Electrochemical mechanical polishing of 4H-SiC by polishing pads with through holes

Yang Zhao, Renke Kang, Yuewen Sun, and Zhigang Dong#

State Key Laboratory of High-performance Precision Manufacturing, Dalian University of Technology, No.2 Linggong Road, Ganjingzi District, Dalian, 116024, China
Corresponding Author / Email: dongzg@dlut.edu.cn, TEL: +86-13998542604

KEYWORDS: 4H-SiC, Electrochemical mechanical polishing, Anodic oxidation, Material Removal Uniformity

Single-crystal 4H-SiC is a typical third-generation semiconductor power-device material. However, in these power devices, the surface roughness and subsurface damage of the 4H-SiC substrate seriously affect their performance. Application of traditional chemical mechanical polishing (CMP) to 4H-SiC substrate can achieve an ultra-smooth surface and no subsurface damage. The extremely low material removal rate because 4H-SiC has extremely high mechanical strength and chemical stability. In this work, we report an efficient polishing method for 4H-SiC substrates that are electrochemically mechanically polished (ECMP) using polishing pads with through holes. The effect of 4H-SiC material removal uniformity in ECMP was investigated using the trajectory point density distribution, and the effect of through-hole arrangement and size variation on the trajectory point density distribution was simulated. The simulation and experimental results show that the use of polishing pads of a 10 mm through-hole structure can lead to a more uniform polishing effect on the whole 4H-SiC substrate surface. At 9 V anodic bias, the Material removal rate (MRR) can achieve 3.16μm/h, and the surface roughness can reach Ra 0.85 nm.

NOMENCLATURE

ω_w = rotation speed of 4H-SiC
ω_p = rotation speed of polishing pad

1. Introduction

Single-crystal Silicon Carbide (4H-SiC) has excellent properties such as high thermal conductivity, high electron mobility, and high breakdown strength. Therefore, the electronic devices prepared with it have good performance in high power, high frequency, high temperature, and strong radiation environments [1, 2]. For these applications, an ultra-smooth surface and no subsurface damage of the 4H-SiC substrate is required to realize its excellent operational performance. SiC substrates are fabricated through crystal growth and subsequent mechanical processing, including slicing, grinding, mechanical polishing, and chemical mechanical polishing (CMP). The surface removal process of the wafer is a key factor in determining the quality and processing cost of SiC substrates[3]. However, SiC is a typical hard-brittle and difficult-to-machine material, and its chemical stability is extremely strong, which makes it not easy to have chemical reactions with acid-base reagents at room temperature. The removal rate using conventional chemical mechanical polishing materials is extremely low, about 0.5-1 μm/h[4, 5].

Li et al. [6] proposed for the first time an electrochemical mechanical polishing (ECMP) process for silicon carbide, which is divided into two steps: oxidation of the silicon carbide surface occurs first to generate an oxide layer, then mechanically removed. Recently, Yang and Yamamura et al. [7, 8] proposed a highly efficient ECMP method using a CeO_2 grinding wheel for 4H-SiC. In their study, only a part of the wafer surface was polished because the diameter of the grinding wheel was smaller than that of the SiC wafer. Gao and Murata et al. [9, 10] proposed a novel ECMP method using core-shell particles for 4H-SiC. The polishing particles in this method need to be prepared by special means, and the stability for large-volume use needs to be further verified. In summary, using ECMP, a scratch-free and subsurface damage-free surface was obtained, and the Material removal rate (MRR) is higher than that of conventional CMP.

To process 4H-SiC substrate sufficiently with good surface quality and high MRR, we report an efficient polishing method for 4H-SiC substrates that are electrochemically mechanically polished using polishing pads with through holes. Anodic oxidation studies of 4H-SiC were carried out, revealing changes in surface composition and hardness before and after oxidation. The effect of 4H-SiC material removal uniformity in ECMP was investigated using the trajectory point density distribution.

2. Experimental section

2.1 ECMP setup

Electrochemical mechanical polishing of 4H-SiC by polishing pads with through holes, as shown in Fig. 1. The experimental setup combines an anodizing system and a mechanical polishing system. The working electrode (WE) was a 4H-SiC substrate that was fixed on a polishing pad with through holes by Additional weight. Polishing pads are bonded to the polishing pad, which acts as a counter electrode (CE). The polishing solution is supplied by a peristaltic pump to ensure the presence of the polishing solution in the polishing area during the polishing process. The polishing solution in the through-hole of the polishing pad conducts 4H-SiC substrate to the polishing disc and forms a closed circuit to achieve anodizing. An electrochemical workstation (CHI 660c, CH Instruments) was used to regulate the anodic oxidation parameters while simultaneously monitoring the current and potential during the polishing process. 4H-SiC and polishing plate rotates to mechanically remove the oxide layer through the abrasive particles in the polishing solution to achieve polishing.

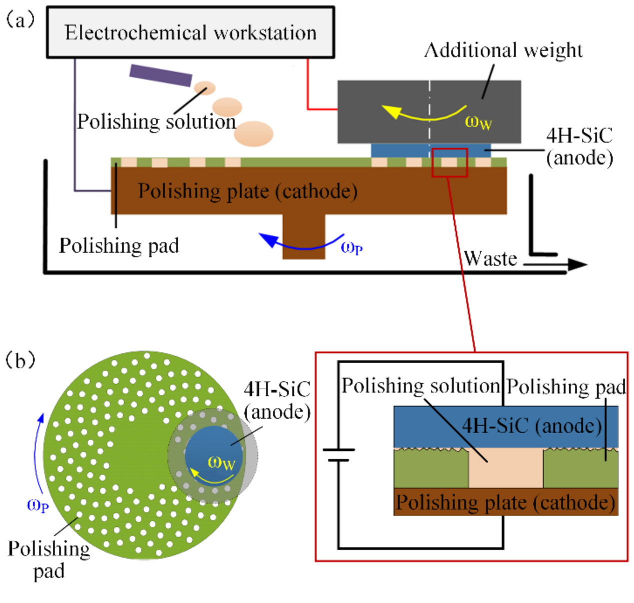

Fig. 1 ECMP setup

2.2 Anodic oxidation setup

Anodic oxidation experiments were carried out on CMP-processed 4H-SiC substrates using the three-electrode anodic oxidation setup shown in Fig. 2a. The WE was a 4H-SiC substrate to be oxidized, the CE was a platinum wire（Pt） and the RE was an Ag｜AgCl reference electrode. The electrochemical workstation was used to regulate the oxidation parameters while simultaneously monitoring the current and voltage during the anodic oxidation process. The area of 4H-SiC surface contact with the electrolyte and exposure to anodic oxidation was a 4mm diameter circle. Neutral electrolyte is the best choice to achieve a high degree oxidation process. K_2SO_4 aqueous solution (K_2SO_4 aq.) was used as the electrolyte due to its inability to etch the oxide layer. Anodic oxidation of 4H-SiC was studied to reveal the composition and hardness changes of the material surface before and after oxidation. This study provides theoretical guidance for electrochemical mechanical polishing.

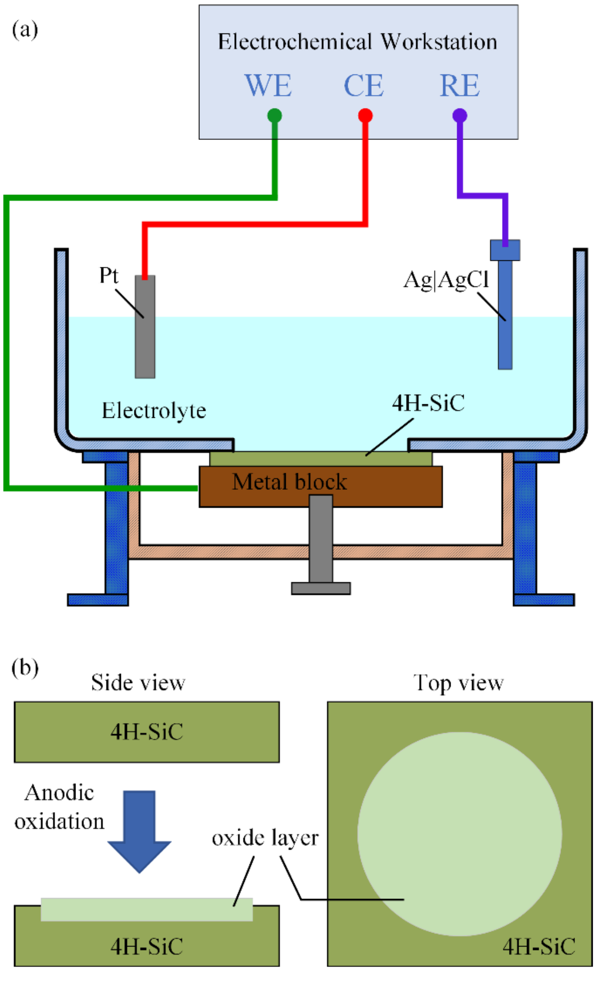

Fig. 2 Three-electrode anodic oxidation setup

2.3 Experiment parameters

The 4H-SiC substrates (on-axis, n-type, thickness: 330 μm, specific resistance: 0.10 Ω·cm) used in this work were supplied by TankeBlue Semiconductor Co. Ltd. The oxygen content was detected by X-ray photoelectron spectroscopy (XPS, K-Alpha+). The surface hardness of SiC before and after anodic oxidation was measured using a nanoindenter (Hysitron TI 950 Triboindenter) to determine the change in hardness. Zygo 9000 3D Surface Profiler for 4H-SiC Surface Roughness Measurement and Morphology Observation.

The details of the experiment parameters are listed in table 1.

Table 1 Experiment parameters

Parameters	Conditions
Rotation speed of 4H-SiC (ω_W)	100 rpm
Rotation speed of polishing pad (ω_p)	100 rpm
Polishing solution	0.1 M K_2SO_4 aq. 5 wt.% SiO_2 particles (25 nm)
Electrolyte	0.1 m k_2so_4 aq.

3. Results and discussion

3.1 Performance of anodic oxidation of 4H-SiC

4H-SiC was anodized at a voltage of 9 V for 30 min, and a comparison of the hardness before and after oxidation is shown in Fig. 3. The results showed that the surface hardness was significantly reduced from 38.650 GPa to 2.402 GPa after anodizing. In the ECMP process, anodic oxidation softens the surface of 4H-SiC, which makes it possible for the surface to be polished by a soft abrasive. This provides theoretical support for the removal of damaged layers.

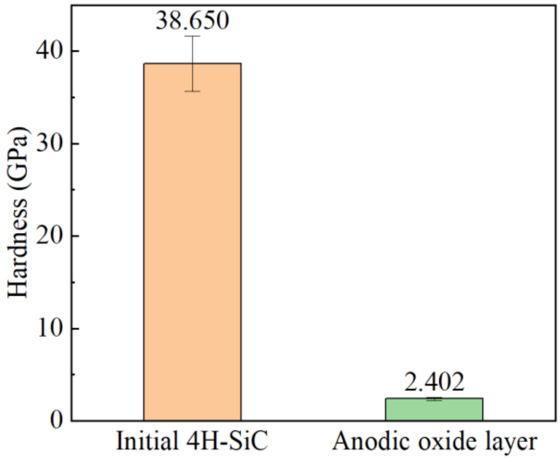

Fig. 3 Change of surface hardness before and after anodizing

Figure 4 shows the XPS spectra of 4H-SiC surfaces before and after being processed by anodic oxidation at a voltage of 9v for 30 min. There was no oxide on the CMP-processed surface because only peaks corresponding to Si-C and Si-C-O bonds were observed. Peaks corresponding to Si-O bonds were observed after anodic oxidation. Therefore, the XPS measurement results also indicate that anodic oxidation is effective.

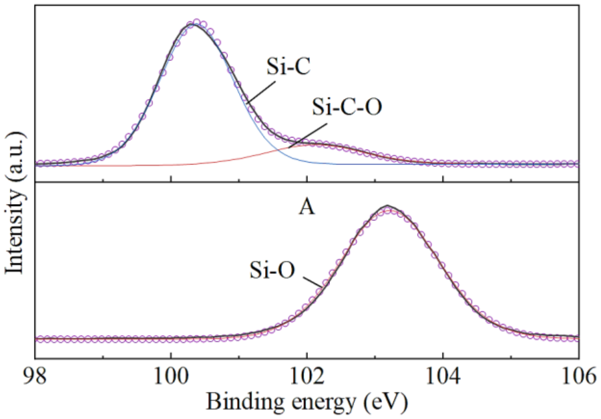

Fig. 4 Si 2p XPS spectra of 4H-SiC surfaces before and after anodizing

3.2 Track point density distribution

The density distribution of trajectory points was simulated for through-hole diameters of 8 mm, 10 mm, and 12 mm, respectively. The results are shown in Fig. 5. The results show that the trajectory points are most uniformly distributed at a through-hole diameter of 10 mm during the simulation period.

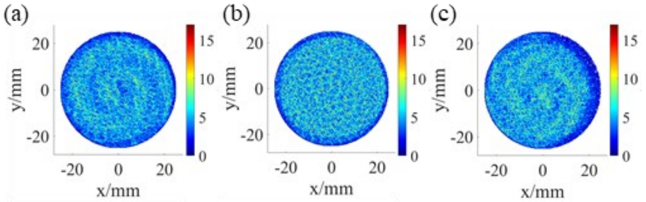

Fig. 5 Track point density distribution cloud map: through-hole diameters of (a)8 mm, (b)10 mm, and (c)12 mm

Selection of polishing pads with a through-hole diameter of 10 mm for electrochemical mechanical polishing of 4H-SiC substrate. At 9 V anodic bias, the MRR can achieve 3.16μm/h, and the surface roughness can reach Ra 0.85 nm, as shown in Fig. 6.

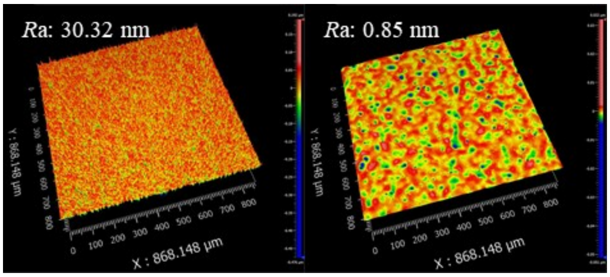

Fig. 6 4H-SiC substrate surface morphology (a) as-received, (b) After ECMP

4. Conclusions

In general, Electrochemical mechanical polishing of 4H-SiC by polishing pads with through holes to reach low roughness and high MMR. The simulation and experimental results show that the use of polishing pads of a 10 mm through-hole structure can lead to a more uniform polishing effect on the whole 4H-SiC substrate surface. At 9 V anodic bias, the MRR can achieve 3.16 μm/h, and the surface roughness can reach Ra 0.85 nm.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support National Natural Science Foundation of China (No. 51975095, 51991372, 52325506).

REFERENCES

1. F. Roccaforte, P. Fiorenza, G. Greco, R. Lo Nigro, F. Giannazzo, F. Iucolano, and M. Saggio, "Emerging trends in wide band gap semiconductors (SiC and GaN) technology for power devices," Microelectronic Engineering, vol. 187-188, pp. 66-77, 2018.
2. J. B. Casady and R. W. Johnson, "Status of silicon carbide (SiC) as

a wide-bandgap semiconductor for high-temperature applications: A review," SOLID-STATE ELECTRONICS, vol. 39, pp. 1409-1422, 1996-1-1 1996.

3. C. N. S. B. Zulkifle, K. Hayama and J. Murata, "High-efficiency wafer-scale finishing of 4H-SiC (0001) surface using chemical-free electrochemical mechanical method with a solid polymer electrolyte," Diamond and Related Materials, vol. 120, p. 108700, 2021.
4. W. C. M. R. C. L. NESLEN, "Effects of Process Parameter Variations on the Removal Rate in Chemical Mechanical Polishing of 4H-SiC," Journal of ELECTRONIC MATERIALS, 2001.
5. X. Yang, Y. Ohkubo, K. Endo, and K. Yamamura, "AFM Observation of Initial Oxidation Stage of 4H-SiC (0001) in Electrochemical Mechanical Polishing," Procedia CIRP, vol. 68, pp. 735-740, 2018.
6. C. H. Li, R. J. Wang, J. Seiler, and I. Bhat, "Electro-Chemical Mechanical Polishing of Silicon Carbide," Materials Science Forum, vol. 457-460, pp. 801-804, 2004.
7. X. Yang, X. Yang, K. Kawai, K. Arima, and K. Yamamura, "Dominant factors and their action mechanisms on material removal rate in electrochemical mechanical polishing of 4H-SiC (0001) surface," Applied Surface Science, vol. 562, p. 150130, 2021.
8. X. Yang, X. Yang, K. Kawai, K. Arima, and K. Yamamura, "Novel SiC wafer manufacturing process employing three-step slurryless electrochemical mechanical polishing," Journal of Manufacturing Processes, vol. 70, pp. 350-360, 2021.
9. J. Murata, K. Yodogawa and K. Ban, "Polishing-pad-free electrochemical mechanical polishing of single-crystalline SiC surfaces using polyurethane–CeO2 core–shell particles," International Journal of Machine Tools and Manufacture, vol. 114, pp. 1-7, 2017.
10. B. Gao, W. J. Zhai, Q. Zhai, Y. L. Xia, C. Wang, and K. X. Peng, "Electro-Chemical Mechanical Polishing of 4H-SiC for Scratch-Free Surfaces with Less Oxide Layer at High Efficiency," ECS journal of solid state science and technology, vol. 8, pp. P677-P684, 2019-1-1 2019.