7.8nm$ ($10\mu m\times 10\mu m$), and Si-face was in the range of $-4.9nm$ to $4.4nm$ ($10\mu m\times 10\mu m$)

through AFM. This work provided the key to CMP and verified the importance of *MRR* to ultra-smooth polishing. It has some guidance for semiconductor equipments and processes technology.

Author' contributions Peng Zhang: conceptualization, experiments, and writing; Jingfang Yang: data analysis; Huadong Qiu: supervision, investigation.

Data availability All the data have been presented in the manuscript.

Declarations

Competing interests The authors declare that they have no conflict of interests.

Ethical approval Not applicable.

Consent to participate The authors declare that they all consent to participate this research.

Consent to publish The authors declare that they all consent to publish the manuscript.

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Figures

Figure 1

Model of double-faced MP of SiC single crystal substrate

Figure 2

Slice of the influence of parameters on MRR

Figure 3

Proportion of the influence of parameters on MRR

Figure 4

Influence trend of single factor on MRR

Figure 5

Pareto Chart of t-Values for Coefficients

Figure 6

Surface response diagram of MRR

Figure 7

Surface response diagram of MRR

(a) C-face after MP

(b) Si-face after MP

Figure 8

Micro-morphology of C-face and Si-face after MP by SEM at 10000×

(a) C-face 3D (b) Si-face 3D (c) C-face 2D (d) Si-face 2D

Figure 9

Surface roughness of C-face and Si-face after MP by AFM at 10 μm × 10 μm