

Effects of Processing Passes on Laser-Sliced SiC

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Keywords: Laser slicing; Crack propagation; Kerf loss.

Abstract. Silicon carbide (SiC), a representative of next-generation wide-bandgap semiconductors, exhibits enormous application potential in fields such as new energy vehicles, aerospace, and photovoltaic power generation. Conventional cutting methods based on diamond wire sawing suffer from high material loss and are prone to causing fractures. In contrast, laser slicing, as a kerf-free processing technology, enables the acquisition of high-quality wafers with minimal material removal. This study systematically investigates the effect of processing cycles on crack propagation and delamination strength during laser slicing of SiC. The experimental results demonstrate that under optimized parameters, an appropriate number of processing cycles can achieve successful wafer separation while maintaining surface integrity, reducing material loss, and lowering delamination strength. The established processing window provides practical guidance for improving SiC slicing quality and holds significant implications for advancing innovative wafer manufacturing technologies in power electronics applications.

Introduction

Silicon carbide (SiC), as one of the core representatives of third-generation wide-bandgap semiconductor materials, has become a critical supporting material in strategically emerging fields such as rail transit traction converters, 5G base station radio frequency devices, aerospace extreme environment sensors, and new energy vehicle power modules, thanks to its excellent high-temperature stability, high breakdown electric field strength, high-frequency signal response capability, and high-power bearing characteristics^[1,2]. In the manufacturing process of SiC power chips, it is first necessary to grow high-quality single-crystal ingots via techniques such as Physical Vapor Transport (PVT). Subsequently, precision processing procedures including slicing, grinding, and polishing are performed to produce substrates that meet epitaxial requirements. Finally, device fabrication steps such as epitaxial growth, photolithographic patterning, ion implantation, and annealing activation are sequentially completed^[3,4]. Throughout the entire process mentioned above, the processing accuracy and quality control of the crystal slicing step are particularly critical—the thickness uniformity, surface roughness, and subsurface damage layer depth of the substrate after slicing directly determine the crystalline quality and interface integrity of the subsequent epitaxial layer, thereby exerting a significant impact on the on-resistance, breakdown voltage, and long-term reliability of the final power device. However, the extremely high hardness (Mohs hardness of 9.2–9.5) and brittle nature of single-crystal SiC pose challenges such as difficult material removal and easy accumulation of processing damage during precision slicing, making it difficult for traditional processing technologies to balance efficiency and quality^[5,6]. Currently, the mainstream SiC slicing technologies in industry and academia are mainly divided into two categories: laser slicing and wire saw slicing. Among them, laser slicing, based on the principle of non-contact processing, has significant advantages including high processing efficiency, low kerf loss, high dimensional accuracy, and strong damage controllability, and has become an important development direction for slicing

large-size SiC ingots. The core principle of this technology is as follows: a pulsed laser with a specific wavelength is focused to a preset depth inside the SiC ingot, so that the energy density in the focused area reaches the material damage threshold and a modified layer (e.g., amorphized region, microcrack region) is generated; by designing a high-precision laser scanning path, adjacent modified regions are connected to form a continuous separation surface, weakening the internal bonding force of the ingot; finally, with the assistance of ultrasonic vibration-assisted peeling, mechanical tensile separation, or electrochemical etching, efficient separation of the wafer from the ingot is achieved^[7,8].

Continuous technological iterations and mechanism research have driven the rapid development of the field of SiC laser slicing. Kim et al.^[9,10] took the lead in focusing ultrafast pulsed lasers with a dual-pulse structure into 4H-SiC crystals, realizing the precise separation of thin wafers; through Raman spectroscopy and high-resolution microscopic characterization, they found that significant structural transformation occurred in the laser-affected region, specifically manifested as the amorphization of 4H-SiC crystals and their decomposition into amorphous silicon and amorphous carbon phases; mechanical tests further confirmed that the tensile force required for wafer separation under the dual-pulse processing method was significantly lower than that under single-pulse processing. Han et al.^[11] used a 1064 nm picosecond laser to induce multiphoton-induced micro-explosions in 4H-SiC; these micro-explosions confined the micro-explosion layer to the vicinity of the laser beam focus, and due to the generated instantaneous high temperature, 4H-SiC decomposed into amorphous silicon and carbon, and two 4H-SiC wafers with a thickness of 250 μm were successfully prepared. Geng et al.^[12] proposed a composite slicing technology combining femtosecond laser irradiation and bandgap-selective photoelectrochemical (PEC) peeling, achieving high-yield (yield > 95%) separation of 4H-SiC wafers. Characterization and analysis via optical absorption spectroscopy, micro-Raman, and photoluminescence (PL) showed that the damage layer induced by femtosecond lasers inside 4H-SiC was mainly composed of amorphous silicon (a-Si) and amorphous carbon (a-C), with its bandgap width reduced to 0.4 eV, which was significantly different from that of intact 4H-SiC (bandgap of 3.26 eV); using this characteristic, the damage layer could be selectively removed from the intact region of 4H-SiC via bandgap-selective PEC etching, avoiding secondary damage to the wafer surface caused by mechanical separation. Jiang et al.^[13] proposed a continuous laser-assisted SiC wafer splitting method based on a picosecond laser-modified layer, showing that the modified layer prepared by picosecond lasers in SiC samples significantly improved laser absorption rate, and the absorption coefficient of the modified SiC samples at 1064 nm was increased by 2720 times. Lv et al.^[14] designed orthogonal experiments on ultrasonic-assisted peeling for laser-modified 4H-SiC single crystals, systematically investigating the influence of ultrasonic frequency, vibration time, and ultrasonic power on the bonding force of the modified layer. The results showed that ultrasonic vibration could promote the propagation of microcracks inside the modified layer through cavitation effect, reducing the bonding force between the modified layer and the matrix by 25%–60%. Wang et al.^[15] conducted laser cutting experiments on 4H-SiC samples with different surface roughness. The study found that good surface quality could reduce damage to the wafer surface during laser cutting, decrease the occurrence of cleavage, and improve the flatness and uniformity of the modified layer. Chen et al.^[16] combined experiments with two-temperature model analysis to explore the influence of different doping concentrations on the laser cutting of n-type 4H-SiC; the results showed that an increase in nitrogen doping concentration led to a decrease in resistivity and an increase in laser absorption rate, which in turn affected the crack propagation length and modified line width. By optimizing processing parameters, high-quality laser cutting of SiC wafers with five gradient doping concentrations was successfully achieved. Finally, an 8-inch N-type 4H-SiC wafer was successfully sliced.

Although existing studies on laser slicing of 4H-SiC wafers have achieved breakthroughs in multiple aspects, there is a lack of systematic research on the key variable of laser repeated processing cycles. In actual industrial production, to achieve efficient slicing of large-size 4H-SiC ingots (e.g., 6–8 inches), multiple laser scans are often required to enhance the continuity of the modified layer, thereby reducing the difficulty of subsequent separation; however, the cumulative effect of energy during repeated processing may lead to excessive expansion of the modified layer, causing problems

such as an increase in the depth of longitudinal microcracks and an expansion of the subsurface damage range, which in turn affect the material removal efficiency of subsequent grinding processes and the final quality of the substrate.

Based on this, this study takes semi-insulating 4H-SiC single crystals as the research object. On the basis of fixing the core laser parameters (wavelength of 1030 nm, pulse width of 10 ps) and optimizing process conditions (C-face incidence, scanning along the $[1\bar{1}00]$ orientation), experimental groups with 1–9 laser repeated processing cycles were designed. Optical microscopy was used to analyze the influence of processing cycles on crack morphology, and an electronic universal testing machine was employed to measure the change in tensile force required for wafer separation. The study aims to clarify the quantitative relationship between the number of laser repeated processing cycles and the slicing quality of 4H-SiC, reveal the cumulative mechanism of longitudinal damage caused by multiple processing cycles, and avoid discontinuous modified layers and excessively high separation tensile force due to insufficient processing cycles, or excessive damage diffusion caused by excessive processing cycles. Based on the comprehensive evaluation of crack propagation uniformity, separation tensile force stability, and damage controllability, the optimal number of laser repeated processing cycles and supporting process parameters are determined, providing a quantitative basis for reducing longitudinal damage and improving slicing efficiency. The results of this study can not only fill the research gap in the optimization of processing cycles in existing laser slicing technologies but also provide technical guidance with both theoretical value and engineering practicality for the precision processing and advanced manufacturing of 4H-SiC wafers.

Experiment

The experimental material used in this study was a 6-inch SiC wafer, which was laboratory-fabricated with a thickness of 700 μm and a surface roughness (R_a) of approximately 1 nm. This wafer was then cut into rectangular cuboids with dimensions of 20 mm \times 20 mm \times 700 μm . A schematic diagram of the laser slicing system used in the experiment is shown in Fig.1. The laser cutting parameters were as follows: wavelength $\lambda = 1030$ nm, pulse width $\tau = 10$ ps, pulse repetition frequency (PRF) of 100–1000 kHz, and scanning speed of 100–400 mm/s. A Liquid Crystal Spatial Light Modulator (LCSLM) was used to accurately compensate and correct the spherical aberration caused by the difference in refractive index between air and 4H-SiC, realizing distortion correction of the laser-focused spot. Under the conditions of a power of 1 W and a step distance of 200 μm , the samples were subjected to complete laser modification with different numbers of cycles (1 to 9 cycles). An industrial microscope was used to observe the connection of crack propagation in the top and side views. To further quantify the laser modification effect and slicing feasibility, a mechanical peeling experiment was conducted on the modified samples using an electronic universal testing machine. Both ends of the samples were fixed to the fixtures with high-strength epoxy adhesive, a tensile force was applied at a constant speed, and the peeling force was recorded simultaneously. The cutting quality was evaluated based on the changes in crack propagation and peeling force.

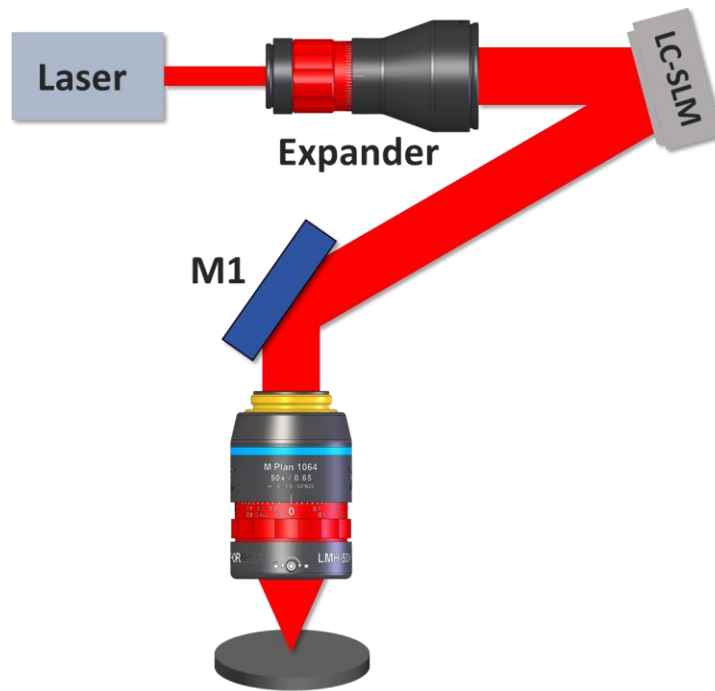


Fig. 1. Schematic of laser-slicing system.

Results and Discussion

Top-View Observation of Crack Propagation.

The integrity, continuity, and morphological regularity of crack propagation are core indicators for evaluating laser slicing quality, as they directly determine the feasibility of subsequent wafer separation and the flatness of the separation surface. In this study, an industrial inspection microscope was used to conduct top-view observations of 4H-SiC samples after 1–9 laser processing cycles, and the crack propagation morphologies under different processing cycles were obtained; the results are shown in Fig. 2 (a–i). From Fig. 2 (a) (1 processing cycle), clear laser scanning traces can be observed on the sample surface, with an interval of approximately 200 μm between adjacent traces. This interval completely matches the preset scanning step parameter in the experiment, verifying the accuracy of the laser scanning path. Measurements of typical regions in this group of samples revealed that the width of the laser traces was approximately 19.8 μm , and the total crack propagation length was about 65.6 μm . Notably, the cracks between adjacent traces did not form effective connections. This phenomenon is attributed to the limited energy input of a single laser processing cycle, which only generates a local modified layer (mainly composed of amorphized regions and microcracks) near the scanning path. A continuous separation surface is not established between adjacent modified layers, resulting in a relatively high internal bonding force of the wafer and significant difficulty in subsequent separation.

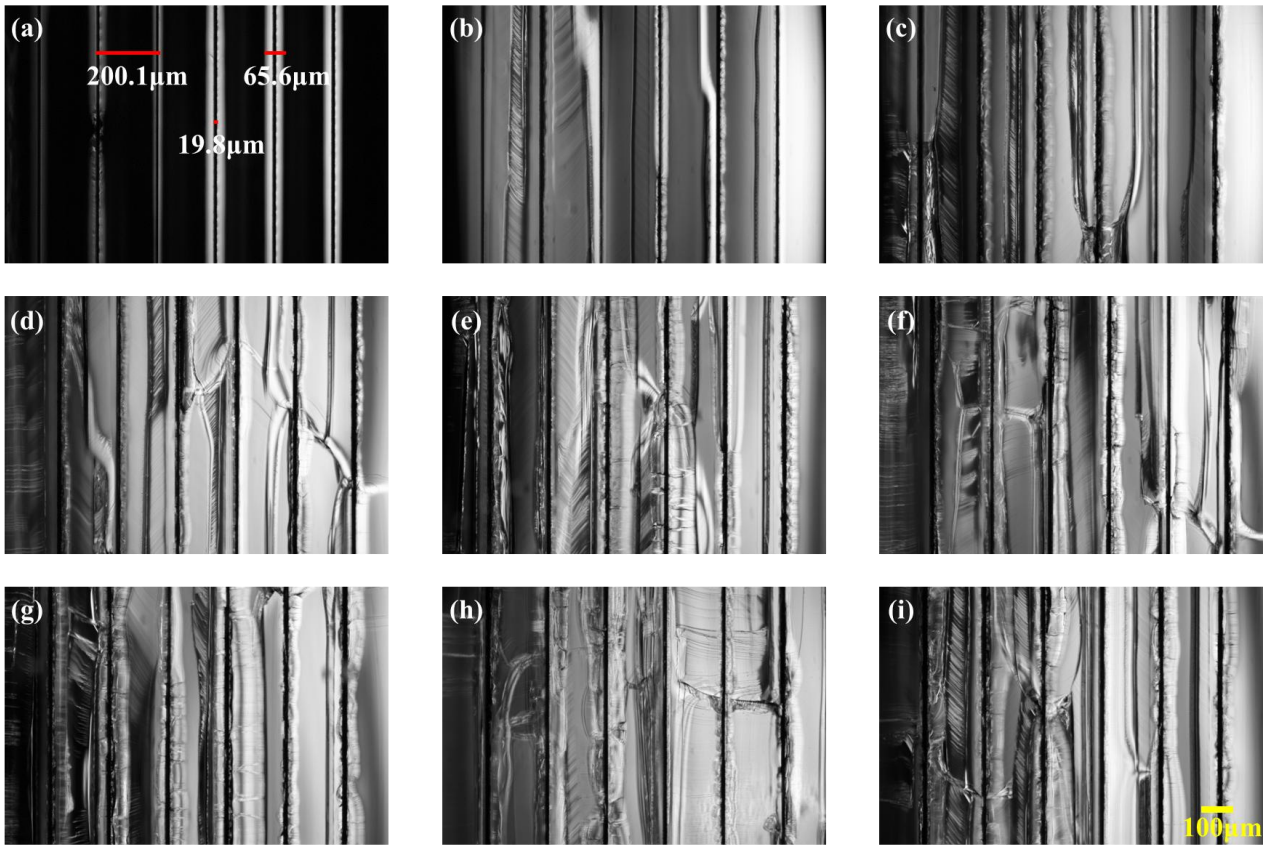


Fig. 2. (a)-(i) Top-view optical micrographs corresponding to 1–9 processing passes.

When the number of processing cycles increased to 2–3 (Fig. 2 (b–c)), the cracks induced by adjacent laser traces began to connect with each other, forming a preliminary continuous separation path. However, the crack morphology exhibited partial irregular feather-like branches. This is because during the second and third laser scans, the laser energy caused a stress concentration effect at the tips of the already formed microcracks; while this effect promotes the lateral propagation of cracks, it also triggers local irregular branching. As the number of processing cycles further increased to 4–6 (Fig. 2 (d–f)), the cumulative effect of laser energy became increasingly prominent. On one hand, multiple scans increased the width of the laser traces and further expanded the range of crack propagation; on the other hand, obvious ablation marks appeared in local areas of the samples. When the number of processing cycles reached 7–9 (Fig. 2 (g–i)), the surface ablation marks deepened further, and significant height differences emerged in some regions. This is because excessive laser energy input not only intensifies crack propagation but also causes stress accumulation inside the modified layer, leading to tiny bulges or depressions in local areas and damaging the surface flatness. To meet the substrate requirements, a thicker damaged layer must be removed through subsequent grinding processes, which increases processing costs and material loss.

Side-View Observation of Cracks and Peeling Force.

To further investigate the effect of laser processing cycles on the longitudinal damage of 4H-SiC samples, side-view observations were conducted on the samples after side polishing to analyze the propagation depth of transverse cracks and the distribution of longitudinal damage. Meanwhile, an electronic universal testing machine was used to measure the peeling force of the laser-modified samples, establishing a correlation among "processing cycles–crack morphology–peeling force". As shown in Fig.3, different numbers of processing cycles exhibit a significant regulatory effect on the transverse propagation of cracks and longitudinal damage. When processed only once (Fig.3 (a)), crack propagation is limited and the cracks are disconnected; the typical spacing between cracks induced by adjacent laser traces is approximately 30.6 μm , and no continuous damage layer is formed.

This result mutually confirms the "disconnected cracks" observation from the top-view analysis. When processed twice (Fig.3 (b)), the cracks extend further and begin to transition toward a continuous state, though local disconnected regions still exist. When processed 3–4 times (Fig.3 (c–d)), the transverse cracks are completely connected, accompanied by slight longitudinal delamination damage. This phenomenon occurs because multiple laser scans increase the thickness of the modified layer; while transverse cracks are connecting, the accumulation of longitudinal stress triggers local delamination. When the number of processing cycles increases to 5–9 (Fig.3 (e–i)), the transverse cracks are already fully and stably connected, but the longitudinal damage intensifies significantly. The core reason for this phenomenon is that under a large number of processing cycles, the modified layer formed by previous laser scans alters the energy absorption and focusing state of subsequent lasers (the refractive index of the modified layer differs from that of intact SiC, leading to the deviation of the laser focus point). This causes excessive energy accumulation in the longitudinal direction, triggering damage diffusion along the depth. Such diffusion not only increases the amount of material to be removed in subsequent grinding but may also reduce the thickness uniformity of the substrate.

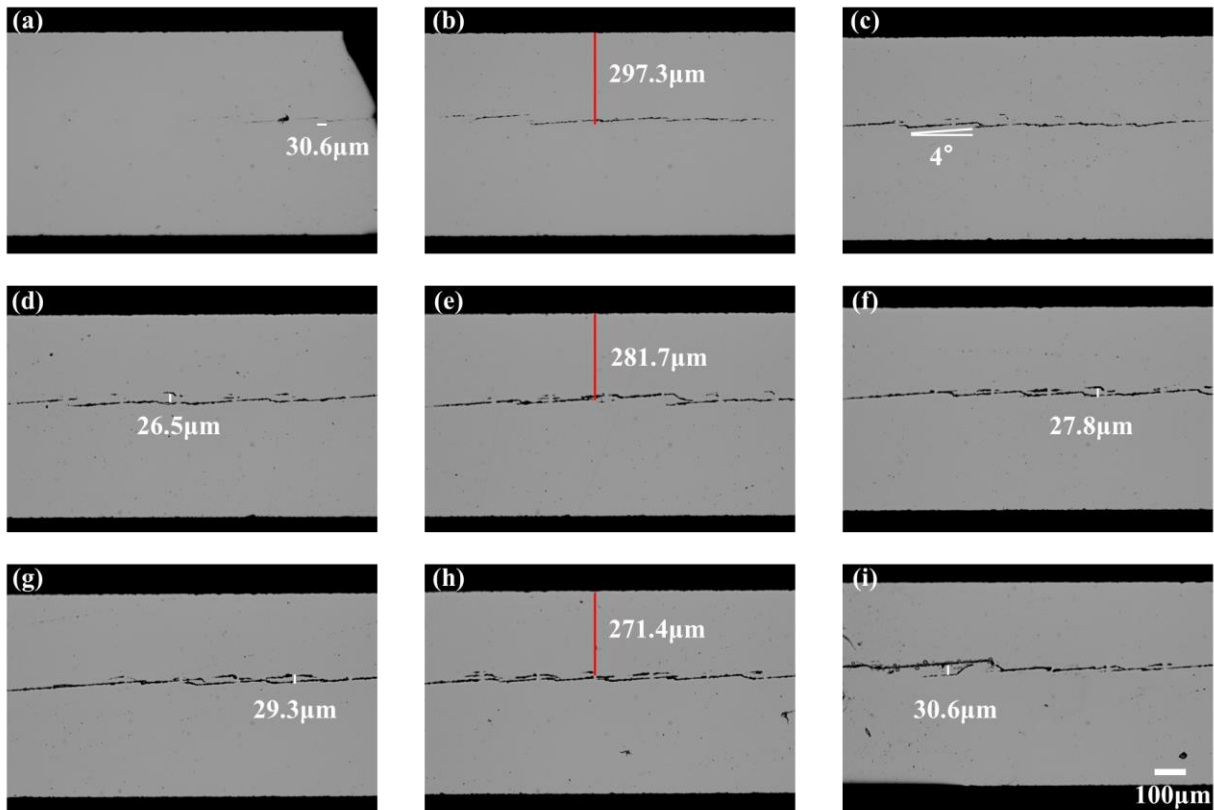


Fig. 3. (a-i) Cross-sectional crack morphology images corresponding to 1–9 processing passes.

The variation trend of tensile strength shows a strong correlation with the crack propagation effect (as shown in Fig.4). When processed only once, due to disconnected cracks and high internal bonding force of the wafer, the peeling force required for sample separation is as high as 3.01 MPa. With the increase in processing cycles, the transverse cracks gradually connect, the bonding force weakens progressively, and the peeling force decreases accordingly. When the number of processing cycles reaches 5, the peeling force drops to 0.68 MPa and then stabilizes. This indicates that an appropriate number of processing cycles can not only reduce longitudinal damage but also lower the peeling force during the cutting process.

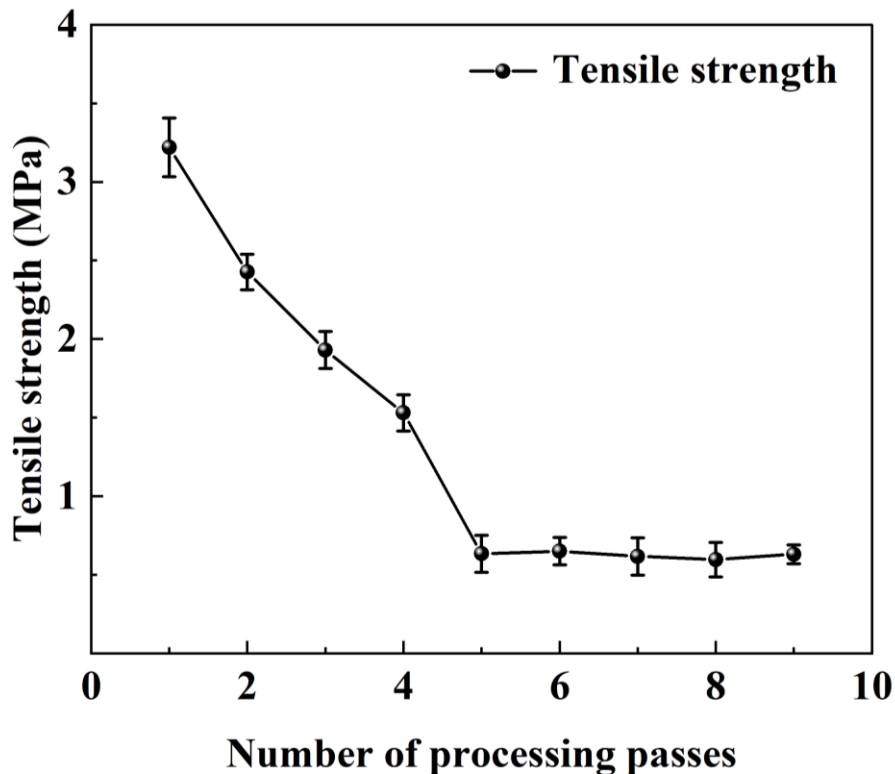


Fig. 4. Trend chart of tensile strength versus number of processing passes.

Summary

This study systematically investigates the regulatory law of laser processing cycles on the slicing quality of 4H-SiC wafers, with a focus on analyzing the evolutionary characteristics of crack propagation morphology and peeling force. The key findings are as follows: When processed only once, limited by the constraints of energy input, the generated cracks are limited in scope and disconnected from each other. In this case, the internal bonding force of the wafer is not effectively weakened, resulting in a relatively large peeling force. For 2–4 processing cycles, the cumulative effect of laser energy promotes the transverse propagation of cracks and enables their connection; however, there is a risk of longitudinal delamination. When the number of processing cycles reaches 5–9, although the transverse cracks are already fully connected, the longitudinal damage intensifies significantly, which increases cutting loss. The test results of peeling force show a strong correlation with the crack propagation morphology: the peeling force decreases with the increase in processing cycles, and stabilizes when the number of processing cycles reaches 5. This indicates that an optimal balance is achieved between crack connectivity and damage minimization at this point. An appropriate number of laser processing cycles can reduce longitudinal damage and peeling force during the cutting process, providing practical references for improving the quality of SiC laser slicing and advancing the development of wafer manufacturing technology.

Authorship Contribution Statement

Jianfei Zhang: Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. Bixue Li: Writing original draft, Validation, Data curation, Conceptualization. Qiu Chen: Data curation, Formal analysis. Linlin Che: Conceptualization, Validation. Xing Zhang: Writing – review & editing, Supervision. Haoyu Fan: Visualization, Formal analysis. Yangyang Jia: Visualization, Formal analysis. Jiawei Wang: Visualization, Formal analysis. Yufeng Xue: Visualization, Formal analysis. Rongkun Wang: Project administration, Methodology. Xiufang Chen:

Writing review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. U23A20569), the Key R&D Program of Shandong Province, China (2022ZLGX02).

References

- [1] Zhao J, Ji P, Li Y, et al. Ultrahigh-mobility semiconducting epitaxial graphene on silicon carbide[J]. *Nature*, 2024, 625(7993): 60-65.
- [2] Nakamura D, Gunjishima I, Yamaguchi S, et al. Ultrahigh-quality silicon carbide single crystals[J]. *Nature*, 2004, 430(7003): 1009-1012.
- [3] Eddy C R, Gaskill D K. Silicon Carbide as a Platform for Power Electronics[J]. *Science*, 2009, 324(5933): 1398-1400.
- [4] Chen X, Yang X, Xie X, et al. Research progress of large size SiC single crystal materials and devices[J]. *Light: Science & Applications*, 2023, 12(1): 28.
- [5] Wang G, Sheng D, Yang Y, et al. High-Quality and Wafer-Scale Cubic Silicon Carbide Single Crystals[J]. *ENERGY & ENVIRONMENTAL MATERIALS*, n/a(n/a): e12678.
- [6] Li Y, Zhang Z, Song Q, et al. Surface micromorphology and nanostructures evolution in hybrid laser processes of slicing and polishing single crystal 4H-SiC[J]. *Journal of Materials Science & Technology*, 2024, 184: 235-244.
- [7] Peng Y, Zeng J, Xie X, et al. Laser machining of silicon carbide: current status, applications and challenges[J]. *Optics & Laser Technology*, 2025, 191: 113376.
- [8] Jiang K, Zhang P, Song S, et al. A review of ultra-short pulse laser micromachining of wide bandgap semiconductor materials: SiC and GaN[J]. *Materials Science in Semiconductor Processing*, 2024, 180: 108559.
- [9] Kim E, Shimotsuma Y, Sakakura M, et al. Ultrashort pulse laser slicing of semiconductor crystal[C]//Jitsuno T, Shao J, Rudolph W. *Pacific Rim Laser Damage 2016: Optical Materials for High Power Lasers*. Yokohama, Japan, 2016: 99831B.
- [10] Kim E, Shimotsuma Y, Sakakura M, et al. 4H-SiC wafer slicing by using femtosecond laser double-pulses[J]. *Optical Materials Express*, 2017, 7(7): 2450.
- [11] Shifei Han, Haijuan Yu, Chaojian He, et al. Laser slicing of 4H-SiC wafers based on picosecond laser-induced micro-explosion via multiphoton processes[J]. *Optics & Laser Technology*, 2022, 154: 108323.
- [12] Geng W, Shao Q, Pei Y, et al. Slicing of 4H-SiC Wafers Combining Ultrafast Laser Irradiation and Bandgap-Selective Photo-Electrochemical Exfoliation[J]. *Advanced Materials Interfaces*, 2023, 10(21): 2300200.
- [13] Lu Jiang, Zhao S, Han S, et al. CW laser-assisted splitting of SiC wafer based on modified layer by picosecond laser[J]. *Optics & Laser Technology*, 2024, 174: 110700.

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- [14] Lv B, Ye L, Zhu X, et al. Ultrasonic-assisted stripping of single-crystal SiC after laser modification[J]. *Ceramics International*, 2024: S0272884224042081.
- [15] Hanwen Wang, Chen Q, Yao Y, et al. Influence of Surface Preprocessing on 4H-SiC Wafer Slicing by Using Ultrafast Laser[J]. *Crystals*, 2023, 13(1): 15.
- [16] Chen Q, Yao Y, Zhang J, et al. Effect of nitrogen doping concentration on 4H-SiC laser slicing[J]. *Journal of the American Ceramic Society*, n/a(n/a): e20555.