



Comparative Study of Cutting Methods for Silicon Carbide Wafers

Yuting Liu

Glasgow College, University of Electronic Science and Technology of China, 611731
Chengdu, China

2023190501023@std.uestc.edu.cn

Abstract. Silicon-based electronic products are the main devices in the world's market. However, silicon has a relatively narrow bandgap and it is difficult for silicon-based electronic products to work in extreme environments. Therefore, silicon carbide emerged as the third-generation semiconductor. An important problem in the production of silicon carbide wafers is how to cut such material. This paper reviews three main methods: diamond wire saw cutting, electrical discharge machining (EDM), and laser cutting. As for the depth of the damaged layer, three methods are close to each other, but laser cutting can control the depth with controlled energy. Another factor is thickness. The thickness of the slice is limited when using diamond wire sawing since the width of the wire should be considered, but the other two methods do not restrict the thickness. Future direction for diamond wire sawing is to make the diameter of the wire smaller and the laser pulse width of laser cutting should be lower. EDM is mainly used in the cutting of metal material, whereas for semiconductors it needs more improvement.

Keywords: Silicon Carbide, Diamond Wire Saw, Electrical Discharge Machining, EDM, Laser Cutting.

1 Introduction

Silicon-based electronics have developed rapidly since the 1950s and continue to dominate the current information technology landscape. However, with the progress of times and the development of technology, the many shortcomings of silicon-based electronic products gradually appeared. Silicon has a relatively narrow bandgap energy, low electron mobility and low breakdown electric field, and is sensitive to high temperature environments, making it difficult to broaden the application of silicon in high temperature, high voltage, high frequency, and high-power environments [1]. In order to solve a series of problems and bottlenecks in silicon-based electronic products, the second generation of semiconductors, represented by gallium arsenide (GaAs) and indium phosphide (InP) has been widely studied. Their high electron mobility has led to the further development of semiconductors. However, the lack of sufficient resources for the material and the pollution of the environment still makes them difficult to broaden their application. The third generation of semiconductor materials, represented

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by silicon carbide (SiC) and gallium nitride (GaN), has become a new trend. This material can be widely used in extreme high temperatures, high pressures and other operating environments due to their wide bandwidth nature, which provides a major advantage.

The purpose of this paper is to discuss the advantages and disadvantages of diamond wire saw cutting, EDM cutting and laser cutting in the production of silicon carbide wafers, and the article synthesizes a comparison of the various methods. This study suggests a better way forward for the future cutting of hard and brittle materials like silicon carbide.

2 Main Cutting Technologies of Silicon Carbide

Cutting is an important processing step in the manufacture of silicon carbide wafers. Silicon carbide materials are hard, with a Mohs hardness between 9 and 9.5, second only to diamond. It is also brittle and chemically stable, making it difficult to process. The current process includes diamond wire saw cutting, EDM cutting, and laser cutting. Diamond wire saw cutting is widely used. Low cost and ease of fabrication are the main advantages of this method, but there are problems with cracks in the wafer caused by the cutting, and a high degree of surface wear. EDM cutting and laser cutting allow higher precision and avoid mechanical damage, but the corresponding costs will be correspondingly higher. This paper will focus on the specific implementation and effectiveness of these three methods and will analyze and discuss the advantages and disadvantages of each method.

At present, the diamond wire saw cutting technology is more mature. The diameter of the traditional wire saw cutting is large ($>180\ \mu\text{m}$). This paper will also discuss the optimized way of preparing diamond wires, which are small-diameter, high-strength electroplated diamond wire saws [2]. Laser technology also exists in many ways, such as ultrashort pulsed lasers, femtosecond lasers, and so on.

3 Analysis of Various Cutting Methods

3.1 Wire saw cutting

Wire saw cutting has two main forms. The first form is free abrasive wire saw cutting; it is which uses of wire saw drive slurry in the abrasive grains to cut the solids [3]. The other is the solidified abrasive wire saw cutting, which is through the plating method or resin bonding agent bonding method to bond diamond abrasive grains and abrasive wire and then cut the solids [3]. As for the solidified abrasive wire saw, the following three production methods are available: resin, brazing and plating, but there is a significant problem for the resin bonding method is that when the temperature rises, the diamond abrasive grains fall off due to the melting of the resin, which will lead to a decrease in the efficiency of cutting [2]. For the structure of the baseline, ring baseline, single saw wire baseline, double twisted baseline, triple twisted baseline, and helical baseline are

presented, in order to meet the performance requirements for tensile strength, fatigue strength, torsional strength and flexural strength [2]. There are two main ways of cutting: the first is reciprocating cutting and the second is unidirectional cutting [3].

For the wire saw cutting method, this paper firstly refers to the tungsten wire matrix diamond wire saws formed by using the sulfamate system as the electroplating solution used by Li Zheng et al. in their study, where the diameter and strength of the wire saws were optimized to be smaller and larger by the new electroplating method and diamond wire saw production method proposed in that article, respectively [2]. The cutting method used was reciprocating [2]. Silicon carbide was cut using the above diamond wire saw and the roughness and warpage of the silicon carbide slices were statistically analyzed. The roughness was measured using a surface profiler, and the average roughness in the horizontal direction was about $0.4 \mu\text{m}$ while the average roughness in the vertical direction was about $0.86 \mu\text{m}$ [2]. The maximum warpage height is about $44.3 \mu\text{m}$ [2].

In addition to the data study on the surface roughness, in the study of Wang Peizhi et al. proposed a model of the surface texture damage mechanism of slices, abstracted the diamond particles as a positive triangular cone with a spherical tip, and mentioned that there are sub-surface lateral cracks and median cracks in the cracks generated during the diamond cutting process [4]. Such a model demonstrates the cracking mechanism produced by diamond wire saw cutting and shows the inevitable damage cracks in the cut. The exact depth of cracks is mainly determined by the vertical speed and horizontal speed in the research model [4]. For brittle materials, cracks are mainly classified into two forms, the first is the radial central crack and the other is the lateral crack, in which the radial crack spreads directly into the crystal interior [5]. In addition, when referring to the damage layer on the surface of the material in some studies, it is divided into the microcrack damage layer and the plastic deformation layer, and in some studies, the crack damage layer is directly made as the damage layer, so to measure the thickness of the crack damage layer [6]. In the study of Wang Peizhi et al. the average depth of radial cracks obtained after seven sets of experiments was $29.3 \mu\text{m}$ [4]. In the research data of Li Lun et al. the thickness of the damage layer is between $10\text{-}50 \mu\text{m}$ [6]. These results are indicative of the possible depth of the radial crack, i.e. the depth of the damage layer. The precision of diamond wire saw cutting is poor and only suitable for rough machining, the research data of Li Lun et al. mentioned that the minimum thickness of the slices is 0.5mm , and the diameter of the cut wafers is less than 200mm [6].

In general, diamond wire saw cutting has unavoidable mechanical damage (cracks), as well as physical limitations. The thickness and diameter of the slices are unable to meet the increasing demand for precision, which is a major problem to be overcome by diamond wire saw cutting at present.

3.2 Electrical discharge machining(EDM)

EDM cutting uses a tool as the electrode, approaches the workpiece and emits a continuous high-frequency pulse signal. The resulting electric spark releases high temperatures between the plates, melting the workpiece and generating metal vapors, etc.,

which in turn produces a slight explosion and thermal expansion to carry away the waste material [3]. Such a cutting method can achieve better precision for brittle materials like SiC and ensure better surface quality of the slices. Figure 1 shows the EDM principle diagram, and Figure 2 shows the principle of EDM wire cutting.

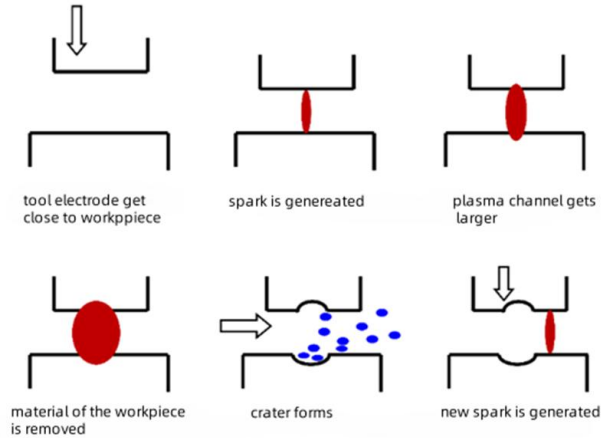


Fig. 1. EDM principle.

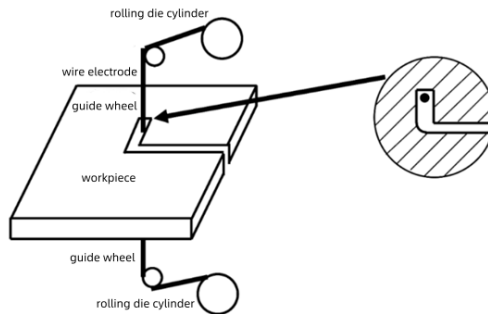


Fig. 2. Principle of EDM wire cutting.

In principle, spark cutting is a discharge between two poles to produce an electric spark, usually used to cut metal materials. Due to the conductivity of semiconductor materials between conductors and insulators, SiC can still be used in such a cutting method. Similar to laser processing, EDM cutting also utilizes the thermal energy generated by an electric spark to etch the material. In the study of Zhang Huigang et al, it was proposed that EDM is specifically divided into four steps, dielectric breakdown, channel discharge, melting gasification and de-ionization, in which the temperature of the discharge channel is able to reach tens of thousands of degrees Celsius [7]. Multi-wire EDM cutting has the problem of broken wires. However, in a study by Masumi Ogawa et al. in which experiments were carried out on multi-wire EDM cutting by means of an EDM pulse control system and by immersing silicon carbide in pure water.

Cutting speeds up to 300 $\mu\text{m}/\text{minute}$ for 3-inch ingots and 700 $\mu\text{m}/\text{minute}$ for 2-inch ingots. The above two sets of experiments used 4 wire cuts. Ten wires with a diameter of 140 microns were also used to cut SiC single-crystal ingots ranging from 2 to 4 inches, and no wire breaks occurred. And the roughness of the surface of the 3-inch finished product was measured as $R_a=1\mu\text{m}$ [8]. Yonghua Zhao et al. proposed a cutting method using blade electrodes, which also solves the problem of EDM wire cutting and allows for finer cuts and it is shown in Figure 3 [9].



Fig. 3. Two different cutting electrodes.

The thickness of the wafer changes during EDM cutting, as shown in Figure 4.

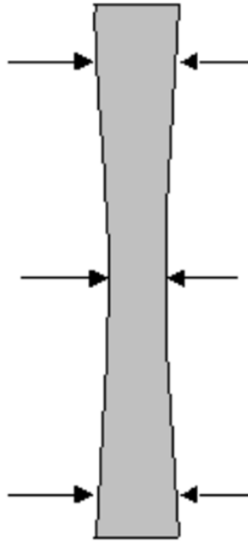


Fig. 4. Side view of the finished product formed by cutting

At a line spacing of 1.0 mm, the thickness variation is about 20 μm for 3-inch wafers and 30 μm for 4-inch wafers. The removal of the center portion of the wafer increases as the ingot size increases [8]. This is due to the effect of lateral sparking during machining and the fact that as the size of the wafer increases, it is more difficult for the

water flow to enter to dislodge the debris [8]. EDM cutting has the problem of wafer thickness variation due to lateral EDM and wire breakage in case of high voltage, and there may be the problem of heat-affected zone similar to that of laser cutting, as it is cutting by utilizing the thermal effect of EDM. However, the more appropriate cutting speed and the absence of mechanical damage are still its advantages.

3.3 Laser cutting

The main feature of laser cutting lies in the non-contact cutting, which avoids the mechanical stress damage brought by traditional cutting, such as chipping and peeling off the metal layer [4]. Laser's highly directional, high power density and better focusing characteristics are the main reasons why lasers can be used as precision processing, the main laser cutting techniques in existence are laser ablation cutting, water-assisted laser cutting, laser thermal fracture cutting and laser invisible cutting[10].

For laser, the main parameters are laser wavelength and pulse width. In terms of pulse width, when the power and frequency are the same, the smaller the pulse width, the smaller the heat-affected zone, which can reduce the impact on the edge [11]. The current major lasers are femtosecond and picosecond lasers used in formal production, and the attosecond laser is still in the experimental stage and not yet in use due to its price [1]. The main discussion of cutting methods in this paper will focus on the consideration of ultrashort pulsed lasers of the femtosecond and picosecond classes for the precision cutting of silicon carbide materials.

Of the laser cutting talked about in the second part, the study of laser ablation cutting dominates. The main principle of laser ablation cutting is the use of laser energy greater than the ablation threshold of the wafer material, forcing the material in the local gasification, melting, decomposition, which is essentially a kind of use of high temperature on the material cutting method, and then because of the thermal effect of the formation of a molten layer in the chip sidewalls, known as the heat-affected zone (Heat-affected zone) [10]. The heat-affected zone affects the quality of wafer production and needs to be further removed in subsequent steps using polishing, so reducing the depth of the heat affected zone has become an important proposition for research.

In the study by Yang Tingkai et al. a clear relationship between the modified layer and the laser energy density is given, and the depth of the modified layer is further increased with the increase of the laser energy density, and the overall trend is close to linear in the interval between the energy density of 0.40 J/cm² and 0.65 J/cm² [12]. The relationship between ablation line width and energy density is given, and the same trend exists with the depth of the modified layer, as the energy increases, the ablation line width also increases [12]. In the study by Nan Jurong et al, the surface of silicon carbide wafers was cut by laser, giving the depth of the laser cut surface damage layer to be about 100 μm, and the roughness Ra of the peeled surface to be 0.934 μm and 1.389 μm, respectively [1].

In general, the depth of the damage layer of laser cutting can be controlled by controlling the pulse energy, but researchers also need to consider that when the energy density is low, it will have an impact on the efficiency of the cutting. Of course it can also be seen that the width of the laser ablation can be controlled in a very small range.

The surface roughness of laser cutting is common and has no obvious advantages. Laser cutting can realize more complex cutting forms, such as curve cutting and more precise cutting process that requires higher wafer thickness.

4 Conclusion

For the surface damage layer, the mechanical damage cracks caused by the mechanical stresses existing on the diamond wire saw cutting surface are usually in the tens of micrometers. The undulation of the curved surface due to lateral sparking in EDM cutting is also in the range of a few tens of micrometers, but this value may be even larger, taking into account the effect of the possible presence of a heat-affected zone. The heat-affected zone of laser cutting is between a few tens and a hundred micrometers, which is usually determined by the energy of the laser. There is a direct relationship between the thickness of the damaged layer and the amount of material consumed in the later stages of polishing, which is aimed at removing the damaged layer. The thickness of the damage layer in the three methods is influenced by a number of factors; there are obvious physical limitations in diamond wire saw cutting, which are correlated with the direction of the grinding speed, while the damage layer in EDM cutting is directly linked to the diameter of the wafer and the parameters of the cut such as voltage, and the damage layer in laser cutting is highly linked to the energy of the laser. But there is little overall difference in the damage layers of the three. In terms of surface roughness, the Ra data for EDM, laser and diamond wire saw cuts are usually in the range of 0.3 μm to 1.5 μm , with laser cuts may having greater roughness than diamond wire saw cuts. However, considering that the process of grinding and polishing may have little to do with surface roughness, this point can be considered relatively weakly.

For diamond wire saw cutting, there is a limitation on the thickness of the slice due to physical factors such as the diameter of the diamond wire saw, and there is also a limitation on the diameter of the slice, which is not mentioned for laser and EDM cutting, and the line width of the laser etching can also be controlled by changing the energy density. Meanwhile, the cost of diamond wire saw cutting is significantly lower than laser cutting. From the above, it can also be seen that the role of diamond wire saw cutting in the field of precision cutting is far less than that of laser cutting and EDM cutting.

In the future, diamond wire saws need smaller diameters and better coating processes to achieve higher levels of precision machining. EDM cutting is more widely used in metal cutting, mainly due to its discharge principle, cutting control in the semiconductor field requires more in-depth research to improve. Laser cutting at present the mainstream femtosecond laser can be put into use in large quantities, but the attosecond laser is still in the experimental stage due to cost reasons. Attosecond laser needs more in-depth research to improve the performance of laser cutting.

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