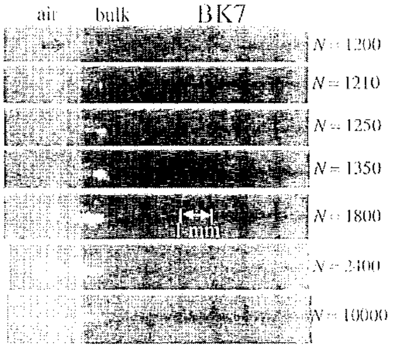


CFK1 Fig. 2. Side-view of the development of the damage inside BK7 starting after 1200 laser shots [5].

electron plasma and super continuum generation (SCG) [3] take significant influence on the beam propagation inside the material. Although SCG is proposed to occur as an interplay of self-focusing and multi-photon excited self-phase modulation [4], the fundamental mechanisms of the SCG are presently still not well understood. Group velocity dispersion may limit the achievable maximum intensity inside the bulk considerably, similar to plasma formation. The use of lenses with shorter focal length reduces the penetration depth of the pulse inside the dielectric, hence, decreases the spectral broadening of the laser pulse due to SCG. This may explain our observations.

To obtain equal conditions for the different experiments the laser beam was focused onto the front surface of the different samples. At a low fluence below surface damage threshold it was possible to initiate damage inside the bulk and with increasing shot numbers the damage track moves towards the surface, as shown in Fig. 2. Here, the pulse duration was 1.1 ps, characterizing a limit at which the self-focusing driven bulk damage was observable. While at sub-ps pulses no permanent damage was registered, at 5.3 ps only 10 laser shots were necessary to introduce damage inside the bulk of BK7.

1. E.E.B. Campbell, D. Ashkenasi, A. Rosenfeld, "Ultra-short-pulse laser irradiation and ablation of dielectrics" in Lasers in Material Science, Material Science Forum Vol. **301**, pp. 123–144 (Trans Tech Publications, Switzerland, 1999).
2. D. Ashkenasi, H. Varel, A. Rosenfeld, S. Henz, J. Herrmann, E.E.B. Campbell, "Application of self-focusing of ps laser pulses for three dimensional microstructuring of transparent materials," Appl. Phys. Lett. 72, 1442–1444 (1999).
3. M. Wittmann, A. Penzkofer, "Spectral superbroadening of femtosecond laser pulses," Opt. Comm. **126**, 308–317 (1996).
4. A. Brodeur and S.L. Chin, "Band-gap dependence of the ultrafast white-light continuum", Phys. Rev. Lett. **80**, 4406–4409 (1997).
5. David Ashkenasi, Markus Lorenz, Arkadi Rosenfeld, "Beam propagation of high-power ultrashort laser pulses inside transparent dielectrics for controlled 3D microstructuring" in High-Power Lasers in Manufacturing, Proc. SPIE 3888, in print (2000).

CFK2 10:30 am

Femtosecond micro-machining of high index and photo-sensitive glasses in air

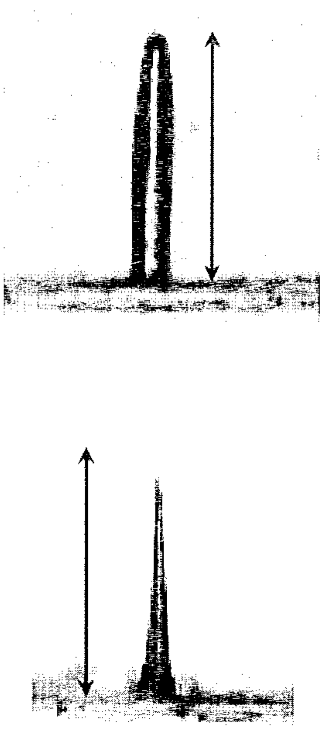
Lawrence Shah, Martin Richardson,
Jesse Tawney, Kathleen Richardson, *School of Optics & CREOL, Univ. of Central Florida 4000, Central Florida Blvd., Orlando, FL 32816-2700; E-mail: mcr@creol.ucf.edu*

It is well-known that micromachining with high intensity femtosecond pulses has significant advantages over nanosecond laser pulses[1,2] including increased ablation rates,[3,4] although there are many complex interaction processes involved.[5-7] They have been shown to be effective in creating microstructures in fused silica, particularly gratings.[8,9] We are investigating the interaction of high intensity ($\sim 10^{14}$ W/cm^2) 110 fs laser pulses with a variety of glasses to determine their potential for detailed structural micro-fabrication in transparent media,[10,11] and through analysis of the changes in material structure and chemical properties, assess the interaction processes involved.

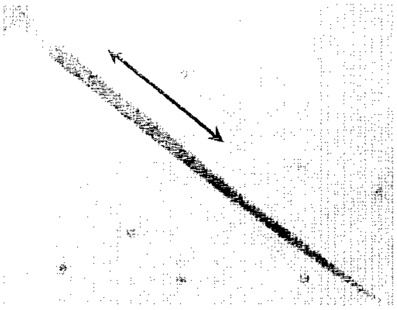
Our studies are performed with single, 845 nm, ~1 mJ pulses from a chirped-pulse-amplified Ti:Sapphire/Cr:LiSAF femtosecond laser. Whereas some earlier work was performed in vacuum,[1] our studies are made in an ambient gas environment. Moreover, by using the uncompressed, 250 ps duration chirped pulse from the Cr:LiSAF regenerative amplifier, we can compare interaction processes in both the femtosecond and subnanosecond regimes. The laser output in these two regimes is focused with a 20 cm focal length lens onto various glass substrates mounted on a precision three axis micrometer stage. The samples are prepared with polished surfaces on three sides, in order to allow photographic and spectroscopic analysis.

Figure 1 illustrates the differences to the material structure when holes are drilled in un-doped glass with single subnanosecond 4 mJ laser pulses (left-hand feature) and with single 110 fs, ~1 mJ pulses (right-hand feature). Whereas femtosecond pulses create a sharp well-defined tapered hole in the material with little evidence of bulk material modification, features made with subnanosecond pulses tend to occupy a greater volume with several small cracks extending into the bulk material. Electron microscopic analysis shows similar differences in the surface topology and thermally affected regions for these two regimes. We are now making more detailed investigations of the structural and chemical changes induced in the material using Raman spectroscopy, x-ray photo-electron spectroscopy and pulsed probe analysis. In addition, with the aid of a newly developed focused ion beam sectioning technique we are able to expose without degradation the inner surface of the hole and characterize its microscopic topological and chemical features. The hole shown in Fig. 2, illustrates another advantage of femtosecond pulse micromachining. This hole, drilled with 10,000 femtosecond laser pulses has an overall length of 3.1 mm with a diameter of 100 µm at the entrance, diminishing to a sharp point at the far end. High aspect ratio holes of this type have many important applications. The large aspect ratio (>30:1) provides strong evidence for laser beam guiding during the ablation process. Future materials studies will provide additional data on the effectiveness of this process.

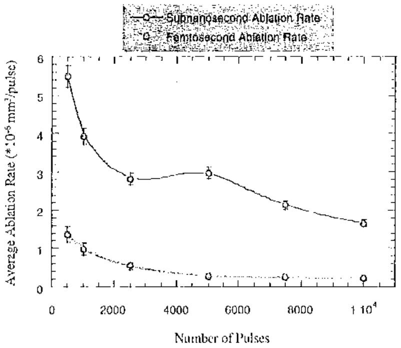
Initial calculations reveal that both femtosecond and subnanosecond ablation rates are inversely proportional to the number of pulses incident, i.e. the depth in the material. Fig. 3.



CFK2 Fig. 1. The hole on the left was made by 1,000 subnansecond laser pulses. The hole on the right was made using 1,000 femtosecond laser pulse. The arrows in the figure represent 500 µm relative scale.



CFK2 Fig. 2. This hole was drilled with 10,000 femtosecond laser pulses in lead doped glass. The scale arrow is 1 mm in length, thus the entire feature is greater than 3 mm long.



CFK2 Fig. 3. Average subnanosecond vs. femtosecond ablation rates in un-doped glass as a function of the number of incident pulses.

shows that the subnanosecond ablation rate decreases steadily as the number of pulses increases, while the femtosecond ablation rate effectively reaches a minimum value after ~5000 pulses. The fact that the femtosecond ablation rate does not continue to reduce significantly beyond 5000 pulses may also indicate that beam guiding is taking place during the femtosecond machining process.

Studies are now ongoing with high density and photo-sensitive glasses, which should provide more detailed information on the various processes involved.

1. C. Momma, B. Chichkov, S. Nolte, F. von Alvensleben, A. Tunnermann, H. Welling, B. Wellegehausen, Opt. Comm. **129**, 134, (1996).
2. P.S. Banks, B.C. Stuart, M.D. Perry, M.D. Feit, F. Rubenchik, J.P. Armstrong, H. Nguyen, F. Roeske, R.S. Lee, B.R. Myers, J.A. Sefcik, CLEO **98**, paper CFD2 (1998).
3. P.R. Pronto, S.K. Dutta, J. Squier, J.V. Rudd, D. Du, G. Mourou, Opt. Comm, **114,** 106 (1995).
4. J. Ihlemann, A. Scholl, H. Schmidt, B. Wolff-Rottke, Appl. Phys **A60,** 411 (1995).
5. D. Ashkenasi, A. Rosenfeld, H, Varel, M. Wahmer, E. Campbell, Appl. Surf. Sci. **120,** 65, (1997).
6. O. Efimov, K. Gabel, S.V. Garnov, L.B. Glebov, S. Grantham, M. Richardson, M.J. Soileau, JOSA, B**15**, 193, (1998).
7. P.S. Banks, B.C. Stuart, M.D. Feit, A.M. Rubenchik, M.D. Perry, CLEO'99 paper CThC4.
8. K.M. Davis, K. Miura, N. Sugimoto, K. Hirao, Opt. Lett, **21,** 1729, (1996).
9. K.P. Chen, A. Oettle, P.R. Herman, R.S. Marjoriebanks, CLEO'99, paper CThC3 (1999).
10. K.A. Richardson, K. Zollinger, J. Evans, M. Marchivie, A. Schulte, C. Meneghini, K. LeFoulgoc, A. Saliminia, T. Galstian, A. Villeneuve, Proc. SPIE vol. 3849, (1999).
11. T. Cardinal, K.A. Richardson, H. Shim, A. Schulte, R. Beathy, K. LeFoulgoc, C. Meneghini, J.F. Viens, A. Villeneuve, J. Non-Cryst. Solids **256 & 257,** 353 (1999).

CFK3 **10:45 am**

Threshold and morphology of femtosecond laser-induced damage in silicon

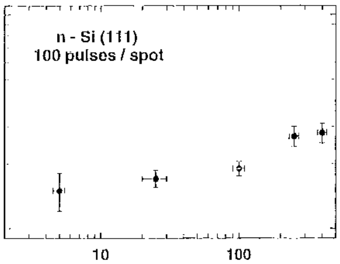
Matthias Lenzner, Jörn Bonse,*
Steffen Baudach,* Jörg Krüger,*
Wolfgang Kautek,* *Photonics Inst., Vienna Univ. of Tech., Gusshausstr. 27, A-1040 Wien, Austria; E-mail: lenzner@tuwien.ac.at*

Micromachining with femtosecond laser systems has evolved since these lasers have been readily available for a wide set of parameters. However, this application also pushes basic research because a detailed investigation of fundamental processes in the interaction between light and matter is now possible on an ultrashort time scale. It has been shown that ultrashort pulses bear the potential for (laterally and vertically) precise micromachining in transparent dielectrics.[1] In this paper we want to extend the existing investigations on laser-induced damage in silicon to pulse durations down to 5 fs.

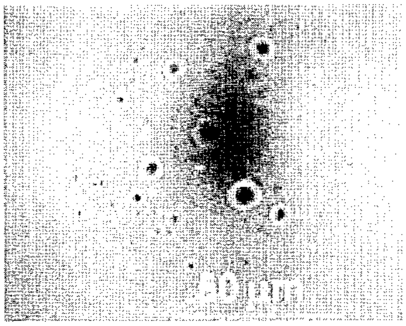
We carried out experiments on a polished (111)-surface of n-doped silicon samples with a Ti:sapphire laser system.[2] The pulse duration was changed between 5 fs to 400 fs by inserting dispersive material, pulses with varying energy have been focused to a diameter in the order of 100 μm onto the sample surface. For higher applied fluences (in the single-shot case) the sample was placed in a slightly evacuated chamber.

The damage threshold was determined using the established reliable technique of measuring the diameters of the generated craters in dependence on the pulse fluence and extrapolating to zero.[3] Damage thresholds of multi-shot experiments for different pulse durations are shown in Fig. 1. Interestingly—and in contradiction to experiments in transparent dielectrics—single shot measurements with 5-fs pulses yielded identical values of the damage threshold. Obviously—for these short pulses—there is no such rapid chemical modification of silicon (or one that leaves the threshold unchanged) when irradiated with pulse energies below the damage threshold as for example in fused silica.[4]

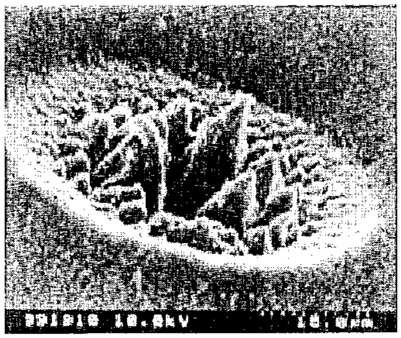
Pictures taken with an atomic force microscope (AFM) and a scanning electron microscope (SEM) reveal interesting morphological features of the damaged areas. For single-shot ablation the formation of circular substructures (holes) within the cavities can be observed (see Fig. 2), these holes vanish when the same spot is illuminated with subsequent pulses. This phenomenon might be due to an inhomogeneous surface absorption which leads to locally enhanced ablation. It becomes more pronounced at higher pulse fluences.



CFK3 Fig. 1. Threshold fluence of laser-induced damage in silicon for several pulse durations of a Ti:sapphire laser.



CFK3 Fig. 2. AFM picture of damage in silicon generated with a single Ti:sapphire laser pulse ($\tau = 5$ fs, $F = 7.7$ J/cm^2). Dark areas indicate more ablated material, the depth of the crater is about 200 nm.



CFK3 Fig. 3. SEM picture of damage in silicon generated with 100 Ti:sapphire laser pulses ($\tau = 130$ fs, $F = 2.8$ J/cm^2). Columnar structures arise from the bottom of the ablated area which protrude above the original silicon surface.

In a certain range of fluence and pulse duration we can observe a re-structuring phenomenon in the center of the ablation areas (see Fig. 3). Here, a re-growth from the molten and/or vapor phase takes place, leading to the column-like structures that even tower above the surface of the silicon. Furthermore, we observed the well-known wavelength ripples that are due to interference and subsequent local field enhancement.[5]

**Federal Inst. for Materials Res. and Testing, Germany; E-mail: Joern.Bonse@bam.de*

1. M. Lenzner "Femtosecond Laser-Induced Damage of Dielectrics," Int. Journ. of Mod. Phys. B **13**, 559 (1999).
2. S. Sartania, Z. Cheng, M. Lenzner, G. Tempea, Ch. Spielmann, and F. Krausz, "Generation of 0.1-TW, 5-fs optical pulses at a 1-kHz repetition rate," Opt. Lett. **22,** 1562 (1997).
3. J.M. Liu "Simple technique for measurements of pulsed Gaussian-beam spot sizes," Opt. Lett. **7**, 196 (1982).
4. M. Lenzner, J. Krüger, W. Kautek, and F. Krausz, "Incubation of laser ablation in fused silica with 5-fs pulses," Appl. Phys. A **69,** 465 (1999).