Influence of auxiliary gas on silicon carbide machining by femtosecond laser

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Abstract. A contrast experimental study is reported to characterize the femtosecond (FS) laser grooving process for silicon carbide (SiC) with auxiliary gas and ambient air. The effect of laser powers on the characteristics of grooves is analyzed in this paper. Machining in the presence of auxiliary gas is beneficial to the debris ejection from the grooves. The experiment showed that high quality grooves can be obtained on SiC wafers with auxiliary gas, which demonstrated the potential for this machining technique.

Introduction

Single crystal SiC is the third generation semiconductor material that has been widely used. It has become a substitute for second generation semiconductor materials in many fields for its advantages. Single crystal SiC has excellent physical properties and chemical stability [1]. It has high specific stiffness, good thermal stability, wide band gap, high critical avalanche breakdown electric field, high thermal conductivity, and high hardness and brittleness. Therefore, it is often used for LED solid lighting and high frequency devices, especially for devices in high temperature and harsh environment [2, 3].

The internal atoms of SiC are connected mainly in the form of covalent bonds, which provide strong bond strength and prevent them from obvious dislocation motion. Therefore, SiC is difficult to be fabricated [4, 5]. FS laser becomes an effective way to fabricate SiC because of its high peak power and short pulse [6]. However, the heat affected zone (HAZ), recast layer and debris, which are often not removed efficiently, would generate in SiC after FS laser micro-machining [7-9].

Therefore, plenty of studies have been focused on the way to improve surface quality. Farsari et al. [10] proposed a new way to increase the micro-machining speed by obtaining laser directly from a FS laser oscillator without an amplifying system. Li et al. [11] investigated alcohol-assisted photoetching of 6H-SiC to remove the debris around the hole. The flow and evaporation of alcohol was also helpful to further reduce the ablation debris and thermal damage. Khuat et al. [12] investigated a simple method using combination of an 800-nm FS laser with chemical selective etching. The better surface quality of SiC grooves was attributed to the chemical reactions of laser modified zone and mixed solution of hydrofluoric acid and nitric acid. Nevertheless, the knowledge in FS laser ablation mechanism of SiC is less reported and further studies are imperative.

During the FS laser ablation process of semiconductors, enough energy is deposited to excite the electrons by electron avalanche and strong multiphoton absorption [13]. During electron-lattice relaxation time, laser energy is transmitted to lattice subsystem through carrier subsystem [14]. As lattice temperature gradually increases to phase transition temperature, at which the material begins to melt, the atomic motion becomes disorganized. By the non-linearity interaction of phonon - phonon, atoms are transferred to new positions in other crystalline phases [15].

HAZ, recast layer and re-deposition of debris after machining are caused by the gas micro-explosion between air and material after material gasification. One simple practice for controlling the thermal damage is the use of auxiliary gas to flow over the laser ablation region. It is devoted to flush the ablated material away, cool the substrate, and prevent from oxidizing reactions.

In this paper, an experimental study is conducted to investigate the machinability of single crystal SiC using FS laser ablation with auxiliary gas and ambient air, respectively. Then a comparison between the processes is performed. The experimental results show that auxiliary gas is beneficial to reduce re-deposition of the ablated material and increase the ablation characteristics in micro-fabrication process. The effects of powers on the width, depth and surface roughness of grooves are investigated.

Setup and Experiments

Setup. The experimental setup of this study is shown in Fig. 1. It mainly includes eight units, i.e. laser generator, amplifying light source, excitation amplification, focusing element, X-Y stage, CCD, gas nozzle, and water-cooling machine, as shown in Fig.1. The laser is a Ti: sapphire FS-pulsed fiber laser with a wavelength of 800 nm. The compressed-air pump can provide a maximum pressure of 68.9 MPa with a flow rate of 2 L/min.

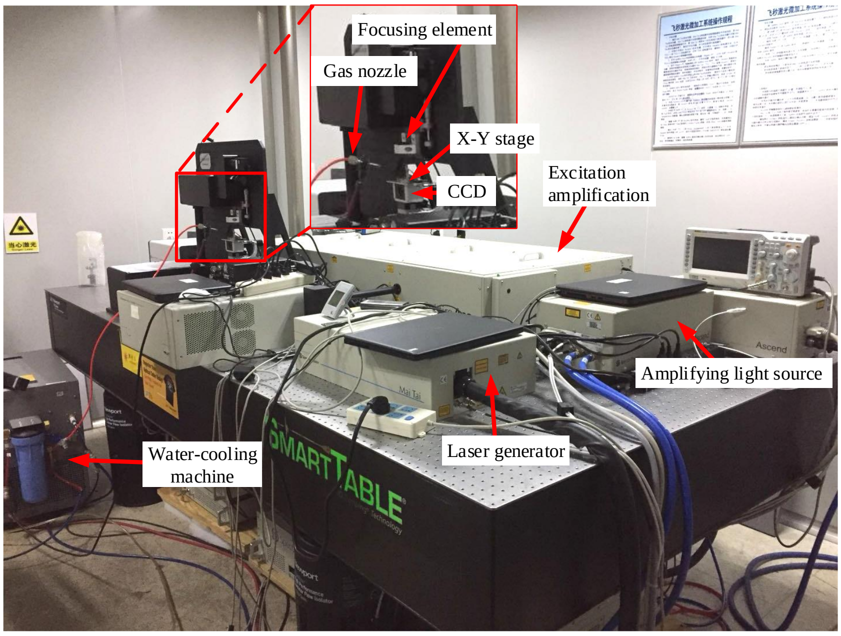

Fig. 1. Experimental setup

Materials. The properties of the single crystal 4H-SiC wafer are shown in Table 1.

Table 1 4H-SiC wafer parameters

	Elastic Modulus [GPa]	Poisson's ratio	Hardness [GPa]	Surface orientation	Thickness [μm]	Fracture toughness [MPa·m$^{-1/2}$]	Surface roughness [nm]	Surface treatment
4H-SiC	424	0.231	24.5	(0001)	362.8	2.5	Si-face: Ra≤0.5 C-face: Ra≤5	Polishing

Experiments. Experiments are performed using FS laser ablation with compressed air and ambient air, respectively. The machined surface morphologies are observed and measured by a 3D laser microscope. The debris generated by FS laser irradiation around the irradiated region was removed by ultrasonic cleaning in alcohol. Parameters used in the experiments are listed in Table 2. Each parameter on each groove was measured 4 times and the average was taken as the final reading.

For the surface micromachining experiments, a 20× microscope objective with numerical aperture (NA) of 0.4 has been employed, which focused the laser pulses on the surface of 4H-SiC wafer. By translating the x-y stage, the grooves were machined.

Table 2 Process parameters used in the experiments

Basic parameter	Auxiliary gas	Ambient air
Laser power, P [mW]	1-3.2, increment of 0.2	1-3.2, increment of 0.2
Scan speed, S [μm/s]	300	300
Repetition rate, R [Hz]	1000	1000

Results and Discussions

Auxiliary gas can effectively intervene in the ablating process, improve the distribution of the air flow, and reduce the HAZ size and recast layer in the machining area during ablation. The airflow can also take away some of the heat and energy, which affects the width, depth and surface roughness of the ablated groove.

The comparison of groove width by FS laser ablation with auxiliary gas and ambient air is shown in Fig. 2. As auxiliary gas can take away most molten amorphous material and reduce the temperature in machining, the size of groove width with auxiliary gas is obviously larger than that with ambient air. When power is less than 2 mW, the maximum difference of groove width under the processes is 1.8 μm.

The comparison of groove depth by FS laser ablation with auxiliary gas and ambient air is shown in Fig. 3. When power is less than 2 mW, the maximum difference of groove depth under the processes is 0.6 μm. But when power is larger than 2 mW, the influence of FS laser ablation with auxiliary gas on groove depth increases significantly. The auxiliary gas increases the material removal when power exceeds 2 mW, which cause the heat penetration depth to increase with the laser power increasing. The incident light isn't scattered by the debris redeposited around the grooves ,which leads to the groove depth increase.

Fig. 4 shows that the surface roughness are increased with power increasing with either auxiliary gas or ambient air. As power increases, more laser energy is deposited into crystallized SiC. Amorphous SiC does not have enough time to be discharged from the groove and the surface roughness of the groove is increased by recrystallization. The surface roughness of the groove can be decreased significantly by using auxiliary gas compared to that by using ambient air with same power. When powers are less than 2mW, the maximum difference of surface roughness under the processes is 0.06 μm.

The surface quality of single crystal SiC derived from the processes is illustrated in Fig. 5. It can be seen from Fig. 5(a) that clean and straight edges are obtained using FS laser ablation with auxiliary gas. There is no obvious thermal damage, such as HAZ and debris, on the surface of SiC. In Fig. 5(b), there is serious thermal damage by using FS laser with ambient air.

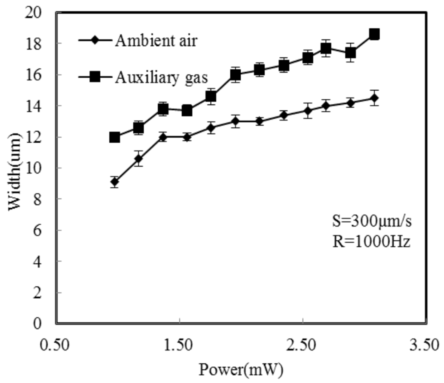

Fig. 2. The groove width in the process of FS laser ablation with auxiliary gas and ambient air.

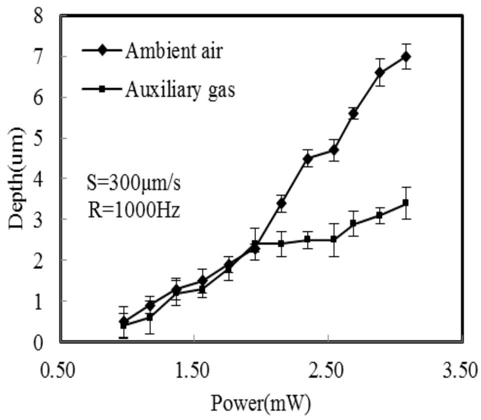

Fig. 3. The groove depth in the process of FS laser ablation with auxiliary gas and ambient air.

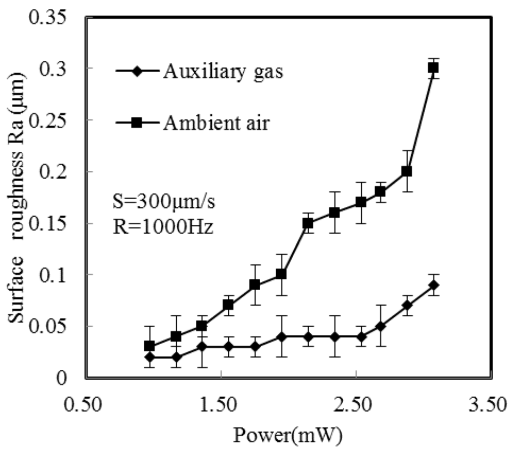

Fig. 4. The surface roughness of groove in the process of FS laser ablation with auxiliary gas and ambient air.

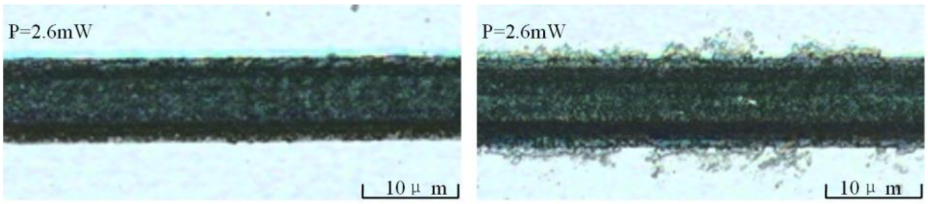

Fig. 5. Top view of machined profiles on single crystal SiC from (a) FS laser ablation with auxiliary gas, (b) FS laser ablation with ambient air.

Summary

An experimental study has been presented to characterize the FS laser grooving process of SiC. A comparison has been carried out with auxiliary gas and ambient air. The effects of powers on the characteristics of grooves have been discussed.

Compared with the machining in ambient air, laser machining assisted by auxiliary gas increased the size of grooves. It has been found that two machining processes caused little difference in the characteristics of grooves when power was less than 2 mW. The maximum differences of groove width, groove depth and surface roughness under the processes were 1.8 μm, 0.6 μm and 0.06 μm, respectively. But when power was larger than 2 mW, the influence of FS laser machining with auxiliary gas on the characteristics of grooves increased significantly. The thermal-damage-free groove would be obtained by the FS laser machining with auxiliary gas.

Acknowledgements

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