Ultra-precision grinding of 4H-SiC wafer by PAV/PF composite sol-gel diamond wheel

Kaiping Feng1,2,3, Tianchen Zhao1,3, Binghai Lyu2 and Zhaozhong Zhou1,3

Abstract
To eliminate the deep scratches on the 4H-SiC wafer surface in the grinding process, a PVA/PF composite sol-gel diamond wheel was proposed. Diamond and fillers are sheared and dispersed in the polyvinyl alcohol-phenolic resin composite sol glue, repeatedly frozen at a low temperature of \(-20^\circ C\) to gel, then \(180^\circ C\) sintering to obtain the diamond wheel. Study shows that the molecular chain of polyvinyl alcohol-phenolic resin is physically cross-linked to form gel under low-temperature conditions. Tested by mechanical property testing machines, microhardness tester, and SEM. The results show that micromorphology is more uniform, the strength of the sol-gel diamond wheel is higher, the hardness uniformity is better than that of the hot pressing diamond wheel. Grinding experiments of 4H-SiC wafer were carried out with the prepared sol-gel diamond wheel. The influence of grinding speed, feed rate, and grinding depth on the surface roughness was investigated. The results showed that by using the sol-gel diamond wheel, the surface quality of 4H-SiC wafer with an average surface roughness \(R_a 6.42 \text{ nm}\) was obtained under grinding wheel speed 7000 r/min, grinding feed rate 6 \(\mu m/min\), and grinding depth 15 \(\mu m\), the surface quality was better than that of using hot pressing diamond wheel.

Keywords
Sol-gel diamond wheel, 4H-SiC wafer, ultra-precision grinding, surface roughness, abrasion

Date received: 1 April 2021; accepted: 18 August 2021

Handling Editor: James Baldwin

Introduction
Single crystal SiC (4H-SiC), one of the third-generation semiconductor materials, has excellent electrical and chemical properties, such as wide energy band gap, excellent thermal conductivity, high breakdown electric field, and appropriate chemical stability. It is widely used in high temperature, high pressure, high power high density, and radiation resistance integrated power electronic and optoelectronic devices.1–3 In those applications, an ultra-smooth and defect-free SiC wafer is essentially important, which directly determines the component performance.4 However, SiC is difficult to be machined for its high hardness and chemical inertness. CMP is regarded as a critical technology to achieve high-quality surfaces, but the relatively weak mechanical removal action and chemical effect applied on the SiC wafer by SiO\(_2\) slurry lead to low polishing.
efficiency. To realize the high-efficiency and high-precision machining of SiC, Yin et al. proposed a novel polishing technique that combines anodic oxidation and mechanical polishing (AOMP), Yan et al. proposed an ultraviolet (UV) photocatalysis-assisted polishing method, Yu et al. employed ultrasonic vibration-assisted polishing (UVP) of single-crystal SiC, but these methods were complicated. Another way to improve the machining efficiency is to improve the surface quality of SiC wafer in semi finishing stage to reduce CMP polishing time, the conventional semi finishing method is to use resin copper disc and diamond slurry. Under the condition of using free abrasive, it is impossible to achieve high speed, high pressure, and high efficiency polishing. Long time and low efficiency polishing will make the polishing surface profile uncontrollable and produce a large amount of slurry waste. Ultra-precision grinding was introduced as a semi-finishing process before CMP of hard and brittle materials to reduce CMP polishing time, Kim and Lee found that a finer super-abrasive wheel could obtain the mirror-like uniformity is the key to prepare the wheel for ultra-precision grinding of SiC wafers. To avoid agglomeration of ultra-fine diamond particles and improve the surface roughness of silicon wafers, Miao et al. introduced a combination of gel casting and pore-forming agent to fabricate vitrified-bonded ultra-fine diamond grinding wheel with ultra-high porosity (up to 75%), the surface roughness Ra and damaged layer of the ground Si wafers are approximately 5 nm and 0.21 μm respectively. Huang et al. developed sol-gel (SG) polishing pad based on the sodium alginate (AGS) binary compound system, which was used for polishing hard and brittle materials to obtain high-quality surfaces. Luo et al. developed a sol-gel polishing tool consisted of gel balls fabricated for green manufacturing of the seal stone, a smooth seal stone surface was obtained after processing by the sol-gel polishing tools. Zhang et al. discussed the differences in structure and properties of vitrified bonds and vitrified diamond composites prepared by sol-gel and melting methods, sol-gel method could apply to the production of grinding tools with high dimensional accuracy. Yiqing et al. combined epoxy resin and a soft gel body containing diamond abrasives to form a hard honeycomb structure. Wang et al. fabricated the diamond/GO/EP abrasive tools via in situ polymerization. The sol-gel method mixing ultra-fine abrasives in solution to obtain uniformly dispersed slurry for manufacturing ultrafine abrasive grinding tools, which solves the problem of fine abrasive dispersion, but the above bonding agent is not a commonly used resin abrasive bonding agent. The heat resistance temperature, impact strength, and friction coefficient stability are all lower than phenolic resin and polyimide resin. A grinding wheel incorporating sol-gel technology and commonly used resin bond will be developed.

Polyvinyl alcohol (PVA) and water-soluble phenolic resin (PF) mixed glue hydrogel were used to make the ultra-precision grinding wheel in this study. The differences in microscopic morphology, structural strength, and surface hardness between the sol-gel diamond wheel and the hot pressing diamond wheel were compared. The influence of grinding process parameters including grinding speed, feed rate, and grinding depth on the surface quality of the 4H-SiC wafer was investigated. Wear of the grinding wheel in different grinding stages and the dressing methods were also discussed.

Preparation and characterization of sol-gel diamond wheel

Preparation of the sol-gel diamond wheel

Polyvinyl alcohol is easy to cross-link intermolecular hydrogen bonds to form a gel at low temperature, the particles can be embedded and fixed in the gel network to form an organic-inorganic gel complex. At the same time, the hydroxyl group in the polyvinyl alcohol can occur a grafting reaction with phenolic resin, as shown in Figure 1(a). Based on the low-temperature freezing physical gel ability of polyvinyl alcohol, after
dispersing diamond abrasives and fillers in the slurry, the inorganic particles are consolidated to form a gel body, which avoids the uneven dispersion of dry powder. On the other hand, the addition of polyvinyl alcohol increases the network structure and plastic deformation ability of phenolic resin and improves the wrapping performance of phenolic resin and diamond abrasive. After sintering at 180°C, the PVA molecules are dehydrated and etherified, lose solubility finally, which helps maintain the strength of the grinding wheel. The principle diagrams of the sol-gel process and the sol-gel wheel forming are shown in Figure 1(b) and (c).

The composition of the sol-gel wheel is shown in Table 1. Fillers are often added to resin bond grinding wheels to improve mechanical properties and polishing performance. The copper powder has good thermal conductivity, which is used to reduce local overheating in the grinding area. SiC powder is used to increase the wear resistance and reduce the blockage of the grinding wheel. Graphite is a lubricant, which is easily crushed during friction to form a layer of lubrication on the friction surface. ZnO is used to prevent continuous furrows from the resin plowing caused by the grinding debris during the grinding process. The functions of the wetting agent and the toughening agent are respectively to improve the wettability of the glue to the inorganic particles and the toughness of the gel body. The preparation process is shown in Figure 2: (1) Disperse diamond micro powder, fillers, and additives in the water to prepare a suspension; (2) Prepare 30 wt% polyvinyl alcohol-phenolic resin blend glue, wherein the mass ratio of polyvinyl alcohol to phenolic resin is 1:5, and then add the mixed glue to the suspension and mix to obtain gel slurry; (3) Pour slurry into a ring mold after sieving, and place it at −20°C for five cycles of freezing; (4) After thawing, dry naturally and put it in an oven for sintering at 180°C.

**Characterization of sol-gel diamond wheel**

The pore structure is an important feature of the grinding wheel. Its purpose is to improve the chip space...
and the self-sharpening ability of the grinding wheel. Compare the surface SEM topography of sol-gel diamond wheel and hot pressing diamond wheel, it can be seen from Figure 3 that the surface phase distribution of the sol-gel diamond wheel is more even compared with the hot pressing diamond wheel, and a large number of capillary micropores are formed inside, and the pores are interlaced and connected. This is because the pores of the sol-gel wheel are caused by the loss of moisture from the cross-linked network resin during the drying process. However, the hot pressing wheel adopts powder dry pressing method, and the resin powder with relatively low density is easy to agglomerate in the mixing process, the agglomerated resin powder forms dense resin body after high temperature curing, which hinders the uniform distribution of pores. Therefore, it is usually necessary to add pore forming agent to hot pressing wheel, it can be seen from Figure 3(b) that the surface of the hot pressing wheel is scattered with large pores, and the size of these pores is very close to the size of the pore former particles, which indicates that it is formed by the vaporization of the pore former.\(^{29}\)

The strength of the grinding wheel bond will directly affect the wear resistance, self-sharpening, surface shape retention. The strength of the two grinding wheels was compared by using a three-point bending tester, tensile tester, and impact strength testing machine. As shown in Figure 4, compared with the hot pressing diamond wheel, the sol-gel diamond wheel had 8.4% higher impact strength, 22.8% higher tensile strength, and 26.3% higher flexural strength. From the fracture morphology of the section, it can be seen that the fracture surface of the sol-gel diamond wheel is smooth and the phase is uniform, while the fracture surface of the hot pressing diamond wheel is relatively

---

**Figure 2.** Flowchart of sol-gel diamond wheel manufacturing process.

**Figure 3.** SEM diagram of: (a) sol-gel diamond wheel and (b) hot pressing wheel surface.

**Figure 4.** Mechanical property of sol-gel diamond wheel and hot pressing wheel.
rough, as shown in Figure 5. On the one hand, the binder powder in the hot pressing diamond wheel is generally micron-sized friction powder, the internal friction between the particles is large, and the fluidity is poor, resulting in uneven molding density, while the gel resin forms a network-like gel structure with good bonding performance, which can better coat the abrasive grains, and has uniform capillary, micropore distribution and high mechanical strength of the grinding wheel. On the other hand, the hot pressing diamond wheel creates pores by adding pore formers. Artificial pore structure has large pore volume and uneven pore distribution, which will reduce the volume and strength of the bonding bridge in the grinding wheel.

The hardness and hardness uniformity of the grinding wheel will directly affect the grinding performance. When the grinding wheel is too hard, the blunt abrasive grains are not easy to fall off, the grinding wheel is easy to be blocked, which increases the grinding heat, burns the workpiece, and affects the surface quality of the workpiece. If the grinding wheel is too soft, the abrasive grains are prone to fall off, which increases the wear of the grinding wheel and easily loses the correct geometry. Two kinds of grinding wheels were taken for the hardness test at eight points respectively, as seen in Table 2. The hardness average and variance are shown in Figure 6, it can be seen from the figure that the hardness of sol-gel diamond wheel is smaller than that of hot pressing diamond wheel, because the resin bond of hot pressing diamond wheel is pure phenolic resin, there are a lot of rigid aromatic rings in the molecular structure of phenolic resin, and only have methylene connection between the aromatic rings, which endows phenolic resin with the characteristics of high brittleness, low impact strength and high hardness. While the sol-gel diamond wheel uses polyvinyl alcohol and phenolic resin as resin bond, by adding polyvinyl alcohol into phenolic resin and introducing flexible methylene segment, the flexibility of phenolic resin can be improved and the hardness can be reduced. Polyvinyl alcohol modified phenolic resin is also used in industry.\textsuperscript{26,30} But the average hardness difference of the two

![Figure 5. Fracture section micrograph of: (a) sol-gel diamond wheel and (b) hot pressing diamond wheel.](image1)

![Figure 6. The hardness average and variance values of hot pressing wheel and sol-gel wheel.](image2)

| Test points | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Hardness (HRF) |     |     |     |     |     |     |     |     |
| Hot pressing wheel | 68.20 | 67.37 | 66.77 | 68.91 | 62.92 | 63.46 | 63.84 | 62.10 |
| Sol-gel wheel | 64.54 | 65.12 | 63.87 | 62.91 | 64.76 | 63.98 | 62.56 | 63.47 |
Grinding wheels is less than 8%, which means the hardness of the grinding wheel made by the sol-gel method is comparable to that of the hot pressing method. The low hardness uniformity of different parts of the grinding wheel leads to inconsistent consumption rates during the grinding process, which causes serious instability of the processing process, resulting in scratches on the surface, uneven surface roughness, and other processing problems. Comparing the two kinds of grinding wheels, the hardness variance value of the hot pressing diamond wheel is greater than that of the sol-gel diamond wheel. This is because the sintering temperature of the powder hot pressing method is often low at both ends and high in the middle. It is difficult to ensure that the sintering pressure and sintering temperature are uniform in all parts of the grinding wheel. While the sol-gel forming method refines the grains of the binder and improves the uniformity of the structure, finally improves the uniformity of the hardness of the grinding wheel.

Grinding experiment of 4H-SiC wafer

Two inch 4H-SiC N-type is used as the grinding workpiece. Due to the low material removal rate of ultra-precision grinding, the grinding depth is controlled within 30 μm, so before ultra-precision grinding, the workpiece needs rough grinding to satisfy the surface roughness and flatness. The test is carried out on the SLG80 optical grinding machine, the positioning accuracy of grinding machine reaches 1 μm. Two grinding wheels are installed on the grinding machine at the same time, the rough grinding and fine grinding can be completed in one clamping. The prepared diamond grinding wheel is pasted on the grinding wheel seat, and several radial diversion grooves of about 2 mm on the surface is carve-out for the flow of coolant, which plays a role in cooling and chip removal. Processing equipment and the prepared sol-gel diamond wheel are shown in Figure 7. The rough grinding wheel uses a 1000 mesh resin-metal composite diamond grinding wheel. After rough grinding, the surface roughness $R_a$ reaches 65 nm, and the flatness PV is less than 1 μm. The surface morphology of the SiC wafer after rough grinding is shown in Figure 8, and there is an obvious plow phenomenon on the surface. To verify the effect of the sol-gel diamond wheel, a comparative experiment is designed to grind the 4H-SiC wafer. The comparison group uses a conventional powder hot pressing diamond wheel. Table 3 shows the corresponding processing parameters.

The grinding machine numerical control system has a power monitoring system (Beckhoff system), which can monitor the grinding power throughout the process. A thickness gauge is used to measure the removal thickness of the workpiece (0.001 mm). White light profiler (KLA Tencor MicroXAM 1200) is used to measure the surface roughness of the workpiece. A laser
interference flatness meter (HSINTEK AK100F3) is used to measure flatness. The laser displacement sensor (KEYENCE CL-3000) is used to measure the thickness of the abrasive layer of the grinding wheel before and after grinding.

Test results and analysis

The influence of grinding wheel speed on surface roughness

In the single factor experiment of the grinding wheel speed, the grinding depth is 15 μm, the grinding wheel feed rate is 6 μm/min, and the trend of surface roughness \( R_a \) with the increase of the grinding wheel speed is shown in Figure 9, the roughness \( R_a \) becomes smaller with the increase of the grinding wheel speed. When the grinding wheel speed is 7000 r/min, the roughness value \( R_a \) reaches the minimum value. But as the speed of the grinding wheel continues to increase, the roughness \( R_a \) shows a gradually increasing trend. This is because increasing the speed of the grinding wheel will reduce the feed per revolution of the grinding wheel, which directly leads to the reduction of the maximum undeformed chip thickness and the reduction of the grinding force of a single diamond abrasive grain. The specific grinding energy increases, the proportion of plastic removal during grinding increases, the brittle removal decreases, and the marks left by abrasive particles on the grinding surface become shallower. Besides, the increase of the grinding wheel speed can bring out the grinding debris faster, and make the grinding fluid update faster, which reduces the grinding temperature and the grinding burn. The surface roughness \( R_a \) of the workpiece becomes smaller with the increase of the grinding wheel speed.

When the grinding wheel speed increases to more than 7000 r/min, the number of effective abrasive grains passing through the surface of the workpiece per unit time increases, and the generation speed of grinding debris per unit time increases too fast and exceeds the critical point. That is when the accumulation rate of debris on the surface of grinding wheel is greater than the rate of debris shedding on the surface of grinding wheel, a lot of these debris will fill the pores of the grinding wheel and adhere to the surrounding of the abrasive, immediately adhesion and blocking of the grinding wheel happen, which reduces the sharpness of the grinding wheel and cannot perform effective grinding force, thereby reducing the quality of the grinding surface. On the other hand, high-speed rotation increases the instability of the grinding wheel, and the longitudinal amplitude of a single abrasive particle on the grinding surface becomes larger, the grinding surface wear marks increase significantly, as shown in Figure 10. It can be seen that by increasing the speed of the grinding wheel appropriately, better surface quality of the workpiece can be obtained.

The influence of grinding feed rate on surface roughness

In the single factor experiment of the grinding wheel feed rate, the grinding depth is 15 μm, the grinding wheel speed is 7000 r/min, and the trend of surface roughness \( R_a \) with the increase of the grinding wheel feed rate is shown in Figure 11. Initially, the surface roughness \( R_a \) becomes smaller with the increase of the grinding wheel feed rate. When the grinding wheel feed rate is 6 μm/min, the surface roughness value \( R_a \) reaches the minimum value. But when the grinding wheel feed rate exceeds 6 μm/min, the surface roughness value \( R_a \) of the workpiece tends to increase. This is because when the feed rate of the grinding wheel is small, the tangential grinding force of the grinding wheel is small, the width of the grinding debris is narrow, the friction between the grinding wheel and the workpiece generates less heat, the temperature of the grinding zone is lower, and the material removal efficiency is relatively low. As the feed rate of the grinding wheel increases to 6 μm/min, the frequency of grinding at the same point

| Item                        | Condition          |
|-----------------------------|--------------------|
| Grinding wheel size O.D x I.D (mm) | 50 x 30            |
| Coolant                     | Water              |
| Workpiece diameter (mm)     | 50                 |
| Rotation speed of workpiece (r/min) | 356                |
| Rotation speed of grinding wheel (r/min) | 4000–9000         |
| Grinding feed rate (μm/min) | 1–11               |
| Grinding depth (μm)         | 3–33               |
| Processing time (min)       | ≤20                |

Figure 9. Effect of the grinding wheel speed on surface roughness \( R_a \).
on the surface of the workpiece becomes higher, and the material removal rate increases. While the material is still removed by plastic deformation, which is beneficial to obtain lower surface roughness. When the feed rate of the grinding wheel exceeds 6 m/min, the undeformed grinding thickness of a single abrasive grain increases, the friction between the abrasive particles of the grinding wheel and the workpiece is intensified, the grinding heat increases and the grinding wheel generates certain thermal stress, which causes some of the abrasive particles to fall off the workpiece and surface scratches, as shown in Figure 12.

**Influence of grinding depth on surface roughness**

In the single-factor experiment of grinding wheel grinding depth, the grinding feed rate is 6 m/min, the grinding wheel speed is 7000 r/min, and the variation trend of the surface roughness $R_a$ with grinding depth is shown in Figure 13. The grinding depth in this paper refers to the downward feed distance of the grinding wheel when it touches the workpiece, considering the actual wear of the grinding wheel, the actual material removal thickness is slightly less than the grinding depth, when the grinding depth is 3 m, the material removal thickness is about 3 m, when the grinding depth reaches 33 m, the material removal thickness is only 29 m. The initial surface quality of the workpiece is the same. When the grinding depth increases from 3 to 15 m, the surface roughness value gradually becomes smaller with the increase of the grinding depth. This is because when the grinding amount is set to be small, the pressure between the grinding wheel and the workpiece is small, the depth of the abrasive particles cutting into the workpiece surface is small, so the grinding wheel abrasive particles have a less cutting effect on the residual peaks on the surface of the workpiece.

![Figure 10. The surface topography of SiC wafer under different grinding wheel speed: (a) 4000 r/min, (b) 5000 r/min, (c) 6000 r/min, (d) 7000 r/min, (e) 8000 r/min, and (f) 9000 r/min.](image)

![Figure 11. Effect of the grinding feed rate on surface roughness $R_a$.](image)
workpiece, and the surface roughness improvement effect is not obvious. When increasing the grinding amount, the contact arc length of the grinding wheel and the workpiece increases, the contact area of the grinding zone increases, and the heat accumulation causes the temperature of the grinding zone to rise rapidly, the surface material of the workpiece soften due to high temperature, which improves the fracture toughness of silicon carbide material and increase the proportion of plastic removal, the surface quality will gradually improve. When the grinding depth exceeds 15 \mu m, the surface roughness value increases slowly. On the one hand, as the grinding depth continues to increase, the scratches on the surface of the workpiece deepen, and the thickness of the grinding layer increases to the critical depth of cut for the transition of material ductility and brittleness removal, the removal mechanism of SiC surface material is gradually transformed from a large amount of plastic removal to mainly brittle removal, which leads to an increase in the surface roughness of 4H-SiC workpieces. On the other hand, the grinding wheel uses 2.5 \mu m diamond powder, the abrasive grains are fine and dense, the porosity of the grinding wheel is small, and the debris generated during the grinding process is relatively small. These pores and cavities will soon be filled with debris and powder produced by the grinding wheel, and the heat is more difficult to disperse, which accelerates the increase of grinding heat, produces adhesive wear, and produces slight friction on the surface of the workpiece, as shown in Figure 14. Therefore, the appropriate setting for the grinding depth is 15 \mu m.

**Orthogonal optimization experiment**

To achieve optimal selection of grinding parameters, it is important to establish a precise grinding quality model for 4H-SiC. The orthogonal experiment method
is used, the single factor experiment provided the parameter optimization range for the orthogonal experiment, the optimization range of grinding wheel speed is 4000–7000 r/min, feed speed is 5–11 μm/min, and grinding depth is 15–33 μm. In the orthogonal experiment, each factor has three levels, which are the representative parameter values selected by the three factors after the single factor experiment, as shown in Table 4, the grinding experiment is carried out by using standard orthogonal table L9 (3)^3. The grinding test data are shown in Table 5.

The conventional empirical formula of grinding roughness is widely expressed by exponential function, so the prediction model of equation (1) can be established, which contains three parameters: 31,32

\[ R_a = KV_s^{C_1}V_w^{C_2}H^{C_3} \]  

(1)

| Table 4. Experimental factors and level factor selection table. |
|---------------------------------------------------------------|
| Level factor | Experimental factors |
|---------------|----------------------|
|               | Grinding speed \( v_s \) (r/min) | Feed rate \( v_w \) (μm/min) | Grinding depth \( H \) (μm) |
| 1             | 4000                 | 5                 | 15       |
| 2             | 5500                 | 8                 | 24       |
| 3             | 7000                 | 11                | 33       |

| Table 5. Orthogonal test results (L3^3). |
|-----------------------------------------|
| Experiment number | Experimental factors | Surface roughness \( R_a \) (nm) |
|-------------------|----------------------|-------------------------------|
|                   | Grinding speed \( v_s \) (r/min) | Feed rate \( v_w \) (μm/min) | Grinding depth \( H \) (μm) |
| 1                 | 4000                 | 5                 | 15       | 8.76 |
| 2                 | 4000                 | 8                 | 24       | 10.21|
| 3                 | 4000                 | 11                | 33       | 12.23|
| 4                 | 5500                 | 5                 | 24       | 9.38  |
| 5                 | 5500                 | 8                 | 33       | 10.82 |
| 6                 | 5500                 | 11                | 15       | 11.39 |
| 7                 | 7000                 | 5                 | 33       | 9.92  |
| 8                 | 7000                 | 8                 | 15       | 6.75  |
| 9                 | 7000                 | 11                | 24       | 10.14 |
Where $K$ is the comprehensive coefficient of grinding conditions; $V_s$ is the speed of grinding wheel; $V_w$ is the feed rate; $H$ is the grinding depth, and equation (1) is a typical nonlinear function, which must be transformed into a linear function. Therefore, taking logarithm on both sides of it, equation (2) can be obtained.

$$
\ln R_a = \ln(K) + C_1 \ln V_s + C_2 \ln V_w + C_3 \ln H
$$

(2)

Define $y = \ln R_a, C_0 = \ln(K), x_1 = \ln V_s, x_2 = \ln V_w, x_3 = \ln H$, then the exponential equation can be transformed into a linear equation (3).

$$
y = C_0 + C_1 x_1 + C_2 x_2 + C_3 x_3
$$

(3)

Using the orthogonal experimental data in Table 5, the multiple linear regression of linear equation (3) can be carried out. Figure 15 is the residual graph of roughness linear regression. To further verify the accuracy of the prediction model, draw the single factor experiment data and the prediction data in the same figure. As shown in Figure 16, it can be seen from the figure that the predicted value of roughness is in good agreement with the experimental value of roughness, which can reflect the change trend of roughness.

In the optimization range of grinding wheel speed, feed rate, and grinding depth, there is a negative correlation between grinding wheel speed and surface roughness, so the grinding roughness value becomes smaller with the increase of grinding wheel speed, the corresponding index of feed rate and grinding depth in the prediction model is positive, so the grinding roughness value increases with the increase of feed rate and grinding depth. The influence of grinding depth on surface roughness is greater than that of grinding wheel speed, and the influence of feed rate on surface roughness is the least.

**Wear and dressing of sol-gel wheel**

Wheel truing on-site is necessary to eliminate the installation error of the grinding wheel and form a good surface condition and accuracy. A 150# electroplated diamond grinding disc was employed. The surface of the grinding wheel before and after the dressing is shown in Figure 17. There is a ring of glazed layer on the surface before dressing. After the dressing, the glazed layer disappears.

A wear test was carried out to grind the SiC wafer by a sol-gel diamond wheel and a hot pressing diamond wheel. The grinding feed rate is 6 $\mu$m/min, the grinding speed is 7000 r/min, grinding 15 times, each feed depth is 6 $\mu$m, the topography and wear amount of the diamond grinding wheel surface are measured and counted every time. The surface morphology of the sol-gel diamond wheel changes with the grinding depth as shown in Figure 18. When the grinding wheel is used for the eighth time (Grinding depth 48 $\mu$m), the pores on the surface of the grinding wheel gradually become blocked. This is because the accumulation of debris and other impurities in the pores under high-temperature contact conditions cause some plastic flow of the binder around the pores. When the blockage rate of the pores is too high, the pores lose their function of holding chips and storing coolant, and the grinding wheel needs to be trimmed. Therefore, it is necessary to dress the sol-gel diamond wheel when the quantity of SiC wafers is up to four pieces. Compared with the sol-gel diamond wheel, the pores on the surface of the hot pressing diamond wheel gradually become blocked when the hot pressing diamond wheel is used for the 12th time (Grinding depth 72 $\mu$m). Therefore, the hot pressing wheel can be used for five times before dressing, the number of times used is one times more than that of
the sol-gel diamond wheel. This is because the sol-gel wheel contains a small amount of thermoplastic polyvinyl alcohol. After long time grinding, thermoplastic materials aggregate on the surface of the sol-gel diamond wheel, which is more likely to cause stomatal clogging on the wheel surface.

The laser displacement sensor is used to measure the change in the thickness of the abrasive layer of the grinding wheel after each grinding. The relationship between the wear of the grinding wheel and the feed depth is shown in Figure 19. In the early stage of grinding, the main form of grinding wheel wear is the crushing of abrasive particles in the initial stage of grinding. The crushing of abrasive particles will lead to rapid changes in the amount of grinding wheel wear, so the growth of grinding wheel wear is more obvious. In the stable wear stage, abrasive wear is the main form of grinding wheel wear. At this time, the contact area between the abrasive particles and the workpiece is slowly increasing, and the wear of the grinding wheel is relatively stable. Continue to grind, the adhesion wear of abrasive grains and the shedding of abrasive grains will increase in the proportion of grinding wheel wear. The form of grinding wheel wear will aggravate the wear of the grinding wheel, so the wear of the grinding wheel shows a rapid upward trend.

Comparation of surfaces processed with sol-gel wheel and hot pressing wheel

A sol-gel diamond wheel and a hot pressing diamond wheel were used to carry out contrast experiments on the SiC wafer, as seen in Figure 20. In order to verify the difference of the grinding performance between the sol-gel diamond wheel and the hot pressing diamond wheel under different process conditions, eight groups of comparative experiments were carried out, the grinding wheel speed was 4000 and 7000 r/min, the grinding feed rate was 6 and 10 μm/min, and the grinding depth was 15 and 30 μm. The experimental results are shown
in Table 6, it can be seen that after grinding with sol-gel wheel, the surface roughness of the workpiece is lower than that of the hot pressing wheel under the same process conditions. Figure 21 is the microscopic morphology of the 4H-SiC wafer after grinding by two kinds of wheels under the process conditions that the grinding wheel speed was 7000 r/min, the grinding feed rate was 6 \( \mu m \)/min, and the grinding depth was 15 \( \mu m \). After grinding with a sol-gel diamond wheel, the scratches formed on the surface of the wafer are slight and uniform, and the scratches can be removed by CMP polishing. After grinding with a hot pressing wheel, larges scratches will occur on the surface of the wafer, and the scratches cannot be removed by CMP polishing. This is because the particles in the powder hot pressing diamond wheel are easily agglomerated, and the “plow” action of the agglomerates can easily cause scratches on the surface of the workpiece, which greatly affects the surface quality of the SiC wafer. On the other hand, the grinding process with the sol-gel wheel is smooth, no friction noise occurs, and the grinding load power is kept stable within 30\%. This is because polyvinyl alcohol can effectively adjust the flexibility of the phenolic resin. The modified resin can produce a certain degree of plastic deformation during friction and heating, which reduces the impact of abrasives on the workpiece. When the frictional heating reaches a certain level, the surface resin will decompose into the tough carbonized film, which is not easy to fall off and helps to increase the thermal decay temperature, thereby ensuring that the friction coefficient of the grinding wheel is relatively stable.

Figure 18. Surface morphology of sol-gel diamond wheel at different grinding depth: (a) initial state, (b) 24 \( \mu m \), (c) 48 \( \mu m \), and (d) 72 \( \mu m \).

Figure 19. Relation between grinding wheel wear and grinding depth.
The uneven flatness of wafer will affect the heating degree of each area of photoresist, and eventually lead to insufficient uniformity of wafer etching. High precision machining of SiC wafer requires not only precision grinding equipment, but also good shape keeping of grinding wheel. The surface profile of the SiC wafer after grinding by the two kinds of grinding wheels is shown in Figure 22, it can be seen that the PV value of the surface profile accuracy is about 0.5 μm. The grinding results show that the sol-gel diamond wheel does not greatly affect the surface profile of the SiC wafer, the hardness and wear resistance of the sol-gel diamond wheel can ensure that the shape accuracy of the grinding wheel will not change obviously during grinding process, and then obtain a good grinding surface profile. The real picture of the ultra-precision grinding of the SiC wafer by the sol-gel diamond wheel is shown in Figures 10 and 23 points were selected to test the surface roughness $R_a$ in the radial direction, the average surface roughness $R_a$ is 6.42 nm, which is better than that of using the hot pressing diamond wheel, as shown in Table 7.

### Conclusion

Ultra-precision grinding of the 4H-SiC wafer by sol-gel diamond wheel was studied in this work. The glue prepared by polyvinyl alcohol and water-soluble phenolic resin was physically gelled after freezing. Polyvinyl alcohol exists in the mixed resin in the form of a semi-interpenetrating network. After the diamond abrasive and filler are dispersed in the mixed glue, it avoids agglomeration and produces large-sized secondary particles. The uniformity of the abrasive distribution is

| Experiment number | Grinding speed $v_s$ (r/min) | Feed rate $v_w$ (μm/min) | Grinding depth $H$ (μm) | Surface roughness $R_a$ (nm) |
|-------------------|----------------------------|--------------------------|-------------------------|-----------------------------|
| Sol-gel wheel     | Hot pressing wheel         |                          |                         |                             |
| 1                 | 4000                       | 6                        | 15                      | 9.21                        | 12.99                      |
| 2                 | 4000                       | 6                        | 30                      | 10.72                       | 14.67                      |
| 3                 | 4000                       | 10                       | 15                      | 9.68                        | 13.39                      |
| 4                 | 4000                       | 10                       | 30                      | 11.59                       | 15.56                      |
| 5                 | 7000                       | 6                        | 15                      | 6.42                        | 10.28                      |
| 6                 | 7000                       | 6                        | 30                      | 7.93                        | 11.26                      |
| 7                 | 7000                       | 10                       | 15                      | 8.55                        | 12.01                      |
| 8                 | 7000                       | 10                       | 30                      | 10.17                       | 14.51                      |

Figure 20. Two kinds of prepared grinding wheel.

Figure 21. The microscopic morphology of the SiC wafer: (a) after being processed by sol-gel diamond wheel and (b) after being processed by hot pressing diamond wheel.
The surface hardness of the sol-gel diamond wheel is close to that of the hot pressing diamond wheel, but the hardness uniformity is significantly improved, and the gel bond shows good bonding performance. Compared with hot pressing diamond wheels, sol-gel diamond wheels have 8.4% higher impact strength, 22.8% higher tensile strength, and 26.3% higher flexural strength.

The grinding experiment was carried out for grinding the 4H-SiC wafer. The prepared sol-gel diamond wheel is used to fine grind the SiC wafer. Single factor experiments show that the surface roughness value of the workpiece shows a trend of first decreasing and then increasing with the setting of the grinding speed, feed rate, and grinding depth. On the basis of single factor experiment, orthogonal optimization experiment shows that when the grinding wheel speed is 4000–8000 r/min, the feed speed is 5–11 μm/min, the grinding depth 15–33 μm, the value of surface roughness decreases with the increase of grinding wheel speed, and increases with the increase of the feed speed and the grinding depth. When the grinding speed is 7000 r/min, the feed rate is 6 μm/min, and the grinding depth is 15 μm, an ultra-precision grinding effect with average surface roughness of Ra 6.42 nm is obtained. The surface quality is better than that of hot pressing grinding wheel, and the surface flatness is equal high.

The cumulative grinding depth of the novel sol-gel diamond wheel reaches 48 μm. The pores on the surface of the sol-gel diamond wheel are gradually blocked, and the sol-gel diamond wheel needs to be dressing. Therefore, it is generally necessary to dress the sol-gel diamond wheel when the quantity of grinding SiC wafers is up to four pieces.

### Table 7. Surface roughness Ra measurement of 10 points on 4H-SiC wafer (Unit: nm).

| Test points | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10    | AVG  |
|-------------|------|------|------|------|------|------|------|------|------|-------|------|
| Sol-gel wheel | 6.52 | 6.37 | 6.54 | 5.92 | 6.39 | 6.61 | 6.16 | 6.74 | 6.47 | 6.44  | 6.42 |
| Hot pressing wheel | 10.77| 10.48| 10.17| 9.92 | 10.21| 10.24| 10.31| 10.43| 9.79 | 10.45 | 10.28|

### Figure 22. The surface profile of the SiC wafer: (a) after being processed by the sol-gel diamond wheel (PV 0.5401 μm) and (b) after being processed by the hot pressing diamond wheel (PV 0.4702 μm).

### Figure 23. 4H-SiC wafer: (a) before, (b) after ground by sol-gel wheel, and (c) the surface roughness of 10 test points.
Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors gratefully acknowledge the financial support from Natural Science Foundation of Zhejiang Province (No. LZY21E050004) and Quzhou science and technology project (No. 2019K10).

ORCID iD
Kaiping Feng https://orcid.org/0000-0003-1317-327X

References
1. Pushpakaran BN, Subburaj AS, Bayne SB, et al. Impact of silicon carbide semiconductor technology in photovoltaic energy system. Renew Sustain Energy Rev 2016; 55: 971–989.
2. Yang X, Sun R, Okubo Y, et al. Investigation of anodic oxidation mechanism of 4H-SiC (0001) for electrochemical mechanical polishing. Electrochim Acta 2018; 271: 666–676.
3. Lu J, Wang Y, Luo Q, et al. Photocatalysis assisting the mechanical polishing of a single-crystal SiC wafer utilizing an anatase TiO2-coated diamond abrasive. Precis Eng 2017; 49: 235–242.
4. Lu J, Luo QF, Mao XY, et al. Fabrication of a resin-bonded ultra-fine diamond abrasive polishing tool by electrophotoreactive co-deposition for SiC processing. Precis Eng 2017; 47: 353–361.
5. Presser V, Krummhauer O, Kailer A, et al. In situ monitoring and depth-resolved characterization of wet wear of silicon carbide. Wear 2011; 271: 2665–2672.
6. Yin XC, Li SJ and Chai P. Investigation of SiC single crystal polishing by combination of anodic oxidation and mechanical polishing. Int J Electrochem Sci 2020; 5: 4388–4405.
7. Yan Q, Wang X, Xiong Q, et al. The influences of technological parameters on the ultraviolet photocatalytic reaction rate and photocatalysis-assisted polishing effect for SiC. J Cryst Growth 2020; 531: 125379.
8. Yu T, Wang Z, Guo X, et al. Effect of ultrasonic vibration on polishing monocrystalline silicon: surface quality and material removal rate. Int J Adv Manuf Technol 2019; 103: 2109–2119.
9. Yan J and Tan TH. Sintered diamond as a hybrid EDM and grinding tool for the micromachining of single-crystal SiC. CIRP Ann Manuf Technol 2015; 64: 221–224.
10. Kim JD and Lee ES. A study on the mirror-like grinding of MgO single crystal with various diamond wheels. J Mater Process Technol 1997; 72: 1–10.
11. Ren Y, Li C, Li W, et al. Study on micro-grinding quality in micro-grinding tool for single crystal silicon. J Manuf Process 2019; 42: 246–256.
12. Zhou W, Su H, Dai J, et al. Numerical investigation on the influence of cutting-edge radius and grinding wheel speed on chip formation in SiC grinding. Ceram Int 2018; 44: 21451–21460.
13. Chen S, Cheung CF, Zhang F, et al. Three-dimensional modelling and simulation of vibration marks on surface generation in ultra-precision grinding. Precis Eng 2018; 53: 221–235.
14. Cheng J and Wu J. Experimental study on the fabrication method of diamond ultra-small micro-grinding tool. Int J Adv Manuf Technol 2018; 97: 1431–1444.
15. Huo F, Zhao H and Zhao D. Nanogrinding of silicon wafer using a novel vitrified diamond wheel. Mater Manuf Process 2011; 26: 977–981.
16. Wang W, Wang S, Zhang D, et al. Preparation of dry grinding diamond wheel with novel thermal conductivity based on resin-Cu-f composite matrix. Mater Express 2016; 6: 444–450.
17. Zhou H, Guo M and Wang X. Ultraprecision grinding of silicon wafers using a newly developed diamond wheel. Mater Sci Semicond Process 2017; 68: 238–244.
18. Miao W, Ding Y, Zhao Y, et al. Modified gel casting technique to fabricate honeycomb structured vitrified-bonded ultrafine diamond grinding wheels. Ceram Int 2020; 46: 4462–4469.
19. Huang S, Lu J, Lin Y, et al. Study on the enhancement of sol-gel properties by binary compounding technology for dry polishing hard and brittle materials. J Solgel Sci Technol 2020; 96: 314–326.
20. Luo Q, Lu J, Li Z, et al. Fabrication of a sol-gel polishing tool for green manufacturing of the seal stone. J Solgel Sci Technol 2020; 96: 576–588.
21. Zhang W, Liu XP, Chen SP, et al. Variations in structure and properties of vitrified bonds and vitrified diamond composites prepared by sol-gel and melting methods at different sintering temperature. Ceram Int 2020; 46: 21202–21210.
22. Yiqing Y, Zhongwei H, Wenshan W, et al. The double-side lapping of SiC wafers with semifixed abrasives and resin–combined plates. Int J Adv Manuf Technol 2020; 108: 997–1006.
23. Wang R, Zhang J, Chen S, et al. Green fabrication of graphene oxide/epoxy nanocomposite and its application in diamond abrasive tools. Compos B Eng 2019; 177: 107383.
24. Lozinsky VI, Leonova IM, Ivanov RV, et al. A study of cryostructuring of polymer systems. 46. Physicochemical properties and microstructure of poly(vinyl alcohol) cryogels formed from polymer solutions in mixtures of dimethyl sulfoxide with low-molecular-mass alcohols. Colloid J 2017; 79: 788–796.
25. Meacham R, Liu M, Guo J, et al. Effect of hydration on tensile response of a dual cross-linked PVA hydrogel. Exp Mech 2020; 60: 1161–1165.
26. Fang Z and Suo J. Synthesis and characterization of phenolic resin blended with Silica sol and PVA. J Appl Polym Sci 2011; 119: 744–751.
27. Zhi M, Chen X, Liu Q, et al. Improved mechanical properties and thermal stability of phenol formaldehyde resin by incorporating poly(vinyl alcohol)-grafted reduced
graphene oxide nanohybrid. *Mater Res Express* 2018; 5: 095306.

28. Denkena B, Krödel A, Harmes J, et al. Additive manufacturing of metal-bonded grinding tools. *Int J Adv Manuf Technol* 2020; 107: 2387–2395.

29. Li KH, Guo Q, Liu MY, et al. Influence of pore-forming agent on the performance of resin bond diamond grinding wheel in back-grinding silicon wafers. *Adv Grind Abras Technol* 2011; 487: 169–174.

30. Yang M and Nie YJ. Study on modification of phenolic resin/glass fiber composite by polyvinyl alcohol. *Appl Mech Mater* 2010; 44–47: 3045–3048.

31. Chai H, Huang Y, Wang YJ, et al. Research on the optimization of predictive model for surface roughness of magnesium alloy. *Mech Sci Technol* 2012; 31: 968–971.

32. Jin CZ, Chen ET and Xu C. Analysis and establishment of a predictive model for surface roughness of turn-milling. *J Harbin Instit Technol* 2009; 41: 224–226.