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Micro-Laser Assisted Machining (µ-LAM): Scratch Tests on 4H-SiC

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Abstract: In the nanomachining of semiconductors and ceramics, especially brittle materials such as silicon carbide, the presence of high pressure phase transformation is of great importance for accomplishing ductile regime machining [1]. To augment the ductile regime machining of these nominally brittle materials, the high pressure phase can be preferentially heated and thermally softened by using concentrated energy sources such as laser beams [2]. Notably, the results of scratch tests at 1µm/sec show a doubling of the scratch depth which suggests a ~40% reduction of calculated relative hardness due to thermal softening by the laser heating.

1. Introduction: Semiconductors and ceramics share common characteristics of being nominally hard and brittle, which stem from their covalent chemical bonding and crystal structure. Both types of materials are important in many engineering applications, but are particularly difficult to machine in traditional manufacturing processes due to their extreme hardness and brittleness [3]. Ceramics have many desirable properties, such as excellent wear resistance, chemical stability, and high strength even at elevated temperatures. In spite of all these characteristics, the difficulty in machining has been a major obstacle that limited the wider application of these materials [3]. The plastic deformation of these brittle materials at room temperature is much less than in metals, which means they are more susceptible to fracture during material removal processes. Surface cracks generated during machining are subsequently removed in lapping and polishing processes, which significantly increases the machining cost. Machining these mirror-like surface finishes contribute significantly to the total cost of a part. In some cases, grinding alone can account for 60-90% of the final product [4]. In this context, developing a cost effective method to achieve a flawless surface in ultra fine surface machining of an optical lens or mirror has become a challenge. In many engineering applications, products require a high quality surface finish and close tolerances to function properly. This is often the case for products made of semiconductor or ceramic materials. The real challenge is to produce an ultra precision surface finish in these nominally brittle materials at low machining cost.

Current limitations for brittle material machining include the high cost of processing and product reliability. The cost is mainly due to the high tool cost, rapid tool wear, long machining time, low production rate and the manufacturing of satisfactory surface figure and form. The low product reliability is primarily due to the occurrence of surface/subsurface damage and brittle fracture. In order to develop a suitable process, ductile regime machining, considered to be one of the potential precision machining techniques, has been continuously studied in the last two decades [5-13]. Laser assisted micro/nano machining is another important development in this direction [14, 15].

The objective of the current study is to determine the effect of temperature and pressure in the µ-LAM of the single crystal 4H-SiC semiconductors using scratch tests. The scratch tests examine the effect of temperature in thermal softening of the high pressure phases formed under the diamond tip. The tests also evaluate the difference with and without irradiation of the laser beam at a constant loading and cutting speed. The laser heating effect is verified by atomic force microscopy (AFM) and white light interferometric measurements of the laser heated scratch grooves.

2. Experimental Procedure: An IR diode laser (λ=1480nm and P_{max}=400mW,) with a Gaussian profile and beam diameter of 10µm is used in this investigation.

The laser beam is guided through a 10µm fiber optic cable to the ferrule, which is attached to the diamond stylus. The µ-LAM set-up with a laser beam integrated diamond tool on a given substrate is shown in Figure 1. In this setup, the laser beam passes through the diamond tip (tool) and impinges on the 4H-SiC work piece material. The laser emerges from a 90° conical single crystal diamond tip with 5µm radius spherical end, as shown in Figure 2.

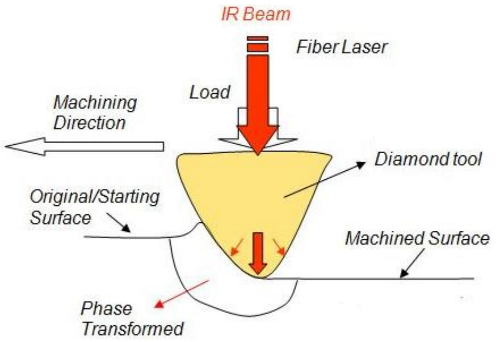

Figure 1: µ-LAM machining of SiC substrate.

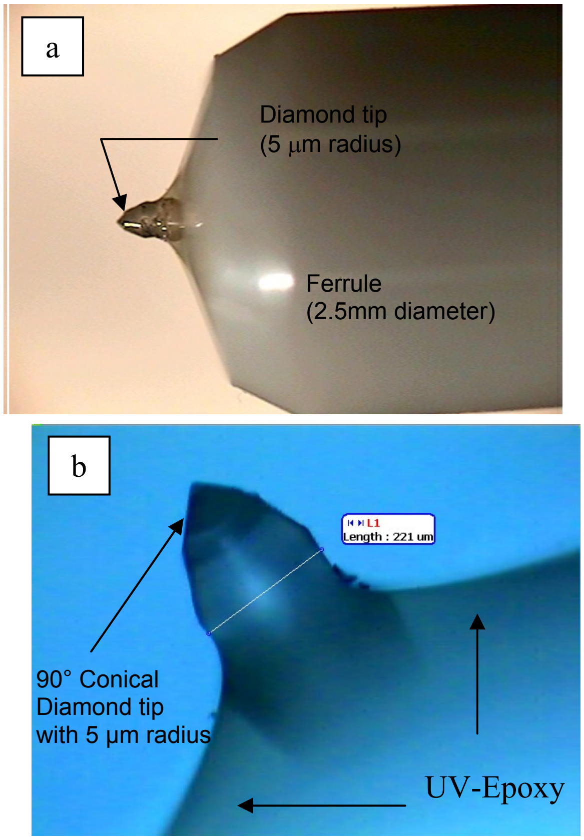

Figure 2: Diamond tip attachment: (a) 5µm radius diamond tip attached on the end of the ferrule using epoxy, (b) Close up on diamond tip embedded in the solidified epoxy.

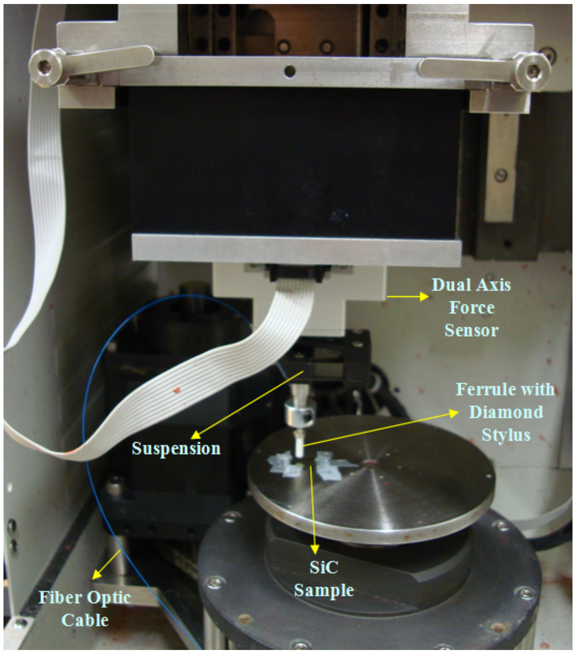

Figure 3: µ-LAM system used in the experiments.

The details of the diamond tip attachment were depicted in Figure 2 (a and b), while the overall µ-LAM experimental setup is shown in Figure 3. The µ-LAM set-up is commissioned within a Universal Micro-Tribometer (UMT) from the Center for Tribology Research Inc. (CETR). This equipment was developed to perform comprehensive micro-mechanical tests of coatings and materials at the micro scale. This system facilitates the cutting speeds as low as 1µm/sec at nanometric cutting depths.

The specimens are single crystal 4H-SiC wafers (provided by Cree Inc). The primary flat is the {1010} plane with the flat face parallel to the <1120> direction. The primary flat is oriented such that the chord is parallel with a specified low index crystal plane. The cutting direction is along the <1010> direction.

Scratch tests were chosen to be the principle method in this study. Scratch testing is a better candidate for evaluating machining than indenting because the scratching parameters are more applicable to the machining process, such as depth of cut, width of cut and cutting speed parameters.

In this experiment, scratches were performed with and without laser heating. The results obtained from these tests are compared to previously obtained results [16]. The load used for the scratch tests is 2.5g (~25mN) with a cutting speed of 1µm/sec. The results of these tests were summarized in Table 1 along with the previously reported results in [16].

Table 1: Scratch parameters.

Scratch No.	Load g (mN)	Machining Condition	Cutting Speed (µm/sec)	Laser Power (mW)
*1**	*2.5 (25)*	*w/o laser*	*305***	*0*
*2**	*2.5 (25)*	*w/ laser*	*305***	*350***
3	2.5 (25)	w/o laser	1	0
4	2.5 (25)	w/ laser	1	350**

**Experiments performed previously [16].*
***350mW is the laser power, approximately 150mW is actually delivered to the work piece material, the balance of the laser power is lost due to scattering and reflections [2].*

3. Results and Discussion: The scratch profiles along with the groove width and depth were measured using AFM. Figures 4 and 5 are the AFM profiles that clearly indicating the depth and width of the scratch grooves without and with laser heating respectively. These clearly depict laser heating effect of the scratches made on 4H-SiC. The results of all the scratch tests are presented in the Table 2, including the experiments at higher speed of 305µm/sec conducted previously.

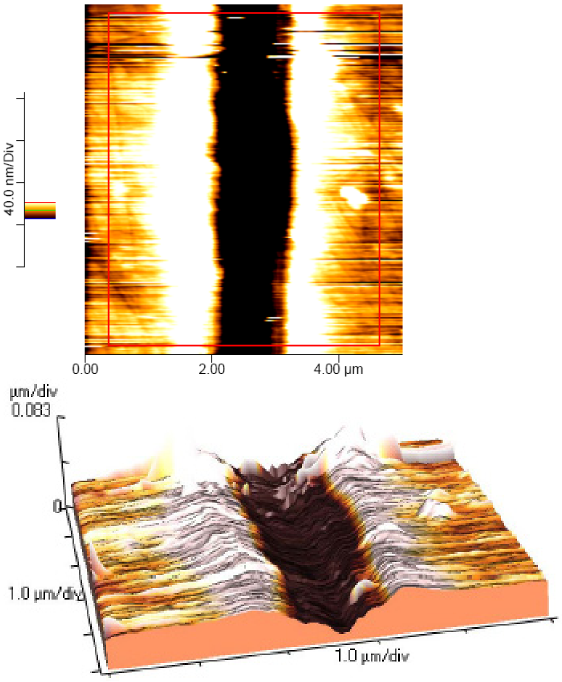

Figure 4: AFM image of the scratch#3; no laser heating, 25mN load, 1µm/sec scratching speed.

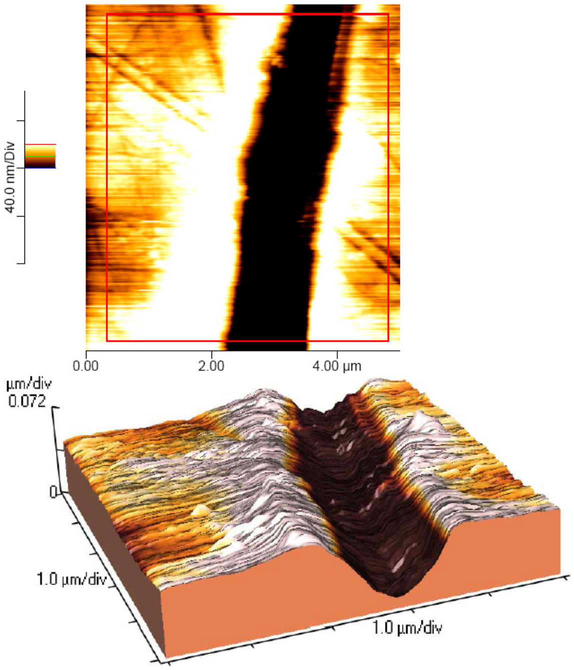

Figure 5: AFM image of the scratch#4; w/ laser heating, 25mN load, 1µm/sec scratching speed.

Table 2: Average groove depths measured on AFM.

Scratch #	Machining Condition	Cutting Speed (µm/sec)	Average Groove Depth (nm)
*1**	*w/o laser*	*305**	*41*
*2**	*w/ laser*	*305**	*46*
3	w/o laser	1	54
4	w/ laser	1	90

**Experiments performed previously [16].*

Apart from the major difference in the cutting speeds, 305µm/sec (at UNC Charlotte) and low speed 1µm/sec (at WMU), in the two sets of data presented in Table 2, there may be minor differences in the test equipment (profilometer and tribometer respectively) used, operator variability, and other test conditions in which the scratches were performed.

The applied load (thrust force) was kept constant (25mN) throughout the entire experiment enabling the evaluation of heating effects on the material. The high pressure phase, due to the HPPT, of the 4H-SiC occurs within the contact interface as a result of externally applied pressure (>25GPa) and is the common phenomenon in all of the scratches made on the 4H-SiC specimen. As the result of heating by the laser beam, the temperature of the surface material adjacent to the diamond stylus rises to achieve the desired thermal softening. Previous work on silicon demonstrated that the temperature increased to ~600°C [2, 17], which thermally softened the HPPT phase and assisted the machining process.

The depth of cut is a crucial parameter and if it exceeds the critical depth (ductile to brittle transition depth), this will shift the ductile regime machining to an unfavorable brittle condition, which is avoided in this study.

In the previous set of scratches performed at 305µm/sec, the difference in the depth of cut for w/ and w/o laser heating was measureable but not significant, indicating some but not much laser heating and thermal softening. In the current set of scratches with 1µm/sec cutting speed, the depth of cut significantly increased with laser heating, nearly doubled, from 54 (w/o laser heating) to 90nm (with laser heating, see Figure 6). This indicates significant laser heating and resultant thermal softening. This result shows that temperature plays a significant role in enhancing the ductile regime machining of 4H-SiC specimen at the cutting speed used in this experiment.

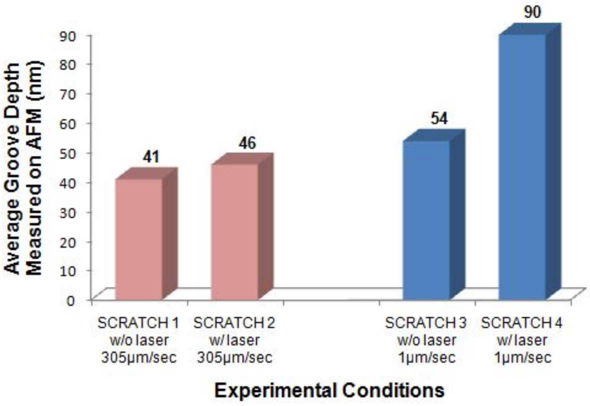

Figure 6: Average groove depth measured with AFM in (nm) with two different speeds and w/ and w/o laser.

Based upon the scratch (groove) depth and load, the relative hardness of 4H-SiC with laser heating is estimated to be 18GPa and the relative hardness of the scratch with no laser heating is calculated to be 30GPa [18]. Estimating the temperature achieved for the laser heated 4H-SiC, based upon published hardness-temperature data [19] suggests a temperature increase of 700-800°C in the scratch #4. At the laser power (350mW) used in these experiments, (150mW actually delivered to the work piece surface), significant laser heating is achieved at the low speed, while minimal heating occurred at the higher speed, as reported in previous work. Thus increasing the cutting speed reduces the thermal softening compared to that observed at lower cutting speed.

4. Conclusion: Laser heating was successfully demonstrated as evidenced by the significant increase in groove depth, i.e., reduced calculated relative hardness, indicative of enhanced thermal softening. AFM measurements of the laser-heat assisted scratch grooves show deeper and wider grooves compared to scratches made without the laser heating assisted methods; which indicates favorable thermal softening effects.

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