Semiconductor and Ceramic Microstructure Made by Single Mode Fiber Laser

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Abstract. In the paper the results of micromachining of 3D microstructures of microsystems made from silicon and alumina ceramic using a single mode fiber laser (1064 nm) are presented. The quality of obtained structures and its smallest dimensions with acceptable maintained quality were examined. The influence of variable parameters of laser processing with changing of mapping scale on geometrical features of structures was identified.

1. Introduction
3D elements of microsystem are most commonly made of silicon, glass, polymers or ceramic. Main technologies in case of Si are acquired from microelectronics anisotropic wet etching or plasma etching. Wet etching, realized as batch processing, provides high quality of the structures, however, it requires masking and its effectiveness is crystallographic orientation dependent. In case of ceramic materials, which are indispensable for microsystems to work in harsh environment, complex moulding processes or micromachining of green ceramic are used. Among other techniques applied to micromachining of microsystems some subtractive and additive laser technologies have been developed: Laser micromachining LM (2,5D – 3D structures)[1,2], laser micro-stereolithography (LMS)[3] and Direct Laser Interference Patterning (DLIP)[4]. All these techniques are applicable to ceramic materials, while LM only to silicon. Generally the attractiveness of the laser beam as a technological tool follows from an immense surface concentration of power (energy) and the possibilities to influence on the material in a very short time. High spatial resolution achieved by focusing the beam to the size of a few micrometers, local character of the energy interaction, and high flexibility allow to achieve good quality of elements - high precision, small tolerances, precise control and dimensions of components - from several hundred nm to 1 mm. Use of the pulsed nano- pico- and more recently the femtosecond laser beam is presently the standard in laser micromachining. The use of Nd:YAG lasers operating at the second (532 nm), third (355nm) or fourth (266nm) harmonic, Ti: sapphire lasers and the most important types of excimer lasers provides the best results. New types of laser technology, primarily fiber lasers, which today have replaced Nd:YAG lasers in many applications, are also dynamically developing. The effectiveness of thermal ablation of semiconductor and ceramic materials using multimode fiber laser was reported earlier [5,6]. In this paper we discuss
the problems connected with microfabrication structures of complex 3D shapes with features of micrometer range by ablation using single mode fiber laser.

2. Experimental part
Two-step experimental tests were carried out in order to determine the smallest dimensions of the ceramic and silicon microstructures produced by laser micromachining with an acceptable maintained quality. In the first step, the analysis of the accuracy of mapping of the elaborated test structure developed by a single line of laser ablation was performed. The effects of laser micromachining were confronted with the results of modelling the ablation process [5]. In the second step – the test structures with different scales were prepared with the process parameters defined on the basis of the first phase of experiment.

2.1. Equipment and process parameters
A single mode fiber laser redENERGY G3 SM 20W (SPI) was used which guaranties the quality of the beam $M^2<1.3$. Laser beam was scanned by 2-Axis Scan Head (Xtreme, Nutfield Techn. Inc.) equipped with F-theta lenses 100mm and 160 mm and software SB-1P Waverunner. The experiments were performed in the following ranges of work parameters: power of the beam – (8-20W); pulse duration – (60-200ns); pulse repetition frequency-(30-90kHz); scanning velocity – (200-4600 mm/s). The beam expander 2,6x and optic head have focused laser beam to the spot of diameter of 50 µm.

![Figure 1](image)

**Figure 1.** Equipment used for microfabrication structures (a); microfabrication of capillary separator.

Figure 1 presents a fiber laser redENERGY G3 SM 20W (SPI) with Scan Head and a positioning system. Microfabrication of a capillary separator in silicon is shown in figure 1 b). There is visible characteristic lighting of laser plume. Such treatment is accompanied by sound, what indicates ablation character of this treatment. The maximum efficiency value of this ablation has been presented in table 1 with parameters of nanosecond pulse of 1060 nm fiber laser.

| material | efficiency of laser ablation [µm/scan] | Parameters of the process |
|----------|---------------------------------------|---------------------------|
|          |                                       | $t_i$ duration of the pulse [ns] | $f$ frequency [kHz] | $E_i$ energy of the pulse [µJ] |
| Si       | ~100 µm                               | 220 ns                     | 35                      | 560                      |
| $Al_2O_3$| 35                                    | 120 ns                     | 36                      | 560                      |
Parameters in table 1 are not sufficient to ensure proper mapping of the pattern in a diminished scale. Scan velocity and frequency become more important in micro scale than efficiency of laser ablation.

2.2. Test pattern
Dimensions of the test pattern were adjusted taking into account the resolution of the used laser beam - spot diameter $D = 50 \, \mu m$ (figure 2).

Features of the test pattern include main problems which occur with laser micro-machined 3D shapes: spatial resolution of adjacent ablation lines affecting hatching for surface treatment; mapping polyline segments with different angles of bending, projection of arcs of small radius of curvature. Dimensions of these "traps" were determined relatively as multiples of the laser beam diameter (figure 2).

2.2.1. Fidelity of the test pattern
Test structures were prepared on silicon and alumina ceramics using conditions of ablative process with moderate dynamics, with a small contribution of the plasma cloud, determined experimentally and confirmed by modelling [5]. For example, an image of a test pattern for a different scale is shown in figure 3 and for different scanning velocity in figure 4.

Variable energetic parameters of the laser beam included average value of power (9-20 W), pulse duration (60 to 200 ns for Si), and repetition frequency (30 - 90 kHz). Re-creation of the test pattern, however, is not a simple reflection of ablative process of material removal, which depends on these parameters. Operation of the laser beam scanner substantially affects mapping quality, which is particularly visible in the manufacture of polylines, and arcs. Images of test structures allow to affirm a beneficial effect of lower scan speeds and optimal power of the beam (12 - 14 W). A clear, local deepening of arcs and sharp bends is observed for the highest power values (16 - 20 W). Application of the smallest power (slightly above the ablation threshold) worsens the continuity of line and uniformity of the depth of the groove, especially for sharp angles.

Accuracy of the test pattern was evaluated in three-point scale relating to the fulfilment of different criteria: a) mapping of line of test structure - its continuity and uniformity of the depth of the groove, b) mapping of geometric details of shape - sharp angles, arcs, resolution of the pattern. Results of the
qualitative assessment of different variables on the process conditions have been summarized in table 2.

**Figure 4.** Test pattern for different velocity 1- 500 mm/s, 2- 1000 mm/s, 3- 1500 mm/s, 4- 2000 mm/s, 5- 4000 mm/s.

**Table 2.** Qualitative assessment of accuracy of the test pattern.

| Criterion                | Scale | Scanning velocity [mm/s] | Power of laser beam [W] |
|--------------------------|-------|--------------------------|-------------------------|
|                          | 2:1   | 1:1                      | 1:2                     | 1:4                     | 500 | 1000 | 1500 | 2000 | 4000 | 20 | 14 | 12 | 10 | 9 |
| the continuity of the line| H     | H                        | H                       | M                       | H | H | M | M | L | H | H | H | L | L |
| uniformity               | H     | H                        | M                       | M                       | H | H | H | M | M | H | M | M | L | L |
| sharp angles             | H     | H                        | H                       | M                       | H | H | H | H | H | H | H | M | L | L |
| arcs                     | H     | H                        | M                       | L                       | H | H | H | H | H | M | H | H | H | M | M |
| resolution of line       | H     | H                        | L                       | L                       | H | M | M | M | M | M | H | H | H | M | M |
| Levels of quality criteria: | H – high; M – medium; L - low |

2.3. Selecting of microstructures

Among a large number of different elements of microsystems three of them have been selected for testing, and are characterized below. The two test structures (figure 5) were chosen as typical structures used for microfluidics, yet presenting geometry, complicated enough to show capabilities of micromachining technique: the Staggered Herringbone Mixer [7] and phase separator [8]. Scale length ranges of the presented structures were adjusted for typical microfluidics applications, between (approx.) 500 to 50 microns in transverse direction and channel as well as 50-10 micron of length scale of details [9,10]. Both structures present fabrication challenge for typical rapid fabrication techniques like micro milling due to restricted access to bottom wall in case of a mixer, mechanically fragile, narrow splitting “array” for a splitter and generally complicated layout. Typically such structures are fabricated by lithography and/or hot embossing, however, in opposition to presented here laser ablation technique, such techniques cannot be treated as “rapid”.

The herring bone mixer (figure 2a) is a commonly used device for mixing in microfluidics. Typical microfluidic flows are deeply laminar, with viscosity dominating over (often negligible) inertia meaning that the fluid flows in layers and all the flow disturbances are damped by viscosity. In such conditions mixing relies on diffusion between fluid layers which is simply slow, therefore mixing in microfluidics is challenging and a couple of novel ways to overcome this problem has been presented [11]. One of them is to force secondary flow pattern for chaotic advection and laminar flow destabilization, perpendicular to main flow direction [12]. That can be done by specific three-dimensional channel layout or by patterned wall structure, as presented in case of herringbone mixer.

The second presented structure (figure 5b) is less popular (yet), however it deals with very practical problem of phase separation in microfluidics. Microfluidic two-phase flow is given a lot of interest nowadays [13] and several successful applications have been shown in this area. The presented device can be used as a splitter utilizing phases surface tension differences as splitting force. The principle of operation is simple: while the two-phase flow is introduced on the inlet, the two single-phase streams
are present at two outlets. The geometry, the length scale of passages between the splitting chambers determine the splitting parameters permitting only one phase to overcome the surface tension and pass through.

![Image](image1)

**Figure 5.** Structures selected for testing: a - the herring bone mixer; b - capillary separator of two phase mixture.

The third structure (figure 6) is used for micro-channel cooling in semiconducting devices, generating a considerable amount of heat. Dissipation of heat power, higher than 1000W/cm², is possible in such circuits. The greatest cooling efficiency is obtained in two-phase systems with forced circulation of a cooling refrigerant [14, 15]. Such systems with the phase change heat are more efficient than single-phase systems. Optimal use of cooling effect of bubble boiling provides an appropriate choice of the shape and dimensions of the micro-channels. Typical cooling channel widths are between 50 µm to 500 µm with a depth of about 100 µm [16].

![Image](image2)

**Figure 6.** Cooling microchannel: a) width of 500 µm, b) - width of 50 µm.

Laser ablating method for producing micro-channels allows to create micro-channels on a semiconductor substrate directly without any additional pre-processes. Creation of channels of any shape or a resolution lower than a few micrometers is possible depending on the laser source and the optical system. Application of our SPI fiber laser with 1060 nm wavelength resulted in micro-forming the structures of microcoolers with different dimensions and shapes of surface caps- with square or circle cross-section (cylindrical ones). In figure 6 there are shown microcoolers with cylindrical caps of 500 µm and 50 µm width. Fiber laser ablation microtreatment has proved possibility of keeping circular and square shapes even for 50 µm size.
2.4. The quality of the variable scale microstructures

The quality of microstructures produced in variable process conditions is in good agreement with observations for mapping the test structure. There are also additional factors affecting the quality associated with the relationship between a spot diameter (50 µm) and hatching (10, 20, 30 µm) when processing partial surfaces of the structures. Though some roughness of the surface after laser ablation is permissible for large scale, in micro scale it can totally destroy functionality of microdevices. The flow of fluid cannot be correct on undulations on the bottom of channel, resulting from unsuitable selection of the scan velocity, frequency and hatching of the laser pulses (visible on figure 7 and 8).

![Figure 7. Details of the bottom of capillary separator of two phase mixture - roughness >10 µm.](image)

![Figure 8. Details of the micro herring bone mixer made by improper selected scan velocity, frequency and hatching-roughness ~10 µm](image)

![Figure 9. Micro herring bone mixer made by proper selected scan velocity, frequency and hatching.](image)

Micro herring bone mixer presented in figure 9 proves that proper selection of scan velocity, frequency and hatching of laser beam can help avoid ripples on the bottom of treated region. The sidewalls of grooves are sufficiently smooth for fluid flow, and edges and angles are sharp and precise. Laser ablation has not caused any dangerous mechanical stresses around the treatment zone and there have not been any cracks.

The microstructures of capillary separators of two phase mixture in the scale 1:1, 1:2 and 2:1 have been performed (photos a) and b) in figure 10), using the evaluation results of the quality of mapping the test structures. When the lateral dimensions become closer to the hatching feature, the quality significantly decreases. Small scan speeds contribute to a stronger local heating of the material intensifying the ablation and worsening the quality of the mapped 3D shapes. Increasing energy of pulses with higher scan velocity increases the efficiency of ablation and saves time but there is optimum value of energy for obtaining sufficiently smooth and proper details for effective separation.
of two phase fluids. Figure 10c presents SEM photos of details made in silicon by an accurate laser beam. There the middle splitting seam is very regular. The bottom of the channel is smooth. To ensure the best quality of the scanned surfaces, required energy should be just on the limit of the ablation threshold for particular materials. For such conditions, during one cycle of laser treatment the removed layer is very thin (even less than 1µm). This allows to determine geometric dimensions accurately and obtain a smooth surface. It should also be remarked that the values of fluence are calculated assuming ideal laser pulse shape in time. According to the manufacturer a real pulse shape is far from perfect rectangle. The given energy value is the mean value throughout the whole duration of the pulse, while its instant values are strongly fluctuating.

![Figure 10c](image)

**Figure 10.** Microstructures made by SPI fiber laser ablation in different scale: a – in alumina ceramic; b – in silicon; c – SEM photo of details of smallest structures of (a)

3. Conclusions
The quality of micro-treatment of different microsystems in silicon and alumina was determined by microscopic images (optical and SEM microscopes), whose selection has been presented in figure 4, 5, 6, 9 and 10. In particular the depth of ablation and its uniformity, reproduction of the edges and representation of shapes were assessed. Our experiments have proved that the main obstacles in microtreatment of ceramics and silicon (its brittleness and hardness) can be easily overcome by fiber laser ablation method proposed in section 2.1.

The results of the experiment in manufacturing the microstructures with features of dimensions close to the diameter of nanosecond laser beam, indicate the need to optimize the conditions for such treatment. Optimization must be based not only on the beam energy parameters (reaching the ablation threshold), but also on the properties of the scanner, and the geometric details of the microstructures shapes. Adequate selection of laser beam pulse (duration of the pulse, frequency, scan velocity, hatching and energy) guarantees sufficiently smooth sidewalls and bottoms of the channels as well as sharp edges of pattern lines.

Laser ablation by SPI fiber laser is a rapid process, useful for prototyping and quite convenient because of a relatively low price of such equipment.

4. References
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