High resolution patterning of sapphire by F₂-laser ablation

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Abstract The ablation behavior of single crystalline sapphire with nanosecond laser pulses at 157 nm wavelength is investigated. Ablation rates of about 10 to 100 nm/pulse are obtained at fluences ranging from 1 to 9 J/cm². At moderate fluences, incubation behavior is observed, i.e. ablation starts after material modification by a number of laser pulses. The ablation can be utilized to fabricate sapphire micro-optics. The capability of creating lenses or gratings on the tip of sapphire fibers is demonstrated. Multilevel diffractive optical elements and high resolution gratings with 1 μm period are fabricated on planar sapphire substrates.

1 Introduction

Single crystal sapphire (α -Al₂O₃) is aluminum oxide in the purest form with no porosity or grain boundaries and mechanical and thermal properties similar to technical ceramics. It is characterized by high mechanical, chemical and thermal resistance and offers a high optical transmission between 200 nm and 4 μm. Therefore sapphire fibers are used for laser power delivery, especially for infrared light in medical applications [1, 2]. In combination with a high operational temperature up to 1800 °C it is also often used as a protection window or for sensor applications at high temperatures and pressures [3–5]. Concerning the excellent properties as an electrical insulator it is used in Silicon-on-Sapphire (SOS) substrates [6] to build semiconductors circuits [7], which can operate at very high voltages and have a

very high radiation resistance. Recently SOS attracted attention as a material for waveguides in the mid-infrared [8] for telecommunications or sensor applications. Wherever extreme demands in wear resistance, hardness, inertness, thermal and chemical resistance occur, sapphire is the best solution. But due to its excellent material properties, it is a mechanically and chemically difficult to machine material. Laser processing of sapphire appears here to be a promising method for precise machining. One example is the laser micro-patterning of sapphire flats to improve the tribological characteristics as a bearing application [9].

The laser ablation behavior of sapphire was investigated with nanosecond lasers at various wavelengths (532 nm, 266 nm, 248 nm, 193 nm) [10, 11]. As the linear absorption in the visible and UV is rather weak, ps- and fs-pulses were applied to induce multiphoton absorption [12, 13]. For UV nanosecond laser pulses electronic sputtering with no direct evidence for thermal ablation appears to be the main ablation mechanism [14]. The ablation behavior for the excimer laser wavelengths of 193 nm and 248 nm is rather similar. In regions of uniform illumination there was no evidence of obvious melting, frozen-in capillary waves, thermal-stress-induced fracture, or exfoliation [10, 11].

In this paper we show results applying a nanosecond F₂-laser with a wavelength of 157 nm for ablation. The high photon energy (7.9 eV) of the radiation provides a strong interaction with almost all materials and allows for laser machining of transparent materials with a large band gap such as fused silica [15] or polymers as PET [16], PMMA [17] or PTFE [18]. The absorption of the radiation in a thin surface layer enables precise removal of material down to ~10 nm and the production of optical surfaces free of micro cracks. The absorption of sapphire is steadily increasing toward the UV, and, as can be seen in the case of fused silica, a material

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with comparable UV-absorption, the controllability of laser ablation is usually improved with growing absorption.

First, we explain the F₂-laser processing system, show the results of ablation rate, incubation behavior and obtained surface morphology, and discuss these results in terms of laser induced melting and exfoliation. Then some applications like micro machining of sapphire fibers and fabrication of gratings and diffractive optical elements on sapphire substrates are demonstrated.

2 Optical system and setup

The F₂-laser processing system consists of a F₂-laser (Lambda Physik LPF 220i), a 157 nm beam-shaping and -delivery system (MicroLas Lasersystem), high-precision target positioning drives, and beam and sample-alignment diagnostics. It has been described in detail previously [19]. Ablative processing of materials is performed in a mask projection configuration. The laser delivers up to 25 mJ single-pulse energy with 15 ns pulse duration at 1–200 Hz repetition rate. Homogenization and imaging optics are assembled in a 3 m long aluminum chamber, which is flushed with nitrogen gas to provide transparency at 157 nm. The mask is illuminated with the homogenized laser beam and imaged onto the work piece at 25× demagnification using a Schwarzschild objective of 0.4 NA. The optical system provides a uniformly illuminated target field of size $240 \times 240 \mu\text{m}^2$. The target sample is positioned outside the chamber on a high-precision translation stage. A gas flow nozzle separates the imaging optics from the sample to provide a protective and transparent stream of nitrogen gas to the working area on the target surface. With this setup ablative machining even of transparent materials like glass and quartz is possible, as the short wavelength of 157 nm serves for efficient absorption. For the alignment and surface detection of the samples an integrated optical coherence tomography (OCT) device is used [20]. The OCT-System consists of a commercial Spectral-domain (SD)-OCT imaging system (Thorlabs Inc.), including the data acquisition and the illumination, combined with a customized Michelson-Interferometer and a galvanometric scanner system. The OCT imaging system has a point sample rate (A-Scan) of 1.4 kHz and is capable to detect surfaces with an accuracy of ~ 126 nm.

3 F₂-Laser ablation characteristics of sapphire

For the ablation experiments commercially available plane single crystal substrates with a diameter of 25.4 mm and a thickness of 3 mm were used (Laser Components GmbH). The surface quality is $5/4 \times 0.063$ according to ISO-10110

Fig. 1 Ablation depth as a function of the number of pulses for various laser fluences

Fig. 2 Fluence-dependence of the ablation rate of sapphire at 157 nm

with a surface figure of $\lambda/2$. The sample surface was cleaned with ethanol and then air-dried. Afterwards $50 \times 50 \mu\text{m}$ squares with different fluences and pulse numbers were ablated. The remaining debris was removed by an ultrasonic bath in a commercial available glass cleaner (Deconex 15). This cleaning procedure was applied to all samples presented in this paper. The depth of every spot was determined with the integrated OCT.

Figure 1 displays the ablation depth as a function of the number of pulses for various laser fluences. In a wide range of pulse numbers the depth increases linearly with the number of pulses. The fluence-dependence of the ablation rate resulting from these data is shown in Fig. 2. Ablation rates of more than 100 nm/pulse are obtained at high fluences. In the initial phase of ablation, sapphire shows an incubation effect for low fluences. At 0.7 J/cm^2 ablation starts after 10 pulses. As the fluence increases, the number of incubation pulses decreases. Near the ablation threshold, material removal starts at some spots of the irradiated field, before after some further pulses the whole field is ablated. Also some flaky structure (partial exfoliation) at the edge of the ablation fields is observed near the threshold.

Comparable results for the ablation threshold and the occurrence of incubation have been described in literature also for other wavelengths and pulse durations [11, 14, 21, 22].

Rothenberg et al. [11] observed at 248 μm the appearance of surface damage in form of formation of small craters (heterogeneous nucleation); these craters are growing and then disappear, while continuous ablation is leading to a high degree of uniformity over the entire beam area. Also exfoliation at the edge of the illuminated area has been found by Kelly et al. [10]. This exfoliation seems to be crystallographic with fragments having a thickness of $<1\ \mu\text{m}$ and is explained by thermal stress, which is promoted by the combination of high linear expansion and high Young's modulus of sapphire. Thus, this exfoliation occurs, if the melting point is not reached, especially at positions with large temperature gradients (edge of the spot). At higher fluences the melting temperature is exceeded leading to stress relief by melting and to homogeneous ablation.

As our results regarding the ablation behavior at 157 nm are basically very similar to those obtained at longer laser wavelengths, one can conclude that the ablation mechanism is rather similar, too. The striking difference is the improved precision at 157 nm (see application examples in the following sections) which is probably enabled by higher absorptivity at 157 nm compared to longer wavelengths. However, the large difference between the low level absorption coefficient of sapphire at 157 nm of about $\alpha = 1.4\text{--}25\ \text{l/cm}$, which is dependent of the crystal quality and the measurement type [23, 24] and the so called effective absorption coefficient $\alpha_{\text{eff}} = 2.3 \times 10^5\ \text{l/cm}$ derived from the ablation data according to

$$\alpha_{\text{eff}} = 1/d \cdot \ln(F/F_T) \quad (1)$$

with d ablation rate, F fluence, F_T threshold fluence, indicates a defect initiated ablation process even in the case of F₂-laser ablation [25].

4 Fiber-integrated optical elements

Optical fibers are used in many kinds of applications ranging from communication and sensor technology to materials processing and medical surgery. In many applications, micro-optical devices for shaping the output beam of optical fibers are essential. Conventionally, this is accomplished by external optical elements like ball lenses or gradient index (GRIN) lenses. This leads to rather bulky applicators, which often do not fulfill the requirements of miniaturization and ease of handling. A number of examples can be found in telecommunication networks, where microlenses are used to improve the coupling efficiencies between sources, detectors and optical waveguides, and also to relax tight alignment tolerances. Integration of the optical functionality into the fiber leads to more compact, durable, and adjustment free applicators; also it minimizes the number of optical surfaces. Fewer optical components improve the

Fig. 3 Schematic diagram of the lateral mask projection arrangement. The center of the fiber is aligned with the rotation axis and the mask pattern is projected onto the side of the fiber

thermal and long-term mechanical stability while also simplifying the assembly and packaging that is normally tedious and costly in multi-element fiber optic systems and opens up various possibilities of beam shaping required for medical or metrological fiber applications. Lens-tipped fibers can be used to improve the properties of fiber optic sensors, or, in medical equipment, they are employed to tailor the emission characteristics of endoscopic instruments. Recently it was shown that it is possible to use a grating on the end face of a fiber to influence the emitting properties. This allows one, for example by means of crossed grating structures, to build a multiplexer based on such a diffraction beam splitter for telecommunications devices [26].

4.1 Fiber end lenses

For the fabrication of the fiber end lenses and gratings a single crystal sapphire fiber with a diameter of $425 (\pm 25)\ \mu\text{m}$ (Laser Components GmbH) was used. The machining of the fiber-lenses is based on a mask projection arrangement perpendicular to the fiber axis (Fig. 3).

The center axis of the fiber is aligned with the rotation axis and the mask pattern is projected onto the side of the fiber. The final alignment of the rotation axis to the projected laser beam is provided by a xyz -positioning stage. The fiber is rotated around its axis while the laser ablation is in progress, yielding a rotationally symmetric tip with a shape defined by the mask aperture. The alignment of fiber axis, rotation axis and apex of the circular mask contour are facilitated by a white light illumination of the fiber and an imaging camera that shares the Schwarzschild lens with the processing optics.

Among other shapes, convex lenses (spherical or aspherical) can be fabricated this way. Fibers with small and medium diameters can be processed in one working cycle [27]. Because the processing field is limited to $240 \times 240\ \mu\text{m}^2$ a $425\ \mu\text{m}$ diameter sapphire fiber is processed in a two step conformal mask- and fiber displacement method,

Fig. 4 SEM image of the 425 μm sapphire fiber with a micromachined lens at the fiber tip with a radius of 200 μm . Ten full rotations with a velocity of 6°/s for each mask position with a repetition rate of 50 Hz (30000 pulses) and a fluence of 9.7 J/cm² were applied

Fig. 5 SEM image of the surface of the end lens from Fig. 4. There is a prominent line structure with thin lines running parallel and thicker ones perpendicular to the direction of rotation (indicated by *black arrow*)

which allows processing of thick fibers without significant stitching errors [26]. For this kind of lateral processing no pretreatment like cleaving or polishing is necessary, because the resulting shape does not depend on the original fiber surface, but only on the precision of centering of the fiber on the rotation axis and on the precisely correlated displacement of mask and fiber between the processing steps.

For machining the fiber shown in Fig. 4 ten full rotations with a velocity of 6°/s for each mask position with a repetition rate of 50 Hz (30000 pulses) and a fluence of 9.7 J/cm² were applied. After completing the lens, about 15000 pulses with the same fluence as before were applied additionally for each mask position to clean and smooth the lens surface.

There are no stitching errors or any kind of cracking or noticeable roughness. But scanning electron microscopy (SEM) reveals that there is a prominent line structure with thin lines running parallel and thicker ones perpendicular to the direction of rotation (Fig. 5). Apparently the rotation of the fiber has an influence on the surface quality. For higher fluences (9.7 J/cm²) it looks like the melting point was exceeded and the lines were formed by molten material. Isolated droplets confirm this assumption. The fiber shown in Fig. 6 was machined with the same parameters as the first one, but the fluence was reduced to 6.0 J/cm². At this fluences exfoliation of small sapphire flakes can be observed.

4.2 Fiber tip gratings

For the machining of the grating structures, the fiber was orientated parallel to the optical axis of the laser beam with the end face of the fiber showing toward the exit nozzle of the F₂-laser processing system. Each line was written by

Fig. 6 SEM image of a lens surface. At a fluence of 6.0 J/cm² exfoliation of small sapphire particles can be observed

imaging a 5 μm diameter spot on the fiber face by moving the fiber relative to the laser to produce a line grating with a period of 10 μm and a trench depth of 5 μm . For this method precise cleaving or polishing prior to laser processing is required to obtain good results. The generated profile is controlled by the spot size, the fluence and the scanning speed. Figure 7 shows a SEM image of a line grating on the end face of a 425 μm multimode sapphire fiber. The laser was triggered with 50 Hz and the fluence was 10.6 J/cm². The fiber was moved with a velocity of 8 $\mu\text{m}/\text{s}$ to produce a trench depth of 5 μm with approximately 30 pulses. OCT scans show that a grating period of 10 μm and a trench depth around $5 \pm 1 \mu\text{m}$ were achieved (Fig. 8).

Fig. 7 SEM image of a line grating on the end face of a 425 μm multimode sapphire fiber. The grating has a period of 10 μm and a trench depth of 5 μm . The fluence was about 10.6 J/cm^2 and the laser was triggered with 50 Hz. The fiber was moved with a velocity of 8 $\mu\text{m}/\text{s}$ to produce a trench depth of 5 μm with approximately 30 pulses

Fig. 8 Surface OCT image scan of the line grating at the central area of the fiber end face reveals a grating period of 10 μm with a trench depth around $5 \pm 1 \mu\text{m}$

5 Diffractive phase elements (DPE)

Diffractive optical elements are important tools for beam shaping and the generation of complex irradiation patterns. Especially for applications in transmission, diffractive phase elements (DPE) are generally implemented by a surface profile on a transparent optical material and used for beam homogenization, beam splitting or efficient mask illumina-

Fig. 9 SEM image of a 4-level DPE with a pixel size of $10 \times 10 \mu\text{m}$ and overall size of $1 \times 1 \text{ mm}$. The pixels were produced with a moving speed of 0.5 mm/s and a fluence of 9.7 J/cm^2

tion. Various design concepts have been applied; the iterative Fourier-transform algorithm (IFTA) has been proven to be very flexible and versatile [28]. Design concepts taking into account the properties of partially coherent beams (excimer lasers) have been developed to provide beam shaping for efficient excimer laser micro machining [29, 30].

The manufacturing of the DPE on sapphire was performed by an on the fly pixel writing method using a square aperture as mask to ablate the pixel on the target. During the machining the sample is moved with a constant velocity, and at precalculated breakpoint positions a trigger pulse for the laser is released. Compared to step by step writing, the manufacturing time can be significantly reduced. Due to the dynamic character of this method the position accuracy is reduced to $\pm 0.5 \mu\text{m}$ by bearing friction and mechanical inertia and tolerances of the setup. Nevertheless, it is particularly suitable for the rapid prototyping of relatively large pixelated structures. The presented DPE is a 4-level DPE with a random pattern which can be used as a beam diffuser. For characterization of the DPE, the surface relief was inspected by SEM, OCT and confocal microscopy. The 4-level DPE shown in Fig. 9 has a pixel size of $10 \times 10 \mu\text{m}$ and overall size of $1 \times 1 \text{ mm}$. The pixels were produced with a moving speed of 0.5 mm/s and a fluence of 9.7 J/cm^2 .

The investigation of the surface quality and the pixel depth by OCT and confocal microscopy shows that the manufacturing of 4-level DPE in sapphire by laser ablation is in principle possible. The correct and uniform depth of the pixels, which leads to the desired phase shift and thus to the correct function of the DPE, was achieved for all manufactured DPE (Fig. 10). The most obvious quality limitation is the position accuracy of the setup which leads to little gaps or stripes causing light scattering in the diffraction image. Furthermore higher fluences cause the presence of melting remnant within single pixels (Fig. 11).

Fig. 10 Color coded confocal microscopy depth profile of a 4-level DPE. The different step heights are clearly distinguishable. The pixels have a size of $10 \times 10 \mu\text{m}$ and were produced with a moving speed of 0.5 mm/s and a fluence of 5.8 J/cm^2

Fig. 11 OCT image of a 4-level DPE with a pixel size of $20 \times 20 \mu\text{m}$. The moving speed was 0.5 mm/s and the fluence was about 9.3 J/cm^2 . Within the pixel area, in addition to small gaps and stripes, melting remnants caused by the high fluence are observed

6 High resolution gratings

Laser ablation is a flexible approach for rapidly generating custom grating designs in several micro-optic applications such as grating demultiplexers for telecommunication components, light couplers for planar optical waveguides, Bragg reflectors, and alignment grooves for liquid crystals. Sub micrometer surface-relief gratings have been generated in various materials such as polymers, glasses, dielectrics, and metals by direct UV laser ablation [31–33].

The laser processing window for forming high resolution gratings on sapphire was explored by varying the laser pulse number in the range of 1–40 pulses, and the laser fluence in the range of 1.9 – 4.5 J/cm^2 . Amplitude grating mask with periods between 15 – $25 \mu\text{m}$ were imaged by the Schwarz-

Fig. 12 SEM image of a $1 \mu\text{m}$ period grating on sapphire produced with 22 laser pulses and a fluence of 2.9 J/cm^2

schild objective onto the surface across a $200 \times 200 \mu\text{m}$ field size. Several gratings with periods between 0.6 – $1 \mu\text{m}$ were produced and investigated by SEM and Atomic force microscopy (AFM).

Most of the gratings especially the ones with periods between 0.6 – $0.9 \mu\text{m}$ are very shallow with cracks or melting artifacts at the edges of the illuminated area. Estimates regarding the thermal diffusion length based on literature values [34, 35] confirm the assumption that the good heat conduction properties of sapphire prevent a higher resolution. The thermal diffusion length L varies from 800 nm at 25°C and 200 nm at the melting point ($T_m = 2030^\circ\text{C}$) according to

$$L \approx 2 \cdot (D(T) \cdot \tau)^{1/2} \quad (2)$$

with the heat diffusivity $D(T)$ and the laser dwell time $\tau = 15 \text{ ns}$. Best results could be achieved with fluences between 2.9 – 3.6 J/cm^2 with grating periods of $1 \mu\text{m}$. But at least 20 pulses were necessary to generate a uniform grating pattern over the whole illuminated area. Figure 12 shows a $1 \mu\text{m}$ period grating on sapphire obtained with 22 laser pulses and a fluence of 2.9 J/cm^2 . The grating patterns are highly uniform and smooth and AFM revealed a modulation depth of 50 nm (Fig. 13).

7 Conclusion

The ablation behavior of sapphire for 157 nm is basically very similar to that obtained at longer laser wavelengths with nanosecond laser pulse length, which leads to the conclusion that the ablation mechanism is rather similar, too. An ablation threshold of 0.7 J/cm^2 and an effective absorption coefficient of $\alpha_{\text{eff}} = 2.3 \times 10^5 \text{ l/cm}$ for 157 nm were found. Several micro structures on single crystal sapphire bulk material

Fig. 13 The AFM image revealed a highly uniform and smooth grating pattern with a modulation depth of 50 nm

and fibers were manufactured by F₂-laser ablation. The precise treatment of sapphire fiber end tips to produce lenses or gratings for beam manipulation purposes is possible. We also demonstrated that F₂-laser ablation is suitable for rapid prototyping of DPE or high resolution gratings with structure sizes of approximately 1 μm. Our results show that sapphire can be successfully processed with a good precision at 157 nm, so that a wide range of new applications for sapphire based devices can be made possible.

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References

1. R.W. Waynant, S. Oshry, M. Fink, *Appl. Opt.* **32**, 390 (1993)
2. N.M. Fried, Y. Yang, C.A. Chaney, D. Fried, *Lasers Med. Sci.* **19**, 155 (2004)
3. Y. Zhu, A. Wang, *Appl. Opt.* **45**, 6071 (2006)
4. M. Bonetti, P. Calmettes, *Rev. Sci. Instrum.* **76**, 043903 (2005)
5. M.R. Arnold, H.R. Kalbitzer, W. Kremer, J. Magn. Reson. **161**, 127 (2003)
6. H.M. Manasevit, W.I. Simpson, *J. Appl. Phys.* **35**, 1349 (1963)
7. R.A. Johnson, P.R. de la Houssaye, C.E. Chang, P.-F. Chen, M.E. Wood, G.A. Garcia, I. Lagnado, P.M. Asbeck, *IEEE Trans. Electron Devices* **45**, 1047 (1998)
8. T. Baehr-Jones, A. Spott, R. Ilic, A. Spott, B. Penkov, W. Asher, M. Hochberg, *Opt. Express* **18**, 12127 (2010)
9. A. Blatter, M. Maillat, S. Pimenov, G. Shafeev, A. Simakin, *Tribol. Lett.* **4**, 237 (1998)
10. R. Kelly, J. Cuomo, P. Leary, J.E. Rothenberg, B. Braren, C. Aliotta, *Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms* **9**, 329 (1985)
11. J.E. Rothenberg, R. Kelly, *Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms* **1**, 291 (1984)
12. A. Tam, J.L. Brand, D.C. Cheng, W. Zapka, *Appl. Phys. Lett.* **55**, 2045 (1989)
13. D. Ashkenasi, A. Rosenfeld, H. Varel, M. Wähmer, E. Campbell, *Appl. Surf. Sci.* **120**, 65 (1997)
14. R. Dreyfus, R. Kelly, R. Walkup, *Appl. Phys. Lett.* **49**, 1479 (1986)
15. P.R. Herman, R.S. Marjoribanks, A. Oetli, K. Chen, I. Konovalov, S. Ness, *Appl. Surf. Sci.* **154**, 577 (2000)
16. P.E. Dyer, J. Sidhu, *J. Opt. Soc. Am. B, Opt. Phys.* **3**, 792 (1986)
17. M. Lapczyna, M. Stuke, *Appl. Phys. A* **66**, 473 (1998)
18. S. John, S. Langford, J. Dickinson, *Appl. Phys. A* **92**, 981 (2008)
19. P.R. Herman, K.P. Chen, M. Wei, J. Zhang, J. Ihlemann, D. Schäfer, G. Marowsky, P. Oesterlin, B. Burghardt, *Proc. SPIE* **4274**, 149 (2001)
20. M. Wiesner, J. Ihlemann, H. Müller, E. Lankenau, G. Hüttmann, *Rev. Sci. Instrum.* **81**, 033705 (2010)
21. A. Pedraza, *Nucl. Instrum. Methods Phys. Res., Sect. B, Beam Interact. Mater. Atoms* **141**, 709 (1998)
22. D. Ashkenasi, R. Stoian, A. Rosenfeld, *Appl. Surf. Sci.* **154–155**, 40 (2000)
23. M. Innocenzi, R. Swimm, M. Bass, R. French, A. Villaverde, M. Kokta, *J. Appl. Phys.* **67**, 7542 (1990)
24. V.V. Harutunian, V.A. Gevorgian, N.E. Grigorian, G.N. Eritsian, *Phys. Status Solidi B* **160**, K71 (1990)
25. P.E. Dyer, S.R. Jackson, P.H. Key, W.J. Metheringham, M.J.J. Schmidt, *Appl. Surf. Sci.* **96–98**, 849 (1996)

26. J. Zinn, M. Schütte, J. Meinertz, J. Ihlemann, J. Laser Micro Nanoeng. **5**, 6 (2010)
27. T. Fricke-Begemann, J. Li, J. Dou, J. Ihlemann, P. Herman, G. Marowsky, in *Proceedings of the Third International WLT-Conference on Lasers in Manufacturing, LIM 2005* (2005), p. 733
28. F. Wyrowski, J. Opt. Soc. Am. A **7**, 961 (1990)
29. D. Schäfer, J. Ihlemann, F. Simon, in *DOMO 2002*. OSA Tech. Digest (2002), p. 149
30. M. Schulz-Ruhtenberg, J. Ihlemann, J. Heber, Appl. Surf. Sci. **248**, 190 (2005)
31. P.E. Dyer, R.J. Farley, R. Giedl, D.M. Karnakis, Appl. Surf. Sci. **96–98**, 537 (1996)
32. P. Simon, J. Ihlemann, Appl. Phys. A **63**, 505 (1996)
33. M.A. Bader, C. Kappel, A. Selle, J. Ihlemann, M.L. Ng, P.R. Herman, Appl. Opt. **45**, 6586 (2006)
34. D.G. Archer, J. Phys. Chem. Ref. Data **22**, 1441 (1993)
35. E.R. Dobrovinskaya, L.A. Lytvynov, V. Pishchik, *Sapphire Material, Manufacturing, Applications* (Springer, Berlin, 2009)