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Influences of Nonaqueous Slurry Components on Polishing 4H-SiC Substrate with a Fixed Abrasive Pad

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Abstract: 4H-SiC wafers are more likely to sustain a lower material removal rate (MRR) and severe subsurface damage in conventional chemical mechanical polishing (CMP) methods. To overcome the material removal bottleneck imposed by aqueous chemistry, a high-efficiency polishing of 4H-SiC wafers method by applying reactive nonaqueous fluids to self-sharpening fixed abrasive pads has been proposed in our former research works. Furthermore, to improve the material removal rate and reduce the surface roughness Sa value of 4H-SiC substrates of the Si face, the effect of organic acid, H_2O_2, and Triton X-100 in nonaqueous slurry on 4H-SiC polishing was investigated. The MRR of 12.83 μm/h and the Sa of 1.45 nm can be obtained by the orthogonally optimized slurry consisting of 3 wt% H_2O_2, 0.5 wt% Triton X-100 at pH = 3. It is also found that the addition of different levels of oxidant H_2O_2 and surfactant Triton X-100 components not only increased the MRR of the 4H-SiC substrates of the Si face but also achieved a lower Sa value; in that, the polishing efficiency of the Si side of the 4H-SiC wafers and the surface quality of the 4H-SiC wafers could be effectively improved by the optimization of the polishing slurry.

Keywords: silicon carbide (SiC); nonaqueous slurry; methanol; H_2O_2 oxidizer; chemical mechanical polishing; fixed abrasive pad

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1. Introduction

The third-generation semiconductor substrates of silicon carbide (SiC) material are rapidly and widely used in short-wavelength optoelectronic devices, high-temperature devices, anti-irradiation devices, and high-power/high-value electronic devices [1–4]. Compared to 6H-SiC and Si, 4H-SiC has a higher band gap, so 4H-SiC is the crystal of choice for most researchers [5]. Surface planarization of 4H-SiC wafers is a critically important segment in the manufacture of semiconductor devices; the most commonly used method is chemical mechanical polishing (CMP) [5,6]. However, two fundamental challenges to efficiently obtaining ultrasmooth 4H-SiC substrates are their nature of super hardness and strong chemical stability [7–9].

Based on the abrasive movement mode, CMP can be mainly divided into loose abrasive and fixed abrasive polishing. Most academics and researchers who study CMP have focused on polishing slurry and pads to solve the inefficiencies in the Si-face polishing processes of the 4H-SiC substrate [10–12]. The material removal rates (MRRs) of 4H-SiC substrates have been accelerated by using mixed abrasives, such as silica sol [13], alumina (Al_2O_3) [14], cerium oxide (CeO_2) [15], etc. Lu et al. [16] synthesized a new diamond abrasive coated with silica sol to enhance the MRR to 0.66 μm/h. Wang et al. [14] applied two polishing slurries, microscale α-Al_2O_3, and nanoscale SiO_2, respectively. The ultra-smooth surface of the 4H-SiC substrate could be achieved by two-step polishing with the slurries. The MRR rose to 1.4 μm/h using α-Al_2O_3 in the first polishing stage.

On the other hand, fixed abrasive pads (FAP) have been gradually applied to polishing silicon carbide substrates [17–23]. A kind of FAP made of Fe, Al_2O_3, and diamond was prepared by Ho et al. [20] to polish single-crystal silicon carbide substrates with a 20 wt% H_2O_2 polishing slurry at a pH of 4, obtaining an MRR of 0.74 m/h. Yu et al. [24] promote the MRR of the 4H-SiC substrate 0 to 6.0 µm/h by using a semifixed abrasive pad at a pressure of 2.9 psi and a speed of 100 rpm; however, the polished surface roughness was more than 120 nm. Luo et al. [25] achieved an MRR of 7.83 µm/h by polishing 6H-SiC substrate at a pressure of 1.5 psi and a speed of 120 r/min with a FAP.

In the past, the abundance of the aqueous liquid carrier, which in typical tradition is water, determined the chemical properties of each component in a polishing slurry. With decades of efforts, researchers on raising the MRR of aqueous-based 4H-SiC polishing systems have run out of resources and are currently confronting formidable obstacles. A high-efficiency polishing of 4H-SiC wafers of the Si face method by applying reactive nonaqueous fluids to self-sharpening fixed abrasive pads has been proposed in our former research works [26]. In this work, to increase the material removal rate (MRR) and reduce the surface roughness Sa value of 4H-SiC substrates of the Si face, the effect of organic acid, H_2O_2, and Triton X-100 in nonaqueous slurry on 4H-SiC polishing was investigated. The MRR of 12.83 µm/h and the Sa of 1.45 nm can be obtained by the orthogonally optimized slurry consisting of 3 wt% H_2O_2, 0.5 wt% Triton X-100 at pH = 3. A polishing pressure of 0.7 psi, a polishing carrier speed of 45 rpm, platen speed of 50 rpm, and a polishing slurry flow rate of 50 mL/min have been attained.

2. Materials and Methods

2.1. Materials and Instruments

The names, specifications, and manufacturers of the materials and reagents used in the experiments are recorded in Table 1. For instance, Jiangyin Lanka Crystal Materials Co., Ltd. (Wuxi, China) produced 4H-SiC single cry substrates with a diameter of 50.8 mm and a surface roughness of 1 ± 0.2 nm. A hydrophilic self-conditioning fixed abrasive pad with a diameter of 300 mm was provided by Nanjing University of Aeronautics and Astronautics; the reactive polishing reagents, methanol (CH_3OH, CAS no.67-56-1, $\geq$99.5%), hydrogen peroxide (H_2O_2, CAS no.7722-84-1, $\geq$31%), and oxalic acid ($C_2H_2O_4$, CAS no.144-62-7, $\geq$99.0%) were purchased from Shanghai Titan Co., Ltd. (Shanghai, China), and Triton X-100 was obtained from Shanghai McLean Biochemical Technology Co., Ltd. (Shanghai, China).

Table 1. The experiment mainly uses a list of reagents.

Reagents	Specification	Manufacturers
4H-SiC single-cry substrates	Φ50.8 mm	Jiangyin Lanka Crystal Materials
Fixed abrasive pad	Φ300 mm	Nanjing University of Aeronautics and Astronautics
CH_3OH	(AR)	Shanghai Titan Co., Ltd.
Triton X-100	(AR)	Shanghai McLean Biochemical Technology Co., Ltd.
H_2O_2	(AR)	Shanghai Titan Co., Ltd.
$C_2H_2O_4$	(AR)	Shanghai Titan Co., Ltd.

2.2. Polishing Experiment

By our previous research, a fixed abrasive polishing pad with diamond grains of 3–5 µm was recommended and optimized, methanol slurry was used as the primary polishing slurry, hydrogen peroxide was added as the oxidizing additive, Triton X-100 acted as the active ingredient, and oxalic acid was available to adjust the pH of the nonaqueous system. Figure 1 shows the polishing scheme in detail and the ultraprecision polishing machine utilized for all characterization tests. Before polishing, the process for preparing the polishing fluid involved mixing a nonaqueous solvent with chemical additions mentioned in Table 1 for roughly three minutes while employing a magnetic stirrer. 4H-SiC substrates were attached into beakers, filled with ethanol and deionized water, cleaned for 10 min in an ultrasonic cleaner individually, and then dried. Experimental approaches were implemented to ensure that surface flaws do not affect the polishing outcomes.

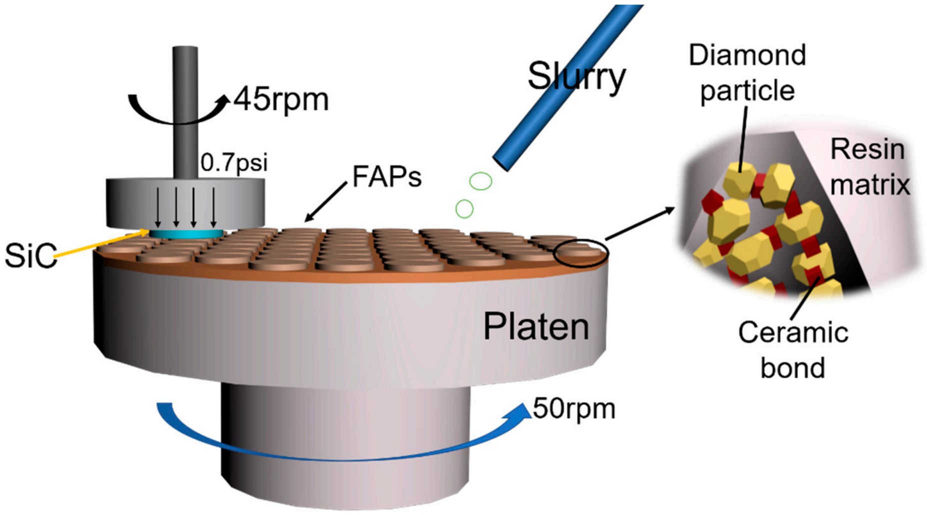


Figure 1. Schematic diagram of fixed abrasive polishing 4H-SiC [26].

The ultraprecision ring polishing machine was used for the CMP polishing studies. As the experimental procedure depicted in Figure 1, the polishing machine was connected to the SiC-laminated polishing carrier disc, which was positioned on the polishing head fixture. First, we set the necessary polishing parameters for the experiment, the parameters including 0.7 psi pressure, 45 r/min carrier speed, 50 r/min platen speed, 50 mL/min polishing rate, and 3 min polishing time; next, we turned on the peristaltic pump, and last, we adjusted the buttons to regulate the flow rate of the polishing slurry so that it dripped onto the polishing pad.

The hydrophilic self-conditioning fixed abrasive pad with a diameter of 300 mm was provided by the Nanjing University of Aeronautics and Astronautics and utilized in the CMP trials on an ultraprecision polishing machine. A diamond dressing disc was used for 10 min to fully expose the diamond abrasive grains on the surface of the polishing pad before polishing. Deionized water was then applied dropwise. The specific polishing parameters were shown in Table 2, and each CMP experiment was repeated three times to prevent the generation of accidental errors.

Table 2. 4H-SiC substrates of Si face polishing experiment parameters.

Process Parameters	Conditions
Pressure/(psi)	0.7
Carrier speed (r/min)	45
Platen speed/(r/min)	50
Polishing rate (mL/min)	50
Polishing time (min)	3

Equation (1) for calculating the *MRR* (μm/h) for SiC is as follows:

$$MRR = \frac{M_0 - M}{\rho \times r^2 \times \pi \times t} \times 10^4 \times 60 \tag{1}$$

where M_0 and M (g) are the mass of SiC substrate before and after polishing, t (min) is the processing time (3 min), ρ is the density of SiC (3.2 g/cm^3), and r is the radius of the substrate (25.4 mm).

2.3. Characterization

The weight loss of the 4H-SiC substrate before and after polishing was measured using an electronic balance with a 0.01 mg precision (PMK224 ZH/E, OHAUS Instruments Co., Ltd., Changzhou, China). The CMP polishing experiments were carried out using the ultraprecision ring polishing apparatus (ZDHP-30, Dongguan Sacred Technology Co., Ltd., Dongguan, China). The Benchtop pH meter (PHS-25, Shanghai Remagnetics Instruments Co., Ltd., Shanghai, China) was available to adjust the pH of nonaqueous slurries. A metallographic microscope (BH200 M, Ningbo Sunny Instruments Co., Ltd., Ningbo, China) was first used to evaluate and record the surface morphology of the polished SiC surface. The 4H-SiC surface of the Si face topography was profiled, the 4H-SiC surface roughness of the Si face in contact mode was measured, and a three-dimensional topographical map was created using an atomic force microscope (AFM, CSPM4000) from Beijing Nano Instruments Ltd. (Beijing, China) On the 4H-SiC substrate of the Si face, the average surface roughness (Sa) was determined to be the assessment criterion for the surface topography after each sample was examined five times, and the average roughness was then obtained.

3. Results

3.1. Optimization of Nonaqueous Polishing Slurry

According to our previous experimental results [26], it was necessary to research the significance levels and synergistic effects of the factors explored. Three factors and three levels of tests were designed by using the method of orthogonal testing. The pH of the slurry, the concentration of the H_2O_2, and the concentration of the Triton X-100 surfactants were the independent variables of the model, and the surface roughness (Sa) of the 4H-SiC substrate of the Si face was the response value. The test design and results are shown in Tables 3 and 4.

Table 3. Three factors and levels of pH, H_2O_2 concentration, and Triton X-100 concentration are designed by orthogonal test.

Factors	**A** **pH**	**B** **H_2O_2 Concentration (wt%)**	**C** **Triton X-100 Concentration (wt%)**
Level 1	2	1 wt%	0.1 wt%
Level 2	3	3 wt%	0.3 wt%
Level 3	4	5 wt%	0.5 wt%

Table 4. Orthogonal test and results of L9 (3^3).

Number	**A** **pH**	**B** **H_2O_2 Concentration (wt%)**	**C** **Triton X-100 Concentration (wt%)**	**Sa (nm)**
1	1 (2)	1 (1)	1 (0.1)	5.12
2	1	2 (3)	2 (0.3)	4.89
3	1	3 (5)	3 (0.5)	3.99
4	2 (3)	1	2	2.84
5	2	2	3	2.23
6	2	3	1	3.56
7	3 (4)	1	3	3.27
8	3	2	1	3.38
9	3	3	2	3.2
K1	14	11.23	12.06	
K2	8.63	10.5	10.93	
K3	9.85	10.75	9.49	
R	5.37	0.73	2.57	

The orthogonal test arrangement and specific factor levels are provided in Table 3. Three main research factors are the pH, H_2O_2 concentration, and Triton X-100 concentration. Denoting the pH as the experimental group A, H_2O_2 concentration as the experimental group B and Triton X-100 concentration as the experimental group C. Three main research levels are as follows: The pH of the polishing slurry was adjusted to 2, 3, and 4, the H_2O_2 concentration was optimized in the range of 1 wt%, 3 wt%, and 5 wt%, and the Triton X-100 concentration was applied to between 0.1 wt%, 0.3 wt%, and 0.5 wt%. The surface roughness (Sa) of the 4H-SiC substrate of the Si face was designated as the assessment index, and the results are illustrated in Table 4.

Table 4 described the orthogonal test and results of L9 (3^3). The nine sets of experimental data in Table 4 are the specific presentation of the three-factor, three-level experimental design for pH, H_2O_2 concentration, Triton X-100 concentration, and the surface roughness Sa values as the feedback results of the experiment. In the column of pH, the number 1 indicates that the pH environment of the polishing slurry is 2, the number 2 indicates that the pH environment of the polishing slurry is 3, and the number 3 indicates that the pH environment of the polishing slurry is 4. Similarly, in the column of H_2O_2 concentration, the number 1 indicates that the oxidant content in the polishing slurry is 1 wt%, the number 2 indicates that the oxidant content in the polishing solution is 3 wt%, and the number 3 indicates that the oxidant content in polishing slurry is 5 wt%. In the data of the column of Triton X-100 concentration, the number 1 indicates that the concentration of surfactant in the polishing slurry is 0.1 wt%, the number 2 indicates that the concentration of oxidant in the polishing slurry is 0.3 wt%, and the number 3 indicates that the concentration of oxidant in the polishing slurry is 0.5 wt%. By computing the sum of the three levels of surface roughness values corresponding to the three separate columns of components, it was possible to work out K values in Table 4. The pH values K1, K2, and K3 for nonaqueous polishing slurries are the same as those in the first column. The specific calculating steps are as follows.

The sum of three surface abrasion levels at level 1: K1 = 5.12 + 4.89 + 3.99 = 14 nm
K2 = Sum of three surface abrasion levels at level 2 = 2.84, 2.23, and 3.56, or 8.63 nm
3.27 + 3.38 + 3.20 = 9.85 nm is the sum of the three surface roughness levels for level 3.

Table 4 showed the parameters of the fifth set of experiments. According to the statistic in Table 4, A2B2C3 has the lowest surface roughness at 2.23 nm. Table 5 offers a detailed summary of the parameters in the fifth grouping in Table 4. In terms of the 4H-SiC substrate of the Si face surface roughness, the group with a smaller K value has higher surface quality than a group with a greater K value. Since K2 has the smallest impact on the pH of the first column, A2 was preferred, and so on. Table 5 depicted that among the three better A2B2C3 levels of K1, K2, and K3, the polishing slurry pH value of 3, H_2O_2 concentration of 3 wt%, and Triton X-100 concentration of 0.5 wt% are the desirable level combinations for the surface quality of 4H-SiC substrates of Si face.

Table 5. Experimental parameters with low surface roughness.

Number	**A** **pH**	**B** **H_2O_2 Concentration (wt%)**	**C** **Triton X-100 Concentration (wt%)**	**Sa (nm)**
5	3	3	0.5	2.23

The formula for the extreme difference analysis for each element was as follows:

$$R = \max(K1, K2, K3) - \min(K1, K2, K3) \tag{2}$$

where, RA in the first column: 14 − 8.63 = 5.37, RB = 11.23 − 10.5 = 0.73 in the second column, and RC = 12.06 − 9.49 = 2.57 in the third column.

The surface roughness findings vary between the three levels of the factor, as determined by the range analysis of each parameter. To put it another way, the higher the extreme difference value, the more significant an impact the factor has on the experimental results, but the lower the range analysis value, the less significant an effect the factor's three levels of results have on surface roughness. From the experimental results in Table 4, it can be inferred that pH plays a crucial role in surface roughness, follows by Triton X-100 concentration and that H_2O_2 concentration had the least impact on the results. Since RA > RC > RB, it is indisputable that pH has a significant effect on surface roughness. Through orthogonal experiments, we learned that the best experimental values obtained for the three factors were pH of 3, hydrogen peroxide content of 3 wt%, and Triton X-100 of 0.5 wt%, respectively. To further validate the experimental results, a single-factor test method, and orthogonal experimental results validation were then used for comparison. The specific details are presented in Figure 2.

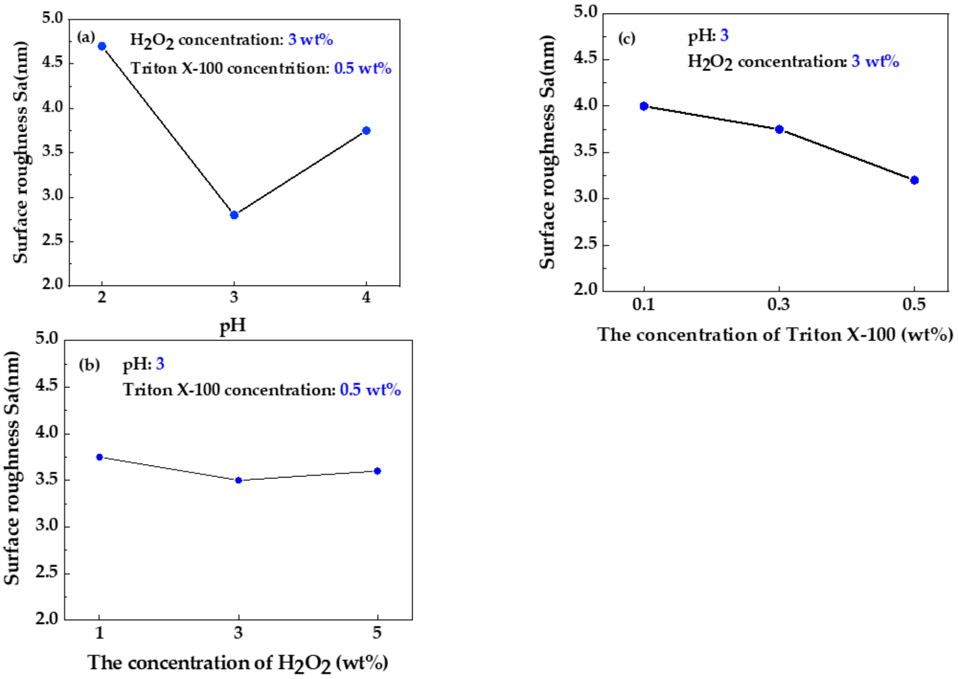


Figure 2. Trend graphs of factor-level effect: (**a**) pH value, (**b**) H_2O_2 concentration, (**c**) Triton X-100 concentration.

The experimental statistic is used to determine pH = 3 as the ideal value. Figure 2 depicted the trend graph of the factor-level effect. Along with Figure 2a, the surface roughness of the 4H-SiC substrate of Si face rose steadily as the pH rose, dropped swiftly as the pH fell, and reached its highest maximum level value at pH 3. It is suggested that better surface quality may be obtained by polishing the 4H-SiC substrate of Si face in a nonaqueous methanol slurry system with a pH of 3. Meanwhile, the optimal point of H_2O_2 concentration was 3 wt%. The surface roughness of the 4H-SiC substrate of Si face steadily decreased until settling within a specific range, as shown in Figure 2b, which exhibited the impact level effect of H_2O_2 concentration.

When the H_2O_2 concentration continued to increase, the surface roughness of the 4H-SiC substrate of the Si face rose significantly, indicating that the H_2O_2 concentration should not be too high in the reactive nonaqueous slurries. Furthermore, a Triton X-100 concentration of 0.5 wt% was strongly recommended. As can be seen from the factor level effect response diagrams for the surfactant Triton X-100 concentration in Figure 2c, the surface roughness of the 4H-SiC substrate of Si face initially fell and then dropped rapidly as the Triton X-100 concentration increased, illustrating that a range of concentrations of Triton X-100 can effectively improve the surface quality of the 4H-SiC substrate of Si face.

When the composition of Triton X-100 is 0.5 wt%, the surface roughness was the lowest and the polishing effect of the 4H-SiC substrate of the Si face was the most optimal.

The results and analyses of the orthogonal tests had shown that pH = 3, H_2O_2 concentration of 3 wt%, and Triton X-100 concentration of 0.5 wt% were the three components' ideal values. Nine sets of orthogonal trials yielded the microscope images of the 4H-SiC substrate of Si face morphology shown in Figure 3. In groups 1, 2, and 9, the 4H-SiC substrate of the Si face had all undergone considerable scratching to varying degrees. Experiments (1) and (2) showed the most pronounced surface dings and grooves. When the pH of the 4H-SiC substrate of the Si face was 2, the local chemical corrosion was intense under the influence of strong acid during the CMP process, causing the 4H-SiC substrate of the Si face to develop grooves and scratches. Due to the reduced interfacial mechanical interaction of the surfactant and the accelerated oxidation of the hydrogen peroxide, the higher concentrations of Triton X-100 and H_2O_2 utilized in Experiment (3) produced a significantly superior 4H-SiC substrate of Si face than in Experiments (1) and (2). The 4H-SiC substrate of Si face quality of experiment (5) was the best; at pH = 3, the chemical effect was less pronounced than before, which was consistent with the results of other experiments. The combination of Triton X-100 and hydrogen peroxide may further enhance the 4H-SiC substrate of Si face quality.

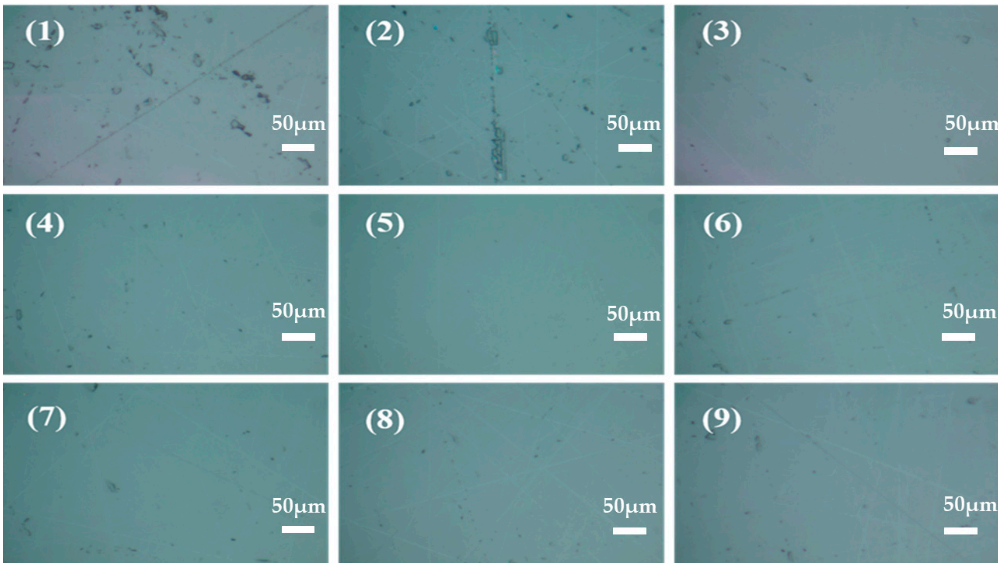


Figure 3. Microscopic surface morphology of polished 4H-SiC substrate of Si face obtained by orthogonal testing. The numbers in the pictures correspond to the 9 sets of experiments in Table 4.

It was clear that the results of the above orthogonal tests showed that pH = 3, H_2O_2 concentration of 3 wt%, and Triton X-100 concentration of 0.5 wt% were the best values for the three main components. The pH range of the polishing solution was expanded in this test to further investigate the effect of pH on the polishing performance of the 4H-SiC substrate of the Si face. Additionally, among the component factors of the nonaqueous polishing slurry, pH had the greatest impact on the CMP polishing performance of the 4H-SiC substrate of the Si face. However, due to the inherent limitations of the orthogonal test, only the effects of pH = 2, pH = 3, and pH = 4 on the surface roughness of the 4H-SiC substrate of the Si face were investigated.

3.2. *Effect of pH on Polishing 4H-SiC Substrate of Si Face*

By changing the pH of the methanol polishing slurries to 2, 3, 4, 5, and the pure methanol slurry devoid of oxalic acid to pH 6.67, it was determined how various pH values affected the polishing effect of 4H-SiC substrate of Si face. The other conditions identified a 3 wt% concentration of H_2O_2 and a 0.5 wt% concentration of Triton X-100.

Figure 4 depicted the pattern of how pH impacted the MRR and surface roughness of the 4H-SiC substrate of the Si face. As indicated by the graph, the pH range for the nonaqueous slurry system was between 2 and 4. The MRR of the 4H-SiC substrate of Si face grew quickly when the pH of the polishing slurry was between 2 and 3; as a result, as the pH steadily rose, the MRR first dropped slowly and then rapidly. Surprisingly, when pH increased, the surface roughness of the 4H-SiC substrate of Si face reduced quickly, then progressively increased, with pH = 3 yielding the highest MRR (13.61 μm/h) and the lowest Sa (2.13 nm). Friction catalysis can weaken the Si-C bonding on the 4H-SiC surface to oxidation due to the accelerated oxidation of H_2O_2 under acidic circumstances, resulting in softer siloxane material that can be easily removed on the FAP. The pH of the polishing slurry was chosen to be around 3.0 because a higher pH caused the polishing slurry's chemical action to weaken, the oxidation rate to slow down, and the oxidation layer that was produced on the 4H-SiC substrate of Si face to gradually thin out. The results in a lower removal rate and lower-quality surfaces of 4H-SiC substrate of Si face.

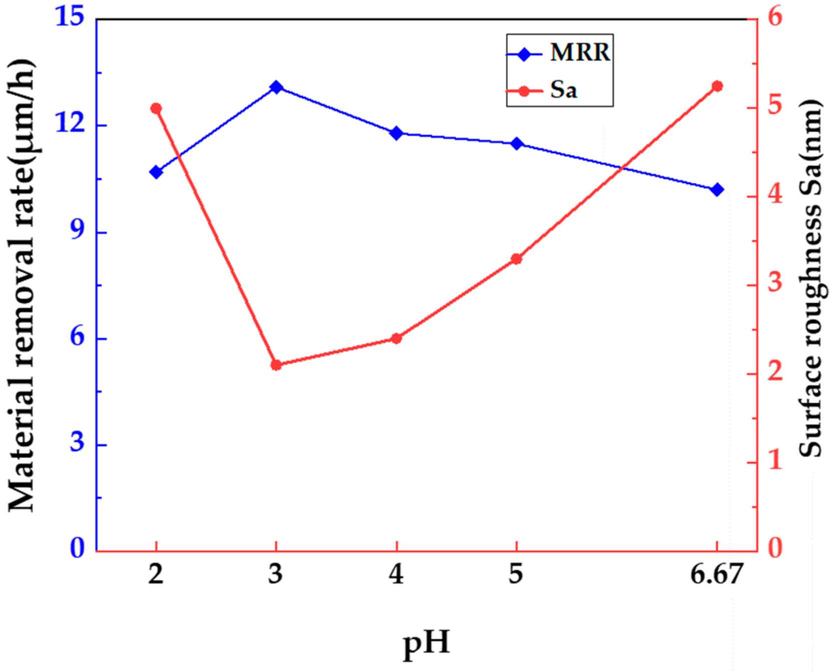
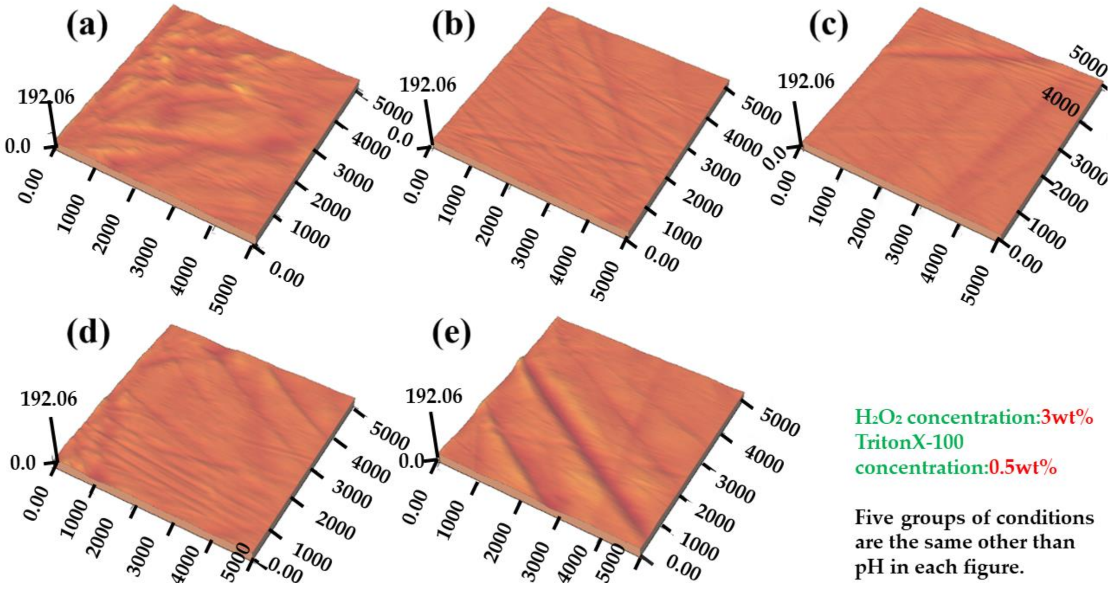


Figure 4. The MRR and surface roughness of polished 4H-SiC substrate of Si face at different pH.

Figure 5 depicted the three-dimensional surface morphology of AFM after polishing the 4H-SiC substrate of the Si face with distinct methanol pH levels. Five groups of conditions are the same other than pH in each figure. H_2O_2 concentration is 3 wt% and the Triton X-100 concentration is 0.5 wt%. The pH in Figure 5a is adjusted at 2, the pH in Figure 5b is adjusted at 3, the pH in Figure 5c is adjusted at 4, the pH in Figure 5d is adjusted at 4, the pH in Figure 5d is adjusted at 5, and the pH in Figure 5e is adjusted at 6.67. It is clear from Figure 5 that after polishing the 4H-SiC substrate of Si face with various pH levels, the surface quality radically changed and the surface morphology differed dramatically. The surface quality improved overall after the addition of oxalic acid, and the scratches and bumps were reduced in turn. Particularly at pH = 3, the substrate surface was the flattest, without obvious scratches and bumps, and the surface roughness was also the lowest, which was owing to the appropriate amount of oxalic acid being added at this time. A flattened surface is produced as a result of the mechanical action of the diamond abrasive grains on the hydrophilic self-conditioning fixed abrasive pad, which effectively counteracts the creation of a film on the 4H-SiC substrate of the Si surface. It was important to note that surface grooves and bumps were severe at pH = 2, which may be the result of a surface quality decline brought on by severe local chemical corrosion.



H_2O_2 concentration:3wt%
TritonX-100
concentration:0.5wt%

Five groups of conditions
are the same other than
pH in each figure.

Figure 5. AFM morphology of polished 4H-SiC substrate of Si face at different pH: (**a**) 2, (**b**) 3, (**c**) 4, (**d**) 5, (**e**) 6.67.

In an acidic environment, using methanol as the primary solvent, hydrogen peroxide as the oxidizing agent, and Triton X-100 as the surfactant results in higher levels of oxidation products on the 4H-SiC substrate of the Si surface compared to a conventional aqueous slurry, which strongly suggests that the nonaqueous slurry and the 4H-SiC substrate of the Si surface are chemically reacting. By judiciously selecting a highly reactive nonaqueous slurry system rather than using a conventional aqueous system, the kinetics of the chemical reaction between Si-C and the polishing solution are greatly accelerated, resulting in the rapid formation of a softened oxide material on the polished 4H-SiC substrate of the Si surface. The softened surface oxide layer is easily removed by the fixed abrasive pad without strong mechanical friction. Thus, chemical mechanical polishing in a nonaqueous slurry system allows for greater interaction on the 4H-SiC substrate of the Si surface and the polishing results are more efficient.

4. Conclusions

Through the use of an orthogonal test sieve, it was distinguished how different pH adjusters (organic acids), oxidizing agents (H_2O_2), and surfactants (Triton X-100) affected the polishing of the 4H-SiC substrate of the Si face in reactive nonaqueous system fluids. The primary conclusions reached were as follows. Through orthogonal tests, the three polishing solution components (pH, H_2O_2 concentration, and Triton X-100 concentration) were analyzed. The degree of influence on the surface roughness of 4H-SiC substrates was then motivated for each component, starting with pH and going down to H_2O_2 concentration and Triton X-100 concentration. It was found that a nonaqueous polishing slurry component of pH = 3, with an H_2O_2 concentration of 3 wt%. The 4H-SiC of Si surface had a Sa value of 1.45 nm at the optimal nonaqueous methanol fraction pH = 3, an H_2O_2 concentration of 3 wt%, a Triton X-100 concentration of 0.5 wt%, a polishing pressure of 0.7 psi, a polishing pressure of 0.7 psi, a polishing carrier speed of 45 rpm, platen speed of 50 rpm, and a polishing slurry flow rate of 50 mL/min. Meanwhile, 12.83 µm/h, a high cutting rate, was attained.

Author Contributions: J.Z. designed the experiment project. J.C. proposed the analysis of the effective theoretical model. H.W. performed the experiment results. J.Z. wrote the manuscript and sent it to all authors. H.C., Y.G. and J.S. revised the paper and suggested some advice. T.S. promoted the funding support. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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