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GHz femtosecond processing

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Abstract

Most current future industrial applications of ultrafast lasers require high processing quality, but also high throughput and productivity. While ultrafast lasers excel processing with an exquisite precision, each laser pulse only removes a small amount of material. This disadvantage can be counterbalanced by distributing the energy into a burst of pulses at a GHz-level repetition rate. Indeed, we conceptually show that GHz ablation efficiency is achieved through the balance of the pulses dedicated to heat accumulation and effective ablation. For that, several inter-related parameters, such as pulse energy, number of pulses per burst, intra-burst and inter-burst repetition rates must be optimized. A new high-average power GHz-burst femtosecond laser source, delivering output powers from 20 W to 100 W allowed for reaching specific ablation rates up 2.5 mm^3/min/W for Si.

Keywords: femtosecond laser processing; GHz laser, ultrafast ablation ;

A new step of the ultrafast technology revolution is now underway and will further increase penetration of ultrafast lasers in new domains. Most current future industrial applications of ultrafast lasers require high processing quality, but also high throughput and productivity. The laser ablation rate, *i.e.* the amount of matter removed by minute, becomes then a good proxy for industrial throughput.

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Ablation in the GHz regime reduces the thresholds and increases the ablation efficiencies by an order of magnitude [K. Kerse *et al.* 2016, G. Bonamis *et al.* 2018, 2019]. This specific interaction mode, with efficient ablation eliminating excessive heat, prevents damages caused by high temperatures. In practice, GHz laser sources emit bursts of tens to hundreds of pulses with a typical interval of 1 ns and a total burst width of ten to 100 ns. At such time scales, from fs to sub-µs, several physical mechanisms are involved simultaneously. As a result, the GHz processes are sensitive to all of the laser parameters, including the fluence, the number of pulses in the burst and the intra-burst repetition rate. Careful selection of experimental parameters is necessary to achieve a high quality and efficient process.

In this work, we present ablation of silicon performed with a new industrial laser source delivering amplified bursts of fs pulses (pulse duration of 550 fs) at a repetition rate from 0.88 to 3.52 GHz. Silicon is an excellent candidate for the study of GHz ablation, since fs or ps ablation of silicon has already been the subject of many studies and has also many industrial applications. Using our compact and integrated laser system, the number of pulses per burst was adjustable for selected intra-burst repetition rates and the burst repetition rate was fixed to 100 kHz [Mishchik *et. al.* 2019].

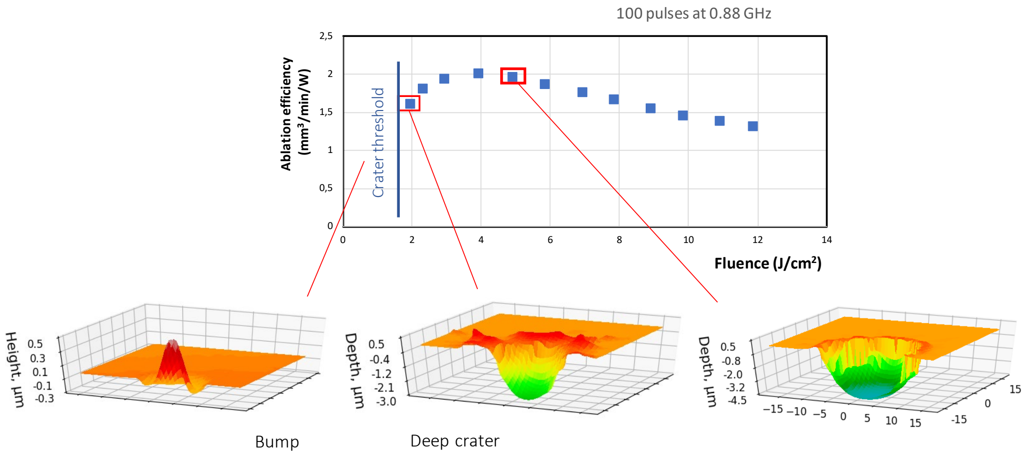

Fig. 1. Efficiency and morphology of silicon modification after GHz ablation, experimental conditions: bursts of 100 pulses at 0.88 GHz intra burst repetition rate. 3D reconstructions produced from optical confocal microscopy measurements. Left: bumps few hundreds of nm height, obtained for a fluence higher than 1.2 J/cm². Middle: the crater near the threshold of 1.8 J/cm². right: deeper crater with higher fluence.

Studies of the morphology of the ablation results show deep craters of high quality with very little remelting deposits when bursts of energy containing a large number of pulses are applied. We found two different types of laser modifications. Bumps are formed at low fluences, and ablation craters appear for higher fluence, above a crater threshold F_{th} (Fig. 1). The bumps are usually elevated in the center of a few hundred nanometers and surrounded by areas of depressions. This could result from the expansion of the silicon during the fusion and is the signature of the thermal character of a first phase of the ablation. The craters may be surrounded by a splash of molten material near the crater threshold, but the splash becomes negligible compared to the volume ablated (less than 3% for a burst energy more than 10 J/cm^2). We note that the crater formed just above the threshold is already deep, with for instance a depth of 2.6 µm in the case of 100 pulses at 0.88 GHz. The ablation rate increases principally with the increase of the crater depth. For similar fluences, longer bursts generate deeper craters, while the diameter does not vary significantly.

The highest ablation efficiency is obtained for 200 pulses at 0.88 GHz and a total burst fluence of 6.8 J/cm2. It corresponds to a specific removal rate for line ablation of 2.5 mm3/min/W, that is higher than so far reported GHz ablation efficiencies.

The GHz ablation mechanisms are a combination of thermal and non-thermal ablation mechanisms, which can dominate at specific burst parameters and laser fluences. Thermal ablation occurs when the material is slowly heated by heat accumulation. In this low-fluence regime, each pulse contributes to an increase in the material temperature until the evaporation point is reached. The material is removed by sublimation or by the critical point phase separation process, removing heat before dissipation in the material. Therefore, we must consider two different time scales within the burst: the heating time and the ablation time. When the maximum ablation efficiency is reached, we observe that the average fluence of the pulses in a burst is about one-tenth of the ablation threshold of a single pulse for silicon (0.43 J/cm^2). This means that in all cases, the effects of heat accumulation are important to start the ablation process by preparing the surface of the material. During the heating phase, the pulses within the burst contribute to an increase in the material temperature. Since the linear absorption coefficient of silicon depends on the temperature and can increase by an order of magnitude as the temperature increases from zero to 1400 ° C, the absorption of each subsequent pulse will be more efficient. Once the ablation condition is reached, subsequent pulses will effectively remove the material because a hot target surface will require less energy to induce ablation.

The used laser source is both flexible and based on mature industrial architecture and is suited for refined process optimization. For example, having high power will allow to probe wider ranges of parameters (burst energy, number of pulses in the burst). Moreover, harmonic generation will allow to evaluate the effects of several wavelengths on the involved ablation mechanisms. For moderate average power up to a few 10 W, the source is based on a compact fiber amplifier associated with a solid-state GHz oscillator. For higher average output power exceeding 100-W, our previous developments [Hönninger *et. all.* 2018] have shown the interest of an hybrid fiber-/crystal-based amplifier. Further key components of the laser systems are the pulse pickers that are used for the generation as well as for temporal and amplitude shaping of the GHz bursts. The pulse energy and peak power of the individual femtosecond pulses forming the GHz burst is another free parameter that is used for process optimization. This parameter is particularly important for the generation of secondary light by nonlinear frequency conversion of the GHz burst laser, e.g. to green or UV wavelengths.

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