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Nanogrinding of SiC wafers with high flatness and low subsurface damage

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Abstract: Nanogrinding of SiC wafers with high flatness and low subsurface damage was proposed and nanogrinding experiments were carried out on an ultra precision grinding machine with fine diamond wheels. Experimental results show that nanogrinding can produce flatness less than 1.0 μm and a surface roughness R_a of 0.42 nm. It is found that nanogrinding is capable of producing much flatter SiC wafers with a lower damage than double side lapping and mechanical polishing in much less time and it can replace double side lapping and mechanical polishing and reduce the removal amount of chemical mechanical polishing.

Key words: SiC wafer; nanogrinding; cup wheel; flatness; surface roughness; damage

1 Introduction

SiC single crystal has a unique combination of electrical and thermophysical properties such as wide energy band gap, high thermal conductivity, large break down field and high saturation velocity. These properties make it an ideal semiconductor material for high temperature, high power, high voltage and high frequency electronic devices. In addition, it is used as the substrate material for III−V nitride film deposition for manufacturing electronic and optoelectronic devices [1,2]. While manufacturing these devices, high quality epitaxial SiC thin film or gallium nitride film is required, but they can only be grown on SiC wafers with extremely flat, smooth and damage free surfaces [3,4]. SiC wafer preparation starts with growth of single crystal ingots and then a series of steps are needed to turn an ingot into acceptable wafers. They typically consist of slicing, double side lapping, mechanical polishing (MP) and chemical mechanical polishing (CMP) [5,6]. However, good quality SiC wafers are very difficult to obtain, as SiC is extremely hard, extremely brittle and extremely chemically stable. Double side lapping is usually applied after slicing to remove the slicing induced waviness and yield acceptable flatness, but it involves material removal through brittle fracture characterized by chipping and cracking and would generate large subsurface damages. This damaged layer is then removed by mechanical polishing. Mechanical polishing of SiC wafers is typically accomplished with diamond slurries in multiple steps where the grain size is successively reduced until a surface roughness (R_a) 1 nm or less is produced [5]. Since very smooth surface can only be obtained by using diamond slurry of small grain size down to submicron, the material removal rate is typically less than 1 μm/h and the total process time for mechanical polishing is more than 6 h. Nevertheless, it results in insufficiently smooth wafer surfaces characterized by deep and wide scratches [7−9]. The mechanical polishing step is followed by chemical mechanical polishing. Chemical mechanical polishing can achieve damage-free surfaces. However, it is typically very slow, as effective CMP process is not available since SiC is generally unaffected by exposure to acid or alkali at temperatures less than about 300 °C. The material removal rate of chemical mechanical polishing is typically 50 to 150 nm/h [10]. Mechanical polishing and chemical mechanical polishing are the most time-consuming and therefore most expensive machining operations in SiC wafers preparation processes. Therefore, there is a need to develop a new method for flattening SiC wafers with lower cost and higher efficiency. Nanogrinding is an aspect of advanced grinding that has been growing rapidly in recent years [11]. It utilizes ultra precision machines with high

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motion accuracy and high stiffness, and it can precisely control the kinetics of the grinding wheel at the nanometer level and generate surfaces with high dimension and form accuracy [11,12]. The surface roughness and subsurface damage can be sharply reduced by using fine diamond wheel and controlling the grain depth cut down to nanometer level [13,14]. In this work, nanogrinding of SiC wafers with fine diamond wheels was proposed. Its capability to achieve flatter wafers with a lower subsurface damage at higher throughput in comparison with the conventional technologies is investigated.

2 Experimental

2.1 SiC wafers

SiC single crystal is commercially available in various polytypes such as 2H, 3C, 4H and 6H. 4H-SiC is the most favorable substrate for high-power, high-frequency and high temperature device applications and it is more available. Thus 50.8 mm N-type 4H-SiC wafers having an off-axis orientation of 4 degrees were selected. Sliced SiC wafers were used as the grinding specimens. Double side lapped, mechanical polished and chemical mechanical polished SiC wafers were used for contrast and comparison with grinding results. All the SiC wafers were research grade and were made by TankeBlue Semiconductor Co. Ltd., Beijing, China.

2.2 Nanogrinding experiments

Nanogrinding experiments were performed on an ultra precision surface grinding machine (Okamoto, VG401MK). It uses a rotary table and a cup wheel to perform an infeed grinding, as shown in Fig. 1. The wafer is fixed on the center of the rotary table and the cup wheel is offset by a distance of the wheel radius relative to the rotational axis of the rotary table. While grinding, both the cup wheel and the rotary table rotate and the cup wheel is fed down to the wafer [12,15].

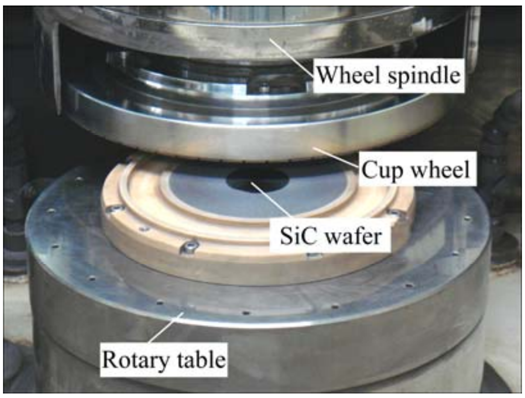

Fig. 1 Photograph of grinding set-up

Both the wheel spindle and the rotary table spindle were supported by high accuracy air bearings with axial and radial motion error less than 50 nm. The radius and the rim width of the cup wheel were 175 mm and 3 mm, respectively. #600, #2000 and #12000 vitrified diamond cup wheels were used for rough, fine and finish grinding, respectively. The wheel rotational speed was 2000 r/min and the rotary table rotational speed was 100 r/min. The wheel infeed rate was 2, 1 and 0.25 μm/min for the #600, #2000 and #12000 diamond cup wheels, respectively, and the corresponding material removal amount was 30, 10 and 5 μm, respectively. The cup wheels were trued and dressed using a cast iron lapping plate with #360 silicon carbide abrasives. Deionized water was used as the coolant.

2.3 Characterization of SiC wafer surfaces

After nanogrinding experiments, the ground specimens were measured to determine the surface roughness, surface morphology and flatness. The surface roughness and the morphology of double side lapped, mechanical polished and chemical mechanical polished wafers were measured as well for contrast and comparison. Flatness was measured with a Tropel Flatmaster 200 surface form measurement. Surface topography was measured with a Zygo Newview 5022 3D surface profiler over a scanning area of 70 μm× 53 μm. The surface morphology was examined using a field emission environmental scanning electron microscope (SEM, SUPRA 55, Carl Zeiss, Germany). Atomic force microscope (AFM, XE200, Park Systems Inc, Korea) was used to characterize the scratches induced by nanogrinding and mechanical polishing.

3 Results

Photographs of the ground SiC wafers are shown in Fig. 2. There are a large number of obvious grinding traces on the wafer ground with the #600 diamond wheel and only a few faint grinding traces could be seen on the wafer with the #2000 wheel. Whereas grinding with the #12000 diamond wheel produced a nominally defect-free specular surface.

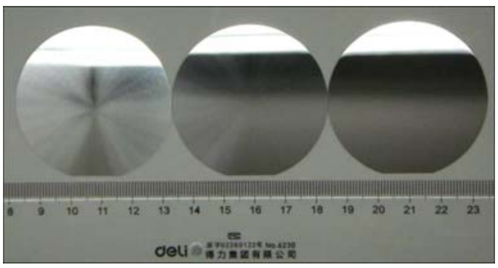

Fig. 2 Photographs of SiC wafers ground with #600, #2000 and #12000 diamond wheels, respectively

3.1 Surface roughness

The surface topography of the SiC wafers measured using the 3D surface profiler is shown in Fig. 3. Figures 3(a)−(c) are Zygo images of typical double side lapped, mechanical polished and chemical mechanical polished SiC wafers, respectively. Figures 3(d)−(f) are Zygo images of SiC wafers after grinding with #600, #2000 and #12000 diamond wheels, respectively. It can be seen that the surface of the double side lapped wafer was extremely rough. It was characterized by a surface roughness R_a of 64.07 nm, rms of 124.4 nm and PV of 1582 nm. The surface roughness R_a, rms and PV of the mechanical polished wafer were 0.612, 0.76 and 5.685 nm respectively. The SiC wafer after chemical mechanical polishing had a surface roughness R_a of 0.398 nm, rms of 0.495 nm and PV of 4.499 nm. The wafer ground with the #600 diamond wheel had a surface roughness R_a of 18.37 nm, rms of 30.06 nm and PV of 1067 nm. Whereas, grinding with the #2000 diamond wheel resulted in a surface roughness R_a of 2.58 nm, rms of 3.41 nm and PV of 28.66 nm. They were 0.421, 0.522 and 4.071 nm respectively when grinding with the #12000 diamond wheel.

3.2 Surface morphology

Figures 4(a)−(d) are the SEM images of the double side lapped and ground SiC wafers. SEM observation shows that the lapped wafer surface consists of a great number of small fracture craters induced by lateral cracks propagation. This indicates that material is removed predominately by brittle fracture in lapping. However, the material is removed predominately by plastic deformation in nanogrinding, as can be seen from the smooth grooves generated by individual diamond grains and the residual plastic chips adhered to the outside of the grooves. The majority of the wafer surface is smooth and exhibits a ductile removal appearance even when ground with the #600 diamond wheel, though chipping pits and medium cracks can be seen occasionally. A #2000 diamond wheel can produce a smoother wafer surface, but slight brittle fractures still exist. The grooves on the SiC wafer ground with #12000 diamond wheel were very smooth and no brittle fracture was observed even at the high magnification.

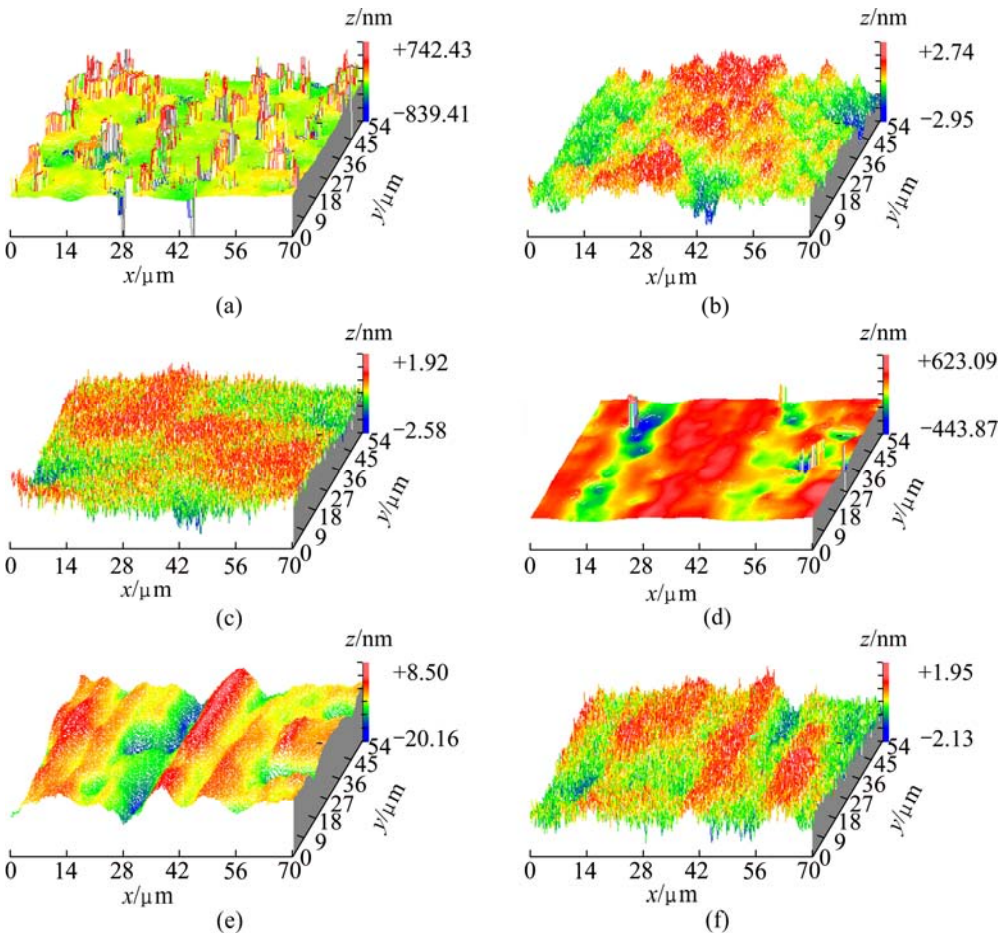

Fig. 3 Surface topographies of SiC wafers: ((a) Double side polished; (b) Mechanical polished; (c) Chemical mechanical polished; (d) Ground with #600 diamond wheel; (e) Ground with #2000 diamond wheel; (f) Ground with #12000 diamond wheel

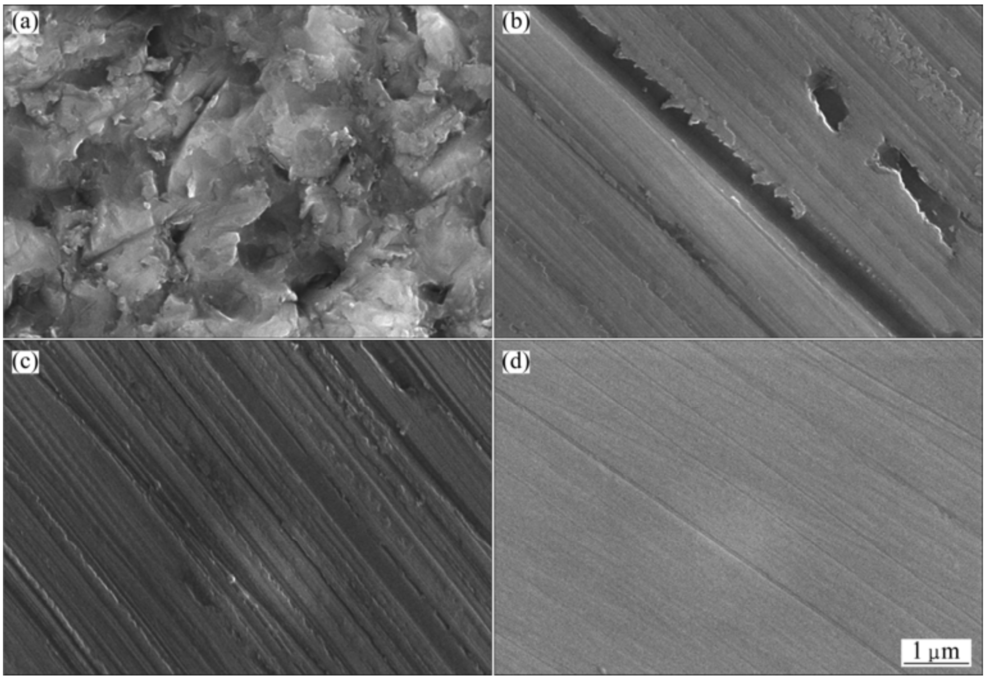

Fig. 4 SEM images of SiC wafers: (a) Double side lapped; (b) Ground with #600 diamond wheel; (c) Ground with #2000 diamond wheel; (d) Ground with #12000 diamond wheel

The width of the generated grooves is very small while ground with the #12000 cup wheel, as can be seen that the maximum was measured to be 70 nm, and an overwhelming majority of the grooves is less than 20 nm in width. This indicates that single crystal silicon carbide is completely ductile when ground with the #12000 diamond wheel, as shown in Fig. 4(d). AFM measurements with a scan area of 20 μm×20 μm in noncontact mode show that there are high density of grooves on both surfaces of the wafer ground with the #12000 diamond wheel and the mechanical polished wafer, as seen in Fig. 5. However, the grooves on the ground surface are much finer and they are much similar in width and depth than that on the mechanical polished surface. Most of these grooves on the ground wafer were measured to be only 2−3 nm in depth. On the contrary, large scratches up to 10 nm in depth and 0.3 μm in width were found on the mechanical polished wafer surface.

3.3 Flatness

The surface of the sliced wafer is extremely rough and has obvious waviness, as shown in Fig. 6. Its flatness was measured to be 25.035 μm. However, it reduced to 0.836 μm after grinding with a #600 diamond wheel. Further flatness measurements showed that grinding with #600, #2000 or #12000 diamond wheels resulted in similar flatness. This indicates that nanogrinding can produce SiC wafers with lower bow, warp and total thickness variation (TTV).

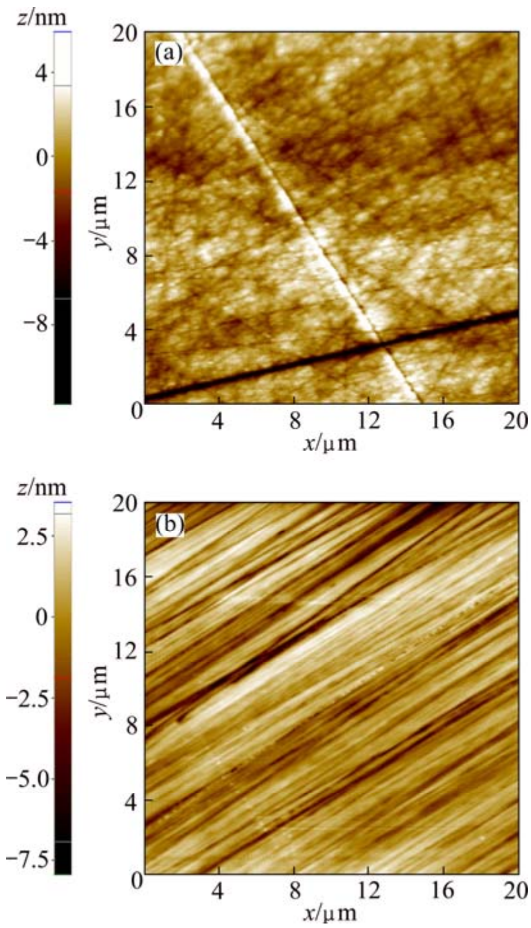

Fig. 5 AFM micrographs of SiC wafers: (a) Mechanical polished; (b) Ground with #12000 wheel

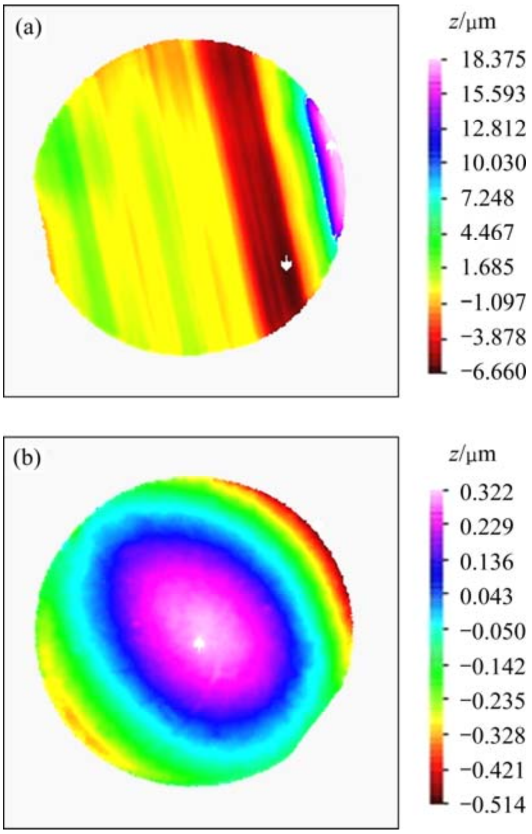

Fig. 6 Flatness error of sliced (a) and ground with #600 diamond wheel (b) SiC wafers

4 Discussion

The grinding wheel in nanogrinding typically rotates at a high speed in the range of 1500−5000 r/min; whereas the lapping plate in lapping rotate at a speed less than 300 r/min and polishing is typically done at lower speeds. It takes several hours to lap the sliced wafer to an acceptable flatness. However, the experiments show that the sliced wafer could be flattened by nanogrinding for less than 15 min. Therefore, nanogrinding is a faster and more cost effective process than lapping and polishing. In infeed grinding using a rotary table and a cup wheel, the rotational speeds of the rotary table range from 50 to 500 r/min and the infeed rate may range from several tens microns down to submicron per minute. Since the wheel depth of cut is the ratio of the infeed rate to the rotational speeds of the rotary table, the wheel depth of cut can be set to be several tens of nanometers or less. The depth of cut made by individual diamond grains is generally equal to or smaller than the wheel depth of cut. The wheel depth of cut in these grinding experiments was calculated to be 20, 10 and 2.5 nm for the #600, #2000 and #12000 cup wheel, respectively [13,14]. When cutting at depth of cut of such a nanometer scale, the resultant subsurface damage can be very low. Moreover, the depths of cut of the individual abrasive grains can be set to be a level equal to or less than the critical depth of cut so that ductile mode grinding can be realized based on ductile removal rather than brittle fracture, and thereby making it possible to suppress the generation of microcracks [15]. For example, the undeformed chip thickness cut by a single grain was measured to be only 2−3 nm when ground SiC wafer with #12000 diamond wheel using the grinding conditions described in the previous section. When ground at an undeformed chip thickness of such level, only a few layers of atoms are removed from the wafer surface each time, the resisting shear stresses at the cutting edges of the diamond grains become extremely large, the plastic yield limit is lower than the brittle fracture limit, the material is removed in ductile mode and it was unlikely to induce any cracks [12,15].

Mechanical polishing basically uses the same ductile mode removal mechanism as grinding with diamond abrasives in submicron level or less and very gentle polishing pressure. However, mechanical polishing suffers deep scratching, as shown in Fig. 5(a). Scratching is a primary defect that is caused by very low levels of large, oversize particles in the slurry. Despite the grain size distribution of the diamond slurry used in mechanical polishing is stringently controlled, the existence of oversize grains is inevitable. When the wafer being polished is placed in contact with the slurry on the polishing pad, the oversize grains will support a disproportionate amount of the load placed on the wafer and have tendency to produce high depth of cut. If the grain depth of cut exceeds the critical depth of cut, brittle fracture that can extend into the crystal structure beneath the wafer surface by more than several microns may occur. On the contrary, no obviously large, deep scratches generate when ground with the #12000 diamond cup wheel.

It is well accepted that the subsurface damage generally increases linearly with increasing surface roughness during grinding, lapping or polishing hard and brittle materials [16,17]. A comparison of the surface roughness of SiC wafers obtained from grinding, mechanical polishing and double side lapping enabled us to evaluate the subsurface damage induced by these three processes. It can be found that the surface roughness of the SiC wafer ground with the #600 diamond wheel is significantly smaller than that of the double side lapped. Grinding with a #2000 diamond wheel produces a relatively rough surface than mechanical polishing. However, the surface roughness with a #12000 diamond wheel is significantly smaller than mechanical polishing. Moreover, the surface roughness of the SiC wafer ground with the #12000 diamond wheel is very close to that of the chemical mechanical polishing, as shown in Fig. 7. Therefore, the subsurface damage induced by grinding with #12000 diamond cup wheel is better than that by mechanical polishing. Thus, the removal amount for chemical mechanical polishing can be reduced significantly.

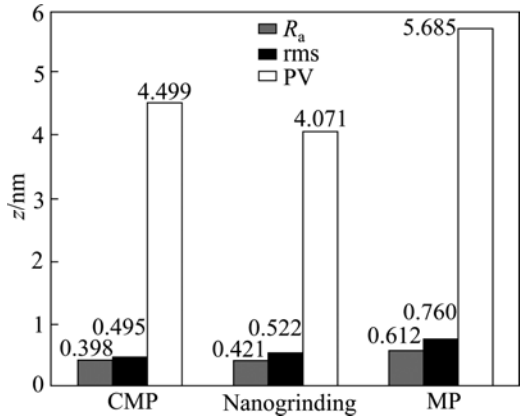

Fig. 7 Comparison of surface roughness among chemical mechanical polishing (CMP), nanogrinding and mechanical polishing (MP)

In traditional wafer preparation processes, the flatness of SiC wafers mainly depends on double side lapping. Mechanical polishing does not improve wafers' flatness since they use soft polishing pad and the pad is prone to deform according to the shape of the wafers. On the contrary, the flatness may deteriorate after a great amount of polishing due to edge effect [5]. During double side lapping, the down force exerted by the upper lapping plate has a tendency to bend the wafer, and hence it is difficult for double side lapping to produce very flat SiC wafers. Nevertheless, SiC wafers with high warp, bow and TTV are undesirable. Producing a large number of high quality SiC wafers with low bow, warp and TTV remains a constant technical commercial goal. Since nanogrinding utilizes ultra precision machines with high motion accuracy and high stiffness, it can precisely control the kinetics of the grinding wheel at the nanometer level. The cutting paths of the individual grains are highly deterministic, all the irregularities on the wafer surface can be removed and hence it is possible to control the wafer flatness to a higher degree.

The above analyses show that nanogrinding is capable of producing much flatter SiC wafers with lower damages than double side lapping and mechanical polishing in much less time and it could replace double side lapping and mechanical polishing and reduce the removal amount for chemical mechanical polishing. These results provide useful information for preparing high quality SiC wafers with high efficiency and low cost.

5 Conclusions

1) Nanogrinding can produce a flatness less than 1.0 μm and a surface roughness R_a of 0.42 nm for 508 mm SiC wafers.

2) Grinding with #600 diamond wheel is less damaged than double side lapping and grinding with #12000 diamond wheel is less damaged than mechanical polishing.

3) Nanogrinding is capable of producing much flatter SiC wafers with a lower damage than double side lapping and mechanical polishing in much less time.

4) Nanogrinding can replace double side lapping and mechanical polishing and reduce the removal amount for chemical mechanical polishing.

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高平整度和低损伤碳化硅晶片的纳米磨削技术

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摘 要：采用细粒度砂轮的纳米磨削来实现碳化硅晶片高平整度和低损伤加工新方法。磨削试验表明采用纳米磨削 50.8 mm 碳化硅晶片时其平整度在 1.0 μm 以内，表面粗糙度可达 0.42 nm。纳米磨削比双面研磨和机械抛光更能高效地对碳化硅晶片做更高平整度、更低损伤加工，可以取代双面研磨和机械抛光，并减小化学机械抛光去除量。研究结果对高效低成本制备高质量碳化硅晶片有参考价值。

关键词：碳化硅晶片；纳米磨削；杯形砂轮；平整度；表面粗糙度；损伤

(Edited by LI Xiang-qun)