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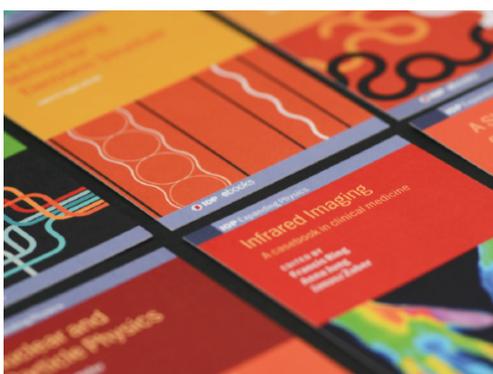
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Micromachining of Silicon Carbide using femtosecond lasers

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Abstract. We have demonstrated micromachining of bulk 3C silicon carbide (3C- SiC) wafers by employing 1028nm wavelength femtosecond laser pulses of energy less than 10 nJ directly from a femtosecond laser oscillator, thus eliminating the need for an amplified system and increasing the micromachining speed by more than four orders of magnitude.

1. Introduction

Crystalline Silicon Carbide (SiC) is a very attractive material in the field of microelectronics and MEMS, mainly due to properties such as its chemical inertness, mechanical strength and wide band gap. There are various examples of SiC-based devices being used as sensors, micro motors and resonators, designed to operate in harsh environments [1,2].

Currently, the main method used for patterning silicon carbide is reactive ion etching (RIE) [3,4] a technique with very high accuracy and the ability to create high-aspect ratio structures. However, it also presents several significant disadvantages such as low processing rate and the necessity of having micro-masks in the etch field.

Laser processing has been recently proposed as an alternative to RIE for surface patterning [5,6]. It promises fast removal rates and does not require masking or other pre-lithographic treatments. In addition, as it does not depend on crystallographic direction, it allows the generation of complex curved structures with high aspect ratios.

Due to the low thermal diffusion, femtosecond laser writing produces results superior to conventional laser micromachining [7,8]. Since the micromachining process can be dominated by multiphoton absorption, there is no requirement for absorption in the laser-operating wavelength; the method is therefore particularly suitable for large band gap, chemically inert materials such as silicon carbide. In addition, as the efficiency of the nonlinear process of multi-photon absorption scales with the power of the incident light intensity, only a well-defined volume around the focal center of the incident laser beam is affected by the ablation process.

Up to now, high-power Ti:Sapphire oscillator–amplifier systems have been used for the femtosecond laser micromachining of SiC [9,10]. Because such systems are operating exclusively at kilohertz repetition rates, they severely limit the maximum processing speed desirable for many applications.

In this paper we demonstrate that surface micromachining of bulk SiC can be achieved by the use of a tightly focused beam from a compact, infrared femtosecond laser oscillator operating at 50 MHz. As the limiting factor in laser scribing is the laser repetition rate, this work shows that the scribing speed can potentially increase by more than four orders of magnitude [11].

2. Experimental

For the surface-micromachining experiments we employ an Amplitude Systemes t-pulse laser femtosecond oscillator operating at 1028 nm. This source is a compact diode-pumped femtosecond laser oscillator, which delivers a train of high energy, short duration pulses. The small size of the laser permits the whole set-up to be extremely flexible. The average power of the laser is 1 Watt, the pulse duration less than 200fs and the repetition rate 50MHz. The maximum laser power on the specimen is 500mW. Using the above specifications, the maximum energy of a single pulse at the sample is calculated to be 10nJ. Emitted within 200fs, and focused onto a small focal spot, this corresponds to an extremely high intensity and provides for a higher probability for generating non-linear phenomena.

The beam is delivered through appropriate optics to an x-y-galvanometric mirror scanner (Scanlabs Hurryscan II), controlled by SAMLight (SCAPS) software. The scanner has been adapted to accommodate a high numerical aperture focusing lens (Nikon 50X N.A. 0.8) directing the beam onto the target. The focused beam waist is $w=670$ nm.

3. Results and discussion

For the surface-micromachining experiments the maximum pulse energy on the sample is $E=10$ nJ, which corresponds to a fluence of

$$F = \frac{E}{\pi w^2} = 0.71 \text{ J/cm}^2 \quad (1)$$

Because the maximum fluence available is close to the ablation threshold, detailed ablation rate studies were not feasible. The ablation threshold could be determined and was found to be 7.8 nJ, corresponding to a fluence of 0.55 J/cm².

An SEM image of a laser-micromachined structure is shown in Figure 1. This specific structure has been produced using a scanning speed of 50 mm/s and a fluence of 0.71 J/cm². The width and the depth of the ablation kerf are approximately 1 micron. Figure 2 shows a magnified section of a different structure, obtained at 10 mm/s scanning speed and the same fluence. The scribing is of very good quality, with no obvious pulse marks and complete lack of chipping. Increase of the scanning speed up to 200 mm/s had no visible deterioration of the quality of the kerf; in which case, the width of the kerf reduced to 0.5 microns.

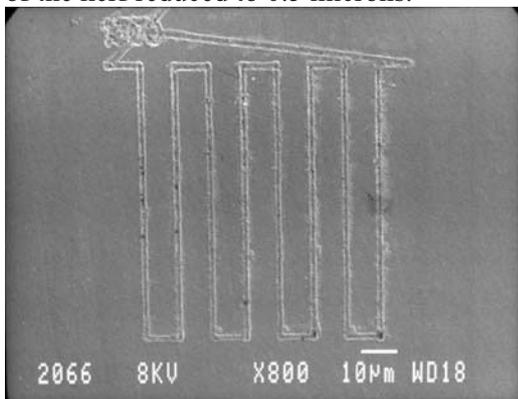


Figure 1 Micro-machined structure on SiC.

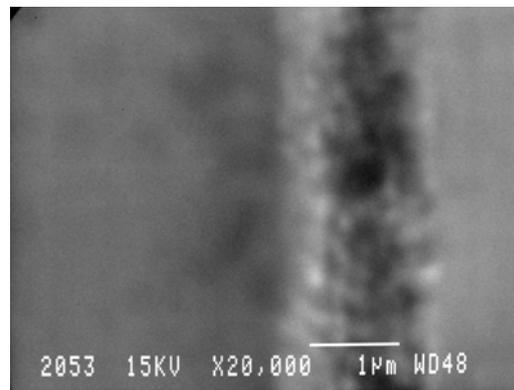


Figure 2 Magnification of a micro-machined kerf.

Dong et al. [9,10] have theoretically modelled the ablation of SiC by femtosecond pulses. They suggest that the mechanisms involved in the high and low fluence regimes are qualitatively different: while laser processing of SiC at high fluences is a result of thermal processes, it is essentially non-thermal at low laser fluences and a result of multi-photon defect activation. In contrast to these studies, however, that employ a low repetition rate amplified laser, a possible temperature rise due to thermal build-up under high repetition rate irradiation has to be considered in our case. To estimate this temperature rise, our 50 MHz laser can be treated approximately as a cw source. Assuming a Gaussian beam profile, the temperature rise reaches, due to heat conduction, a saturation value given by [12]

$$\Delta T_{cw}(0,0,t) = \frac{I_{0avg} w_0}{\kappa \sqrt{\pi}} \arctan \sqrt{\frac{4Dt}{w_0^2}} \rightarrow \frac{I_{0avg} w_0 \sqrt{\pi}}{2\kappa} \quad (2)$$

where

$\Delta T(0,0,t)$: the temperature rise on the material surface at the beam centre

I_{0avg} : the average laser intensity absorbed by the material, which we estimated as the product of the applied fluence per pulse and the 50 MHz laser repetition rate, yielding $I_{0avg} = 2.22 \times 10^7 \text{ Jcm}^{-2}\text{s}^{-1}$ if reflectivity of 19% is taken into account. (Reflectivity calculated using the Fresnel equation for normal incidence and a refractive index in the infra-red for 3C-SiC of 2.55[13]).

w_0 : the focused beam waist ($w_0 = 670 \text{ nm}$)

κ : the material thermal conductivity ($\kappa = 3.6 \text{ Wcm}^{-1}\text{ }^\circ\text{C}^{-1}$ for 3C-SiC at 300K [13])

D : the material thermal diffusivity ($D = 1.6 \text{ cm}^2\text{s}^{-1}$ for 3C-SiC at 300K [13])

According to equation 2, the temperature rise on the material surface is $\approx 366^\circ\text{K}$. About 70 % of this temperature rise is reached within the time $w^2/4D$, which is 1 ns in our case. In our scribing experiments with a scan velocity u between 10 mm/s and 200 mm/s, the dwell time w/u is between 67 μs and 3.5 μs , respectively, and thus sufficient to approach the saturation temperature. The actual temperature rise however will be higher due to the reduction of the material thermal conductivity with temperature [14]. The thermal diffusion scale length, in any case, is given by the equation

$$l = \sqrt{4Dt} = 3.6 \mu\text{m} \quad (3)$$

where t is the time between laser pulses. The diffusion length is comparable to the measured scribe depth of 1 μm . It is therefore very unlikely that the melting temperature of 3C-SiC (3103 K [15]) will ever be achieved using the current laser power, so that direct thermal effects can be ruled out. However, this steady state analysis ignores the femtosecond laser heating dynamics, which is expected to drive such high temperatures for short periods following each laser pulse. This steady state analysis therefore shows that heat accumulation effects do not play a significant role in the oscillator-only laser scribing.

The temperature increase could still contribute to the ablation effect in two ways; firstly, it is likely that the temperature gradient induces thermal stress leading to new defects. Secondly, the temperature

may also increase the equilibrium carrier density in the conduction band, therefore increasing the light absorption efficiency of subsequent pulses.

4. Conclusions

We have demonstrated that by employing tightly focused femtosecond laser pulses, surface micromachining of 3-C SiC can be achieved with pulse energies that can be obtained without amplification. This eliminates the need for laser amplification therefore increasing the micromachining speed by more than four orders of magnitude while significantly reducing the likely costs as an industrial process.

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