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Alcohol-assisted photoetching of silicon carbide with a femtosecond laser

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ABSTRACT

Femtosecond lasers have proved to be effective tools for micromachining silicon carbide material. In the drilling process, however, when the debris around the hole was not removed efficiently, the depth of hole would not increase further. In this paper, alcohol-assisted photoetching of 6H silicon carbide was investigated using a femtosecond laser. Machining in the presence of alcohol was beneficial to the debris ejection from the hole. The alcohol flow and volatilization was also helpful to further carry away the ablation debris and reduce the ablated material redeposition. The experiment showed that photoetching assisted by alcohol produced cleaner ablation effect and deeper hole than in ambient air. Moreover, alcohol assistance would not produce additional thermal damage around the hole. Vias were formed in a 250 μm thick wafer with alcohol-assisted photoetching technique using a femtosecond laser, which demonstrated the potential for this processing technique.

1. Introduction

Silicon carbide (SiC) has been identified as a very attractive material in the field of microelectronics and microelectromechanical systems due to its exceptional properties such as its extraordinary hardness, wide band gap, high thermal conductivity and chemical inertness [1–3]. Due to its outstanding physical and chemical characteristics, however, SiC is difficult to etch. Commonly, the main method used for patterning and drilling SiC is dry etching techniques [4–8]. However, dry etching techniques tend to suffer from issues such as low processing rate and the necessity of having micro-masks in the etch field. Recently, laser micromachining has been proposed as an alternative to the dry etching techniques for both surface patterning and via drilling [9–12], which has the advantages of fast removal rates and does not require masking or other pre-lithographic treatments. With the rapid development of ultrashort-pulse technology, femtosecond laser pulses provide a unique micromachining tool that allows the surface or bulk of a transparent material to be modified with micrometer precision. A tightly focused femtosecond laser pulse can deposit energy into a transparent material through high-order nonlinear absorption, producing material ablation either on the surface or in the bulk. Compared with conventional laser micromachining, femtosecond laser direct writing is particularly well suited for large band gap, chemically inert material such as SiC. Therefore, a significant amount of effort has been devoted to the development of SiC processing using femtosecond laser writing [13–18]. In the femtosecond laser micromachining, however, the incident light is usually scattered by the debris redeposited around the microvoids, which decreases the incident energy on the incident spot and leads to the photoetching depth no longer increase.

In this paper, we investigated alcohol-assisted photoetching of 6H silicon carbide (6H–SiC) using a femtosecond laser. The experimental results showed that alcohol was beneficial to reduce the ablated material redeposition and to increase the ablation depth in microfabrication process. In the same laser condition, photoetching in the ambient air can not accomplish the via fabrication in a 250 μm thick SiC wafer due to the influence of ablation debris while the via can be drilled with alcohol-assisted photoetching technique, which demonstrated the potential for this processing technique.

2. Experimental setup

The SiC substrate used in the experiment is a 6H–SiC polytype with a thickness of 250 μm. The schematic diagram of the experimental system for the laser microfabrication is shown in Fig. 1. A regeneratively amplified Ti:sapphire laser system was used, which delivered pulses with duration of 30 fs (FWHM), center wavelength at 800 nm and repetition rate of 1 kHz. The laser beam was focused onto the 6H–SiC wafer by a microscope objective. The energy of the incident pulses could be continuously varied by a variable attenuator. A mechanical shutter was employed to select the appropriate ablation time. The 6H–SiC wafer was mounted on a computer controlled three dimensional translation stage with a resolution of 0.04 μm.

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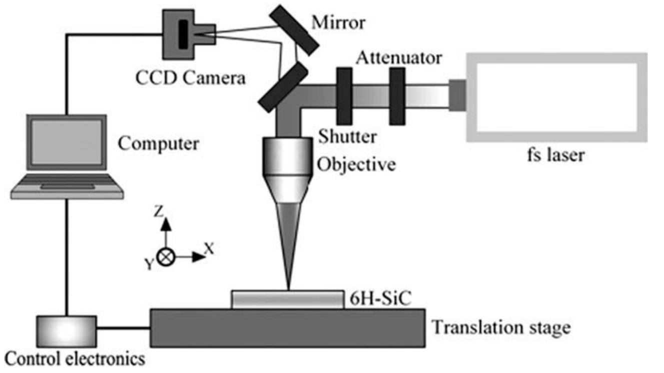

Fig. 1. Experimental setup consists of a femtosecond laser, a variable attenuator, a mechanical shutter, a microscope objective and a CCD camera. The sample was positioned on a mechanical *x*–*y*–*z* stage.

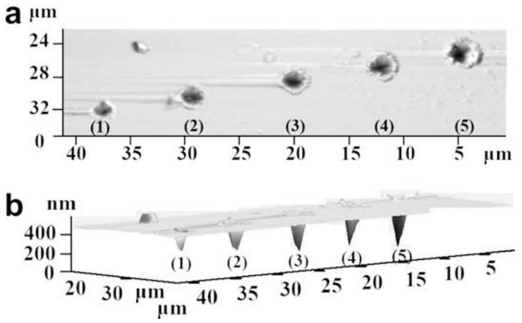

Fig. 2. The top view (a) and side view (b) of AFM micrographs of laser-drilled microvoids in SiC wafer. The laser irradiation time was 1 s and laser power density was set at (1) 0.14 GW/cm^2, (2) 0.34 GW/cm^2, (3) 0.38 GW/cm^2, (4) 0.40 GW/cm^2 and (5) 0.54 GW/cm^2, respectively.

3. Results and discussion

3.1. Surface-micromachining of 6H–SiC

For the surface micromachining experiments, a 100× microscope objective with high numerical aperture (NA) of 0.9 has been employed, which focused the laser pulses on the surface of 6H–SiC wafer. By translating the *x*–*y*–*z* stage, the microvoids and grooves were produced. After being ablated, the wafer was cleaned in an ultrasonic bath with alcohol.

We investigated the influence of the laser power on the drilling of 6H–SiC wafer by varying the pulse power. Fig. 2a and b shows the AFM images for laser-induced microvoids on the surface of the 6H–SiC wafer at different pulse energies, in which the laser power density was set at 0.14 GW/cm^2, 0.34 GW/cm^2, 0.38 GW/cm^2, 0.40 GW/cm^2 and 0.54 GW/cm^2, respectively, and the laser irradiation time was set at 1 s. As shown in Fig. 2a and b, the microvoids are visible on the surface of 6H–SiC wafer. Fig. 3a and b shows the diameter and depth of microvoids as a function of the laser power density, respectively. With increasing laser power, both the diameter and the depth of the microvoids increased. No evidence of typical thermal damage such as cracks could be observed on the surface of the 6H–SiC.

In addition, we also observed the influence of the laser irradiation time on the drilling of 6H–SiC wafer, and found that both the diameter and the depth had no obvious change with the increase of laser irradiation time.

Fig. 4a shows the AFM image of laser-machined groove. The groove was produced at a scan speed of 500 μm/s and the incident power density of 0.084 GW/cm^2. The width of the ablation groove is approximately 1 μm. From the picture, we can see that the surrounding area of the groove has not been cracked [19,20]. When the scanning speed was increased up to 1000 μm/s, both of the width and the depth of the groove decreased, as shown in Fig. 4b.

3.2. Femtosecond laser drilling of 6H–SiC

Drilling vias in the 6H–SiC wafer has very important value in the application of small scale monolithic millimeter-wave integrated circuits. Fig. 5a shows one of the microvoids drilled before any debris removal was carried out. The beam was focused by a 10× microscope objective lens (NA = 0.3) and scanned along a circular path to drill via. The scan speed was 50 μm/s. The power density of the incident laser was 3.1 GW/cm^2 and the drilling duration was 3 s. The diameter of the microvoid was about 40 μm. At the top surface of the microvoid, outwardly extruded material was observed and the redeposition of the material could be seen clearly around the microvoid, as shown in the Fig. 5a. In the micromachining, the incident light was scattered by the debris redeposited around the microvoid, which decreased the incident energy on the incident spot and led to the photoetching depth no longer increase. Therefore, this method of drilling can not produce a via but a microvoid.

To achieve deeper vias, the remove of ablation debris become a critical problem. In the past, one common practice for controlling ablation debris involves the use of an inert gas flow over the laser ablation region. This is intended to prevent oxidizing reactions, cooling the substrate, and flushing the ablated material away. Unfortunately, as the geometry of the laser focus is reduced in size and instantaneous laser power increases, this technique becomes less effective. In our experiment, we used alcohol as an assistance to produce vias on the 6H–SiC wafer. Before laser pulse incident, a drop of alcohol was dropped on the wafer. In the laser ablation process, alcohol evidently reduced the debris redeposition and generated a ‘clean ablation’ effect. Note the surface showed in Fig. 5b. The alcohol flow and volatilization was helpful to carry away the ablation debris and effectively decreased the deposition of debris around and in the hole. For identical laser parameters, compared

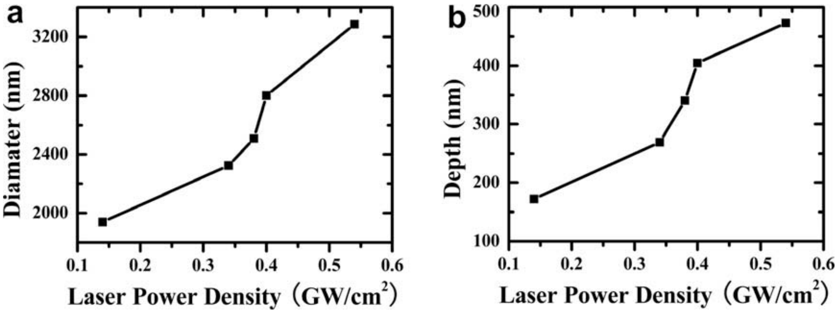

Fig. 3. Dependence of the diameter (a) and depth (b) of the photoinduced microvoids on the laser power density. The laser irradiation time was kept at 1 s.

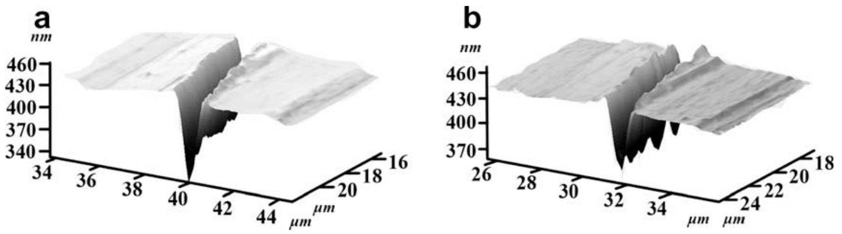

Fig. 4. AFM micrographs of laser-machined grooves in SiC wafer. The scan speed was set at (a) 500 μm/s and (b) 1000 μm/s.

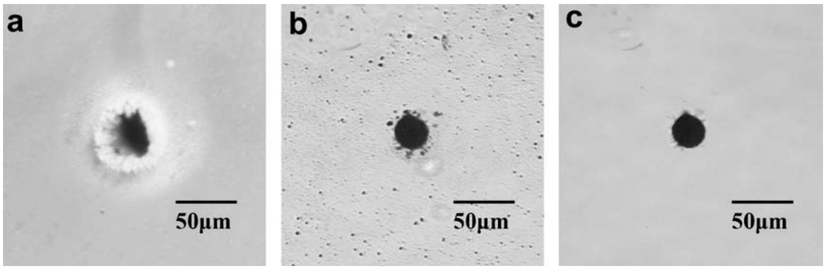

Fig. 5. Microstructural features of the microvoid drilled in a 6H–SiC wafer using a femtosecond pulsed laser. (a) The top surface of the microvoid drilled in air. (b) The top surface of the via drilled with alcohol-assisted. (c) The top surface of the via after alcohol washing.

with the processing in air, laser processing assisted by alcohol increased the depth of the hole, and the via has been drilled in the 250 μm-thickness sample. Fig. 5b shows the surface of wafer without any prior cleaning. It is worth noticing that at such processing condition there is no indication of typical thermal damage around the hole. A nearly circular shape with diameter about 40 μm was produced at the top side. The up side of the wafer displayed very little surrounding debris. These residual surface particles can be very easily removed by alcohol washing. Fig. 5c shows one of vias, the surface of which has been cleaned by alcohol.

4. Conclusions

The result of alcohol-assisted drilling of 6H–SiC with a femtosecond laser has been shown. For the laser drilling in air, it is difficult to increase the photoetching depth because of accumulation of debris and redeposition of ablated material. On the contrary, deeper through-holes could be easily fabricated with the alcohol assistance. Alcohol-assisted photoetching is beneficial to decreasing the redeposition of debris and increasing the ablation depth. In addition, there was not any additional thermal damage around the ablation region in the photoetching process. The via was drilled in a 250 μm thick wafer with alcohol-assisted photoetching technique using a femtosecond laser, which demonstrated the potential for this processing technique.

Acknowledgments

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