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Process characterization of fabricating 3D micro channel systems by laser-micromachining

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Abstract

A novel process technology was developed to create 3D micro channel systems bounded by solid 3D quartz substrates without damaging the bounding surfaces of the substrate. The process uses a Nd:YAG laser to induce thermal energy or plasma to micromachine channels in substrates which are transparent to the spectrum from UV to near IFR wavelength. We have demonstrated that this process is capable of fabricating up to 4 mm long circular cross-section channels with diameters ranging from 25 to 200 μm. The channel diameter can be controlled by a software program that interfaces with the laser system, thus allowing complete channel systems to be designed on a CAD software and then directly fabricated by the laser system. The process technology, process characterization, and initial test results of the fabricated micro channels are presented in this paper. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Micro channel fabrication; Laser-micromachining; Quartz processing; 3D micro channel system

1. Introduction

Micro fluidic systems, which are used to improve performance and add new functionality in many applications such as chemical, blood, DNA, and environmental science analyses, are typically fabricated on quartz or silicon substrates. Quartz is sometimes more suitable than silicon for these purposes because of the following reasons: it is (1) optically transparent; (2) chemically inert and stable; (3) a good electrical insulator; (4) cheaper than silicon. Also, quartz substrates with a wide range of dimensions are available. Currently, almost all quartz micromachining for micro fluidic systems is performed by conventional MEMS technologies such as lithography and etching [1,2]. However, these conventional technologies have many limitations on fabrication, bonding, and packaging of a final system, especially for 3D micro channel systems.

Recently, much attention has been paid to Q-switched Nd:YAG laser-micromachining for MEMS/microsystems applications due to a number of advantages: it is a single-step process with high flexibility; it does not contaminate the material being processed; it allows highly localized treatment of materials with a spatial resolution of tens of microns [3]. However, quartz is an optically transparent material and its average absorptivity for the spectrum from visible to near infrared is less than 5%, and hence there are few reports about micromachining on quartz directly using Nd:YAG laser, since very high laser power is required to process these substrates.

We have recently developed a novel process that uses a computer controlled Nd:YAG laser system to create complex 3D micro channel systems bounded by solid 3D quartz substrates. To the best of our knowledge, besides the related work by Zhang et al. [4], in which a laser-induced plasma was utilized to successfully ablate through a hole on a 0.5 mm thick quartz plate, and by Varel et al. [5], in which ultra-short (100–200 fs) laser pulses were used to create less than 2 mm *straight* micro channels, this is the first work to demonstrate a micro channel system directly fabricated *inside* a 3D quartz substrate. In [6,7], we have shown that straight and bent micro channel systems much longer than those demonstrated in [4,5] can be fabricated by both thermal-induced and plasma-induced laser machining. In this paper, we will present our recent results of a more extensive characterization of this novel process.

2. Theoretical analysis

The physical principle which allowed us to process optically transparent quartz cubes is the so-called electric breakdown effect of the electric field [8]. Based on the effect,

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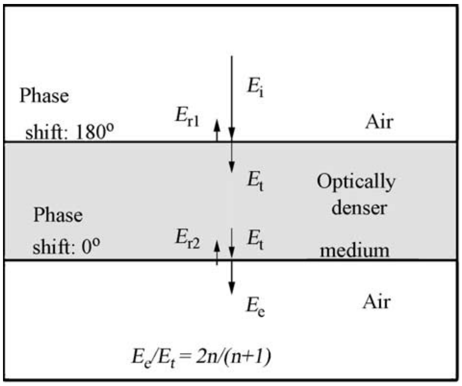


Fig. 1. Illustration of transmitted and reflected amplitude of a light beam incident on an air–medium interface.

the electric field strength at the exit surface can be higher than the electric field strength at the laser beam entrance surface. This is due to the fact that when a light beam incidents from an optically less dense medium to a denser one, there will be 180° phase shift at the entrance surface but no phase shift at the exit surface for the reflected beam (see Fig. 1). The ratio of electric field strength at the exit (E_e) and the entrance (E_t) surfaces can be calculated as:

$$\frac{E_e}{E_t} = \frac{2n}{n+1} \tag{1}$$

where n is the refractive index of the medium.

If the material refractive index is 1.5, e.g. as for quartz, the ratio of electric field strength at the exit and entrance surfaces E_e/E_t is 1.2 and the ratio of laser intensity at both surfaces is

$$\frac{I_e}{I_t} = \left(\frac{E_e}{E_t}\right)^2 = 1.44 \tag{2}$$

So, it is easier to process quartz from the rear surface of substrates. As soon as the first laser pulse drilling occurred at the back surface, the locally damaged site can absorb thermal energy from the following pulses, and *thermal-induced* or *plasma-induced* laser processing can be initiated from the site. Hence, micro channels can be formed in any part of the quartz by pre-defined paths starting from this site. A sample of a channel forming path is shown in Fig. 2.

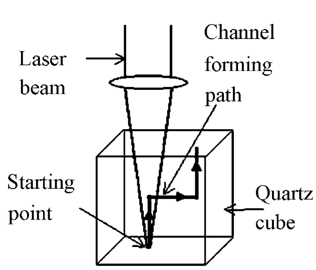


Fig. 2. Illustration of the thermal-induced laser micro channel fabrication technique.

3. Experiments

A Q-switched Nd:YAG laser, 40 W of maximum power (Electrox Scriba II D40, UK), was used in our work. The frequency of the laser pulse was set at 2 kHz and the pulse width of the laser was 100–300 ns. The laser beam was focused by a scanning lens ($f\theta$ lens) with a focal length of 100 mm onto the sample surface. The Gaussian spot size of the beam was determined to be around 400 μm^2 at 1064 nm (diameter d_b of ~22.6 μm at $1/e^2$ intensity). All channels were formed in optical grade fused quartz cubes (bubble free synthetic silica, Almaz Optics, USA). The drilling process was carried out in air with atmospheric pressure with the laser beam directly focused on the substrates (maskless).

Two methods for laser drilling on quartz were studied in our work: laser controlled fracturing and laser melting. Laser drilling by controlled thermal fracturing can usually be accomplished with relatively low power so the Nd:YAG laser beam may be used directly to perform drilling, which we refer to as thermal-induced processing. While laser drilling on quartz by melting usually requires laser powers above 1000 W even with CO_2 lasers [3], we have used laser-induced plasmas in extreme high temperature to process quartz with our 40 W laser system, which we refer to as plasma-induced processing. In our experiments, the laser fluence at the processed surface of the sample were estimated to be about 160–370 J/cm^2 (0.65–1.5 mJ pulse energy) for the thermal-induced process and about 320–620 J/cm^2 (1.3–2.5 mJ pulse energy) for the plasma-induced process. Both technologies are able to construct micro channels in solid 3D quartz substrates, and the latter tends to create better channels.

4. Results and discussion

4.1. Thermal-induced processing

From our experiments, thermal-induced cutting tends to create localize cracks in the channel. A microscope photo of a channel fabricated by thermal-induced processing is shown in Fig. 3. In this process, the focused laser beam ablates the quartz directly. However, fused quartz has residual compressive stress, so the channel cross-sectional shape depends strongly on the state of stress of the quartz during the laser interaction (see Fig. 4). Moreover, as shown, there are many thermal cracks around the channel, which are caused by the high thermal gradient around the channel. From our experiments, the quantity and the size of thermal cracks depend partly on the drilling patterns, which are the trajectory of the beam spot on the surface of the substrate, and will be discussed later.

It is possible to adjust the incoming laser field strength such that the threshold energy needed to locally damage the quartz is reached at the exit surface or at an existing erosion front inside a quartz substrate and not the entrance surface,

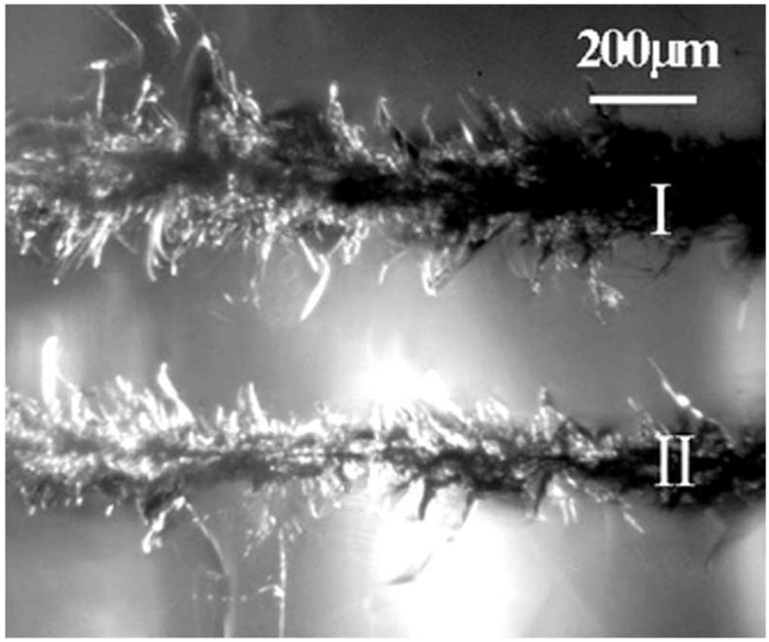


Fig. 3. A microscope photo of micro channels with many thermal cracks drilled by thermal-induced processing using different drilling patterns. Channel I: circular drilling pattern; Channel II: cross drilling pattern.

so laser processing can only occur on a defined path without damaging the surface and any other area even though the laser beam passes through them. Branches of channels can be fabricated by starting from any location of an existing channel by this method. Based on the fabrication of branches of channels, complex 3D channel paths inside the quartz cube can be constructed. Fig. 5 shows photos of different micro channel systems in 3D quartz cubes with the dimension of 10 mm × 10 mm × 10 mm.

4.2. Plasma-induced processing

The thermal cracks around the channels may be reduced or eliminated by locally melting quartz instantaneously. A laser-induced plasma of quartz was used to perform drilling by melting. The re-solidified molten quartz may produce a smooth and clean channel wall surface.

Plasma of most elements can be produced by a high-intensity pulsed laser irradiation. When a series of laser

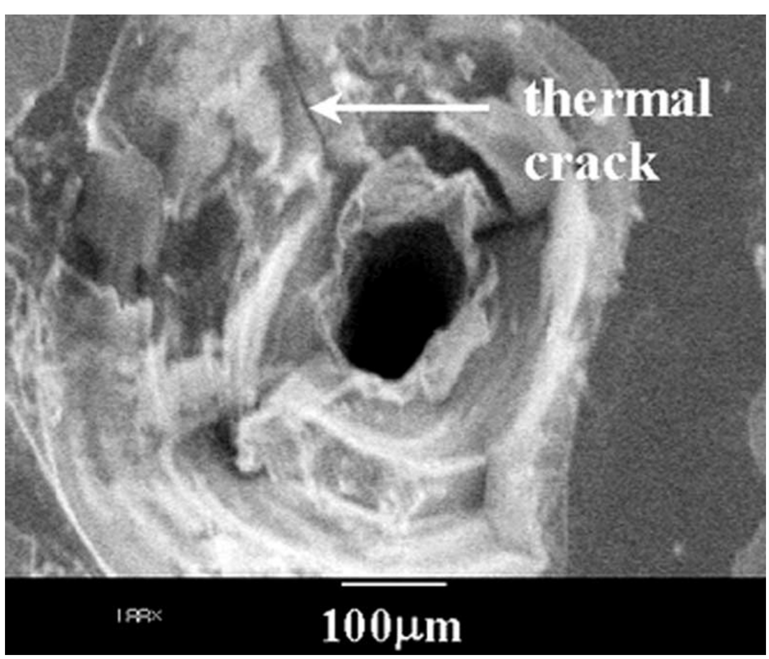
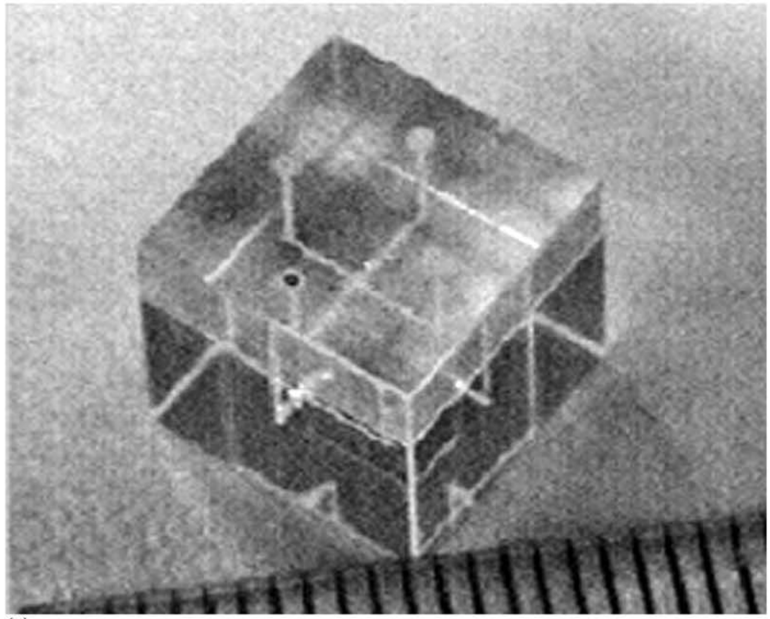
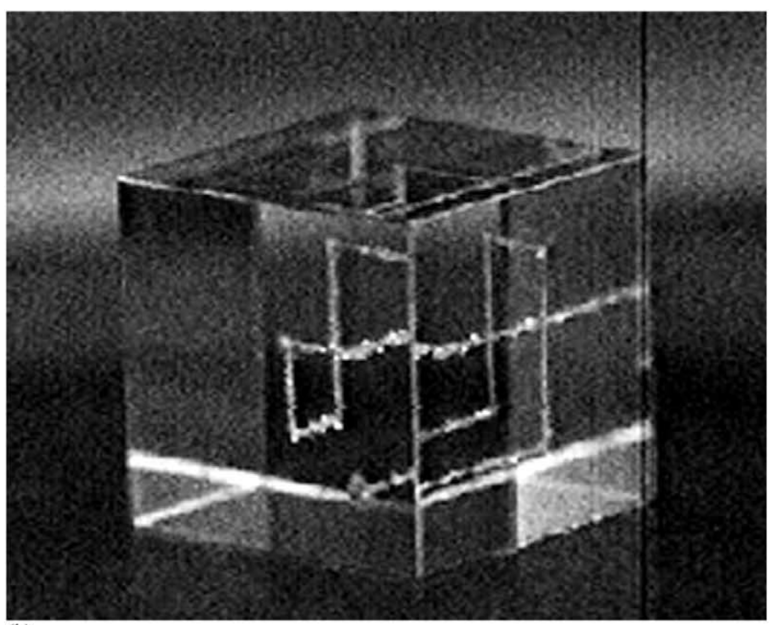


Fig. 4. SEM picture of the cross-sectional view of a channel drilled by thermal-induced processing.



(a)



(b)

Fig. 5. Photos of different channel systems in 3D quartz cubes with dimensions of 10 mm × 10 mm × 10 mm: (a) a fluidic mixer consisting of two U-shape channels with the length of 2 mm × 21 mm; (b) a more complex 3D channel system with total channel length of 34 mm.

pulses strike a solid target and are absorbed by the target, a characteristic sequence of energy conversion processes leads to production of a hot and dense plasma consisting of matter in an extreme state of high-energy concentration [9]. The geometry of the solid target plays a key role during the laser-target interaction. A flat target may just absorb coming irradiation once, while a cavity may store irradiation for a much longer time by reflecting the irradiation on the interior walls of the cavity. Therefore, there are many more opportunities for a cavern target to absorb irradiation energy and plasma may be more easily induced in a cavity.

A quartz substrate was first pre-damaged at a site by the thermal-induced processing, and this locally damaged site can easily absorb the subsequent laser pulses. Then the laser beam was focused on this initiated site on the quartz surface. Once the damaged site began to absorb enough laser energy, hot and dense plasma of quartz was produced around this site. The plasma attacked and melted the neighboring quartz and then a hollow was formed. The hollow functioned as a cavity for the following laser pulses. The laser-induced plasma of quartz was continuously produced in the cavity to drill the hollow further downward, producing a micro

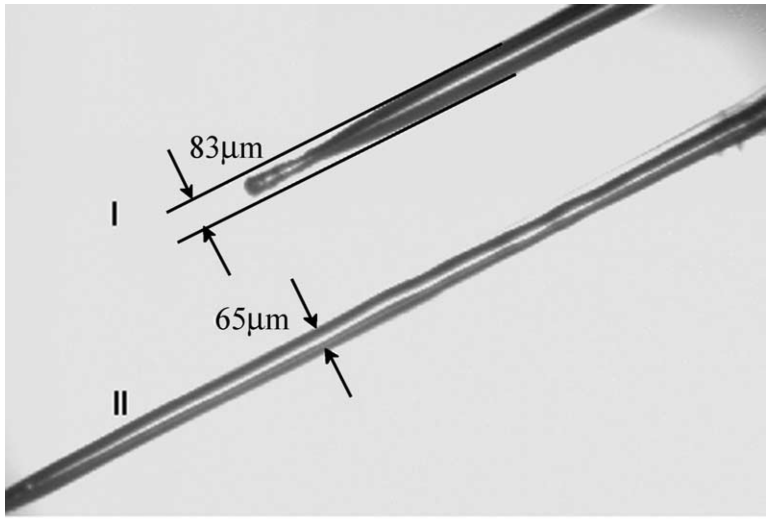


Fig. 6. A microscope photo of micro channels with clean kerf surface drilled by plasma-induced process (the middle part and the end part of two different channels).

channel. The channels fabricated by this process are of high quality with a smooth kerf surface and no thermal cracks are observed, as shown in Fig. 6. The maximum length of channel was approximately 4.2 mm.

4.3. Analysis of drilling processes

The behaviors of both thermal-induced processing and plasma-induced processing were studied and are discussed below. In the drilling process, the laser beam was moved in a different trajectory named as the drilling pattern instead of just focusing on one spot on the processing plane so that the dimension of micro channels can be controlled by setting the dimension of laser drilling pattern using a computer controlled laser system. The dimension of the channels fabricated by both processes can be varied from around 25 to 200 μm. The dependence of the channel diameter on the dimension of the circular laser drilling pattern is shown in Fig. 7.

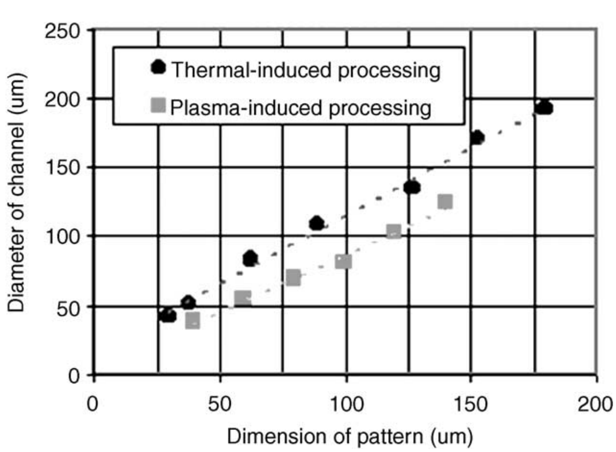
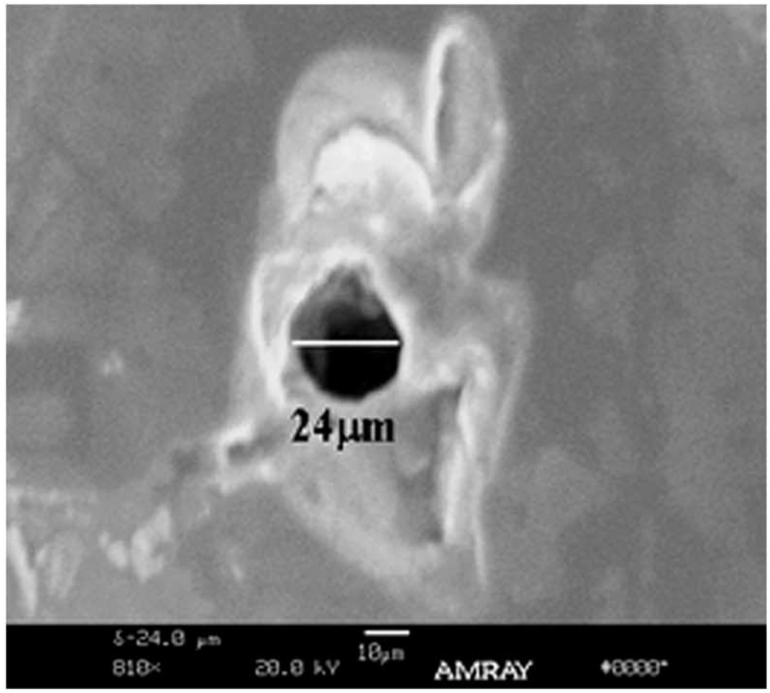


Fig. 7. The dependence of channel diameter on the dimension of circular laser drilling pattern.

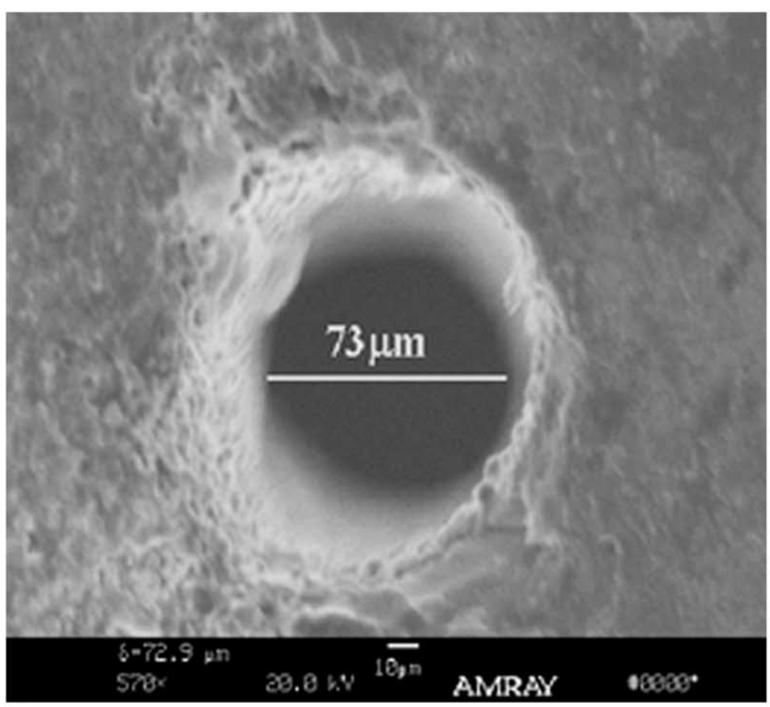
Fig. 8 shows SEM pictures of channels processed by a laser-induced plasma, indicating that channels were basically circular in shape.

Fig. 9 shows a SEM picture of the interior wall of a channel drilled by a laser-induced plasma, showing that smooth interior walls can be produced by plasma-induced processing. The quantitative analysis on the roughness of interior wall was carried out using a WYKO Surface Profiler and an example of a surface curvature measurement is shown in Fig. 10, where the parameters, R_q, R_a, R_t, R_p, and R_v, are root mean square roughness, roughness average, maximum height of the profile, maximum profile peak height, and maximum profile valley depth, respectively. The result indicates that the roughness average, R_a, is less than 0.2 μm for the channel measured.

In plasma-induced processing, the plasma density changed with the depth of hole as well as the laser intensity so that the drilling rate varied with the depth of hole, as shown in Fig. 11. The drilling rate behavior can possibly be explained by dividing the process into three stages: beginning, middle, and end. At the beginning stage, just before the hole was formed, the quartz cube was a flat target for the incident laser beam. The laser-induced plasma of quartz was produced only when the quartz target absorbed enough laser energy at the pre-damaged site. The quartz plasma with high temperature melted and vaporized the quartz exposed to the incident beam, forming a hole. At the middle stage, as the depth of hole increased, the hole functioned as a cavity. The laser beam might bounce in it several times, providing more opportunities for the quartz target to absorb irradiation energy and induce hot and dense plasmas of quartz. During this stage, the quartz plasma was of the highest temperature and density, giving the fastest drilling rate in the whole drilling processes. The depth of hole in this stage was about 0.5–2.5 mm. At the end stage, as the hole got deeper, the laser irradiation might heat the air in the cavity as well as the



(a)



(b)

Fig. 8. SEM pictures of channels drilled by the laser-induced plasma with different diameters: (a) 24 μm; (b) 73 μm.

quartz target, inducing both quartz plasma and air plasma. The front air plasma with a high dielectric constant is of high absorptivity to the laser beam, and can shield part of or all the subsequent laser pulses to reach the quartz target. In this stage the mixture of both plasmas was gradually weakened and therefore the drilling rate was gradually decreased until zero.

A cross pattern and a circular pattern were tested as drilling patterns in the thermal-induced processing. The latter tends to cause more and larger thermal cracks (see Channel I in Fig. 3), but it could directly control the dimensions of the channels. The former may cause less and smaller thermal cracks (see Channel II in Fig. 3) but the channel dimension is unadjustable. Also a cross pattern is

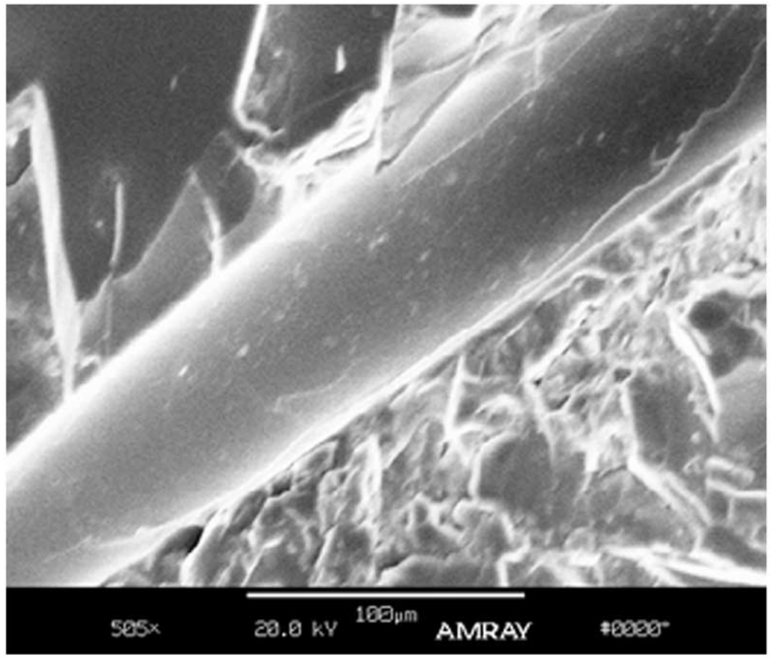


Fig. 9. A SEM picture of a channel interior wall drilled by the laser-induced plasma.

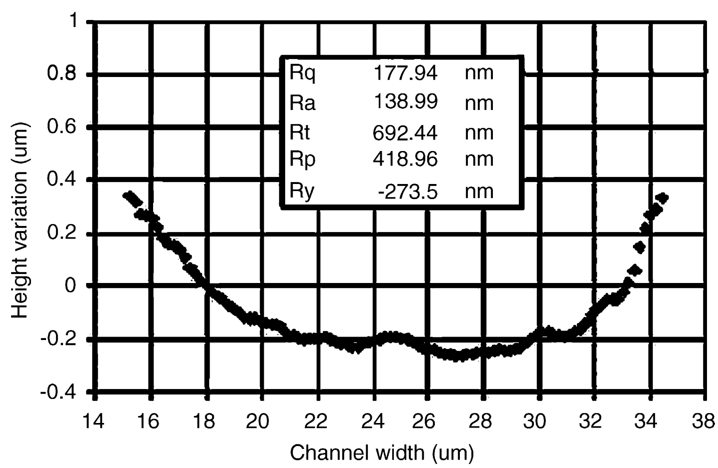


Fig. 10. WYKO interferometer plot of the channel interior surface processed by the laser-induced plasma. The roughness average is ~0.14 μm.

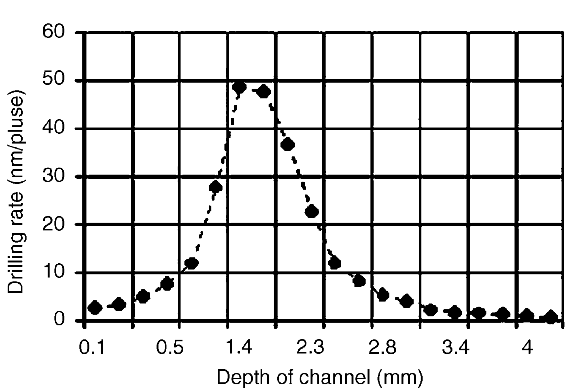


Fig. 11. The dependence of drilling rate on depth of for a channel of ~80 μm in diameter (at laser fluence: 620 J/cm^2, frequency: 2 kHz, pulse width: 200 ns).

harder to induce plasma in the plasma-induced drilling compare to a circular pattern. In plasma-induced processing, a one-circle pattern and a multi-circle pattern were tested. The former tends to produce a ball-shape hole in the middle part of a channel due to the intermittence of the plasma during processing, while the latter may create more uniform channels. As shown in Fig. 12, Channel I was fabricated using a four-circle pattern and Channel II was fabricated using a one-circle pattern. The circular patterns have the same maximum diameter. The results were consistent from more than 10 channels cut by each pattern. We conjecture that this phenomenon is caused by the uniformity of heat distribution in cutting quartz using the laser-induced plasma as explained below. In general, the maximum diameter of the drilling pattern d_p is much larger than the spot size of the

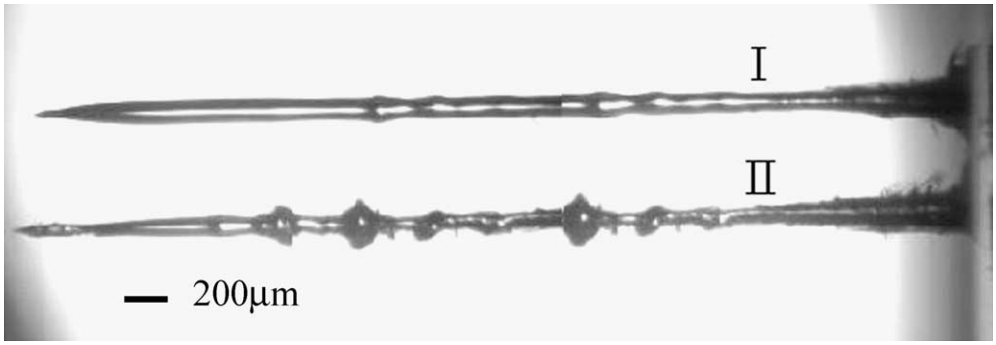


Fig. 12. A comparison of channels drilled by laser-induced plasma using different drilling patterns. Channel I: four-circle pattern; Channel II: one-circle pattern.

laser beam d_b (in our experiment, d_p is about 80–120 μm and d_b is ∼22.6 μm at $1/e^2$ intensity). For a one-circle pattern, there will be some unexposed area to the laser beam in the center of the drilling pattern. However, a multi-circle drilling pattern, which consists of several concentric circles with different diameters, may heat more uniformly the entire processed volume such that a plasma may be more readily induced continuously than just using a one-circle pattern.

We have also characterized the channels fabricated by thermal-induced processing and proved the connectivity of channels from different directions for the purpose of construction of complex 3D micro channel systems. Resistance measurements were carried out on 3D micro channels filled with $FeCl_3$ solution. The resistance of a channel filled with a given solution, which can be conductive due to the contribution from both cations and anions, is theoretically proportional to the length of channel for a given cross-section area of the channel. An example of measured resistance across U-shape channels fabricated by thermal-induced processing is shown in Fig. 13, which verified that through micro channels could be formed by thermal-induced process. The diagram indicates that the dependence of channel resistance on the length of channel is basically linear, which agrees well with theoretical results.

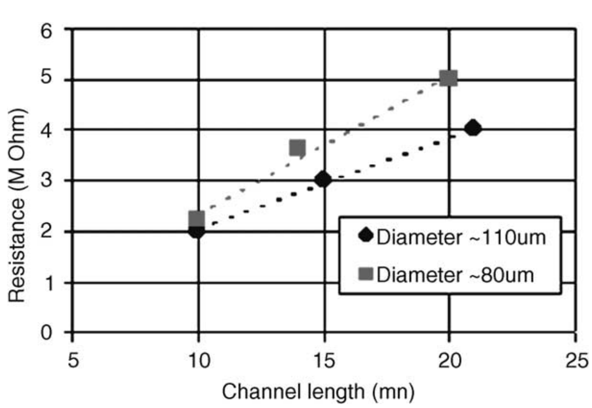


Fig. 13. Measured resistance of electrolyte versus channel length and diameter. The electrolyte used was $FeCl_3$ solution. The channels tested were fabricated by thermal-induced processing.

5. Conclusion

A novel process technology was developed to create 3D micro channel systems bounded by solid 3D quartz substrates. This technology not only allows the rapid construction of complex 3D channel paths inside a quartz cube by thermal-induced laser processing, but also creates high quality micro channels using plasma-induced processing. The channel surface processed by thermal-induced cutting is rough, while the surface processed by the plasma-induced cutting is smooth. Process characterization was presented in this paper in terms of the effects of laser drilling pattern on the diameter and quality of the fabricated micro channels. The application of these micro channels to fluidic devices is being investigated. This new technology will enable flexible and fast fabrication of various kinds of 3D micro fluidic systems such as micro mixers, micro pumps, capillary electrophoresis (CE) systems, and micro total analyses systems (μTAS), and lead to new applications of MEMS in biomedical engineering.

References

[1] T. Kikuchi, T. Ujiie, T. Ichiki, Y. Horiike, Fabrication of quartz micro-capillary electrophoresis chips for health care devices, in: Proceedings of the International Conference on Microprocesses and Nanotechnology'99, 1999, pp. 178–179.

[2] H. Nakanishi, T. Nishimoto, N. Nakamura, S. Nagamachi, A. Arai, Y. Iwata, Y. Mito, Fabrication of electrophoresis devices on quartz and glass substrates using a bonding with HF solution, in: Proceedings of the IEEE, 10th Annual International Workshop on Micro Electro Mechanical Systems, MEMS'97, 1997, pp. 299–304.

[3] G. Chryssolouris, Laser Machining: Theory and Practice, Springer, New York, 1991, p. 52, 163.

[4] J. Zhang, K. Sugioka, K. Midorikawa, High-quality and high-efficiency machining of glass materials by laser-induced plasma-assisted ablation using conventional nanosecond UV, visible, and infrared lasers, Appl. Phys. A 69 (1999) s879–s882.

[5] H. Varel, D. Ashkenasi, A. Rosenfeld, M. Wahmer, E.E.B. Campbell, Micromachining of quartz with ultrashort laser pulses, Appl. Phys. A 65 (1997) 367–373.

[6] S.J. Qin, W.J. Li, Fabrication of complex micro channel systems inside optically transparent 3D substrates by laser processing, in: Proceedings

of the 11th International Conference on Solid-State Sensors and Actuators, Transducers'01, Munich, Germany, June 10–14, 2001.
[7] S.J. Qin, W.J. Li, Micromachining of complex channel systems in 3D quartz substrates using Q-switched Nd:YAG laser, Appl. Phys. A (2001), in press.
[8] C.J. Nonhof, Material Processing with Nd-Lasers, Electrochemical Publications, Ayr, Scotland, 1988, pp. 246–251.
[9] A. Rubenchik, S. Witkowski, Physics of Laser Plasma, North-Holland, Amsterdam, 1991, pp. 64–65.

Biographies

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Wen J. Li received his BS and MS degrees in Aerospace Engineering from USC in 1987 and 1989, respectively. His industrial experience includes The Aerospace Corporation (El Segundo, California), Silicon Microstructures Inc. (Fremont, California), and the NASA/CalTech Jet Propulsion Laboratory (Pasadena, California). He began his PhD studies at UCLA in 1992, and received his PhD degree in 1997 specializing in MEMS. Prof. Li joined the Faculty of the Department of Automation and Computer-Aided Engineering of the Chinese University of Hong Kong (CUHK) in September 1997. He has since then published over 60 papers related to MEMS research, and gave a workshop on *Microsensors and Microactuators for Robotics Applications* at the IEEE/RJS IROS (Kagawa, Japan) in November 2000. He has also helped in organizing several international conferences related to MEMS and robotics research and was the Chair of Organization Committee of the International Symposium on Smart Structures and Microsystems 2000. Prof. Li is also a Visiting Scholar of Chongqin University, China, and a Visiting Professor of Fuzhou University, China. Prof. Li is currently serving as the Director of the Center for Micro and Nano Systems at CUHK. His research interest is to develop micro and nano systems for information technology and cell/protein/DNA manipulations.