Scratching test of single-crystal silicon carbide by abrasives on wire saw

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Abstract. Wire sawing can be regarded as a complex multiple scratching process of the work-piece by the diamond abrasives on wire saw. Single scratch test and repeated scratching test on the (0001) surface of 4H-SiC wafer by the abrasives on wire saw are carried out in order to acquire the fundamental understanding of the wire sawing process. Results show that cracks occurred in brittle material removal mode when the scratching depth is beyond a critical value. Radial cracks will propagate near the $\{1\bar{1}00\}$ plane which is the primary cleavage plane of the (0001) wafer. Besides, multiple scratching grooves generated by two abrasives or two cutting edges of one abrasive can be observed in a single scratching test. Material peeling is more easily to occur in repeated scratch than in a single scratch as a result of the pre-existed cracks generated in the first scratch. The interaction of radial cracks and lateral cracks will lead to the large area removal of materials.

Introduction

Single-crystal silicon carbide (SiC) is an important wide-band-gap semiconductor material used in electronic field due to its excellent chemical and mechanical properties [1]. Wire sawing technology has been used to slice crystal materials into wafers, which has the advantages such as low kerf loss, high efficiency, good machining qualities and low pollution [2]. However, subsurface damage was still generated during the wire sawing process as a result of the hard and brittle properties of single-crystal SiC [3]. The damage layer need to be removed to satisfy the stringent quality requirement of the application of SiC wafers. Thus, it is important to acquire the fundamental understanding of the wire sawing process to improve wafer qualities.

The wire sawing can be regarded as a complex multiple scratching process of the work-piece by the diamond abrasives on wire saw. Hence, the investigation of the scratching process could help to get the fundamental understanding of the wire sawing process. Both ductile and brittle material removal modes for the scratching abrasives were found in the wire sawing process, and the existence of ductile mode helped to improve surface qualities of the sliced wafers [4]. The theoretical relationship between the scratching force and the scratching depth for the abrasives on the wire saw considering both ductile and brittle modes was established by Wang et al. [5]. The geometry of the abrasives was assumed to be a regular triangular pyramid with a spherical tip. Kumar et al. [6] performed a scratching test using the wire saw and found that the sharper abrasive produced more serious subsurface damage.

Investigations of the scratching process have been carried out by many researchers using the standard indenter. The anisotropic scratching-induced stress field in the vicinity of the indenter tip was obtained by the superposition of the elastic stress field and residual stress field in single-crystal SiC [7]. The amorphous phase of 6H-SiC was found at the bottom of the scratch groove during the scratching test using a Berkovich diamond indenter [8]. Wang et al. [9] investigated the scratching-induced cracks for optical glasses, and found that the median crack occurred first and then the lateral crack initiated causing the removal of materials. However, the studies above were mostly dealt with the scratching problem using the standard indenter. The actual scratching process of the abrasives on wire saw need a further investigation.

In this paper, both single scratching test and repeated scratching test are conducted on single-crystal SiC wafer by the abrasives on wire saw. The actual shapes of the abrasives used in the scratching tests are different from the standard indenter. Based on the SEM observation of the surface morphology of scratching grooves, the crack propagation and material removal mechanism are investigated. This paper will provide a better understanding for the removal mechanism in wire sawing process and help to improve wire sawing qualities of brittle materials.

Experiments

Scratching tests are conducted on the (0001) surface of 4H-SiC wafer (HeFei Crystal Technical Material Co., Ltd.). The wafer size was $5\times5\times0.5$ mm^3 and the (0001) surface is polished with the roughness less than 1nm. The scratching direction is along the $<11\bar{2}0>$ direction. The wire saw is fixed on the wire fixture with two screws. The wafer is placed on the workbench which is fixed on the micro-motion platform (Winner Optical Instruments Group Company Ltd.), as shown in Fig. 1(a) and Fig. 1(b). The micro-motion platform can realize the movements along three directions (*x*, *y* and *z*) with the minimum displacement of 0.5μm. The *x* direction is the scratching direction and the *y* direction is the feed direction. It should be noted that the scratching speed is by manual control and is less than 500μm/s.

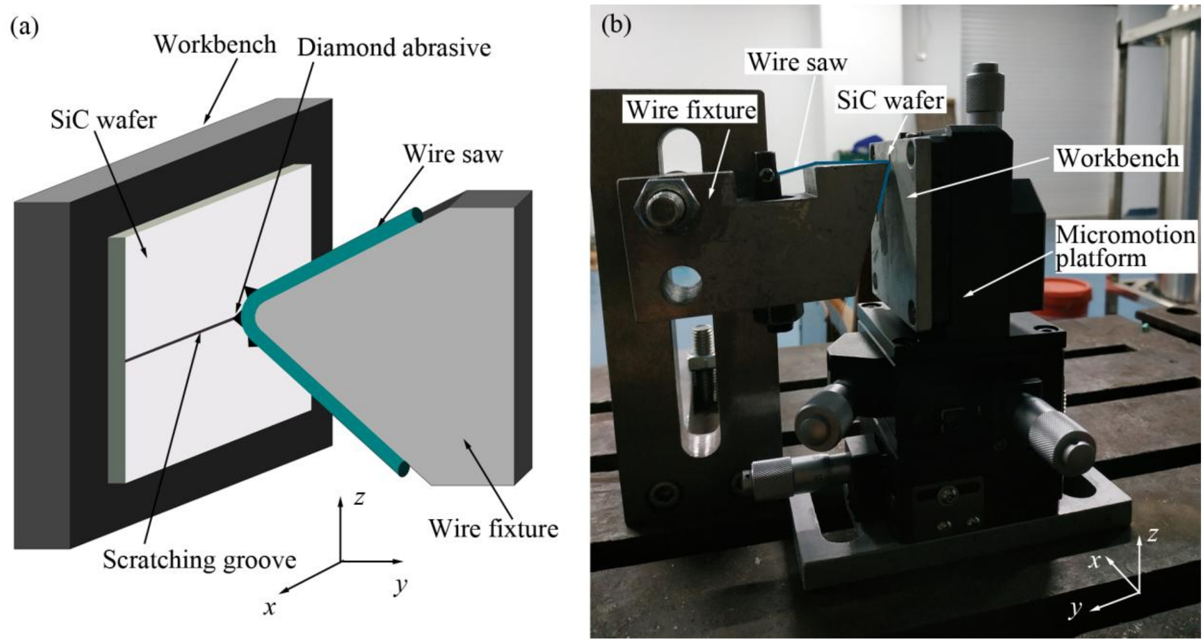

Fig. 1. (a) Principle of scratching tests using the wire saw; (b) Setup of scratching tests.

The core diameter of the electroplated diamond wire saw (DongGuan De Saw Hardware Co., Ltd.) is 150μm and the diameter of the diamond abrasives is between 30μm and 40μm, as shown in Fig. 2(a). The wire saw is mounted on the wire fixture. The scratching zone of the wire saw used in one of a number of scratching tests before scratching is shown in Fig. 2(b). It can be seen that the diamond abrasive generating scratching groove is clear in the red elliptical region observed by the digital microscope (OT-PM200, Insize Co., Ltd.). However, the abrasive is pulled out after several times of scratching tests, as depicted in Fig 2(c).

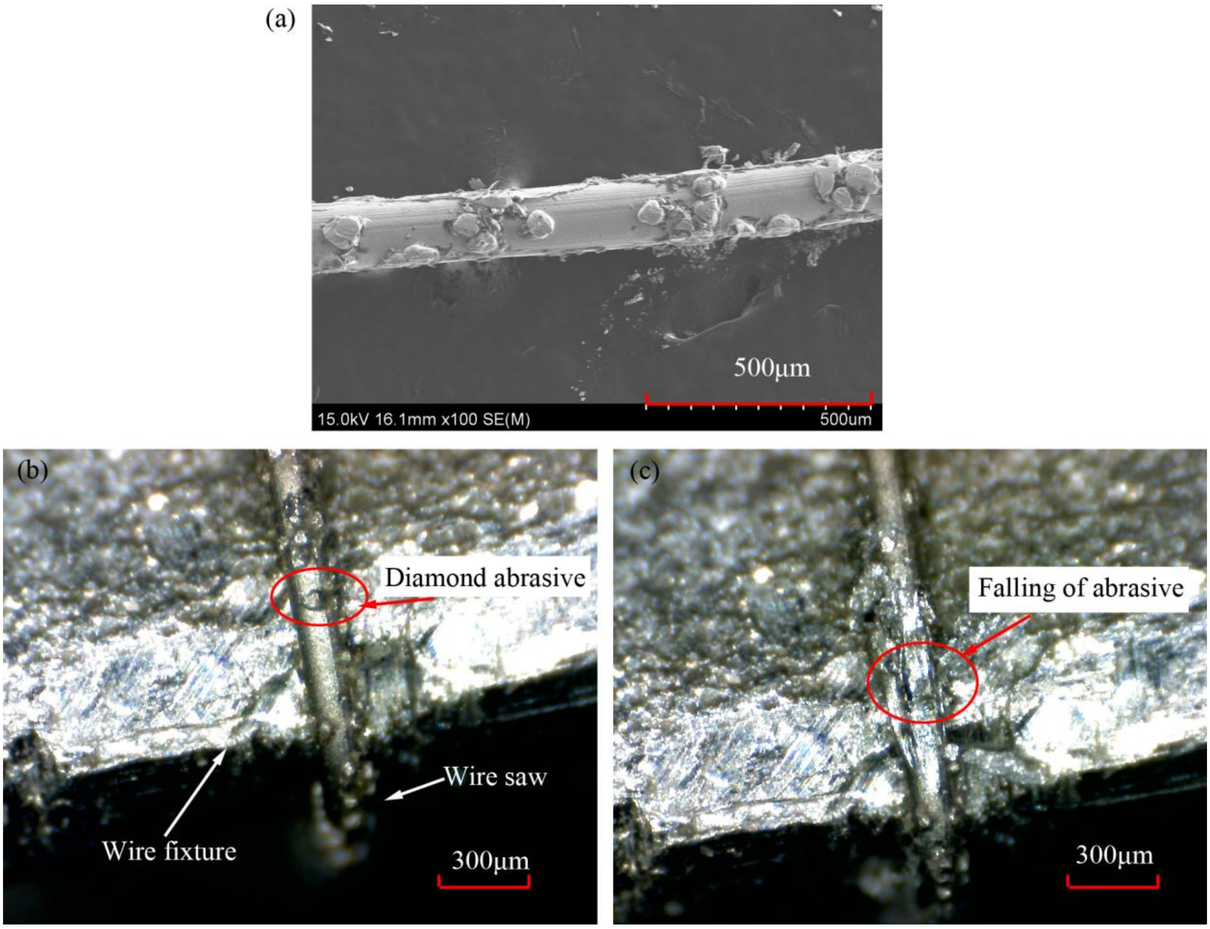

Fig. 2. (a) SEM observation of the diamond wire saw; (b) Image of the scratching zone on the wire saw before scratch; (c) Image of the scratching zone on the wire saw after scratch.

Results and discussion

The result of a single scratching test is shown in Fig. 3. If the scratching depth is smaller than a critical depth value, the ductile groove will be generated, as depicted in Fig. 3(a). The critical depth from ductile removal mode to brittle mode is affected by the properties of materials and the geometry of indenter. The value of this critical depth for 6H-SiC with a Berkovich indenter is measured to be 75nm [10]. Obvious traces of plastic flow can be found in the groove instead of cracks, which is the characteristic of ductile removal mode. Different from the groove scratched with a standard indenter, the groove in Fig. 3(a) is found to be composed of several small grooves because of the actual shape of the diamond abrasive on wire saw. As the scratching depth increased, radial cracks occur in the two sides of the groove, and material peeling is found near the radial cracks as shown in Fig. 3(b). This is the characteristic of brittle removal mode. Besides, the angle values between the radial cracks and the scratching direction are between 27° and 35°. This indicates that the radial crack planes are near the {1$\bar{1}$00} plane which is the primary cleavage plane of (0001) wafer [11].

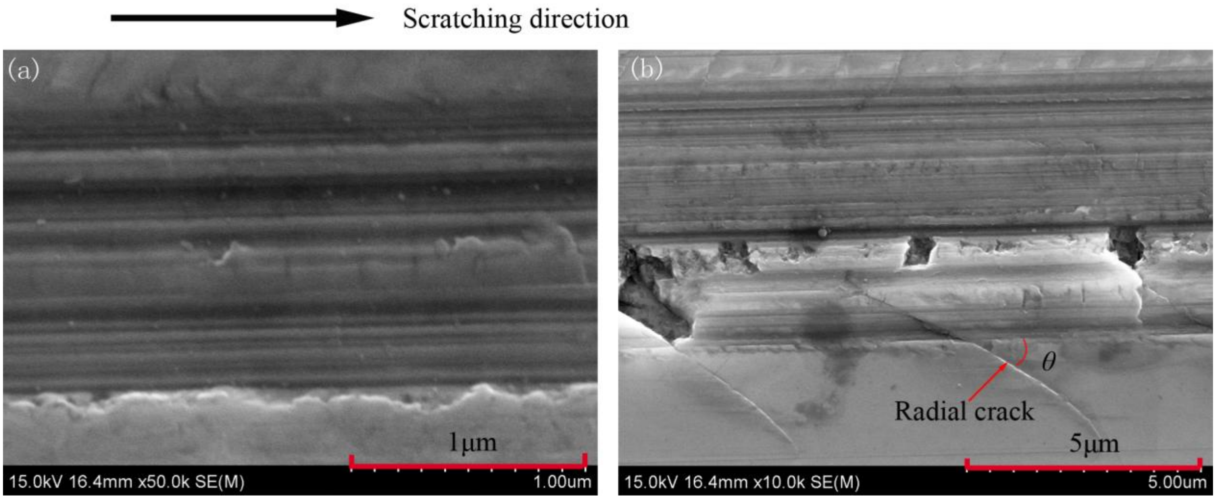

Fig. 3. SEM observation of the single scratching groove: (a) Ductile removal mode; (b) Brittle removal mode.

An interesting phenomenon is observed when we carry out the single scratching test. That is multiple scratching grooves can be found in a single scratching test, as shown in Fig 4(a). The multiple grooves can be generated by two abrasives or two cutting edges of one abrasive. The distance between the two grooves in Fig 4(b) is less than 1.5μm. The radial cracks can be found in the region between the two grooves. The interactions of the radial cracks will lead to the material removal of this region. This phenomenon indicates that there could be multiple scratches with a relatively small distance between them in the wire sawing process, and this situation should be considered.

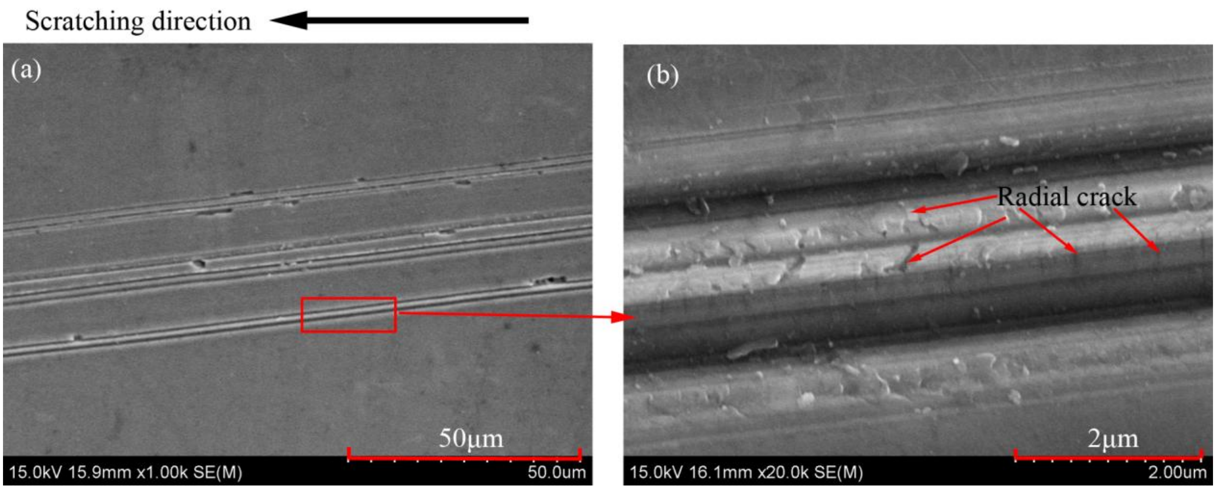

Fig. 4. (a) SEM observation of multiple scratching grooves; (b) The related region at higher magnification.

Repeated scratching test which may exist in the wire sawing process is also carried out. Fig. 5 (a) is the SEM image of a single scratching groove and Fig. 5 (c) is the image of a repeated scratching groove. It should be noted that the scratching depth of the repeated scratch is equal to the scratching depth of the single scratch in Fig. 5(a). It can be seen that the material peeling is more easily to occur in repeated scratch than in single scratch as a result of the pre-existed cracks generated in the first scratch. The interaction of radial cracks and lateral cracks will lead to the large area removal of materials, as shown in Fig. 5(d). Besides, the angle values between the radial cracks and the scratching direction in Fig. 5(b) are between 27° and 34°, which coincide with the observation in Fig. 3(b).

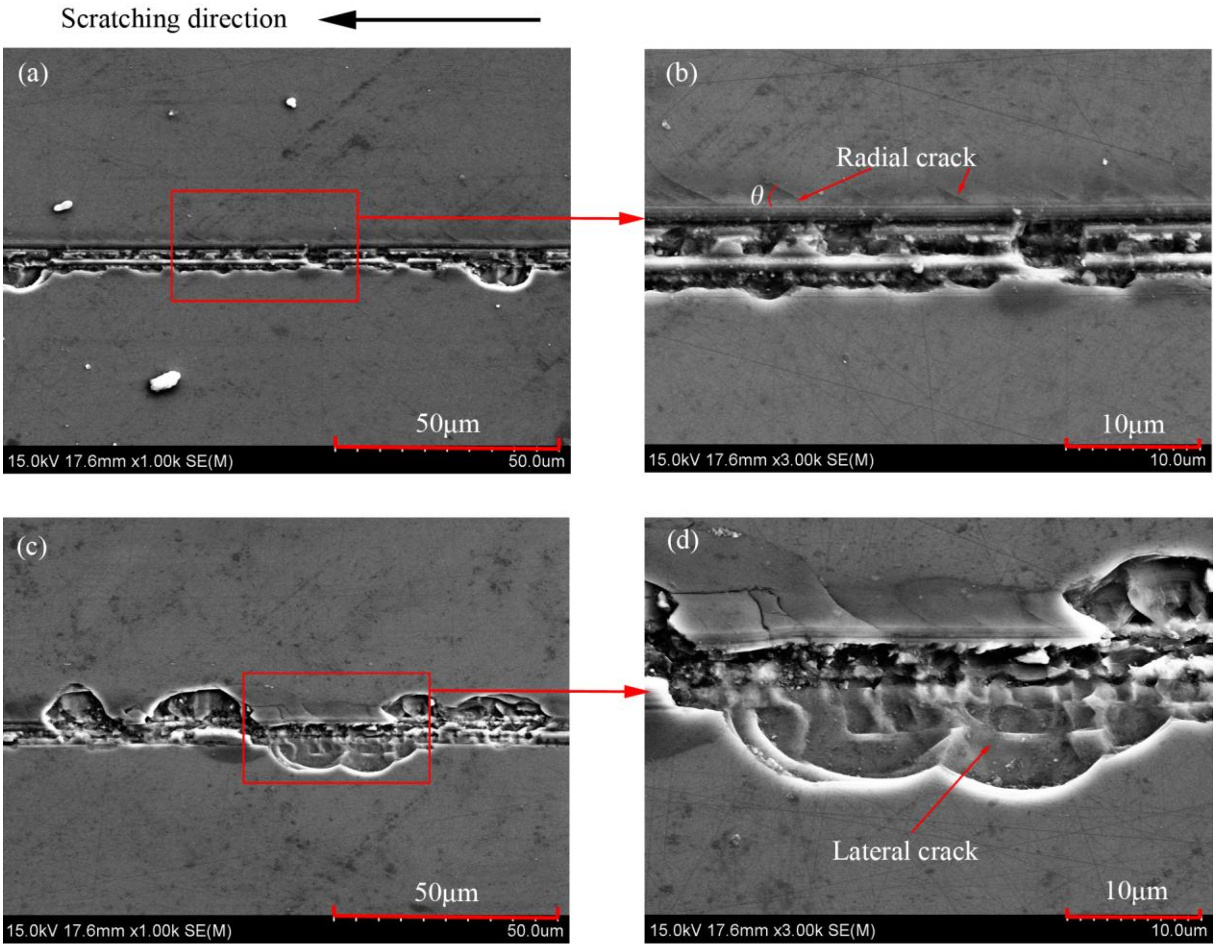

Fig. 5. (a) SEM observation of the single scratching groove; (b) The related region at higher magnification; (c) SEM observation of the repeated scratching groove; (d) The related region at higher magnification.

Summary

Scratching tests on the (0001) surface of 4H-SiC wafer were carried out using wire saw in order to find the fundamental understanding of the wire sawing process. The SEM observation of the used wire saw was given and the diameter of the diamond abrasives was between 30μm and 40μm. It was found that the single scratch groove was composed of several small grooves because of the actual shape of the diamond abrasives on wire saw. The ductile removal mode changed to brittle removal mode with the increase of scratching depth. The radial cracks occurred in brittle removal mode and propagated near the $\{1\bar{1}00\}$ plane, which was the primary cleavage plane of (0001) wafer. Multiple scratching grooves generated by two abrasives or two cutting edges of one abrasive were observed in a single scratching test. Besides, repeated scratching test was performed and showed that material peeling was more easily to occur than that in the single scratching test.

Acknowledgments

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