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Optimizing the flatness of 4H-silicon carbide wafers by tuning the sequence of lapping

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Abstract

In this letter, we optimize the flatness of 4H silicon carbide (4H-SiC) wafers by tuning the sequence of single-sided lapping, enlightened by the different mechanical properties of the Si face and C face of 4H-SiC. After wire sawing, the coarse lapping and fine lapping are carried out to rapidly remove the surface damage and optimize the flatness of 4H-SiC wafers. From the point of view of controlling the values of the bow and warp of 4H-SiC wafers, the coarse-lapping sequence of the C-face lapping followed by Si-face lapping is beneficial, while the preferred fine-lapping sequence is Si-face lapping followed by C-face lapping. Nanoindentation tests indicate that the C face has higher hardness and lower fracture toughness than the Si face. This gives rise to thicker surface damage at the C face after the wire sawing. After removing the same amount of wire-sawing induced surface damage, the thickness of residual surface damage of the C face is higher than that of the Si face after the coarse lapping. The fine lapping basically removes all the surface damage and creates the near-perfect C face and Si face. The higher amount of surface damage of the C face after the coarse lapping and the higher fracture toughness of the near-perfect Si face after the fine lapping can tolerate more plastic deformations, which gives rise to the superior flatness of the C-face-followed-by-Si-face coarse lapped and the Si-face-followed-by-C-face fine lapped 4H-SiC wafers, respectively.

Supplementary material for this article is available online

Keywords: 4H-SiC, lapping, mechanical properties, warpage, material removal rate

(Some figures may appear in colour only in the online journal)

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1. Introduction

As one of the most well-developed wide-bandgap semiconductors, 4H silicon carbide (4H-SiC) has broad application prospects in high-power, high-frequency and high-temperature electronics due to its superior properties of high breakdown field strength, high electron mobility and high thermal conductivity [1–5]. Starting from 4H-SiC boules, the mechanical processing of 4H-SiC wafers includes wire sawing, lapping, and chemical mechanical polishing (CMP) [6]. Lapping is adopted to rapidly remove the surface damage created during the wire sawing, and optimize the flatness, especially thickness variations of 4H-SiC wafers [7–9].

The Mohs hardness of 4H-SiC is as high as 9.5, which increases the sawing-induced surface damage and reduces the processing efficiency of 4H-SiC wafers [10, 11]. Optimizing the lapping process is key to improving the wafering efficiency and optimizing the flatness of 4H-SiC wafers. Since the conventional lapping is single-sided, that is, the lapping can be firstly carried out on either the Si face or C face of 4H-SiC wafers. It has been found that the mechanical properties of 4H-SiC depends on the crystallographic planes [12], which would give rise to the crystallographic-plane dependent generation and removal of surface damage during the processing of 4H-SiC wafers.

Enlightened by the crystallographic-plane dependent mechanical properties, we optimize the flatness of 4H-SiC wafers by tuning the sequence of single-sided lapping. We find that the lapping sequence can significantly affect the warpage of 4H-SiC wafers during coarse lapping and fine lapping. For coarse lapping, the lapping sequence of C-face lapping followed by Si-face lapping is beneficial to controlling the values of the bow and warp of 4H-SiC wafers. While during fine lapping, the lapping sequence of Si-face lapping followed by C-face lapping is preferred. Nanoindentation tests indicate that the C face has higher hardness and lower fracture toughness than the Si face. This gives rise to thicker surface damage at the C face after the wire sawing. After removing the same amount of wire-sawing induced surface damage, the thickness of residual surface damage of the C face is higher than that of the Si face after the coarse lapping. The fine lapping basically removes all the surface damage and creates the near-perfect C face and Si face. The higher amount of surface damage of the C face after the coarse lapping and the higher fracture toughness of the near-perfect Si face after the fine lapping can tolerate more plastic deformations, which gives rise to the superior flatness of the C-face-followed-by-Si-face coarsely lapped and the Si-face-followed-by-C-face finely lapped 4H-SiC wafers, respectively. The higher hardness and lower fracture toughness of the C face also explain the higher material removal rate (MRR) of the C face of 4H-SiC wafers during the lapping.

2. Experimental details

A 100 mm 4H-SiC boule was grown by the physical-vapor-transport technology. 4H-SiC wafers with a thickness of 500 ± 10 μm were obtained by multi-wire sawing. The average roughness of the Si face and C face of wire-sawed 4 H-SiC wafers are 0.18 μm and 0.24 μm, respectively. Before lapping, three 4H-SiC wafers were bonded to a ceramic carrier with a diameter of 248 mm by using wax. Coarse lapping and fine lapping were conducted on a copper disc and tin disc, respectively. The schematic diagram of the lapping equipment is shown in figure 1(a). The slurry was completely dispersed by ultrasonic vibration before machining, and stirred during lapping. The main lapping parameters are tabulated in table 1. All the lapping experiments were conducted at a constant temperature of 24 °C. In order to compare the effect of lapping sequence on the flatness of 4H-SiC wafers, we designed different lapping sequences. As shown in figure 1(b), Process A and Process B indicate that the Si surface and C surface were firstly processed in both coarse lapping and fine lapping, respectively.

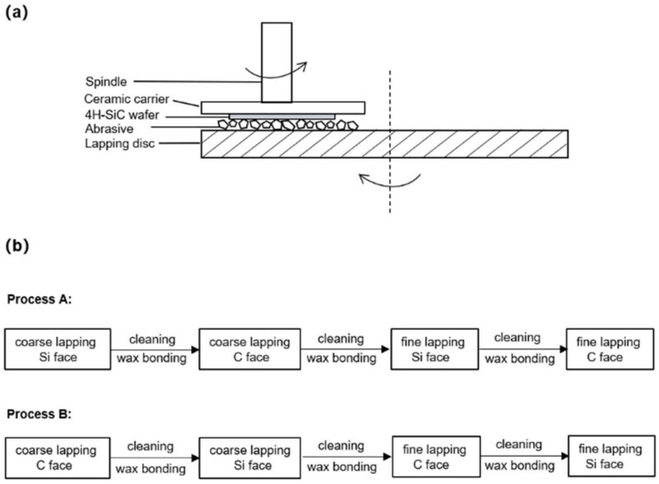

Figure 1. Schematic diagram of (a) lapping equipment and (b) lapping sequences.

Table 1. Main lapping parameters used in this work.

	Coarse lapping	Fine lapping
Abrasive diameter	3 μm	1 μm
Spindle pressure	60 kgf	25 kgf
Spindle speed	35 rpm	35 rpm
Disc rotational speed	40 rpm	40 rpm
Removal thickness of the Si face	65 ± 2 μm	6 ± 2 μm
Removal thickness of the C face	65 ± 2 μm	6 ± 2 μm

The flatness of a 4H-SiC wafer was tested by Tropel FM 200. The thickness was measured by the five-point thickness measurement method, and the MRR of a 4H-SiC wafer was calculated by dividing the removal thickness by lapping duration. Nanoindentation tests were carried out by the Berkovich indenter equipped on Nanointender G200 (Agilent). The peak load was 500 mN. For each nanoindentation test, the loading and unloading times were 10 s and 15 s, respectively. The thermal drift was maintained below ±0.05 nm s^{-1}. The Oliver–Pharr (O&P) method was employed to obtain the hardness and elastic modulus of 4H-SiC wafers [13, 14]. In order to obtain reliable data, each nanoindentation test was repeated for 8 times. After nanoindentation, the indentation topography and crack length were characterized by the scanning electron microscope (Zeiss, SIGMA). The fracture toughness (K_{IC}) of 4H-SiC was calculated by using [15]:

$$K_{IC} = A\left(\frac{a}{l}\right)^{\frac{1}{2}}\left(\frac{E}{H}\right)^{\frac{2}{3}}\frac{P}{c^{2/3}} \tag{1}$$

where P is the applied load, A is a constant related to the indenter geometry ($A = 0.0016$ for Berkovich indenter used in this study), c is the crack length, a is the indent size from center to corner, l is the crack length from indent corner to crack tip ($c = a + l$). E and H denote the elastic modulus and hardness of 4H-SiC, respectively.

3. Results and discussion

Firstly, we measure the flatness of a 100 mm 4H-SiC wafer after wire sawing. As shown in figure 2, the Si-face-upturned 4H-SiC wafer after wire sawing is convex. The values of bow and warp of the wafer are 7.28 μm and 17.42 μm, respectively. In order to investigate the effect of single-sided lapping sequence on the flatness of 4H-SiC wafers, we measure the values of bow and warp of 4H-SiC wafers after single-sided coarse lapping and fine lapping. Figure 3(a) shows the change in the value of bow after different lapping sequences. It is found that the shape of a 4H-SiC wafer significantly changes when the lapping sequence is the Si-face lapping followed by the C-face lapping. A Si-face-upturned 4H-SiC wafer changes from convex to concave after Si-face coarse (or fine) lapping. The following coarse (or fine) lapping changes the shape of the Si-face-upturned 4H-SiC wafer to be convex. When the coarse (and fine) lapping is C-face lapping followed by the Si-face lapping, the shape of the Si-face-upturned 4H-SiC wafer keeps being convex in the coarse and fine lapping processes. By comparing the changes of the values of bow, we find that the lapping sequence of coarse lapping of the C face, coarse lapping of the Si face, fine lapping of the Si face, and then the fine lapping of the C face, is beneficial to control the bow of a 4H-SiC wafer.

As shown in figure 3(b), the value of warp of a 4H-SiC wafer firstly increases after the coarse lapping of the Si face, and the subsequent coarse lapping of the C face decreases the value of warp. Similarly, the value of warp first increases after the fine lapping of Si face, and then decreases after the fine lapping of the C face. We note that the deterioration of warp after single-side lapping, as well as the recovery of warp also happens in Process B. This indicates that the single-side coarse lapping (and fine lapping) increases the value of warp of a 4H-SiC wafer, while the following lapping of the other side of the wafer repairs the flatness of the wafer. More interestingly, we find that the value of warp of the 4H-SiC wafer after Process A is higher than that of Process B after coarse lapping, while the value of warp of the 4H-SiC wafer after Process A is lower than that of Process B after fine lapping. This indicates that from the point of view of controlling the warp of a 4H-SiC wafer, the preferential sequence of lapping is the coarse lapping of the C face, coarse lapping of the Si face, fine lapping of the Si face, and then the fine lapping of the C face. This is consistent with the case in controlling the bow of a 4H-SiC wafer.

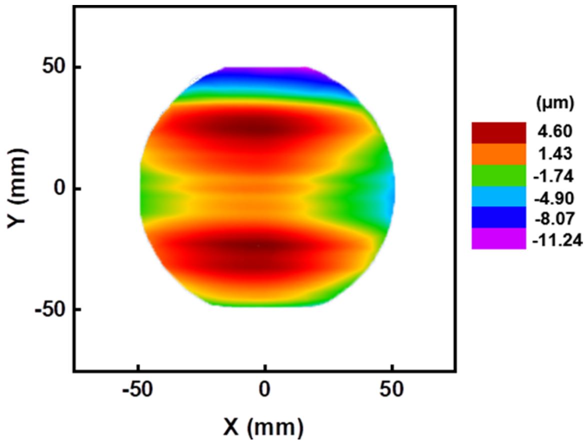

Figure 2. Flatness of a wire-sawed 4H-SiC wafer with the Si face being upwards.

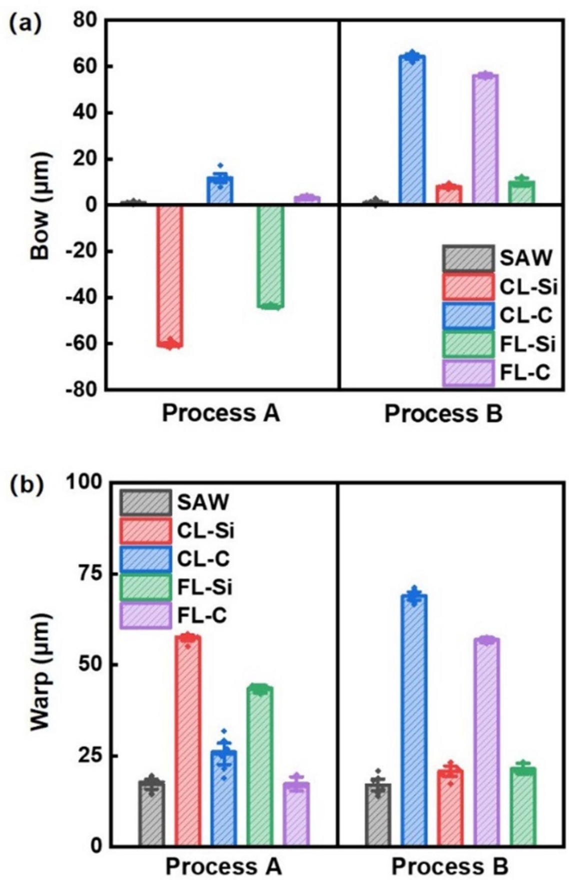

Figure 3. Variations of the values of bow and warp of 4H-SiC wafers after wire sawing (SAW), coarse lapping (CL), and fine lapping (FL).

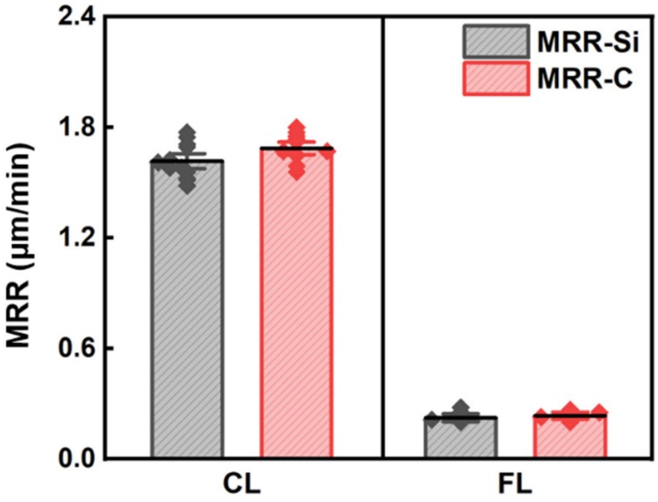

Figure 4. MRR of 4H-SiC wafers during the coarse lapping (CL) and fine lapping (FL).

We then investigate the MRR of the Si face and C face during the lapping of a 4H-SiC wafer. As shown in figure 4, the MRR of coarse lapping is higher than that of fine lapping, because the average size of the diamond abrasives used in coarse lapping (3 μm) is larger than that used in fine lapping (1 μm). More significantly, we find that the MRR of the C surface is slightly higher than that of Si surface during both coarse lapping and fine lapping.

In order to investigate the effect of lapping sequence on the flatness of 4H-SiC wafers, as well as the different MRR of the C face and the Si face, we then investigate the mechanical properties of 4H-SiC wafers after different processing steps. As shown in figure 5(a), the values of the hardness of both the C face and Si face of 4H-SiC gradually increase as the wafering of 4H-SiC proceeds. The wire sawing creates high density of surface damage in 4H-SiC wafers, which includes dislocations, cracks, and amorphous materials [16–19]. The hardness of the surface damage is lower than that of perfect 4H-SiC. As the wafering of 4H-SiC proceeds, the coarse lapping and fine lapping remove the surface damage on 4H-SiC wafers, which increases the hardness of 4H-SiC wafers. During the mechanical processing, we find that the surfaces of the C face and Si face of 4H-SiC wafers become smoother, and the values of the full-width at half maximum of the rocking curve of both the C face and Si face of 4H-SiC wafer gradually decrease (as shown in figures S1 and S2). This indicates that the surface damage created by wire sawing are gradually removed by coarse lapping and fine lapping. Furthermore, the hardness of the C face is always higher than that of the Si face for a 4H-SiC wafer after wire sawing, coarse lapping, and fine lapping. It has been found that the hardness of the C face is higher than that of Si face of a perfect 4H-SiC wafer after CMP [20]. This indicates that the existence of surface damage does not eliminate the crystallographic-plane-dependent hardness of a 4H-SiC. As shown in figure 5(b), the values of the fracture toughness of Si face and C face of 4H-SiC gradually decrease, as a result of reduced surface damage as the wafering of 4H-SiC proceeds. The fracture toughness of C face is lower than that of Si face, because the slip of Si-core partial dislocations is easier to happen on the Si face of 4H-SiC [21].

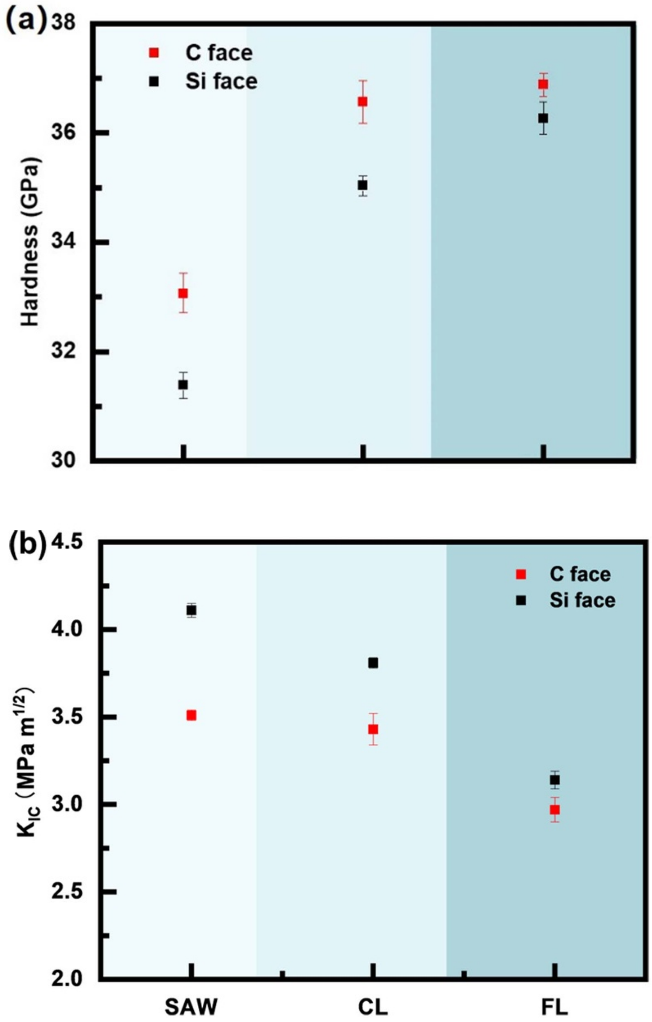

Figure 5. Values of hardness (a) and fracture toughness K_{IC} (b) for the Si face and C face of 4H-SiCs after wire sawing (SAW), coarse lapping (CL), and fine lapping (FL).

At last, we discuss the mechanism of the effect of lapping sequence on the flatness of 4H-SiC wafers. Nanoindentation tests indicate that as the wafering proceeds, the hardness of the C face of a 4H-SiC wafer is always higher than that of the Si face, and the fracture toughness of the C face is always lower than that of the Si face. This means that the surface damage does not change the mechanical-property difference between the C face and Si face of 4H-SiC [22]. Given the lower fracture toughness of the C face of 4H-SiC, the thickness of the surface damage of the C face of a wire-sawed 4H-SiC wafer is higher than that of the Si face. During the coarse lapping, the removal thickness of both the C face and Si face is 65 μm. Therefore, the remaining thickness of the surface damage of the C face is higher than that of the Si face. When the coarse lapping is performed firstly on the C face and then on the Si face (coarse lapping in Process B in this work), the higher amount of surface damage on the C face can tolerate more plastic deformations after the coarse lapping, which is beneficial for the controlling of the bow and warp of a coarse-lapped

4H-SiC wafer. During the fine lapping, the surface damage on both the C face and the Si face are basically removed. When the fine lapping is performed firstly on the Si face and then on the C face (fine lapping in Process A in this work), the higher fracture toughness of the Si face makes the perfect Si face which can tolerate more plastic deformations after the fine lapping, which is beneficial for the controlling of the bow and warp of a fine-lapped 4H-SiC wafer.

4. Conclusion

In conclusion, we have optimized the warpage of 4H-SiC wafers by tuning the single-sided lapping sequence. It turns out the lapping sequence can significantly affect the warpage of 4H-SiC wafers during the coarse lapping and fine lapping. For coarse lapping, the lapping sequence of C-face lapping followed by Si-face lapping is beneficial to controlling the values of the bow and warp of 4H-SiC wafers. While during fine lapping, the lapping sequence of Si-face lapping followed by C-face lapping is preferred. Nanoindentation tests indicate that the C face has higher hardness and lower fracture toughness than the Si face. This gives rise to thicker surface damage at the C face after the wire sawing. After removing the same amount of wire-sawing-induced surface damage, the thickness of residual surface damage of the C face is higher than that of the Si face after the coarse lapping. The fine lapping basically removes all the surface damage and creates the near-perfect C face and Si face. The higher amount of surface damage of the C face after the coarse lapping and the higher fracture toughness of the near-perfect Si face after the fine lapping can tolerate more plastic deformations, which gives rise to the superior flatness of the C-face-followed-by-Si-face coarse lapped and the Si-face-followed-by-C-face fine lapped 4H-SiC wafers, respectively. The higher hardness and lower fracture toughness of the C face also explain the higher MRR of the C face of 4H-SiC wafers during the lapping. Our work opens a pathway to optimize the flatness, especially the bow and warp of 4H-SiC wafers by tuning the sequence of lapping.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

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