Micromachining Publications using Clark-MXR Lasers

Laser Processing and Characterization with Femtosecond Laser Pulses

M. Zamfirescu, M. Ulmeanu, F. Jipa, I. Anghel, S. Simion, R. Dabu, I. Ionita

The nonlinear interaction of femtosecond laser pulses with matter allows the physical and chemical modification of materials at micro and nano-scale. We present an experimental set-up for direct laser structuring by ultra-short laser pulses using nonlinear laser absorption on various materials such as metallic film, transparent photoresists, ceramics etc. A microscope for laser processing and laser characterization was designed and constructed to be coupled with various laser systems. The laser workstation was designed to be used for different laser structuring techniques such as laser ablation, two-photon photopolymerization (TPP), laser induced forward transfer (LIFT), near field laser lithography (NFLL). The configuration of the system allows also the spectroscopic characterization of materials by two-photon excitation (TPE).

Romanian Reports in Physics, Vol. 62, No. 3, P. 594–609, 2010

Femtosecond micromachining in transparent bulk materials using an anamorphic lens

G. Logan DesAutels, Chris D. Brewer, Mark A. Walker, Shane B. Juhl, Marc A. Finet, Peter E. Powers

A unique anamorphic lens design was applied to a circular 780nm femtosecond laser pulse to transform it into an elliptically shaped beam at focus. This lens was developed to give an alternative method of micromachining bulk transparent materials. The challenge for femtosecond laser processing is to control the nonlinear affect of self-focusing, which can occur when using a fast f-number lens. Once the focused spot is dominated by self-focusing the predicted focused beam becomes a filament inside the bulk, which is an undesirable effect. The anamorphic lens resolves this self-focusing by increasing the numerical aperture (NA) and employing an elliptical beam shape. The anamorphic lens was designed to furnish a 2.5μm by 190μm line at focus. Provided the pulse energy is high enough, transparent bulk material will be damaged with a single femtosecond laser pulse. Damage in this text refers to visual change in the index of refraction as observed under an optical microscope. Using this elliptical shape (or line), grating structures were micro-machined on the surface of SiC bulk transparent substrate. SiC was chosen because it is known for its micromachining difficulty and its crystalline structure. From the lack of self-focusing and using energy that is just above the damage threshold the focused line beam generated from the anamorphic lens grating structures produced a line shape nearly identical to the geometrical approximation. In this paper we discuss a new method of writing gratings (or other types of structures) in bulk transparent materials using a single femtosecond laser pulse. We will investigate the grating structures visually (inspected under an optical microscope) and also by use of an atomic force microscopy (AFM). In addition, we test the grating diffraction efficiency (DE) as a function of grating spacing, d.

Optics Express 13139, Vol. 15, No. 20, 2007

Femtosecond versus Nanosecond laser machining: comparison of induced stresses and structural changes in silicon wafers

Amer, M. S., El-Ashry, M. A, Dosser, L. R., Hix, K. E., Maguire, J. F., Irwin, B.

Laser micromachining has proven to be a very successful tool for precision machining and microfabrication with applications in microelectronics, MEMS, medical device, aerospace, biomedical, and defense applications. Femtosecond (FS) laser micromachining is usually thought to be of minimal heat-affected zone (HAZ) local to the micromachined feature. The assumption of reduced HAZ is attributed to the absence of direct coupling of the laser energy into the thermal modes of the material during irradiation. However, a substantial HAZ is thought to exist when machining with lasers having pulse durations in the nanosecond (NS) regime. In this paper, we compare the results of micromachining a single crystal silicon wafer using a 150-femtosecond and a 30-nanosecond lasers.

Induced stress and amorphization of the silicon single crystal were monitored using micro-Raman spectroscopy as a function of the fluence and pulse duration of the incident laser. The onset of average induced stress occurs at lower fluence when machining with the femtosecond pulse laser. Induced stresses were found to maximize at fluence of 44 J cm_2 and 8 J cm_2 for nanosecond and femtosecond pulsed lasers, respectively. In both laser pulse regimes, a maximum induced stress is observed at which point the induced stress begins to decrease as the fluence is increased. The maximum induced stress was comparable at 2.0 GPA and 1.5 GPa for the two lasers. For the nanosecond pulse laser, the induced amorphization reached a plateau of approximately 20% for fluence exceeding 22 J cm_2. For the femtosecond pulse laser, however, induced amorphization was approximately 17% independent of the laser fluence within the experimental range. These two values can be considered nominally the same within experimental error. For femtosecond laser machining, some effect of the laser polarization on the amount of induced stress and amorphization was also observed.

Applied Surface Science 242 (2005) 162-167.

Surface damage effects generated by a fast-pulse laser beam

Burkhalter, P.G., Connert, J.H., Gabl, E.F.

A fast-pulse laser was used to induce damage on the surface of a polished silicon wafer. Effects of focused-laser heating at threshold for damage were examined with high-resolution imaging microscopes. The extent and characteristics of various ripple structures were measured with an atomic force microscope.

STEM (scanning transmission electron microscopy) analysis of femtosecond laser pulse induced damage to bulk silicon

Coyne, E., Magee, J. P., Mannion, P., O'Connor, G. M., Glynn, T., J.

This work reports on the structural changes that take place in wafer grade silicon when it is micro-machined with ultra-short laser pulses of 150 fs duration. A Chirped Pulse Amplification (CPA) Ti : Sapphire laser was used, with an operating wavelength centered on 775 nm and a maximum repetition rate of 1 KHz. The laser induced damage was characterized over the fluence range 0.43–14 J cm−2, and for each fluence a progressively increasing number of pulses was used. The analytical tools used to characterize the samples were all based upon electron microscopy. A 30 KeV scanning transmission electron microscope (STEM) imaging technique was developed to observe defects in the crystal lattice and the thermal-mechanical damage in the area surrounding the laser machined region. Mechanical cross sectioning (in conjunction with Scanning Electron Microscope (SEM) surface imaging) was also used to reveal the internal structure, composition, and dimensions of the laser machined structures. Based on this analysis, it will be shown that laser

machining of silicon with femtosecond pulses can produce features with minimal thermal damage, although lattice damage created by mechanical stresses and the deposition of ablated material both limit the extent to which this can be achieved, particularly with high aspect ratios. A key feature of the work presented here is the high-resolution STEM images of the laser machined structures.
Appl. Phys. A 81, 371-378 (2005).

Microstructure in lithium niobate by use of focused femtosecond laser pulses
Gui, L., Xu, B., Chong, T.C.,

Using a tightly focused femtosecond laser of microjoule energy per pulse, we produced optical waveguide inside the pure Lithium Niobate (LN) substrate. This technique has the potential to generate not only channel waveguide but three-dimensional photonic devices. In this letter, a splitter has been fabricated in LN. The output optical fields through the channel waveguide and splitter were measured and compared with theoretical simulation results. The refractive index change of 6 10 4 was obtained with the transmitted-beam near-field method. The properties of channel waveguide and splitter were discussed for further study.
IEEE Photonics Technology Letters, Vol. 16, Issue: 5, 1337 – 1339.

Photovoltaic Cells using Composite Nanoclusters of Porphyrins and Fullerenes with Gold Nanoparticles
Hasobe, T., Imahori, H., Kamut, P., Ahn, T., Kim, S. K., Kim, D., Fujimoto, A., Hirakawa, T., Fukuzumi

Novel organic solar cells have been prepared using quaternary self-organization of porphyrin (donor) and fullerene (acceptor) units by clusterization with gold nanoparticles on nanostructured SnO2 electrodes. First, porphyrin-alkanethiolate monolayer-protected gold nanoparticles (H2PCnMPC: n is the number of methylene groups in the spacer) are prepared (secondary organization) starting from the primary component (porphyrin-alkanethiol). These porphyrin-modified gold nanoparticles form complexes with fullerene molecules (tertiary organization), and they are clusterized in acetonitrile/toluene mixed solvent (quaternary organization). The highly colored composite clusters can then be assembled as threedimensional arrays onto nanostructured SnO2 films to afford the OTE/SnO2/(H2PCnMPC+C60)m electrode using an electrophoretic deposition method. The film of the composite clusters with gold nanoparticle exhibits an incident photon-to-photocurrent efficiency (IPCE) as high as 54% and broad photocurrent action spectra (up to 1000 nm). The power conversion efficiency of the OTE/SnO2/(H2PC15MPC+C60)m composite electrode reaches as high as 1.5%, which is 45 times higher than that of the reference system consisting of the both single components of porphyrin and fullerene.
Journal of the American Chemical Society, 2005, 127, 1216-1228.

Laser Milling – a Practical Industrial Solution for Machining a Wide Variety of Materials
Henry, M., Harrison, P. M., Henderson, I., Brownell, M.

Laser milling of diverse materials has been demonstrated with short pulse lasers ranging from microsecond to femtosecond pulse durations, and with wavelengths from the far infrared to

vacuum ultra-violet. In all cases a balance between quality, throughput and cost of ownership must be struck in order to determine commercial relevance. Latest generation Q-switched Diode Pumped Solid State Lasers offer the potential to enable the industrial uptake of laser milling for a wide variety of materials including aerospace alloys, thermal barrier coatings, tool steels, diamond and diamond substitutes. This paper will investigate these practical applications of laser milling with reference to comparative laser and non-laser processes.
Fifth International Symposium on Laser Precision Microfabrication, Proceedings of SPIE, Volume 5662, 10.1117/12.596743.

Ultrafast laser-induced melting of glass
Koubassov, V., Laprise, J. F., Théberge, F., Förster, Sauerbrey, R., Müller, B., Glatzel, U. Chin, S. L.

The interaction of intense femtosecond laser pulses with wide band-gap fused silica and quartz is investigated. It is shown that during target irradiation, melting of SiO2 occurs. Laser pulses with fluences above the damage threshold induce partial phase transition of fused silicia into quartz and vice-versa.
Appl. Phys. A 79, 499-505 (2004)

Metallic micro displacement capacitive sensor fabricated by laser micromachining technology
Lai, Y., Bordatchev, E. V., Nicumb, S. K

This paper presents design, fabrication and performance testing results of the micro displacement capacitive microsensor fabricated by femtosecond laser machining technology. The microsensor having overall dimensions of 1,275 (W)·1,153 (L) lm consisted of 20 pairs of comb fingers of 24 (W)·300 (L) lm with a gap between the fingers of 6 lm, suspension springs, inertial mass and support anchors. The sensor structure was fabricated from a 25 lm thick tungsten foil. The fabricated microsensor was able to deliver 230 f capacitance variations for measured displacements up to 25 lm. The results on the performance testing and geometry evaluation under pins the laser micromachining technology as an effective tool to fabricate miniature functional components and mechanisms. The developed microsensor can be used for micro/nano scale displacement measurements in MEMS applications.
Microsyst Technol (2006) 12: 778-785

Ablation comparison with low and high energy densities for Cu and Al with ultra-short laser pulses
Le Harzic, R., Breitling, D., Weikert, M., Sommer, S., Föhl, C., Dausinger, F., Calette, S., Donnet, C., Autouard, E.

The effect of varying fluence for laser microprocessing of Al and Cu is studied at a pulse duration of 120 fs at atmospheric pressure. For low fluences (< 2 J/cm2) quality is relatively good for both metals but completely melt free processing does not seem to be possible. For fluences above 2 J/cm2, a huge difference is observed between Al and Cu. Important roughness and clear evidence for remelted and recast matter solidified like spikes, as well as significant burrs at the edge are observed for Al. In the case of Cu the micromachining quality is high, with practically no redeposit

matter and low roughness in the bottom of the groove. An analysis is given in terms of processes of a thermal nature underlining the role of electron-phonon coupling. The existence of an "optimal point" for micromachining is also evidenced.
Appl. Phys. A80.1598 – 1593 (2005)

Processing of metals by double pulses with short laser pulses
Le Harzic, R., Breitling, D. M., Sommer, S., Föhl, C., König, K., Dausinger, F., Audouard, E.

Experimental results related to the influence of time delayed pulses for ablation efficiency with short multi pulses (pulse duration of 5 ps) are reported. A significant improvement of the micro structuring quality at relatively high fluence regime in metals is obtained. Less removed or recast matter is observed and the processed surface appears to be smoother with better roughness. Ablation depths and burr heights are compared for single pulses and double pulses in steel, Al and Cu as a function of scans number. Best results are obtained for weak time delays, typically less than 1 ps.
Appl. Phys. A 81, 1121 1125 (2005).

Laser-Induced Shape Changes of Colloidal Gold Rods Using Femtosecond and Nanosecond Laser Pulses
Link, S., Burda, C., Nikoobakht, B., El-sayed, M. A.

We studied the shape transformation (by use of TEM and optical absorption spectroscopy) of gold nanorods in micellar solution by exposure to laser pulses of different pulse width (100 fs and 7 ns) and different energies (íJ to mJ) at 800 nm, where the longitudinal surface plasmon oscillation of the nanorods absorb. At moderate energies, the femtosecond irradiation melts the nanorods to near spherical particles of comparable volumes while the nanosecond pulses fragment them to smaller near-spherical particles. At high energies, fragmentation is also observed for the femtosecond irradiation. A mechanism involving the rate of energy deposition as compared to the rate of electron-phonon and phonon-phonon relaxation processes is proposed to determine the final fate of the laser-exposed nanorods, i.e., melting or fragmentation.
Journal of Physical Chemistry B, 2000, 104, 6152-6163.

Influence of diffraction by a rectangular aperture on the aspect ratio of femtosecond direct-write waveguides
Moh, K. J., Tan, Y. Y., Yuan, X-C., Low, D.K.Y., Li, Z. L.

Rectangular apertures have been used as a simple means to approximate elliptical Gaussian beams in femtosecond direct writing systems to correct for the elongated focus inherent in low numerical aperture (NA) systems. In this work it is recognized that the rectangular aperture, more accurately functions as a diffractive element and hence redistributes the intensity gradient around the focus in accordance to the physical effects of diffraction. A diffractive model for the technique was proposed and confirmed experimentally to investigate the effects of diffraction and the extent of its influence on the focus shape over different conditions. It was found that because of diffraction, the radius of curvature for the leading edge of the focal spot is dissimilar from its

trailing edge. However this effect is mitigated when lower processing energy is used and circular waveguides can be obtained.
Optics Express, Vol 13 No. 19, Nov., 2005.

Nanostructuring with spatially localized femtosecond laser pulses
Nolte, S., Chichkov, B.N., Welling, H., Shani, Y., Lieberman, K., Terkel, H.

Spatially localized femtosecond pulses have been produced by a combination of scanning near-field optical microscopy with ultrashort pulse lasers. With these pulses direct ablative writing on metal surfaces is demonstrated. Possible applications of this technique for nanostructuring, repair, and production of lithographic masks are discussed.
Optics Letters, Volume 24, Issue 13, July 1, 1999, pp. 914-916.

Femtosecond laser micro-structuring of aluminium under helium
Perrie, W., Gilla, M., Robinson, G., Fox, P., O'Neill, W.

The interaction of 180 fs, 775 nm laser pulses with aluminium under a flowing stream of helium at ambient pressure have been used to study the material re-deposition, ablation rate and residual surface roughness. Threshold fluence F_{th} ~0.4 J cm^{-2} and the volume ablation rate was measured to be 30 < V < 450 mm3 per pulse in the fluence range 1.4 < F < 21 J cm^{-2}. The presence of helium avoids gas breakdown above the substrate and leads to improved surface micro-structure by minimizing surface oxidation and debris re-deposition. At 1 kHz rep. rate, with fluence F > 7 J cm^{-2} and >85 W cm^{-2} average power density, residual thermal effects result in melt and debris formation producing poor surface micro-structure. On the contrary, surface micro-machining at low fluence F ~ 1.4 J cm^{-2} with low power density, ~3 W cm^{-2} produces much superior surface micro-structuring with minimum melt and measured surface roughness Ra ~ 1.1 ± 0.1 mm at a depth D ~50 mm. By varying the combination of fluence/scan speed during ultra-fast ablation of aluminum at 1 kHz rep. rate, results suggest that maintaining average scanned power density to <5 W cm^{-2} combined with single pulse fluence <4 J cm^{-2} produces near optimum microstructuring. The debris under these conditions contains pure aluminum nanoparticles carried with the helium stream.
Applied Surface Science 230 (2004) 50–59 (CPA-2010).

Femtosecond laser micro-structuring of alumina ceramic
Perrie, W.; Rushton, A.; Gill, M.; O'Neill, W.

Al2O3 ceramic has been micro-structured in air using 180 fs, λ = 775 nm optical pulses in a fluence range 1.4 < F < 21 J cm^{-2} with observed ablation rates of 25 < V < 900 μm^3/pulse. The threshold fluence was F_{th} = 1.1 J cm^{-2} at this ultrashort pulse-length in the NIR. Melting could be minimised using ultrafast optical pulses, improving the edge quality. By optimizing the processing parameters, the residual surface roughness could be reduced below the pristine surface R_a = 0.8 μm. The debris produced consists mainly of single crystal nanoparticles of alumina with diameters from 20 nm to 1 mm with an average diameter of 300 nm.
Applied Surface Science, v. 248, iss. 1-4, p. 213-217 (2005).

Technique to make nano carbon tubes buried inside rubber composite visible using femtosecond pulse laser ablation
Saito, Y., Takeda, T., Takeuchi, A., Nomura, A., Endo, M.

A method to observe the dispersion structure of carbon nanotubes buried inside a molding composite is described in this communication. The idea is that by utilizing the difference in ablation temperature between the tubes and the composite material, only the composite material, which has a lower ablation temperature, is ablated and buried tubes appear. This was applied to a rubber composite mixed with vapor-grown carbon fibers. A 150-fs pulse laser was prepared as an ablation source. In the ablation images observed with a field-emission secondary electron microscope, linear tubes, clusters, and connections of the tubes could be easily found in their original state.
J. Mater. Res., Vol, 20, No., 1, Jan. 2005.

Initial temporal and spatial changes of the refractive index induced by focused femtosecond pulsed laser irradiation inside a glass
Sakakura, M., Terazima, M

The temporal and spatial developments of the refractive-index change in a focal region of a femtosecond laser pulse inside a soda-lime glass is investigated by the transient lens sTrLd method with a time resolution of subpicosecond. In the TrL signal, the oscillation with about an 800-ps period is observed until about 2000 ps. In order to explain the oscillation, the thermoelastic response of a heated material by a short pulsed laser is calculated. It is found that the TrL signal calculated based on the thermoelastic calculation reproduces the observed oscillating signal very well, even though the calculated density at the focal region does not oscillate. The essential feature of the oscillation can be explained in terms of the pressure wave generation and propagation in the outward direction from the irradiated region. Based on the pressure-wave propagation and the phase-retrieval method, the temporal evolution of the refractive-index distribution inside a glass is obtained from the probe-beam deformation sTrL imaged at various delay times between the pump and probe pulses. Two phases of the refractive-index increase at the laser focal region were observed in a range of 20–100 and 500–700 ps, which may cause a permanent refractive-index increase in the laser focal region inside a glass. We discuss the effect of the laser pulse duration on the material deformation process in the laser-irradiated region. This study clearly shows the initial process of the material deformation dynamics inside a glass after femtosecond laser irradiation.
Physical Review B, 71, 024113 (2005).

Optical waveguide amplifier in Nd-doped glass written with near-IR femtosecond laser pulses
Sitkorsky, Y., Said, A.A., Bado, P., Maynard, R., Florea, C., Minick, K.A.

A near-IR (775 nm) femtosecond laser has been used to directly write a 1 cm long optical waveguide in Nd-doped silicate glass. A gain of 1.5 dB/cm was obtained at a signal wavelength of 1054 nm for ~346 mW of 514 nm pump power, in front of the input coupling objective.
Electronic Letters, 36, 3, 226-227.

High-resolution near-field mask repair with Femtosecond laser
Yosi Shani, Ian Melnik, Sasha Yoffe, Yuval Sharon, Klony S. Lieberman, and Hanan Terkel

Nanonics Lithography has demonstrated in the past a mask repair system based on near field optical technology. The basic system consisted of: (1) Near Field sub system -- Including a Near Field Head and the Near Field Optical Aperture (micro-pipette). (2) An X-Y stage with nanometer level accuracy, resolution and repeatability. (3) A doubled Nd:YAG laser for high resolution Near Field Optical Imaging, beyond the diffraction limits of the YAG laser. (4) A Nano- Second (NS) pulse width Arf Excimer laser for ablation of the Cr defect. The repairs performed with the system based on the above configuration suffered from inherent quality problems of Cr removal homogeneity and quartz substrate penetration. This is due to the relatively long duration of the NS pulse, in which the Cr is ablated by melting and evaporating the film accompanied by significant heat diffusion to the surrounding material. In order to improve the repair quality, we have introduced a Femto Second (FS) laser as the ablation source. In the FS regime the metal is evaporated within a time frame that does not allow heat diffusion to the surrounding material. The resultant cut in the metal is clean, without deposition on the edges and with a very limited effect on the substrate. In this paper, we will discuss the interaction of FS pulses with thin metal films and the integration issues of such a laser with Near Field optics. Cr and CrO ablation results of a programmed defect on masks will be presented. Clean homogeneous repairs of Cr. opaque defects with sharp edges and with minimal (less than 10 - 20 nm) Quartz penetration are also shown. Molten material at the line edge, which was common with the NS laser ablation, is also avoided with the FS laser ablation. The resulting mask repair system provides enhanced Cr. and CrO removal without deposition on the edge and with minimal Quartz effect.
Proc. SPIE 3546, 112 (1998)

Formation of an extended nanostructed metal surface by ultra-short laser pulses: single-pulse ablation in the high-fluence limit
Vestentoft, K., Balling, P.

The threshold character of ultra-short-pulse laser ablation allows the formation of sub-diffraction-limited structures. In order to achieve nanostructuring of an extended area in reasonable production times, parallel production is highly desirable. In this paper we analyze the results obtained by nanostructuring using a self-assembled microlens array formed by deposition of quartz spheres directly on a noble-metal surface or on a quartz spacer layer. The quartz spheres are removed by a single laser pulse, so the structures formed are the result of single-shot ablation. The size of the holes formed depends on the laser fluence and the thickness of the transparent spacer layer. The hole depths are significantly larger than the optical penetration depth, indicating that heat diffusion plays an important role. The results are analyzed by solving the two temperature diffusion model numerically in one dimension. The results from the numerical simulation lead to the formulation of a simple analytical model for the ablation at high fluence, which reproduces the results of the simulation quite well and is in qualitative agreement with the experimental data.
Appl. Phys. A 84, 207-213 (2006).

Micromachining with Ultrashort Laser Pulses
Zhao, J.-X., Hüttner, B., Menchig, A.

Practical high precise and efficient micromachining can be realized with computer controlled ultrashort laser pulses suppressing the thermal diffusion effect inside the material to be ablated. A direct translation from solid to the vapor state takes place at sufficient intensity levels. Experimental results of micromachining of different materials (Al, Si, InP and fused silica) with femtosecond laser pulses at wavelengths of 800 nm and 267 nm from a commercial Ti:sapphire laser are presented. Holes down to a diameter below 1 micron have been drilled with 800 nm pulses into aluminum as an interesting metal with an absorption peak in the JR-range nearby 800 nm. Because of their low energy band gap semiconductors have a strong absorption at UV wavelengths. Arrays of holes down to 1 micrometer in diameter have been drilled into silicon and InP using 267 nm pulses. Results of fused silica as an example for transparent insulator materials are compared to results of semiconductors. The hole array manufacturing process takes only a few seconds. Precision can be improved by matching laser parameters to the processed material. Keywords: micromachining, Ti:sapphire laser, UV beam, metal, semiconductor, insulator, ultrashort laser pulses.
SPIE 3618, 1-8 (1999).

Micromachining with a frequency-converted diode-pumped Nd:YAG laser
Hartke, Kevin; King, Kevin; Farson, Dave F.; Ely, Kevin

Laser ablation with a Q-switched diode-pumped Nd:YAG laser was used to produce grooves in H-13 tool steel and 6061 aluminum specimens. The relationships between laser wavelength, power and travel speed and the material removal rate, groove depth and quality were studied. Nondimensional relationships between the process and material variables and groove area and depth were found. The material removal rate was found to be significantly higher for the aluminum material. However, no significant increase in material removal or groove quality was found for the shorter wavelength laser energy. Significant recast was observed in grooves having a depth/width ratio larger than approximately 1 and all grooves had some amount of recast material remaining as a burr at the top edges.
Proc. SPIE Vol. 4088, p. 248-251, First International Symposium on Laser Precision Microfabrication

Femtosecond laser bulk micromachining of Microfluid channels in poly(methylmethacrylate)
Farson, Dave F. and Choi, Hae Woon

Internal channels in a polymer are widely used in biotechnology applications such as DNA stretching and in devices such as micrototal analysis systems and lab on a chip systems. For manufacturing prototype devices, femtosecond pulsed laser energy has been used to implement a convenient direct write bulk-machining process in glass. In this technique, the laser beam is focused inside of a transparent material, resulting in the ablation of an internal channel. Initial experiments for internal channel fabrication in a poly(methylmethacrylate) (PMMA) polymer revealed a significant problem with clogging of channels by debris and rough, fractured channel walls. In this article, we describe a new method to fabricate internal channels in PMMA using

femtosecond pulsed laser energy and a gas-assisted material removal concept. Relatively smooth channels with a minimum diameter of 2 μm, a maximum diameter of 20 μm, and a maximum length of 10 mm were achieved with this technique.
J. Laser Appl. 18, 210 (2006)

Integrating 3D photonics and microfluidics using ultrashort laser pulses
Ya Cheng, Koji Sugioka, Katsumi Midorikawa, and Zhizhan Xu

Femtosecond laser direct writing can form both 3D optical and fluidic microstructures buried in photoetchable glass, enabling integrated photonic fluidic devices.
SPIE Newsroom 10.1117/2.1200611.0484, 2006

Optical gratings imbedded in photosensitive glass my photochemical reaction using femtosecond laser
Cheng, Y., Sugioka, K, Masuda M., Shihoyamma, IK., Toyoda, K., Midorikawa, K.

We describe a new approach to the internal refractive index modification of glass by a Femtosecond (fs) laser. The glass we used is a photosensitive glass Foturan which contains trace amounts of silver. Silver nanoparticles, which is responsible for the refractive index change, can be formed in the glass after exposed to the fs laser and then postbaked at an appropriate temperature between 500 C and 550 C. In this work, latent images of grating structures are first inscribed into the photosensitive glass by photochemical reaction of a tightly focused fs laser beam which an intensity much lower than the threshold of optical breakdown. After this step, no measurable diffraction can be observed by irradiating the gratings with a He-Ne laser beam. The samples are then baked at 520 C for carious durations from 3h to 18 h. Diffraction of the optical grating embedded in the glass can now be observed, and the diffraction efficiency increases this postbaking duration, indicating that a refractive index change occurs in the modified regions. The relationship between the refractive index change occurs in the modified regions. The relationship between the refractive index change and the postbaking duration is systematically investigated.
Optics Express, Vol.11, No., 15, 28 July, 2003.

Direct fabrication of freely movable microplace inside photosensitive glass by femtosecond laser for lab-on-chip application
Masuda, M., Sugioka, K., Cheng, Y., Hongo, T., Shihoyama, K., Takai, H., Miyamoto, I., Midorikawa, K.

We demonstrate the fabrication of complicated three-dimensional (3D) microstructures embedded in a photosensitive glass by a high-order multiphoton process using a femtosecond (fs) laser. Direct writing of the fs laser followed by a post baking process and preferential etching in a dilute hydrofluoric (FH) acid solution results in a microplate that can freely move in hollow structures embedded in the glass. The fabricated structure functions as a microvalve that can control the flow direction of fluids in the microreactor.
Appl. Phys. A, 1029-1032 (2004).

Novel ablation of fused quartz by Preirradiation of vacuum-ultraviolet laser beams followed by forth harmonics irradiation of Nd:YAG laser
Sugioka, K., Wada, S., Tashior, H., Toyoda,, K.

Preirradiation using vaccum-ultraviolet (VUV) beams of anti-Stokes stimulation Raman scattering VUV laser, followed by the fundamental beam (266 nm) irradiation, provides a novel scheme for fused quartz ablation. The preirradiation of 5^{th}-(171 nm) or 6^{th}- (160 nm) order anti-Stokes beams realized significant ablation with the succeeding fundamental beam irradiation of a laser fluence lass that the ablation threshold. X-Ray photoelectron spectroscopy analysis reveals that SiOx(x<2) is created in the fused quartz by photoysis using the anti-Stokes beams. Each effect of the preirratiation and the succeeding fundamental beam irradiation in the ablation process discussed.
Applied Physics Letters 65 (12), 19 September 1994.

Three dimensional microfluidic structure embedded in photostructurable glass by femtosecond laser for lab –on-chip applications
Sugioka, K., Masuda, M., Hongo, T., Cheng, Y., Shihoyama, K., Midorikawa, K.

A new technology for rapid prototyping of lab-on-chip devices is described. Direct write of a new-infrared femtosecond laser forms three-dimensional (3D0 latent images inside photostructurable glass. Modified regions are developed by a post-annealing and then preferentially etched away in dilute hydrofluoric acid solution with an etching selectivity of 40-50 times, resulting in the formation of three 3D hollow microstructures inside the glass. Microfluidic structures with microcells and microchannels embedded in the glass are fabricated by this technique.
Applied Physics A 79, 815-817 (2004)

Multiwavelength excitation by vacuum-ultraviolet beams coupled with fourth harmonics of a Q-switched Nd:YAG laser for high-quality ablation of fused quartz
Sugioka, K., Wada, S., Tashiro, H., Toyoda, K., Ohnuma, Y., Nakamura, A.,

Simultaneous irradiation of multiwavelength beams emitted from a vacuum-ultraviolet (VUV) Raman laser offers great potential for high-quality microfabrication of fused quartz by ablation. In this process, short wavelength components of the beam play two roles, that is, stationary effect and transitional effect. The stationary effect means photodissociation of Si-O bonds and formation of metastable absorption sites to the longer wavelength beam components. The transitional effect increases the absorption to the fundamental beams with a 266 nm wavelength from 0% to more than 60%. This phenomenon may be explained as the excited state absorption (ESA) due to the coupling of the VUV laser beams with the fundamental beam. The mechanism of the high-quality ablation is discussed by making a comparison between these two effects.
Applied physics Letters 67 (19), 6 November, 1995.

High-Speed machining of glass materials by laser induced plasma-assisted ablation using a 532-nm laser
Zhang, J., Sugioka, K., Midorikawa, K.

In this communication, we report high-speed machining of glass materials by a novel laser ablation technique using a conventional visible laser for the first time. A high-quality micrograting structure is fabricated in fused quartz by laser-induced plasma-assisted ablation (LIPPA) using a second harmonic of Q-switched Nd+:YAG laser (532 nm). The plasma generated from a silver (Ag) target by the laser irradiation effectively assists in ablation of the fused quartz substrate by the same laser beam, although the laser beam is transparent to the substrate. A grating with a cross-sectional shape like a square-wave (period~ 20um) is achieved using the mask projection technique. The ablation rate reached several tens nm/pulse. In addition, LIPPA is applied to high-speed hole drilling (700 um in diameter) of fused-quartz (0.5 mm thick) and Pyrex glass (0.5 mm thick).
Applied Physics A, 67, 499-501 (1998)

Control of the cross-sectional shape of a follow microchannel embedded in photostructurable glass by use of a femtosecond laser
Cheng, Y., Sugioka, K., Midorikawa, K., Masuda, M., Toyoda, K., Kawachi, M., Shiyoyama, K.

Theoretical and experimental investigations have been make of the three-dimensional microchannel fabrication of photostructurable glass by use of a femtosecond (fs) laser. Generally, a microchannel fabricated inside glass by the scanning focal spot of a fs laser perpendicular to the direction of laser propagation assumes an elliptical shape with a cross section of large aspect ration. We demonstrate that one can greatly reduce the aspect ration merely by inserting a slit, which is oriented parallel to the laser's scanning direction, before the focusing lens. Computer simulations show that a more symmetrical pattern is optained in the vicinity of the focal point with the help of such a slit, owing essentially to a diffraction effect.
Optical Letters, Vol 28, No. 1, January 1, 2003.

Three-dimensional micro-optical components embedded in photosensitive by a femtosecond laser
Cheng, Y., Sugioka, K., Midorikawa, K., Masuda, M., Toyoda, K., Kawachi, Masako, Shihoyama, K.

We show that three-dimensional micro-optical components can be embedded in a photosensitive glass by a femtosecond (fs) laser. After exposure to the tightly focused fs laser beam, latent images are written inside the sample. Modified regions are developed by a postbaking process and then preferentially etched away in a 10%-dilute solution of hydrofluoric acid. After this process, follow internal structures are formed that act as a mirror and a beam splitter. Furthermore, we find that post-annealing smoothes the surfaces of the fabricated follow structures, resulting in great improvement of their optical properties.
Optics Letters, Vol 28, No 13, July 1,2003.

Microfluidic laser embedded in glass by three dimensional femtosecond laser microprocessing
Cheng, Y., Sugioka, K., Midorikawa, K.

Microfluidic dye lasers three-dimensionally embedded in glass have been fabricated for what is believed to be the first time by integrating micro-optical and microfluidic components by use of a

femtosecond laser. By pumping the microfluidic laser, in which are microfluidic chamber was filled with the laser dye Rhodamine 6G dissolved in ethanol, with a frequency-doubled Nd:ytterbium aluminum garnet laser, lasing action was confirmed by analysis of the emission spectra at different pump powers. In addition, by arranging two microfluidic chambers serially in the glass, we built a microfluidic twin laser that produced an array of to simultaneous laser emissions with one pump laser.
Optics Letters, Vol. 29, No. 17, Sept. 1, 2004.

High-speed machining of glass materials by laser-induced plasma-assisted ablation using a 532-nm laser
Zhang, J., Sugioka, K., Midorikawa, K.

In this communication, we report a high-speed machining of glass materials by a novel laser ablation technique using a conventional visible laser for the first time. A high-quality micrograting structure is fabricating in fused quartz by laser-induced plasma-assisted ablation (LIPPA) using a second harmonic of Q-switched Nd+:YAG (532 nm). The plasma generated from a silver (Ag) target by the laser irradiation effectively assists in ablation of the fused quartz substrate by the same laser beam, although the laser beam is transparent to the substrate. A grating with a cross-sectional shape like a square-wave (period~ 20 um) is achieved by using the mask projection technique. The ablation rate reached several tens nm/pulse. In addition, LIPAA is applied to high speed hole drilling. (700 um in diameter) of fused quartz (0.5 mm thick) and Pyrex glass (0.5 mm thick).
Applied Physics A 67, 499-501 (1998).

Micropatterning of Quartz Substrates by Multi-Wavelength Vacuum-Ultraviolet Laser Ablation
Sugioka, K., Wada, S., Tsunemi, A., Sakai, T., Takai, H., Moriwaki, H., Nakamura, A., Tashiro, H., Toyoda, K.

Photoablation of synthetic fused quartz by simultaneous irradiation of multi-wavelength beams of a vacuum-ultraviolet (VUV) laser using high-order anti-Stokes Raman scattering is described. The VUV laser, which emits widely spread Raman-shifted lines from 133 nm to 594 nm, is ideal for effective laser ablation of the fused quartz. The well-defined patterns with a cross-sectional profiles of a rectangular shape are formed by using a contact mask at an ablation rate as high as 13 nm/s. An effective absorption coefficient of $3.4 \times 10^{-5} cm^{-1}$, which indicates that the multi-wavelength irradiation effect has an important role in the process, is obtained.
Japanese Journal of Applied Physics, Vol.32, (1993) pp. 6185-6189) Part 1, No. 12B, December 1993.

Ultrafast Lasers in Materials Research
Cahill, G. C., Yalisove, S. M.

With the availability of off-the-shelf commercial Ultrafast laser, a small revolution in materials research is underway, as it is not possible to use these tools without being an expert in the development of the tools themselves. Lasers with short-duration optical pulses- in the sub-picosecond (lass than one trillionth of a second) range – are finding a variety of applications, from

basic research on fast processes in materials to new methods for microfabrication by direct writing. A huge range of pulse energies are being used in these applications, from less than 1 nJ (a billionth of a joule) to may joules.
MRS Bulletin, Volume 31, August 2006.

3-D microstructuring inside photosensitive glass by femtosecond laser excitation
Masuda, M., Sugioka, K., Cheng, Y., Aoki, N., Kawachi M., Shihoyama, K., Toyoda, K., Helvajian, H., Midorikawa, K.

We show that a femtosecond laser enables us to produce true three-dimensional (3-D) microstructures embedded in a photosensitive glass, which has superior proprieties of transparency, hardness and chemical and thermal resistances. The photosensitivity arises from the cerium in the glass. After exposure to a focused laser beam, latent images are written. Modified regions are developed by a post-baking process and then preferentially etched away in a 10% dilute solution of hydrofluoric acid at room temperature. We have measured the critical dose for modification of the photosensitive glass, and fabricated 3-D microstructures with microcells and hollow microchannels embedded in the glass based on the critical dose.
Applied Physics A, 76, 857-860 (2003).

Numerical Simulation of Ultrashort Pulse Laser's Ablation on Copper
J.-G. Liang, X.-C. Ni, L. Yang and Q.-Y. Wang

The ablation process of copper foil with ultrashort laser pulses was simulated by the double-temperature equation (DTE), which was formatted simply. The ablation rate of the copper was attained on the basis of the simulation of the electronic and lattice's temperature. The simulation results show that the greater the laser fluence is, the longer the duration of ablation lasts and more material is ablated. The experimental results are accorded with ablation depth.
Chinese Journal of Lasers, Vol.32, No. 9, September 2005

An optimal process of femtosecond laser cutting of NiTi shape memory alloy for fabrication of miniature devices
Chengde Li, Suwas Nikumb, Franklin Wong

The mechanical properties of NiTi shape memory alloy (SMA) components are sensitive to thermal influence during laser machining. To make the femtosecond laser cutting of NiTi material meet the strict fabrication requirements for miniature SMA devices with high precision, complex patterns and minimal heat affected zone (HAZ) along with high throughput, we report an optimal process of sideways-movement path planning in this article. Femtosecond laser processing of NiTi SMA using the fundamental wavelength of 775nm from a Ti:sapphire laser along with its second and third harmonic irradiations were systematically investigated. We observed that the main impact of ultrashort laser pulse induced air breakdown on materials processing was beam widening. The laser beam at fundamental wavelength suffered less widening than its harmonic wavelengths. Femtosecond laser machining of metals is still basically a thermal mechanism. High ablation rates at higher laser fluences causes significant recast formation, while lower fluences resulted in better cutting quality at the expense of efficiency. The optimal process involving the method of sideways-movement path planning enables recast-free high-precision features at higher laser fluences with better throughput.

Optics and Lasers in Engineering, Volume 44, Issue 10, October 2006, Pages 1078-1087

Ultrashort pulse laser micromachined microchannels and their application in an optical switch

H.Y. Zheng · H. Liu · S. Wan · G.C. Lim · S. Nikumb · Q. Chen

The capability of direct writing makes ultrashort pulse laser significant in the microfabrication of MEMS devices based on polymer and glass. In particular, nanosecond and femtosecond lasers are able to transfer the adequate energy in femtosecond intervals for the removal of the materials. Because of its advantages, just like the small feature size, smooth finishing surface, flexible structuring and the minimum thermal effect, ultrashort pulse lasers have become a convincing technique with the high peak power. This paper presents the femtosecond laser machining results of the polycarbonate, aluminosilicate glasses and nanosecond laser machining of aluminosilicate glasses. The microchannels with the critical micron-scale dimensions and the sub-micron scale surface roughness were achieved by the optimized operating parameters of the laser. The major influence factors such as cutting speed, power energy, and power stability were analyzed to obtain the optimized parameters for the fabrication of the microchannels for a bubble switch. The ultrashort pulse laser micromachining was applied in the prototype of a bubble optical switch. By miniaturization of the structure of the microchannel, the switch speed can be promisingly improved.

Int J Adv Manuf Technol (2006) 27: 925–929

The onset of phase explosion and the role of damage accumulation in ultrafast laser processing of common metals in air

Paul Mannion, Gerard M O'Connor, Ed Coyne, Helen Howard, and Thomas J Glynn

The aim of the current work is two-fold: First, the aim is to investigate the transition, for a number of metals, from a smooth ablation process to an explosive one. Secondly we aim to study the dependence of the ablation threshold in metals on the applied laser shot number. Ablation of polycrystalline metal samples was performed with multiple pulses from a femtosecond laser (Clark MXR, CPA2001). Morphological investigations of the laser processed areas were recorded using optical and scanning electron microscopies (SEM) and white light interferometry. The investigations have been carried out on sample matrices which were processed for a range of laser fluences and applied laser shots for four metals. Data obtained on ablation rates, ejected particle sizes and crater morphologies prove that ablation changes from a smooth to an explosive process at high fluences, as identified with changes in the material removal mechanisms. Threshold fluences were measured for both the smooth and explosive ablation processes. The ablation threshold fluence depends on the number of pulses applied to the same spot. It was found that the build up of laser induced mechanical stresses, due to the heating and cooling cycles of the samples between consecutive laser shots, plays an important role in the material modification process. It leads to the observed dependence of ablation threshold on shot number, which is described by a power law based on a mechanical fatigue model. The strength of the dependence is governed by the incubation coefficient, **S**, which has been measured for all materials studied. It is expected that the build up of laser energy or incubation leads to the accumulation of material defects and residual stresses which has the effect of lowering the energy required to cause ablation using a large number of incident laser shots.

High-Power Laser Ablation V, edited by Claude R. Phipps, Proceedings of SPIE Vol. 5448

Femtosecond laser direct writing microfluidic channels inside photosensitive glass
Z. Wang and H.Y. Zheng

In this study, we report our recent research infabrication of microfluidic channels inside bulk Foturan photosensitive glass by femtoseond (fs) laser direct writing. First, a latent image of microchannel was written inside the glass using a fs laser. Then, a visible image of microchannel was obtained when the sample was subjected to a programmed thermal treatment. Next, the sample was soaked in a diluted hydrofluoric (HF) solution in an ultrasonic bath. The laser-exposed region was preferentially etched away with an etching selectivity of 20-40 times and finally, a hollow microstructure was formed inside the glass. The size and cross-sectional profile of microfluidic channels are crucial issues that affect the transport, mixture and /or reaction of reagents in micro-total analysis systems (μ-TAS). We therefore focused our effort on studying how laser processing parameters would affect the microchannel size and aspect ratio. By the one continuous procedure of hollow structure formation, different configuration of microfluidic chambers and channel structure can be easily integrated in single glass chip without the cumbersome alignment and assembly processes of individual components.
PhotonicsGlobal@Singapore, 2008. IPGC 2008. IEEE