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A setup for micro-structured silicon targets by femtosecond laser irradiation

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Abstract. We present a process to fabricate micro-structured thin silicon foils with highly light-absorbing properties over a broad wavelength region based on short-pulse laser treatment. We employ this fascinating technique to the fabrication of targets for high-intensity laser-plasma experiments. A polished silicon wafer is processed with high-intensity femtosecond laser pulses resulting in conical spikes within the irradiated region. Height, distance, and shape of these spikes depend primarily on the number, energy, central wavelength and duration of the incident laser pulses, as well as the ambient medium. This method is of great value for the future development of target fabrication. The broad parameter base offers a huge selection regarding shape and dimensions of the resulting structure. It can be included in existing laser operations within the manufacturing chain while offering a high degree of customisability. Within the reach of higher repetition rates of high-power laser systems and an increased number of requested targets, this manufacturing method can be scaled while being cost efficient and easily adaptable.

1. Introduction

The need for powerful, compact and reliable high energy particle and radiation sources is an ongoing key motivation for new techniques and materials investigated within the field of high power laser plasma science [1-3]. For these experiments the coupling efficiency of laser energy into the interaction is essential. To improve the conversion efficiency of laser energy to ions, electrons or electromagnetic radiation, the precise tuning of laser and target parameters is required. A series of experiments has shown the influence of nano- and micro-structured targets on high power laser experiments [4-7]. We focus on an improved target design with structural modifications of the front surface, intended to increase absorption and alter the emission of electrons, ions, electromagnetic radiation.

Here we produce a structured surface on silicon using a laser driven ablation process described in 1998 by Her. et al. [8]. Following this work, a large number of experiments and further development towards photoelectrical and -chemical applications for micro-structured (black) silicon have been demonstrated for different structural parameters and materials. The dramatically increased absorption over a broad wavelength region is explained to be due to an increased surface area with the cones trapping the light, while a modified band gap further increases the absorption range as a result of laser induced dopants in the surface of the structure. To our knowledge, our work is the first time this fabrication technique has been deployed to the generation of targets for high power laser plasma experiments.

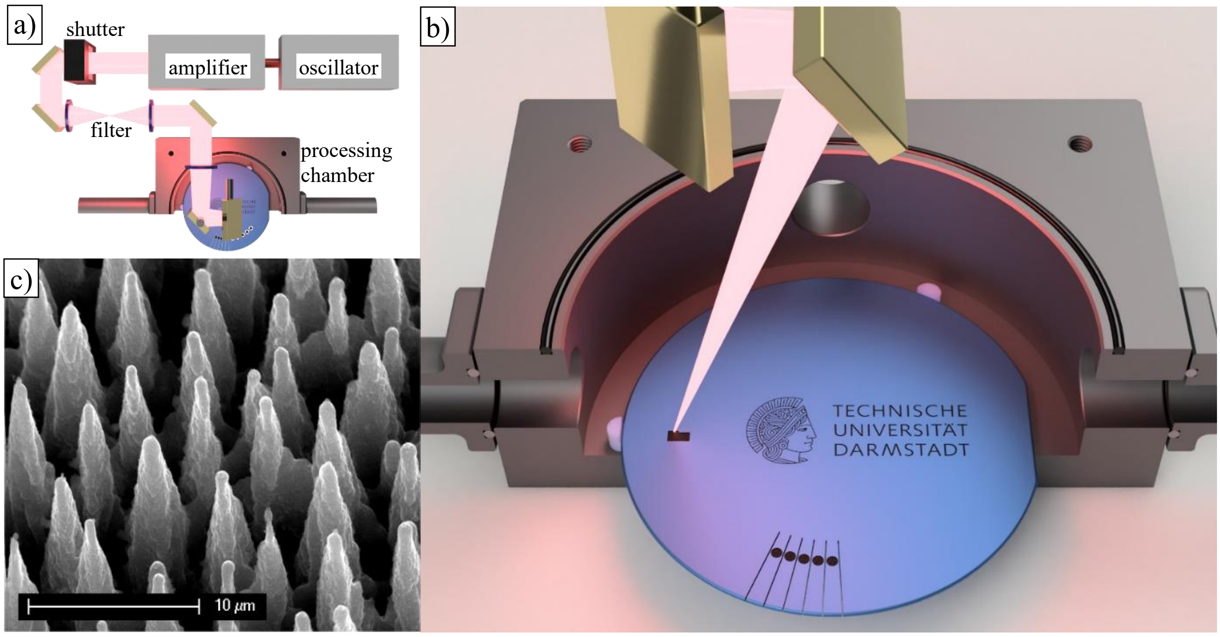

Figure 1: Schematic setup for structuring of silicon. a) shows a simplified overview of the laser system and processing chamber, including the ultrafast shutter and spatial frequency filter. b) is a detailed cross-sectional view of the processing chamber. Precise control of the lateral position of the laser focus on the wafer surface is possible using the two-dimensional galvanometric mirror system. The chamber can be sealed and filled with gaseous and liquid media to influence the general shape of the structure. c) shows a scanning electron microscope image of the targets presented in this work. Conical spikes evolve due to the irradiation of silicon with ultrashort laser pulses in a sulphur hexafluoride ambient.

2. Target Fabrication System

The schematic setup used for the production of structured silicon targets is depicted in Figure 1a). A two-staged Ti:sapphire laser system with a central wavelength of 800 nm, a pulse duration of 100 fs and a repetition rate of 5 kHz is used as driving source for the micro-structuring of silicon. The pulse energy of the laser system can be adjusted continuously in between 10 µJ and 200 µJ. The spatial beam profile is improved by spatial frequency filtering and nearly Gaussian. Using a f=250 mm lens, the laser radiation is focused onto the target surface. Displacement of the focus is possible using a two-dimensional galvanometric mirror system.

Targets described here were produced from mono-crystalline silicon samples with an initial thickness of 25 µm and a ⟨100⟩ surface orientation. These thin membranes were etched in a thicker wafer (600 µm thickness) and placed inside a sealed processing chamber. The chamber can be filled with different gaseous and liquid media. Here sulphur hexafluoride (SF_6) with a pressure of 800 mbar is used. The initially polished silicon surface is illuminated by several hundred femtosecond laser pulses, which results in the ablation of material. Surprisingly, no bulk removal of material will occur, but conical spikes of different height, distance and shape will evolve, depending on the laser fluence, number of incident pulses, central wavelength, pulse duration and ambient medium. It is commonly assumed that these structures are generated by an interference of incoming and scattered light and the excitation of surface plasmon-polaritons. The ultrafast laser-solid interaction causes the electrons in the lattice to heat rapidly. Depending on the pulse intensity this results in melting and rapid solidification of the surface or in an ablation and thereby removal of surface atoms. Respective studies show that processing in air or vacuum creates blunt spikes on a micrometer scale, whereas halogen containing gases result in sharper spikes [9]. Structuring in liquid media will produce smoother variations with a smaller scale length [10].

3. Experimental Campaign

A comprehensive experiment has been realized at the Central Laser Facility located at the STFC Rutherford Appleton Laboratory, UK. Target Area Petawatt with the high power VULCAN OPCPA laser system offers ideal conditions to explore the characteristic of the novel target design presented here.

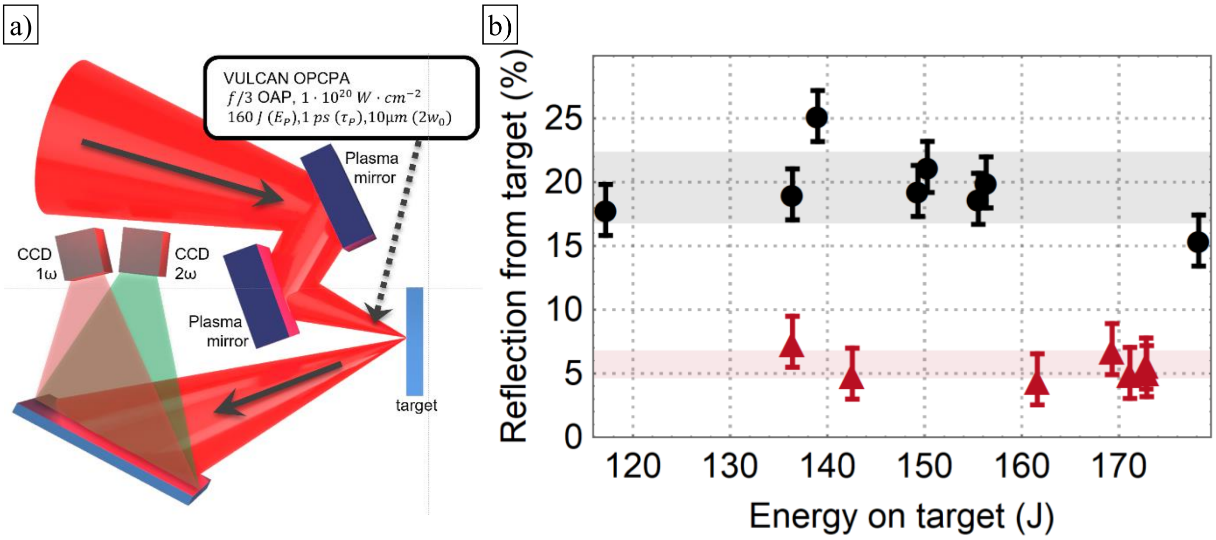

Figure 2: The experimental setup for the campaign at the VULCAN laser system is shown in a). A high intensive, high contrast laser pulse is focussed on the target front. Radiation from the target front is collected on a scattering screen, that is observed by two wavelength selective cameras (fundamental 1053 nm and second harmonic 527 nm radiation). In the campaign, structured targets are compared to flat targets. b) shows the reflection of light from the target front for flat (black) and micro-structured (red) targets. We observe a decrease in reflectivity by a factor of three, using micro-structured silicon targets. The energy coupling to the target is thereby increased.

To observe effects of the front structure interacting with the highest intensity of a laser pulse, the temporal intensity contrast of the laser system is critical, as otherwise the fine structure will be preheated and thereby altered before the main pulse arrives. For this experiment a double plasma mirror system is employed to decrease the pre-pulse intensity below the laser-induced damage threshold for silicon. The pulse energy delivered on target is 160 J with a pulse length of 1 ps, resulting in a peak intensity of $2 \cdot 10^{20}$ Wcm^{-2} for a focus diameter of 10 µm. Incident angle to target normal is 20°. Thereby it is possible to collect light escaping the target front on an energy calibrated scattering screen and gain an absolute measure for the energy reflected from target.

We observe a strong transition in fundamental reflectivity and second harmonic (SH) emission when comparing flat to micro-structured silicon targets. For 1053 nm we observe a decrease by a factor of 3 (20 ± 3 % to 6 ± 1 %) in reflected laser light of fundamental wavelength (compare Figure 2b). In addition, SH emission is reduced by a factor of 10 (1.0 ± 0.5 a.u. to 0.10 ± 0.05 a.u.). The reduction in light escaping the front surface indicates that the energy coupling to the target is enhanced significantly, while the surface energy flux is decreased due to the increase in interacting surface area. This observation is consistent with previous studies using structured surface targets. With an increased absorption of energy to the target, changes to laser-driven particle and radiation generation is expected and observed. However, the thorough description of the experimental results would go beyond the framework of this article.

4. Conclusion

We demonstrate the production of micro-structured silicon targets with highly light-absorbing properties for high power laser experiments. The targets are structured, using ultrafast laser ablation in a sulphur hexafluoride ambient with a straight-forward and robust fabrication system as described. The resulting microstructure consists of conical spikes, that introduce strong light trapping over a broad wavelength region. First experimental results show a great potential of this novel target fabrication technique for high power plasma science, even towards high repetition experiments.

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