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ULTRAFAST LASER WRITING DEEP INSIDE SILICON

Paper # Micro 191

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Abstract

We generate and apply ultrafast trains of infrared pulses with durations ranging from 200 fs to 3.5 ns. We show how this gives unique multi-timescale control parameters for improved energy deposition and reliable 3D laser writing deep inside silicon.

Introduction

The advent of ultrafast laser sources in the near- and mid-infrared domain hold promises for internal structuring of silicon and other semiconductor materials which are extremely challenging to be processed in the three dimensions (3D writing). However, the first experiments using femtosecond lasers for this prospect have revealed strong nonlinear effects affecting energy delivery in the material. These include highly efficient multiphoton absorption and important plasma effects far before reaching the focal region. For the shortest femtosecond pulses, these effects prevent in most cases from localizing enough energy density in the bulk of Si to induce any permanent material modification [1-3].

Our first proposed solution to this problem was relying on an optimization of the spatial characteristics of the interactions. It used hyper-focused beams (solid-immersion focusing) to circumvent pre-focal interactions and achieve microplasmas up to permanent material modifications in the bulk of silicon with sub-100-fs pulses [3]. For more practical alternatives, we now introduce progressively optimizations in the time domain. We investigate the material response with longer pulses to limit the propagation nonlinearities and to improve the process reliability by provoking progressive thermal band gap closure to assist pulse energy deposition [4,5]. An additional optimization in this direction is to rely on transient accumulation strategies. To this aim, we generate and apply ultrafast trains of ultrashort pulses up to Terahertz repetition-rates [6]. Combining these approaches together, we also study the interactions with synchronized pulses of different durations in an experiment that allows us to discuss the influence of the temporal contrast of the pulses [7]. We demonstrate an unusually high level of sensitivity to this parameter making its dedicated investigation a critical step in this growing field of research. This study thus introduces new control parameters to address this rapidly growing field of research after the recent demonstrations of the first in-chip functional microsystems fabricated inside Si by laser writing [8-13].

Results and discussions

The solutions presented in this paper rely on 200-fs pulses generated by Yb:KGW laser source (centered at 1030 nm) and then converted to 1550 nm by optical parametric amplification (OPA). Because of the multi-stage nonlinear amplification inside OPA, the laser pulses show high temporal contrast. For investigations in the picosecond domain, we use a grating pair to stretch the pulses. This allows us to irradiate Si with pulses of different durations from 4 to 21 ps. We also use a commercial nanosecond laser source to generate <5-ns pulses at the same wavelength of 1550 nm. The setup to prepare and potentially combine beams with different pulse durations for interaction studies is described in ref. [7]. Silicon samples are systemically irradiated with NA=0.85 and a focus located 300 µm below the surface of the samples. According to infrared microscopy diagnostics we determine the threshold conditions for internal writing by detecting the occurrence of permanent modifications.

By investigating the pulse-duration dependence of laser writing in silicon (repeated single pulses) [5], a requirement was found on the pulse duration which must exceed 5.4 ps to determine conditions leading to confined modification near focus. Interestingly, we revealed actually a dual threshold response for short picosecond pulses (5.4-11 ps) as there is an energy value threshold to exceed but also another value that should not be exceeded to achieve modification. The measurements show that focused pulses of 4 ps (or less) does not allow to write permanent modifications

independently of the energy. These observations support the idea of a peak power that should not be exceeded to avoid nonlinear delocalization of light as observed in other recent studies [1-4] with shorter pulses. With our longest picosecond pulse (21 ps), we find an energy threshold under 0.15 µJ and create repeatable micro-features depending on the applied laser energy. The repeatability indicates that the peak power is already sufficiently decreased to avoid detrimental nonlinear distortions and it identifies a short-pulse limit to the large panel of applications already demonstrated in the nanosecond regime [8-11].

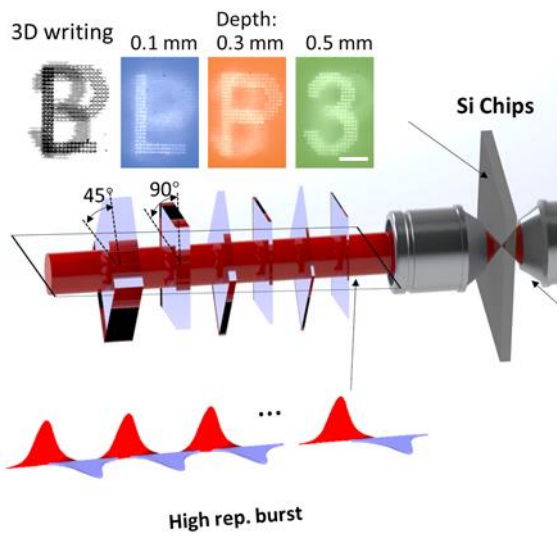

Figure 1. Simplified view of in-line arrangement of birefringent crystals for the generation of ultrafast trains of pulses used for demonstrations of multi-layer data writing deep inside silicon. Top images are infrared microscopy observations of a stack of three letters written with 1.9 µJ, 4-pulse trains (4.7 ps/pulse) at depths of 100 µm, 300 µm, and 500 µm, respectively. Black and white image is an observation with large depth of focus in bright field while color images are high magnification observations in dark filed with varying imaging focus to distinguish the inscriptions between planes. Scale bar: 50 µm.

For comparison, our pulses of <5 ns are accompanied by a threshold pulse energy of ~0.21 µJ that interestingly is not significantly higher than the value found in the picosecond domain.

Supporting the idea of a minimal pulse duration required for bulk modifications, we have also investigated multi-pulse (or burst) approach as another way to increase the apparent pulse duration. With the help of birefringent crystals, we have generated ultrafast trains of pulses (up to 64 pulses) to study the modification conditions [6]. The configuration creating the train of pulses with alternatively horizontal and vertical polarization (see bottom representation with red and blue components) is illustrated with Fig. 1. Working with pulses of 4.7 ps, we show with top-images (Fig.1) that increasing the number of pulses in the train improves the situation as trains of 4 pulses lead repeatable damages inside bulk while it is impossible to exceedteh threshod for modification with single pulses of the same duration (comparisons at fixed energy). To exemplify the writing performance, the top images show binary data inscription by dot arrays fabricated at three different depths: 100 µm, 300 µm, and 500 µm. In black and white, the text is observed with a modest magnification objective (×10, NA=0.3) focused on the "L" so that the depth of field allows to visualize on the same image the other letters which are deeper in the sample. Interestingly, dark field images using a higher NA observation (×20, NA=0.45) of the same inscription (shown with colors) can clearly distinguish between planes. These demonstrations directly support the possibility to rely on energy density accumulation from train of low intensity ultrashort pulses to solve the limitations to ultrafast laser writing. This aspect is also confirmed by measurements of the delivered energy densities in silicon studied with various pulse-train configurations in ref. [6].

Another important asset of our experimental arrangement is the ability to introduce new control parameters in the time domain. This allowed us to unravel the strong contradictions existing between all previous works regarding the threshold conditions for bulk modifications in Si. In brief, our work and others using OPA sources argue that modification in femtosecond regimes are inaccessible with conventional laser machining configurations because of the discussed above nonlinearities delocalizing intense light [1-4]. However, other studies have presented demonstration of waveguide writing in Si with femtosecond fiber lasers under conditions which are very similar to those used in conventional studies (e.g. in dielectrics) [12,13]. This gave us a motivation to study the dependence to the temporal contrast of pulses, an aspect which has been ignored so far. By combining and synchronizing our femtosecond, picosecond and nanosecond pulses, we are able to simulate any contrast imperfection. The detailed quantitative analysis of the problem presented in ref. [7] reveals an extremely high sensitivity with modification ignition at intensity contrasts down to 10^{-6} and below. Such sensitivity has no equivalent in any other laser material processing application and causes these laser-technology dependent results. This important finding allows a comprehensive review of the literature on the topic of 3D laser writing in silicon presented in ref. [7]. It also

provides important guidelines on the most appropriate laser technologies to address the applications.

Summary and conclusion

Bulk modification experiments in crystalline silicon with various combinations of femtosecond and picosecond pulses at 1550-nm have confirmed that the energy flux is strongly affected by nonlinear propagation and plasma effects. However, in contrary to the pure femtosecond regime, we show that the modification threshold can be significantly exceeded at 0.85 NA provided that a long duration component is introduced. This enables us to demonstrate reliable 3D writing in semiconductors, showcased by successful high-density data inscription inside a Si wafer. Overall, this shows the important potential of temporal shaping technologies in the infrared to address this new range of 3D writing applications.

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