# HIGH-THROUGHPUT PULSED LASER MANUFACTURING ETCH PROCESS FOR COMPLEX AND RELEASED STRUCTURES FROM BULK 4H-SIC

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## ABSTRACT

This paper documents the implementation of a one-step process for the manufacture of complex and released structures from bulk silicon carbide (4H-SiC) using a pulsed neodymium-doped yttrium orthovanadate ($Nd/YVO_4$) laser. The process employs a pulsed laser (~1 kW) to scribe a crosshatch pattern in the 4H-SiC substrate, etching features directly from the bulk material. The effective etch rate and resulting surface roughness of the process are characterized with respect to the scribe speed of the laser, the scribed laser line spacing, and the number of laser passes. Finally, a planetary gear assembly is rapidly (15 minutes) manufactured from bulk 4H-SiC. The technique described is a step toward cheaply and efficiently manufacturing SiC microstructures at the die level in lieu of more expensive fabrication techniques such as deep reactive ion etching (DRIE).

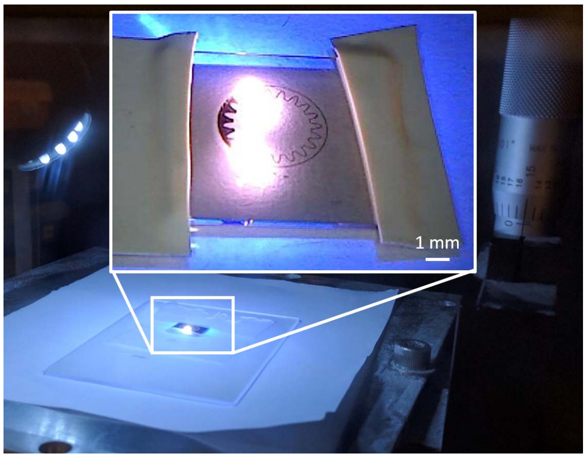


*Figure 1: A gear with 3.5 mm pitch diameter is etched from 4H-SiC.*

## INTRODUCTION

SiC is a material of increasing interest for extreme environment microelectromechanical systems (MEMS) due to its material hardness, chemical inertness, and thermal stability [1]. SiC MEMS can be utilized under high cycles of wear, within elevated temperatures, and within chemically corrosive environments unlike common MEMS materials such as silicon [1]. These applications include sensors for astronautic, volcanic, and radiative environments. However, these material properties also impede efforts to etch features into SiC with conventional micromachining technologies; in particular, the chemical resistance of SiC makes conventional wet etching techniques prohibitive [2]. As a result, bulk SiC machining is needed to realize extreme environment microsystems and electronics packaging architectures.

As a consequence, the majority of recent efforts in SiC micromachining have concentrated on dry etching techniques such as plasma etching, or in femtosecond laser ablation techniques, both of which anisotropically etch SiC [3-5]. Previous work has leveraged femtosecond and picosecond laser ablation with and without chemical etching, as well as focused ion beam machining [6-8]. While etching is capable of machining high aspect ratio features in SiC, it is limited by etch rates typically less than 2 µm/min [9]. In addition, full retail costs of plasma etchers are upwards of $600,000 and require clean room environment gas lines, cooling systems, and high power.

Previous efforts to machine three-dimensional (3D) structures in 4H-SiC have required multiple clean room steps, including several lithography process steps for patterning series of hard masks [10]. A rapid, cost-efficient alternative for manufacturing complex structures at the die level is thus a favorable alternative to etching for prototyping. This work represents an effort to micromachine bulk SiC using a low-cost, commercially available tool.

Using a commercial $Nd/YVO_4$ laser marking system, microstructures are fabricated from 4H-SiC on timescales ranging from 5 seconds to 15 minutes. The microstructures are released from the substrate by etching a release area with the laser in a crosshatch pattern. To characterize the suitability of this process as a rapid prototyping technique, we report the results of experiments that relate the etch rate to the following process parameters: scribe speed, scribed line spacing, and number of laser passes. Etch rates of up to 7.35 µm/sec are demonstrated for a 1 mm diameter via. The surface roughness of the etched material is characterized with respect to the same parameters using optical profilometry; a surface with area-average roughness of 0.504 µm was manufactured, and the roughness of the material was observed to approach 13.0 µm with an increase in line spacing.

## FABRICATION

All experiments reported in this paper were conducted using the Samurai UV Laser Marking System from DPSS (Diode Pumped Solid State) Lasers Inc. This marking system uses a $Nd/YVO_4$ frequency tripled DPSS laser that delivers 1 kW of average power at 355 nm wavelength, 30 kHz Q-switched repetition rate and 25 ns pulse length. The laser beam is linearly polarized and the polarization was not altered during the experiments. The lasing system comprises a lasing chamber, a test bed and a

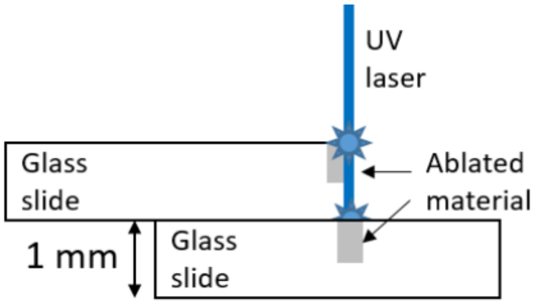


*Figure 2: Schematic of calibration procedure. A laser calibrated to cut at the plane between the two slides will ablate the same amount of material on each slide.*

control panel; Figure 1 shows a sample being etched in the lasing chamber. The lasing system is connected to a computer terminal running WinLase® in order to manufacture structures based on computer aided design (CAD) files.

Damage to the sample's morphology occurs during the ablation process when the laser beam is not calibrated correctly or is out of focus. Figure 2 shows a schematic of the calibration process. The laser is calibrated by performing test cuts on two stacked 1 mm thick Pyrex glass slides, adjusting the height of the test bed in between cuts. The laser is considered properly calibrated when an equal amount of material is ablated from both slides. If the focal plane of the laser is too high, more material will be ablated from the top slide; too low, and more material will be ablated from the bottom slide. Performing this calibration ensures that the focal plane is in the same location for each specimen

The laser is operated with WinLase®, which offers two ways to scribe the bulk material**: parallel lines** and **crosshatch** patterning. In the parallel lines operating mode, the laser beam performs a series of equally spaced horizontal cuts. The crosshatch mode scribes a grid into the etched material with a prescribed spacing. Preliminary experiments showed that the crosshatch operating mode was most appropriate for manufacturing 4H-SiC, so it was selected for further characterization. The line spacing between scribes, number of laser passes for each object, and the marking speed (scribe speed) of the laser are all adjusted in WinLase®.

The laser etching process begins by calibrating the lasing system and placing the samples inside the lasing chamber. The samples are 1 cm x 1cm dies singulated from 100 mm diameter, n-type, development grade 4H-SiC wafers (II-VI Inc.). The SiC die is attached to a sacrificial material slide (Pyrex glass) with electrical tape as shown in Figure 1. The laser beam manufactures the desired structure by etching away the surrounding area, releasing the structure from the die. The removed material is determined by an offset area selected when the structure is designed. The structures to be etched are designed in a CAD based software, then imported to WinLase® as DXF (Drawing Exchange Format) files.

## EXPERIMENTAL METHODS

We present the results of three different experiments.

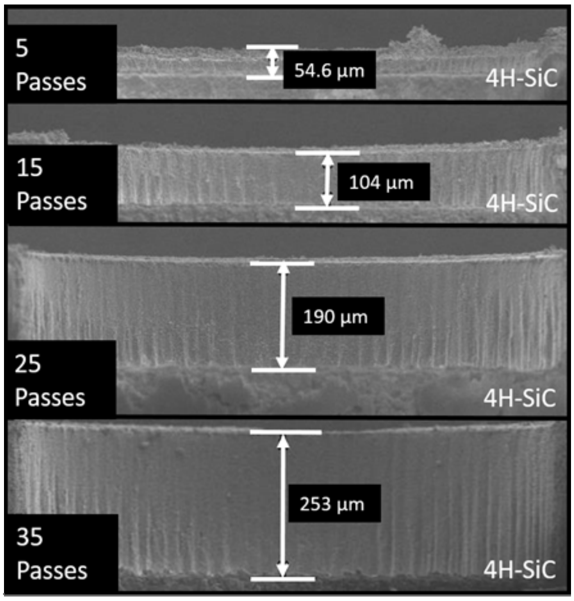


*Figure 3: A 4H-SiC specimen is etched at 200 mm/s with a 20 μm/s scribed line spacing. Grooves are visible in the sidewall near the base of the specimen.*

The first characterizes the etch rate associated with different scribed line spacing and laser pass number settings. The second experiment characterizes the surface roughness of the etched material as a function of scribed line spacing. The final experiment is a demonstration of the manufacturing capability of the process; a planetary gear assembly is etched from 4H-SiC in 15 minutes using the technique characterized in the first two experiments.

Specimens for the characterization experiments were prepared by etching arrays of 1 mm circular vias on a series of 1 cm x 1 cm dies. For the etch rate experiments, each via was cleaved in two, and the resulting halves were mounted and examined using scanning electron microscopy (SEM). Figure 3 shows a series of SEM images taken at a variety of laser pass settings for a via etched at 200 mm/s with a 20 μm/s scribed line spacing.

The surface roughness characterization was performed using a profilometry tool (S-NEOX). In order to obtain images of the resulting surface roughness, the tool was operated in confocal microscopy mode, which takes a series of images spaced at 1 μm at different z-levels in the structure. The tool also reports a variety of surface roughness parameters; in order to obtain area averaged surface roughness for each sample, a 250 μm x 250 μm area was analyzed and averaged using the software packaged with the profilometry tool.

## RESULTS AND DISCUSSION

SEM imaging of the etched specimens showed a roughly linear relationship between etch depth and number of laser passes. The etch rate was slightly retarded during the initial 5 passes. Etch depths for a series of experiments performed at a write speed of 200 mm/s scribed sample are shown in Figure 4. The etch rates associated with these experiments are reported in Table 1. Much of the uncertainty reported is due to uncharacteristically low etch rates obtained from samples that were etched with only 5 laser passes.

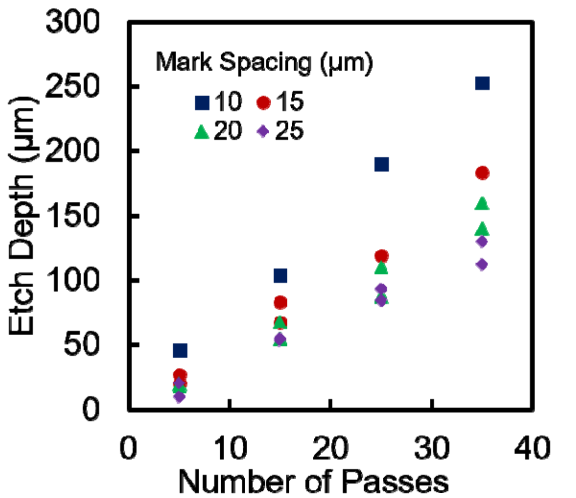


*Figure 4: Etch depth in a 4H-SiC sample at 200 mm/s at selected scribed line spacing.*

*Table 1: Etch rates attained at different scribed line spacing settings with a write speed of 200 mm/s.*

| Spacing (µm) | Etch Rate (µm/sec) | Std. Dev. (µm/sec) |
|---|---|---|
| 10 | 6.35 | 0.83 |
| 15 | 6.49 | 0.80 |
| 20 | 7.06 | 0.74 |
| 25 | 7.35 | 1.33 |

At greater line spacing, the laser has to scribe for a shorter distance to etch the sample. While this is appropriate for etching some structures such as through-holes, vias, and larger gear teeth, the improved surface roughness achievable with a tighter spacing is generally preferable regardless of the marginal decrease in etch rate.

Optical profilometry was used to determine the area-averaged surface roughness of the etched samples. It was found that scribed line spacing greater than 10 µm produced surfaces that were too rough to be appropriate for applications such as microfluidics beds. For line spacings less than 10 µm, a relatively smooth surface was obtained. At the smallest line spacing possible with the marking system (2 µm), the smoothest specimen obtained had an area-average surface roughness of 0.504 µm. This specimen is pictured in Figure 5 compared to a specimen with 20 µm spacing. At scribed line spacing greater than 10 µm, the etched material has high area-averaged surface roughness (> 10 µm) and is generally inappropriate for manufacturing smooth sidewalls or steps. Surfaces machined with these settings often show individually resolved Gaussian shapes.

Figure 6 shows the observed relationship between scribed line spacing and area surface roughness. Specimens etched with a line spacing of 15 µm or greater were shown to have similar surface roughness: approximately 13 µm. In particular, individual scribed laser lines are resolvable at these settings, resulting in a fluted appearance on the sidewalls near the base of the etched material. This phenomenon is observable in Figure 3, which was performed at a 20 µm line spacing.

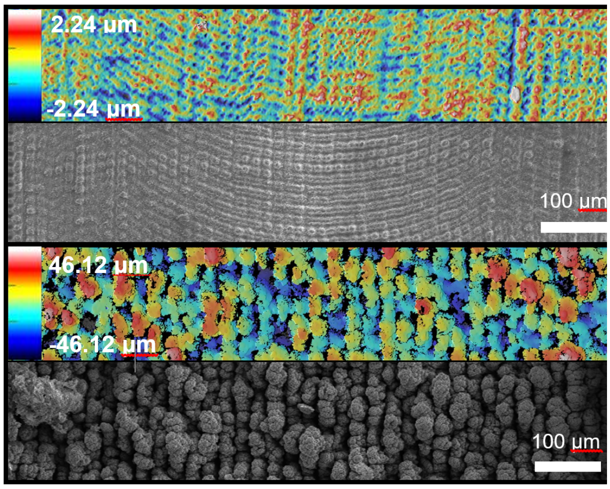


*Figure 5: A specimen etched with a scribed line spacing of 2 µm imaged in an optical profilometer (top) and SEM (second from top) contrasted with similar images from a 20 µm spaced specimen (second from bottom, bottom).*

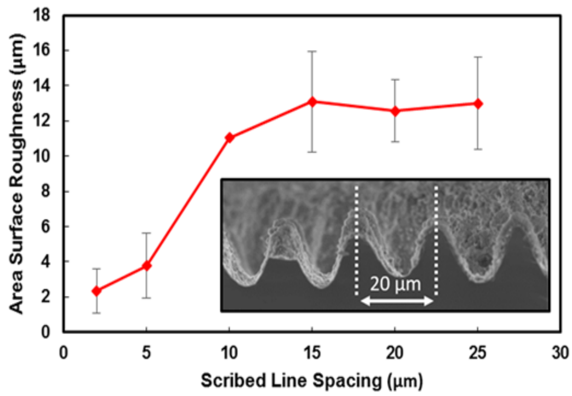


*Figure 6: Observed area surface roughness with increasing line spacing is shown. At high line spacings, individual pulses are resolvable (inset).*

Using the parameters characterized above, the Nd/$YVO_4$ laser ablation release process can be used to quickly fabricate small die-level features in silicon carbide. The planetary gear assembly shown in Figure 7 was manufactured using a 20 µm line spacing and 100 mm/sec write speed. The central gear has outside diameter 4.5 mm and 20 teeth, and the auxiliary gears each have outside diameter of 3.5 mm and 15 teeth. A bed designed to accommodate the entire gear assembly was fabricated from Pyrex glass using the same settings. The entire fabrication process took just under 15 minutes, discounting the time required to design the gears in a CAD program. The gears meshed and traversed the perimeter of the glass bed when the central gear was driven with a pin.

At smaller spacings, Nd/$YVO_4$ laser ablation could potentially be suitable for manufacturing micromixing devices such as those used in microthruster concepts and microreactors that use highly corrosive reagents [11, 12].

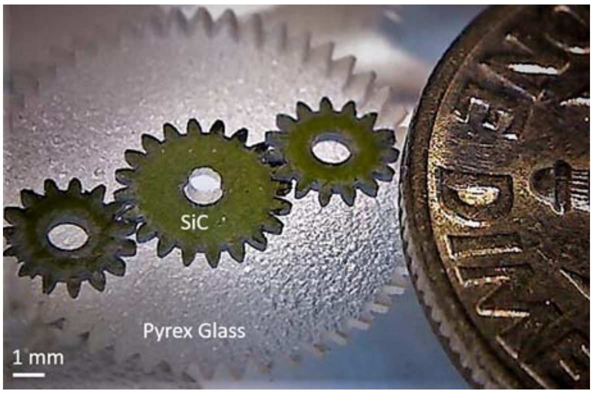


*Figure 7: A planetary gear assembly fabricated from 4H-SiC resting in a Pyrex glass bed.*

Future work is underway to examine the aspect ratio limitations of Nd/$YVO_4$ etching and to characterize the minimum channel size achievable with this process. The process will also be attempted at the wafer level.

## CONCLUSION

A one-step and maskless microfabrication process for machining released, complex structures from 4H-SiC was investigated and demonstrated. Using this process, effective etch rates of up to 7.5 µm/sec were realized at scribed line spacings of 25 µm. At scribed line spacings of 2 µm, area-average surface roughnesses of 0.504 µm were attained. A planetary gear assembly with central gear outside diameter of 4.5 mm was etched in 15 minutes using the laser-based process. Nd/$YVO_4$ laser ablation of crosshatched patterns in 4H-SiC was shown to be an effective method for etching design primitives such as vias, channels, steps, and gear teeth, and can serve as a replacement for more expensive processes when a rapid-prototyping design approach is desired. Future areas for improvement on this process include the exploration of micro-channel and micro-pin/fin device fabrication and determination of the limiting aspect ratio of the process.

## ACKNOWLEDGEMENTS

This work was supported in part by the National Science Foundation Engineering Research Center for Power Optimization of Electro Thermal Systems under Grant EEC-1449548. Also, in part by the National Science Foundation Graduate Research Fellowship under Grant DGE-114747 and Stanford Summer Undergraduate Research Fellowship (SURF) program.

The authors would like to thank Dr. Lydia Marie-Joubert and the Cell Sciences Imaging Facility for their support, the Collaborative Haptics and Robotics in Medicine Lab for facilities and tooling support, and Dr. Noe Lozano from SURF for his mentorship and guidance.

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