Three-dimensional writing inside silicon using a 2-μm picosecond fiber laser

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THREE-DIMENSIONAL WRITING INSIDE SILICON

USING A 2-µM PICOSECOND FIBER LASER

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Abstract

Based on the development of a µJ-class Thulium-doped fiber laser operating in the picosecond regime at 1970-nm wavelength, we introduce a solution for three-dimensional (3D) laser writing technologies inside silicon (Si). We reveal that the nonlinear effects preventing from bulk modification in Si with femtosecond pulses persist in the picosecond regime. However, these are strongly reduced which makes possible to derive conditions for a demonstration of data inscription and reading deep into a Si wafer.

Introduction

First experiments using femtosecond lasers in the prospect of a 3D laser writing technology applicable to silicon (Si) have revealed strong nonlinear effects affecting energy delivery. These include highly efficient multiphoton absorption and important plasma effects far before reaching the focal region, which prevent from localizing enough energy density in the bulk of Si to induce any permanent material change [1-3]. Here, we introduce a solution based on the development of a µJ-class Thulium-doped fiber laser operating in the picosecond regime. Supported by nonlinear propagation simulations and energy flow analyses, we reveal that nonlinear propagation effects persist in the investigated regime near critical power conditions. However, the conditions for reliable writing deep into Si wafers are accessible. Moreover, we anticipate a direct benefit of the Thulium-doped fiber laser technology used in these experiments with the possibility for bulk processing of even narrower band gap materials (e.g. Germanium). This represents a new challenge in this rapidly growing field of research after the recent demonstrations of the first in-chip functional microsystems fabricated inside Si by laser writing [4-6].

Results and discussions

To target a pulse energy level consistent with the application of bulk machining in silicon we rely on the development of a Thulium-doped fiber system delivering 2-ps pulses at 1970 nm. While table-top systems deliver outstanding performances on the order of hundreds of µJ [7], monolithic all-fiber systems are usually limited to sub-µJ energy level [8] [9]. We have developed a 5 µJ-class ultrafast thulium-doped fiber system. The chirped pulse amplification approach was applied to the seed pulses generated in a dissipative soliton oscillator [10]. This concept allows all-fiber integration, high seed average power, adjustable spectrum to fit dispersive transmission band components, and pre-stretched pulse. The power amplifier stage features 25-micron core diameter active fibers instead of rod-type photonic crystal fibers. In order to boost the pulse energy above the µJ level, the nonlinear threshold, imposed by the active fiber core size, was increased by stretching the seed pulse to 550 ps by means of a chirped fiber Bragg grating stretcher. The system also includes pigtailed acousto-optical modulator for repetition rate control. Finally, the output pulse was compressed using chirped volume Bragg grating. The linear amplification regime was observed up to an output average power of 500 mW at a repetition rate of 100 kHz.

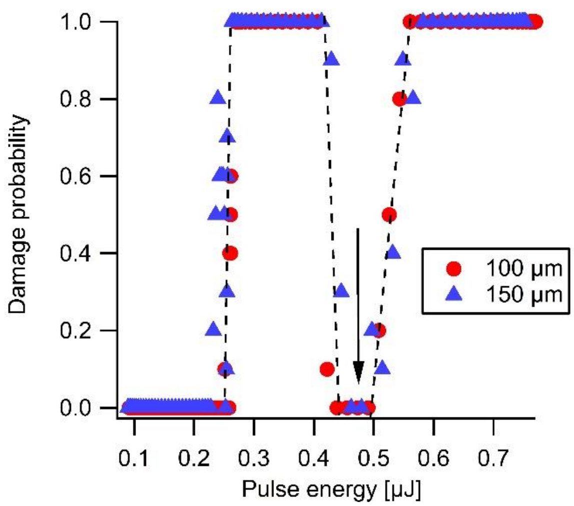

Figure 1. Damage probability measurements with 10000 pulses focused below the surface of Si. Two focusing depths are tested: 100 and 150 µm. Damage occurrence is established using dark field IR microscopy. Several transitions between 0% to 100% damage probability evidence a non-monotonic change of the delivered fluence due to the nonlinear effects. The absence of damage in an energy range above threshold is attributed to nonlinear delocalization of the radiation.

To investigate the damage response of bulk silicon, we carried out measurements using a conventional machining experiment. Linearly polarized pulses are focused with NA=0.85 at different depths in an intrinsic Si wafer (<100>-orientation, double side polished) using an asphere mounted on a motorized stage (along the optical axis Z). XY positioning is performed by motorized motion of the Si wafer. The theoretical spot diameter is about 1.5 µm (FWHM) according to calculations. We employ dark-field microscopy for detecting the light scattered by any produced damage in the bulk. In practice, the sample is illuminated at grazing angle with white-light and a microscope unit equipped with an InGaAs camera is installed for *in situ* observation. Irradiations are systemically repeated 10 times for each tested condition so that we can make a statistical analysis of the damage initiation and discuss the results in terms of damage probability.

The figure 1 illustrates the unusual damage response resulting from irradiation of Si with 10000 pulses. It shows the measured damage probability as a function of the energy of the 2-ps pulses. The corresponding experiments have been repeated after placing the geometrical focus at two different depths: 100 and 150 µm. Each measurement results from irradiations separated by 50 µm to avoid any side effects from previous irradiations. For both depths, we first note a transition from 0% to 100% damage probability for a pulse energy of ≅ 250 nJ thus showing that the damage threshold can be exceeded in contrary to femtosecond laser experiments for similar focusing conditions. In practice, as soon as the transition region near threshold is exceeded, we observe highly repeatable modifications. However, a surprising feature occurs at higher energy (around 450 nJ and shown by an arrow in Fig. 1) where the damage probability drops down to zero indicating a reduction of the delivered fluence below the damage threshold. It is also interesting to note that by increasing the energy, it remains possible to overcome this reduction and retrieve the 100% damage probability with apparently less localized modifications as more important scattering by the damage sites is detected.

To understand this unusual damage response, we turned to nonlinear propagation simulations. All the details on the simulations method were reported in Ref. [11]. The results in the picosecond regime and comparisons to experiment are available in Ref. [12]. In brief, our simulations account for Kerr refraction, nonlinear ionization and the associated plasmas effects. It was originally developed to quantify the intensity clamping process generally experienced by propagating intense pulses and being severely pronounced when ultrashort pulses are tightly focused in bulk Si [3]. In this previous work, the comparisons with measurements showed that the essential contributions to the intensity clamping are correctly accounted in the model [3]. We have identified the progressive depletion of the pulse by pre-focal nonlinear absorption, plasma screening and defocusing as contributing factors to the clamping. However, we also found the importance of Kerr refraction for a fully quantitative agreement. Interestingly, without introducing any additional physical contribution in the simulations, we found a small delocalization and re-localization of the laser energy flux above clamping conditions in the picosecond regime [12]. This can be directly associated to the non-monotonic damage probability which is found above clamping. Kerr focusing being the only nonlinear process localizing the laser energy, it is natural to expect that it is the one competing with the previously mentioned effects clamping the intensity to cause the modulation of the laser pulse energy density.

With the knowledge of this peculiar damage response shown in figure 1 we derived the conditions to achieve well-localized modifications in two distinct planes. The energy of the 2 ps pulses is first set slightly above the modification threshold but below the delocalization energy range (320 nJ per pulse focused with a numerical aperture NA=0.85) for reliable digital writing of binary data at a depth of 150 µm below the surface of a Si wafer. Data of a second information are subsequently inscribed on the surface using the same procedure at reduced pulse energy for pixels defined by clean ablation (confirmed by SEM observations). As shown

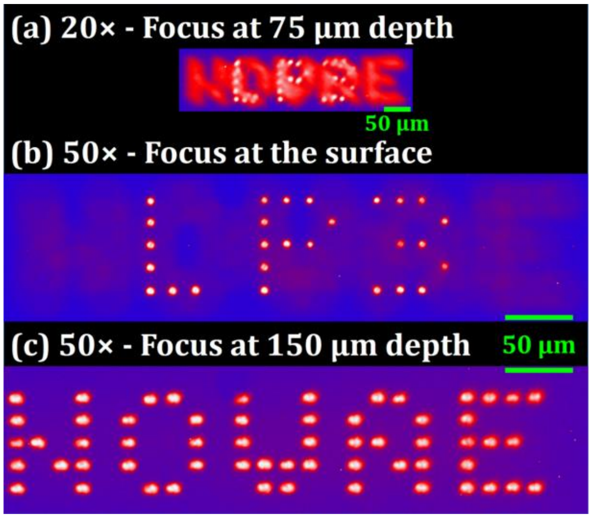

Figure 2. Bulk-surface two-plane data inscription by laser processing. The sample is observed in IR dark field microscopy. With 20× magnification (a), the depth of field allows to observe both planes at the same time but the two layers are clearly distinguished by changing the focusing depth with a 50× magnification objective [(b) and (c)].

in figure 2, the data in the two planes are clearly distinguished using the infrared dark-field microscope provided that the depth of field is short enough using a high magnification microscope objective. This demonstrates the possibility for multi-layer writing and reading information inside silicon wafers by picosecond lasers.

Summary and conclusion

Bulk damage test experiments in crystalline silicon have revealed that the energy flux of 2-µm pulses is strongly affected by nonlinear effects. However, in contrary to the femtosecond regime, the modification threshold can be exceeded when 0.85 NA focusing is used. This enabled us to successfully inscribe data inside a Si wafer and, more importantly this indicated that microfabrication applications can be addressed on the basis of the rapidly developing Thulium-doped fiber laser technologies.

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