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Damage Evaluation and Elemental Analysis of SiC Wafers Processed by Water Jet Guided Laser

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Abstract. Low-process damage dicing technologies are required to improve the reliability of silicon carbide (SiC) devices. Existing methods, such as ultrasonic diamond blade dicing, dry laser dicing, and stealth dicing, introduce mechanical or thermal stresses that lead to cracks and dislocations, including basal plane dislocations (BPDs), which degrade device quality. In this study, we assess the crystalline defects induced by water jet guided laser (WGL) processing on a SiC wafer using X-ray topography (XRT) and investigate the underlying processing mechanisms through Energy Dispersive X-ray Spectroscopy (EDX). The asymmetric contrast observed along the processed grooves in the XRT images was due to the X-ray irradiation direction, and no significant BPD formation was observed. The EDX results showed that the processed surface was oxidized by laser ablation. Thus, WGL processing can provide damage-free dicing of SiC wafers with minimal mechanical stress and defects.

Introduction

In the silicon carbide (SiC) device manufacturing process, technological improvements have been made to reduce defects, especially basal plane dislocations (BPD) on the wafer surface. However, there has been little discussion about BPD on the cut surface of the diced SiC chips after device manufacturing. To ensure high reliability in the long-term use of power devices, damage-free dicing technology that avoids brittle fractures is essential. Conventional dicing methods such as ultrasonic-assisted blade dicing, dry laser dicing, and stealth dicing have been employed to dice the hard and brittle SiC wafers [1–3]. While these methods can effectively cut through SiC, they typically induce mechanical and/or thermal stresses that can lead to microcracks, chipping, and the formation of dislocations, such as basal plane dislocations (BPDs). In power devices, these defects are detrimental, as they can propagate during device operation, leading to performance degradation, reduced reliability, and ultimately device failure [4]. Therefore, developing a dicing method that minimizes or eliminates these defects is crucial for the industrial application of SiC wafers.

Among the various approaches explored to overcome these challenges, water-jet guided laser (WGL) processing has attracted attention as a promising alternative.

Water Jet Guided Laser Technology

WGL processing utilizes a fine water jet, on the order of tens of microns in diameter, to act as an optical waveguide for a pulsed laser beam (Fig. 1) [5]. The laser's optical energy is absorbed by the SiC wafer, resulting in material ablation, while the water jet simultaneously cools the material, mitigating thermal damage and reducing the introduction of mechanical stresses. Finally, the scanning water jet laser removes material from the top to the bottom of the wafer, non-mechanical WJGL dicing can be achieved without the need for cleaving. This dual-action mechanism makes WGL particularly effective for processing materials like SiC, where maintaining structural integrity is critical. Additionally, the water jet removes debris and prevents the redeposition of ablated material, further contributing to a cleaner dicing process with fewer defects.

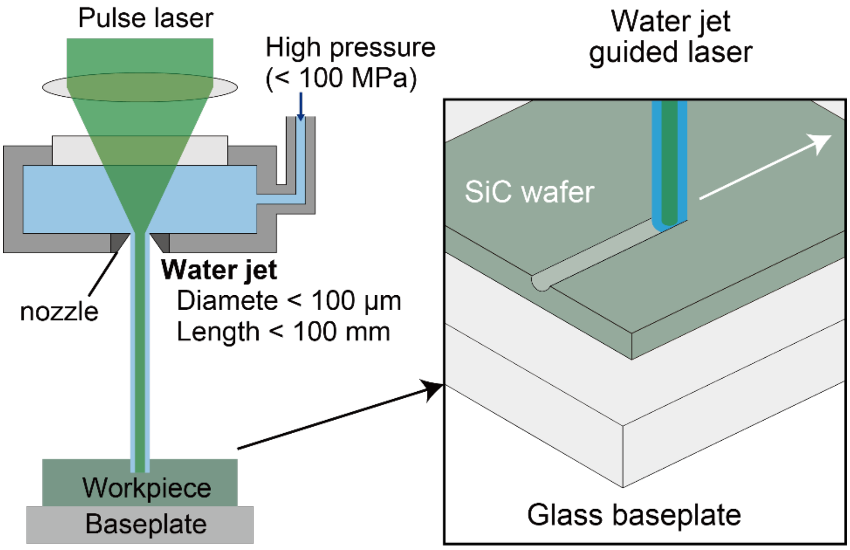

Fig. 1. Schematic illustration of WGL processing of a groove on a SiC wafer.

Progress of Research

Our previous study demonstrated that WGL processing can significantly reduce the incidence of chipping and BPDs compared to conventional blade dicing techniques. Although asymmetric dark and light contrasts were observed in X-ray topography (XRT) images along the WGL-processed grooves (Fig. 2), these contrasts were less severe than those typically observed with traditional methods, indicating that fewer or almost no BPDs were generated during the WGL process [6]. The asymmetric contrast pattern observed in XRT suggested the possibility of localized changes in crystal structure or the X-ray incident direction.

In this report, to elucidate the origin of this asymmetry and further validate the effectiveness of WGL processing, we conducted a more detailed investigation involving XRT from two opposing directions and energy-dispersive X-ray (EDX) analysis of cleaved wafer cross-sections. We present the results of these investigations, focusing on the underlying mechanisms that contribute to the observed contrast variations in XRT and their implications for the dicing process.

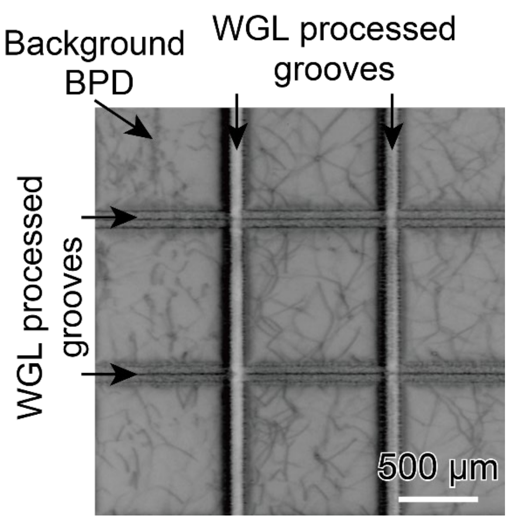

Fig. 2. Asymmetric contrast pattern observed in XRT image along WGL processed grooves on SiC wafer.

Methods and Results

Experimental condition of slit machining

Figure 1 shows a schematic diagram of a grooving experiment on a 4H-SiC wafer using a WGL system (MCS300; Makino Milling Machine Co., Ltd.). The wafer was fixed on a glass base plate, the water pressure was 20 MPa, the assist gas (He) flowed at 1 L/min, and the distance between the nozzle and the wafer was 25–30 mm. The laser irradiation conditions were a wavelength of 532 nm, pulse width of about 200 ns, pulse frequency of 10 kHz, and output power of 30–80 W. The water jet was scanned at the speed of 10–60 mm/s, which was almost same speed of the typical blead dicing method ~10 mm/s

XRT observation

To confirm whether BPDs are formed by WGL processing, SiC with grooves was measured using reflective XRT (XRTmicron, Rigaku). The pixel size is 2.4 μm, and the XRT image is displayed in a negative tone. Therefore, crystal defects, strain, and BPDs appear dark. The contrast variation depending on the incident direction was clarified by comparing the reflected XRT images from the two opposing directions (11-28 and 1-128 reflection).

XRT images of WGL grooved wafers with opposite X-ray illumination are shown in Fig. 3. Some background BPDs were seen throughout the wafers as gray line contrasts. Although dark contrast can be seen on one side of the processed groove, the asymmetric contrast was swapped by reversing the incident direction.

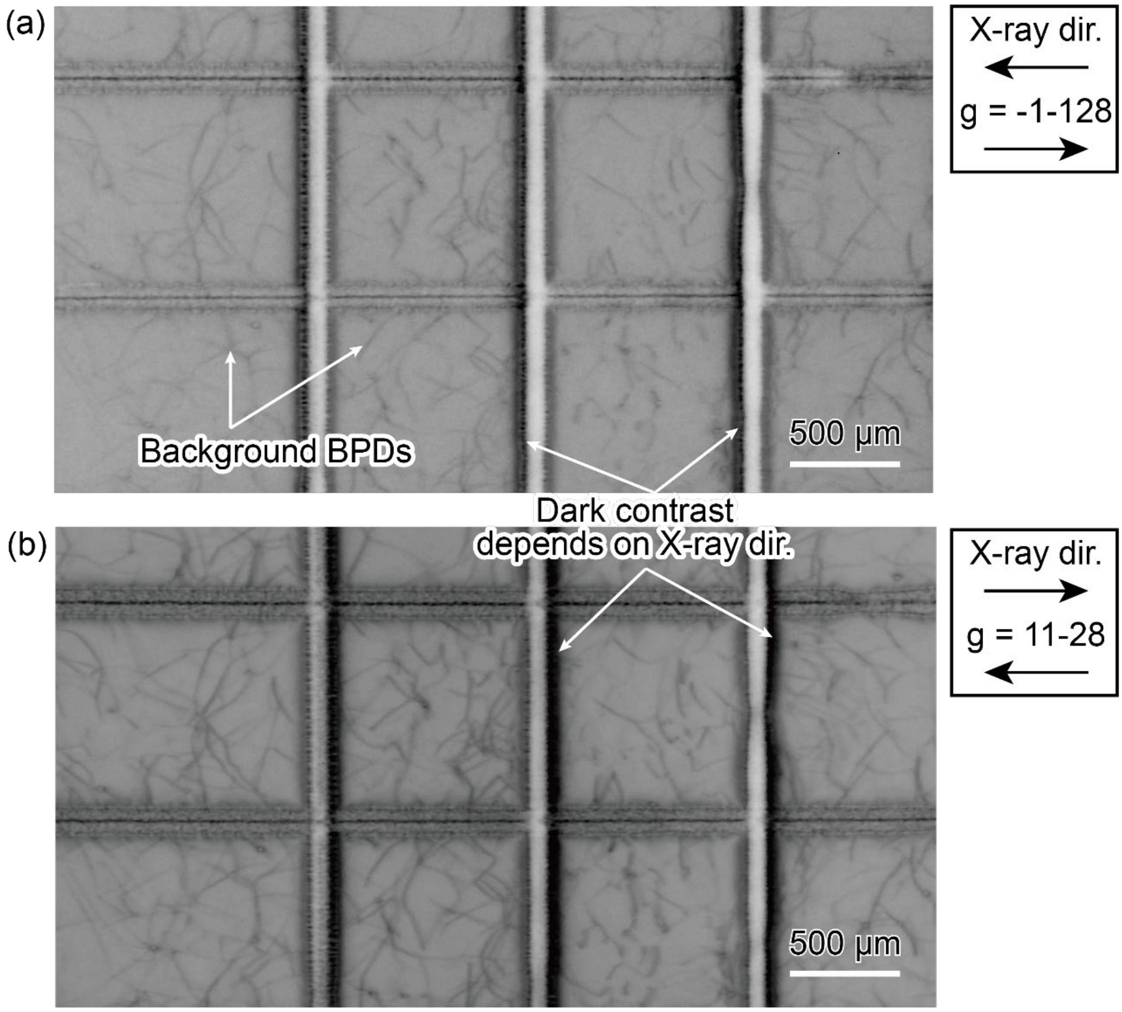

Fig. 3. XRT images with X-ray illumination from (a) right and (b) left sides.

EDX analysis

The grooved wafer was cleaved parallel to the 2nd orientation flat. The processed SiC wafer was evaluated by scanning electron microscopy (SEM; JSM-6010LA, JEOL) and EDX analysis. Since the cross-section is composed of an ablation layer at the upper part and a bulk layer at the lower part, we performed mapping of the elemental distribution by area measurement. Furthermore, to clarify the crystal structure change of the ablation layer, we obtained quantitative elemental composition ratios at four locations #1–4 from the top to the bottom of the wafer.

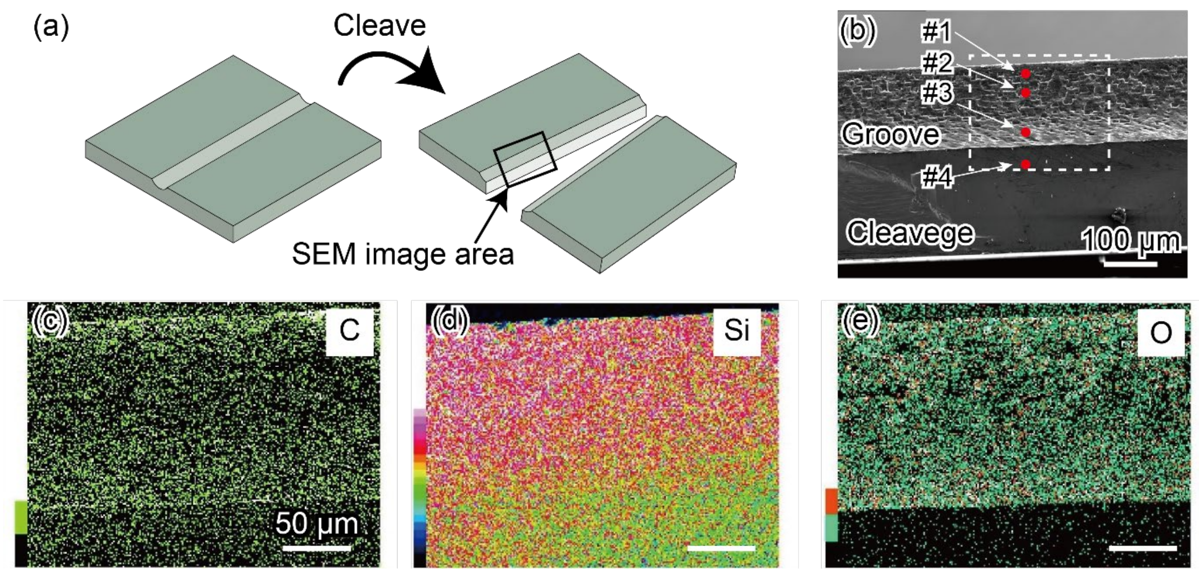

Fig. 4. Cross-sectional SEM images and EDX analysis of groove-processed SiC wafers. (a) Schematic illustration of the cleavage of a grooved SiC wafer. (b) SEM image. EDX results of (c) C, (d) Si, and (e) O. Processing parameters are follows: 6 scans, 20 mm/s, and 80 W.

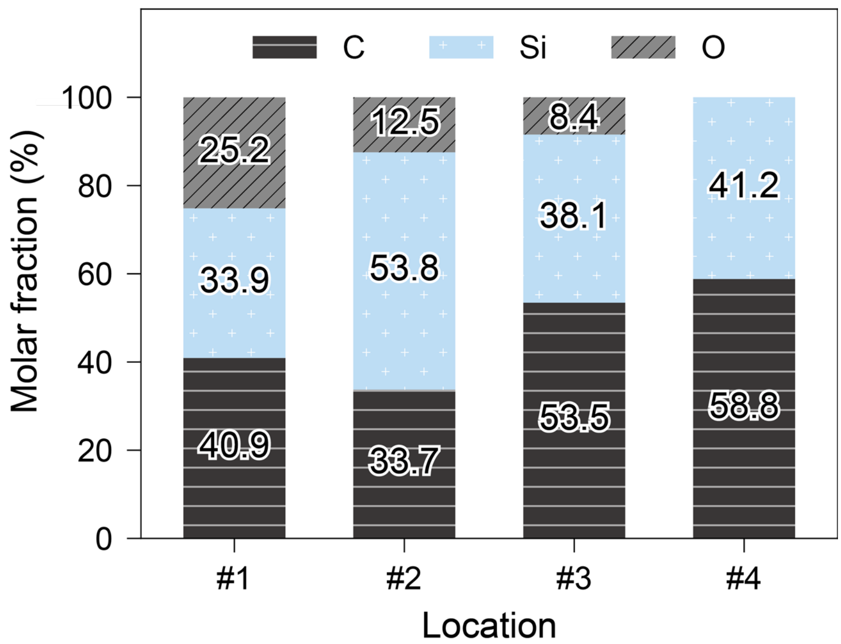

Fig. 5. Point EDX analysis of location #1–4.

Next, to clarify the processed groove morphology and processing mechanism, SEM observation and EDX analysis were performed on the cross-section of the groove-processed SiC wafer, as shown in Fig. 4a. By observing the cross-section of the cleaved SiC wafer, the ablation layer was observed in the processed groove of ~150 µm depth (Fig. 4b). A 2D elemental maps shown in Fig. 4c–e were obtained from the ablation groove on the upper side to the lower the bulk SiC part. As shown in Figure 4c–e, carbon and silicon were observed equally in both areas, but oxygen was detected only in the processed area. Fig. 5 shows the point measurement of the EDX quantitative elemental analysis. The results show that carbon and silicon were approximately 59 and 41% on the cleaved SiC surface (#4), and no oxygen was detected. On the grooved surface, carbon, silicon, and oxygen were 34–54%, 34–54%, and 8–25%, respectively.

Discussion

The asymmetric contrast along the grooves were caused by the difference of the incident direction of X-rays. The contrast variation along the groove may be due to the surface texture and the crystal structure. Therefore, it is necessary to investigate the change in crystal structure using the following EDX analysis, among others. It should be emphasized that, excluding the background BPD, almost no BPD originating from the WGL groove can be confirmed.

According to the EDX result, three times more oxygen was detected in the upper #1 area than in lower #3 area. The results are also consistent with previous reports, such as the generation of SiO_2 and amorphous carbon through laser ablation of SiC [7]. This result suggests that the light contrast along the grooves observed in the XRT was caused by oxidation and graphitization of SiC during the laser ablation process. As a result, BPD-free groove processing can be performed by the WGL processing with laser ablation of the SiC substrate without mechanical stress.

Conclusions

In this study, to verify the damage-free dicing of SiC wafers using the WGL process, the grooved SiC wafer was incident from two directions, the XRT images were analyzed, and the cleavage surface was subjected to EDX analysis to estimate the processing mechanism. As a result, BPD was hardly observed in the WGL grooves of SiC by XRT, and oxidation due to the laser ablation process was confirmed by EDX analysis. For future work, the processing conditions should be optimized regarding wafer damage and processing efficiency.

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