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# In-volume structuring of silicon using ultrashort laser pulses

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**Abstract**

We investigate in-volume structuring of crystalline silicon with ultrashort laser pulses. The processing threshold is analyzed in dependence of pulse length (0.8 – 10 ps), pulse energy, pulse number and repetition rate (30 – 200 kHz). Moreover, the generated morphology of the irradiated region as well as the dynamic evolution during laser irradiation was studied. This work has the potential to pave the way for future silicon processing methods like stealth dicing or even the generation of buried integrated optical elements.

Keywords: ultrashort pulses; in-bulk processing; silicon;

## 1. Introduction

Today, in-volume structuring of different dielectric materials using ultrashort laser pulses is a widely demonstrated method for the generation of buried 3D optical elements like waveguides or Bragg gratings. (Itoh et. al 2006, Tong et al. 2003) First attempts to transfer this process to silicon, which requires ultrashort laser pulses in the IR, were restricted to structures in close vicinity to the surface (Nejadmalayeri et al. 2005). In-volume structuring deep in the bulk of silicon has not yet been achieved with the help of femto- or picosecond pulses (Mouskeftaras et al. 2014, Shah et al. 2013, Verburg et al. 2014). The main reasons are the high refractive index of silicon, leading to large Fresnel losses as well as strong spherical aberrations, as well

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as strong nonlinear effects. Recently, first internal structuring with ns-pulses has been reported (Chambonneau et al. 2016). In this work, we present for the first time confined in-volume structuring of silicon by ultrashort laser pulses.

## 2. Experimental setup

For the internal structuring, an ultrafast fiber laser (Raydiance, Inc.) delivering pulses at a wavelength of about 1550 nm and different repetition rates was used. The pulse duration could be adjusted between 800 fs and 10 ps by detuning the compressor inside the laser system. The pulse energy has been adjusted by a half wave plate in combination with a polarizer. For focusing, a microscope objective (20x magnification, Olympus LCPLN20XIR) with NA=0.45 and an adjustable collar for the correction of spherical aberrations was used. The beam diameter has been adapted to the entrance pupil of the objective by a telescope. The sample positioning was realized by a high-precision 3D positioning system (Aerotech, ANT 130). The experimental setup is depicted in Fig. 1. The different parameter combinations used to generate modifications in the bulk of silicon are listed in table 1.

Table 1. Processing parameters used to introduce in-volume modifications in silicon

| Parameter | Used values |
|---|---|
| Repetition rate [kHz] | 30; 33.3; 50; 100; 200; 400 |
| Pulse duration [ps] | 0.8; 5; 8; 10 |
| Exposure time [s] | 0.1; 0.25; 5 |
| Energy on target [µJ] | 0.7 to 6.72 |

In order to realize in-situ observation of the processing a tungsten lamp illuminated the silicon sample perpendicular to the writing direction. The internal modification was imaged by an NIR objective with a numerical aperture of 0.26 (10x magnification, Mitutoyo, Plan Apo) onto an InGaAs array sensor (WiDy SWIR 320U).

For the analysis of the processing threshold to introduce an in-volume modification, a statistical evaluation has been performed. Therefore, we illuminated at least ten different sample positions with the same conditions. The resulting statistical error was calculated with formula (1) where P denotes the damage probability and $n_{tot}$ the number of tested sample sides.

$$P_{error} = \frac{P(1-P)}{P\sqrt{n_{tot}}}, \qquad (1)$$

The samples used for the investigations were polished crystalline silicon (N/Ph, <100>, 1-10 Ω·cm) pieces with a thickness of 1 mm and a width of about 5 mm. The modifications were generated in the center to avoid edge effects and separated with 100 µm distance. After laser illumination the front and back face of the samples were examined under a microscope. This proved that the modifications occur only inside the bulk, no apparent defects could be observed at the outer facets.

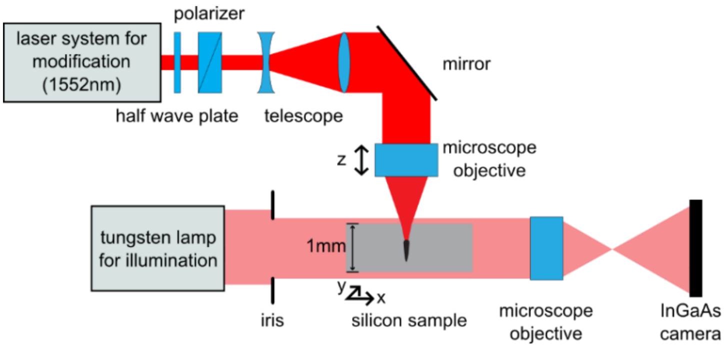


Fig. 1. Experimental setup for bulk modification in silicon

## 3. Results

From the examples in Fig. 2 it can be seen that the modifications for constant focal position in the center of the bulk are aligned along the laser beam propagation direction (vertical). Figure 2a shows these modifications generated by using 10 ps long pulses at a repetition rate of 200 kHz after 0.5 s of illumination (100 000 pulses). On the contrary Fig. 2b and c show modifications for 10 ps (b) and 800 fs (c) induced with 33.3 kHz repetition rate, 16 665 pulses respectively. The morphology of the structure differs strongly for constant processing parameters, especially at higher pulse duration (see Fig 2a and b). Even the basic form of an upturned teardrop shows various numbers and positions of end tips as well as different widths and lengths. At constant pulse energy but decreasing pulse number or pulse duration the shape of the achieved modifications becomes smaller and appears better defined, as shown in Fig. 2b and c. Nevertheless, the damage probability decreases also and for 800 fs only four out of ten tested sides show a change after laser illumination.

The upper limit of these structures is always nearly at the same height for all analyzed parameter combinations. Nevertheless, the modification always starts at the lowest point and grows upwards to the front surface until the fluence provided by the beam caustic is sufficient for material modification. However, the starting position differs dramatically. The reason for this variation is not yet clarified, but can be caused by different parameters, e.g. fluctuations of the energy from pulse to pulse, intrinsic imperfections within the crystalline structure, stress fields resulting from cutting and polishing or surface effects like scratches that alter the in coupled energy distribution.

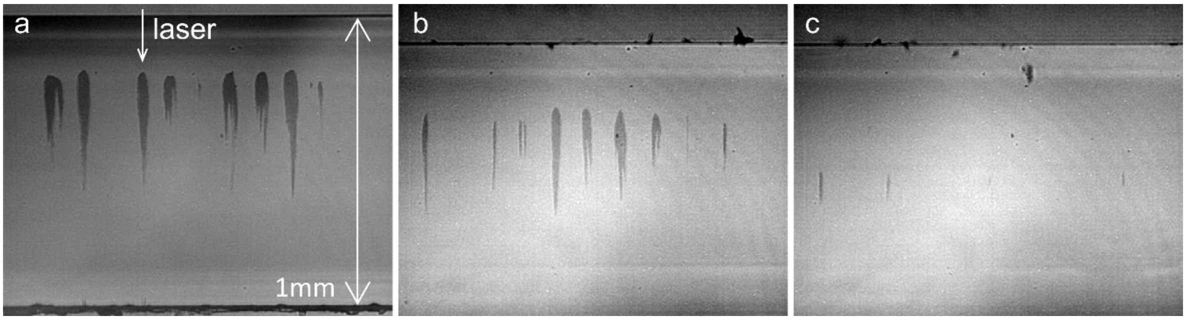


Fig. 2. Examples of laser induced modifications in silicon with constant focal position (center) and 0.5 s illumination time. (a) 200 kHz, 10 ps, 7µJ; (b) 33.3 kHz, 10 ps, 6.6 µJ; (c) 33.3 kHz, 800 fs, 6.6 µJ (all pictures have same scale)

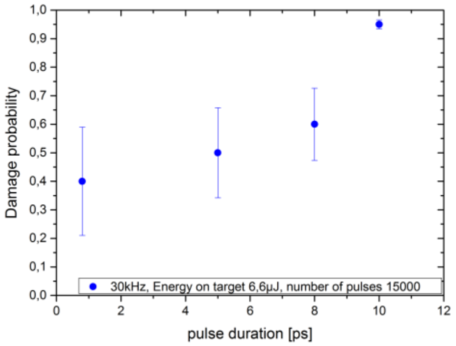


Fig. 3. damage probability depending on pulse duration with 30 kHz repetition rate

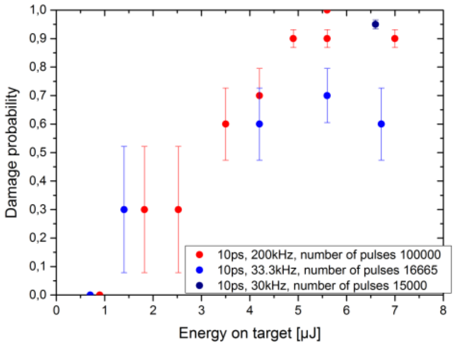


Fig. 4 damage probability depending on energy for different repetition rates

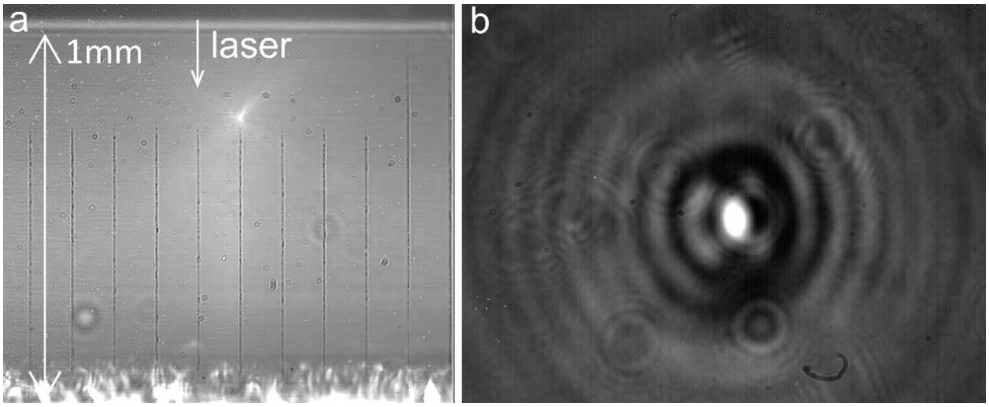


Fig. 2. (a) side view of waveguide structures in silicon; (b) mode field of light guided in one of the structures visible in a)

Fig. 3 and Fig 4. show the dependency of the damage probability on the pulse duration and the pulse energy. If the duration of the pulse is increased the possibility to induce a modification rises. Also for an increasing pulse energy the damage probability is rising. Different repetition rates do not show a significant influence on the incidence of the modifications. However if the energy is increased further damage occur at the front or back surface.

Based on these basic studies different applications can be addressed. One example is the inscription one waveguide structures in silicon. The side view of such a structure is shown in Fig. 5a as well as the resulting image of the mode field (see Fig. 5b). The sample is illuminated with a broad band IR light source around 1500 nm wavelength, coupled into the modification with a microscope objective resulting in a focal spot diameter of 2 µm. Further investigations on laser parameters for modification, writing strategies and the characterization of the written structures are in progress.

## 4. Conclusion

We demonstrated the possibility to achieve in-volume modifications in silicon with ultrashort laser pulses. The probability to induce such structures increases with pulse duration and energy. If the energy is increased above a certain limit damage also at front and back surface is induced. For lower pulse durations the modifications become smaller and more defined. Light could be successfully guided in the structures produced, indicating a local increase of the refractive index in the modification area.

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