# Chapter 6. Applications

Applications of femtosecond technology range from operation in the microelectronics industry to photonic devices or novel optical components. The requirements of lasers as tools in material structuring are high processing speed, high flexibility, no contamination, and extreme focusing possibility. The actual trends in the electronic industry require highly localized treatment of the material with resolution better than 1 µm. The disadvantages of ns lasers are connected to the high processing fluences necessary and related to the strong thermal effects leading to extensive cracking and exfoliation and to the destructive influence of the plasma which is formed above the surface. Efforts have been made to overcome these disadvantages either by using high repetition rates in connection with high fluences, or small laser wavelengths [HLB2000].

Besides the already emphasized advantages of using ultrashort pulsed lasers in basic studies concerning laser matter interactions, the potential of technical applications for ultrashort pulsed laser technology derives from several aspects of the interaction process:

1) Low processing threshold and efficient energy deposition (minimal losses due to the absorption within the plume).

2) Minimization of the unwanted thermal effects, due to the extremely local character of the interaction (compared to ns lasers) and also temporal decoupling between the laser pulse and the transfer process of the energy from the electronic system to the lattice. The deposited energy is mainly carried away by the ablation products as kinetic energy, a small fraction being left as residual heating outside the interaction area.

3) The coherence properties of the radiation and the induced phase relations in the excited electrons can be developed as new methods for surface patterning.

4) Non-linear effects have been applied to increase the local character of the interaction in order to minimize the structures to sub-µm dimensions in dielectric brittle material microprocesssing [LiL2000]. Multiphoton absorption allows one to modify transparent material even inside the bulk and to obtain sub-wavelength structure sizes. Self-focusing due to the non-linear optical Kerr effect may be used to induce long, narrow 3D-modification traces into the bulk of wide band-gap materials [AVR98]. Long, micrometer thin channels can also be drilled taking advantage of the high ablation rates and low heat deposition when employing ultrashort laser pulses [VAR97].

## 6.1 Laser micromachining of dielectrics

The quality and type of the laser-induced structures in wide band-gap transparent materials with ultrashort pulses in the near infrared (800 nm) depends strongly on the choice of the operating laser fluence $F$ relative to the (varying) surface damage threshold level $F_{th}(N,\tau_L)$ as a function of the laser shot number $N$ and pulse duration $\tau_L$.

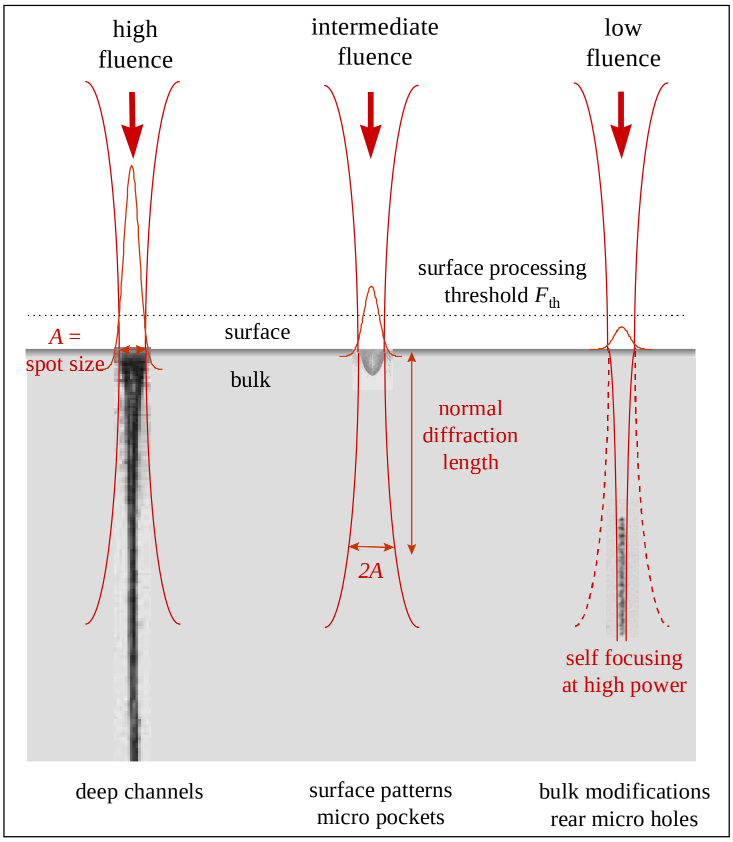

**Fig. 6.1-1** Schematic diagram of beam profile and possible applications illustrating three major fluences regimes for material processing in a side view perspective. Laser pulses are coming from the top. Also included is the energy distribution in the focused laser beam relative to the surface processing threshold (dashed horizontal line). a) high fluence to generate channels, b) intermediate fluence for pockets and patterns, c) low fluence (below surface damage threshold) for bulk modifications and rear side micro-holes utilizing self-focusing effects. The three experimental structures included in the schematic diagram have a diameter size of 20 to 30 µm and were produced in fused silica with laser pulses at 800 nm and a pulse width of a) 0.1 ps (channel), b) 0.2 ps (pocket) and c) 1.4 ps (bulk micro-trace).

As illustrated in Fig. 6.1-1 material processing of dielectrics with ultrashort laser pulses can be divided into three major fluence regimes for the following applications:

- the high fluence regime, $F/F_{th}$>>1 to drill channels with high aspect ratios and little residual damage and stress in the material

- the intermediate fluence regime $F/F_{th} \geq 1$ to generate pockets and surface periodic patterns. Here the laser parameters can be tuned to control the transition from non-thermal effects characteristic of the gentle phase to dominant thermal effects of the strong phase. Incubation plays an extremely important role.
- the low fluence regime $F/F_{th} < 1$ to induce microstructures inside or on the exit side of the material.

$F_{th}$ is the surface processing threshold at which material removal (ablation) is observed and depends on the degree of incubation (for multiple irradiation), wavelength, pulse duration, or material characteristics (band-gap, structure and thermal properties). The schematic picture in Fig. 6.1-1 illustrates examples of laser-induced microstructures in fused silica (channels, pockets and bulk modifications) after multi-shot laser processing at 800 nm in the three different fluence regimes [AHR98].

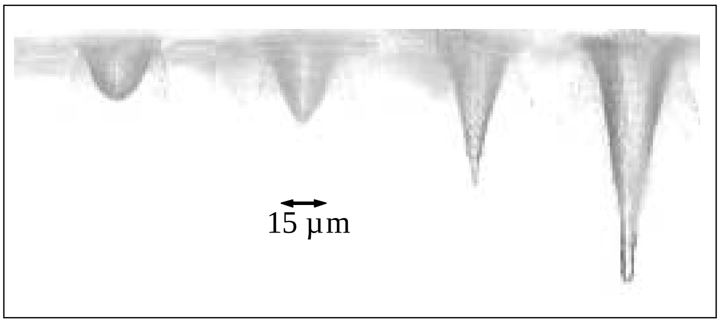

**Fig. 6.1-2** Development of pockets and craters in fused silica with increasing the number of shots. Pulse duration is 200 fs. One can see the characteristic narrowing of the holes from the diameter produced at the entrance surface of the sample, to a diameter much smaller than the laser focus diameter.

Fig. 6.1-2 and Fig. 6.1-3 illustrate the development of channel formation in fused silica with 200 fs pulses and the possibility of drilling at non-normal incidence, respectively.

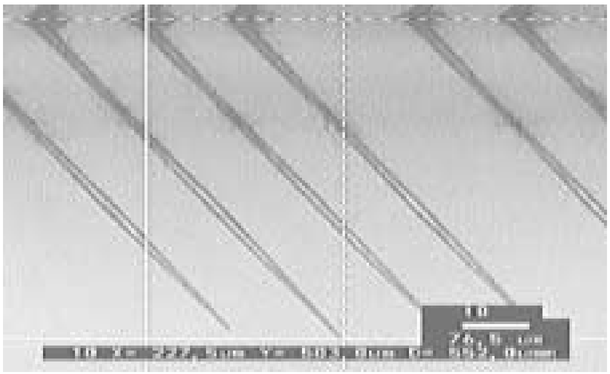

**Fig. 6.1-3** Development of channels at non-normal laser incidence. Laser parameters: fluence 20 J/cm$^2$, pulse duration 100 fs, incidence 37°.

Micromachining with femtosecond laser pulses was found to be more controllable and reproducible than the longer pulse regime and induced far less damage into the material [VAR96, VAR97, AHR98, CAR99,].

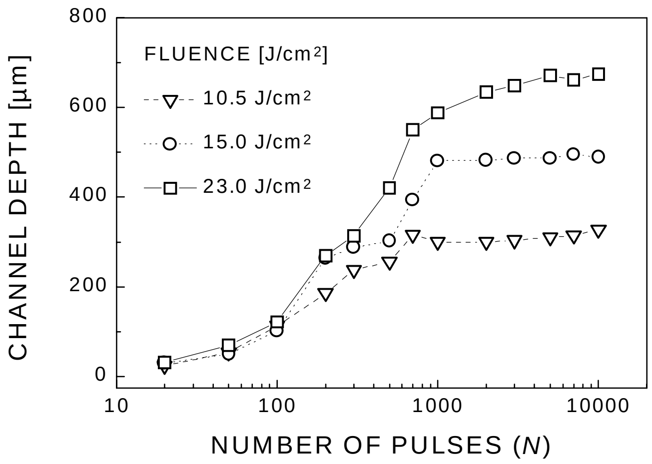

**Fig. 6.1-4** Channel length as a function of the number of pulses for different employed laser fluences at 100 fs irradiation. The asymptotic behavior is due to the channel bottom moving out of the laser focal zone.

Analysis of the channel depth as a function of the number of shots and the laser fluence has produced the following results illustrated in Fig. 6.1-4, and Fig. 6.1-5. The crater deepens with increasing number of shots After the very first few laser shots, beyond the gentle to strong transition, the ablation rate decays slowly until a point of sudden saturation is reached. This point determines the maximum obtainable crater depth and further laser shots only serve to widen the channel. The saturation depth is related to both the motion of the bottom crater out of the focal region and to the ability to evacuate the material from the channel.

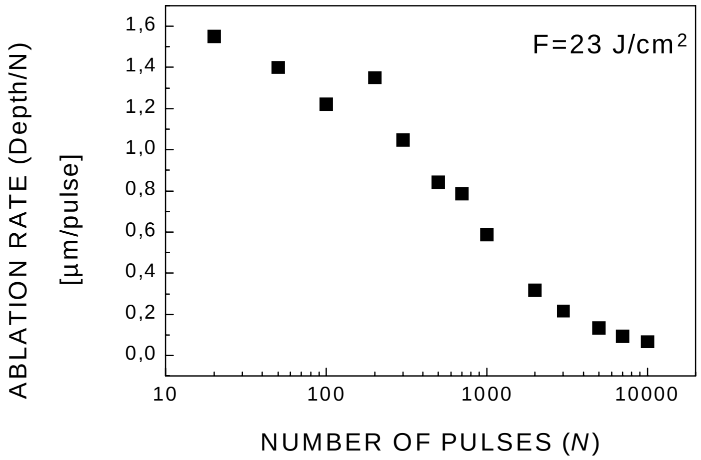

**Fig. 6.1-5** Ablation rate versus the number of pulses. The decay is a result of the channel bottom moving away from the focal point. Pulse duration 100 fs.

The saturation depth (maximum depth) depends linearly on the laser energy as illustrated in Fig. 6.1-6.

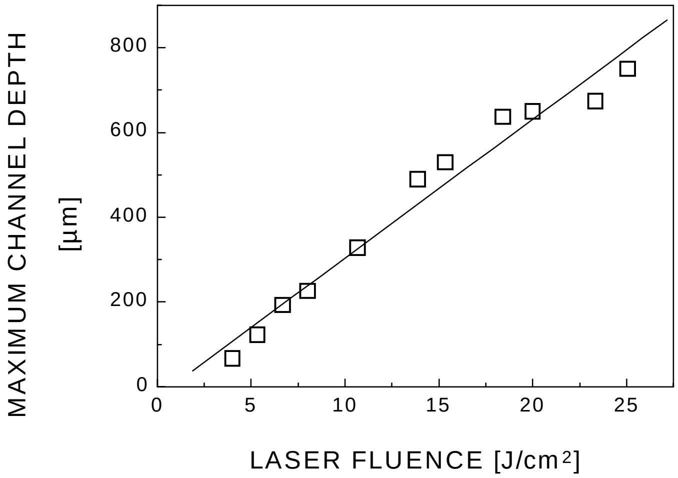

**Fig. 6.1-6** Maximum channel depth versus laser fluence for 100 fs laser irradiation.

Besides the optimization process for drilling of long channels, another path followed in our group was to find a suitable choice of laser parameters that can tune the transition between different processes dominated by either non-thermal or thermal mechanisms respectively, for formation of pockets on the surface. A complementary approach was to use the self-focusing property of Gaussian beams to generate small, controllable sub-micron rear side structures [ALR99, LiL2000]. An example of a laser-induced matrix of microstructures is given in Fig. 6.1-7. These micro-holes have been used for matrix assisted growth of Si crystals.

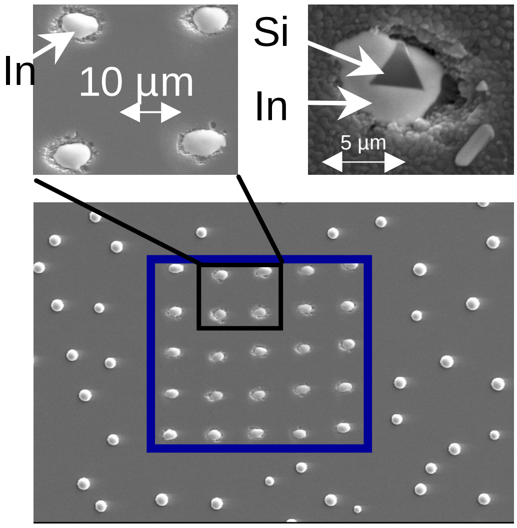

**Fig. 6.1-7** Matrix assisted growth of Si crystals in an array of laser induced micro-holes based on self-focusing on the rear surface.

Another example of controllable structuring of glass with desired patterns is given in Fig. 6.1-8

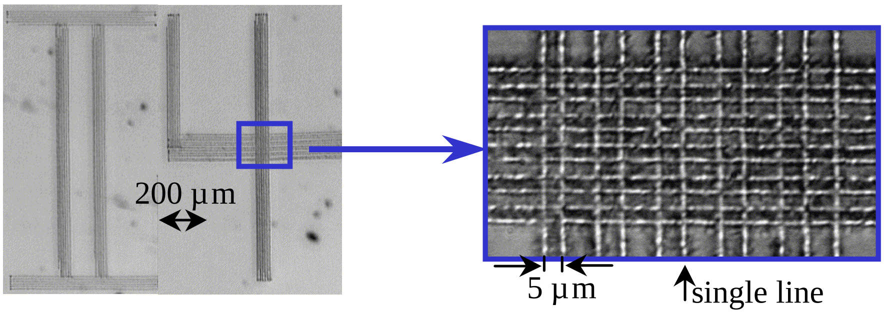

**Fig. 6.1-8** Structures drilled in glass with 200 fs, 800 nm laser pulses.

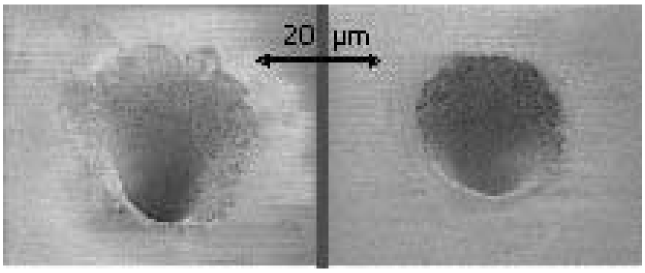

**Fig. 6.1-9** Micropores in sapphire created with ultrashort laser pulses at 800 nm, illustrating the influence of pulse duration (left 4.5 ps, right 200 fs)-same laser fluence.

Fig. 6.1-9 illustrates as an example that good quality micropores can be achieved with 800 nm, 200 fs pulses in sapphire compared to ps pulse duration, due to minimization of the thermal effects. These micropores have been structured with fluences close to the ablation threshold. It was shown in Chapter 3 that this is a regime where ripples can be induced. This regime can be used for regular patterning of the surface [KOS2000].

A last potential application emphasized in this chapter is based on bulk 3D-induced modifications using the non-linear Kerr effect for self-focusing as illustrated in Fig. 6.1-10.

Beam narrowing due to self-focusing will cause the bulk damage threshold to be exceeded for incident fluences well below the surface damage threshold [AVR98]. The induced modifications are based either on localized changes in the material density [GlM97, CBG2000] and stress accumulation or on color centers or other type of structural and morphological defect formation in the irradiated region [ALR2000]. Incubation and defect accumulation due to repetitive irradiation will enable the user to achieve thin traces with controllable length while the pulse length and energy controlling will lead to precise positioning of the modification inside the bulk transparent material. The ability to write three-dimensional objects with micrometer precision promises to have tremendous potential for the generation of high-density 3D data storage and for the creation of periodic bulk structures. Presently exploration of potential applications is being carried on in our laboratory.

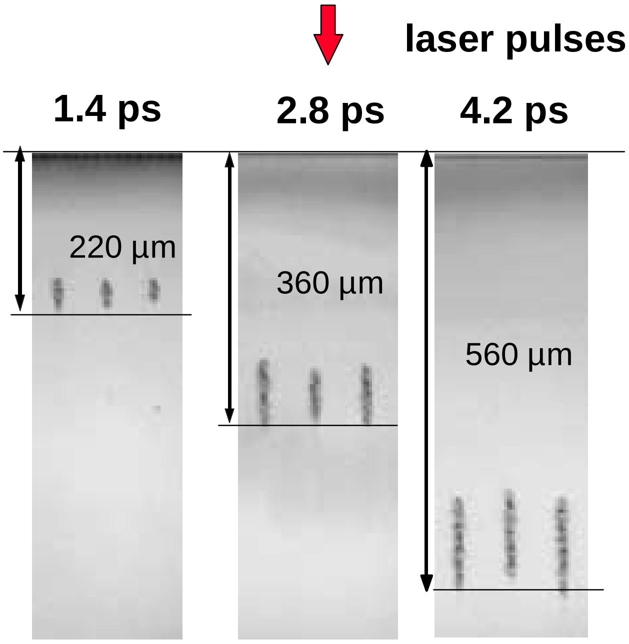

**Fig. 6.1-10** Microscopic side-view of bulk modifications in *a*-$SiO_2$ after 100 laser shots, with laser beam focused at the entrance surface, for three different pulse durations. The energy per pulse was 20 µJ, focus diameter 920 µm$^2$, and λ=800 nm.

## 6.2 Summary

This chapter presents aspects of ultrashort pulsed laser micromachining of transparent materials, underlying the advantages of using ps and sub-ps irradiation regimes. The quality of the induced structures, the high localization of the energy, and low thermal dissipation, as well as the high efficiency of ablation recommends ultrashort pulsed lasers as a suitable tool for dielectrics processing both on the surface and in the bulk.