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Fabrication of three-dimensional microchannels inside silicon using a femtosecond laser

Cunxia Li, Tao Chen, Jinhai Si, Feng Chen, Xu Shi and Xun Hou

Key Laboratory for Physical Electronics and Devices of the Ministry of Education, Shannxi Key Lab of Information Photonic Technique, School of Electronics and Information Engineering, Xi'an Jiaotong University, Xianning-xilu 28, Xi'an, 710049, People's Republic of China

E-mail: jinhaisi@mail.xjtu.edu.cn and chenfeng@mail.xjtu.edu.cn

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Abstract
We report on photo-induced microchannels created within single-crystal silicon using 800 nm femtosecond laser pulses. The 800 nm wavelength is in the absorption region of silicon. Using combined transverse scanning and longitudinal scanning, we can fabricate arbitrary three-dimensional microchannels in the interior of silicon, to a depth of several hundred micrometers, without surface damage. The diameter of the photo-induced microchannels can be controlled by varying laser power, scan velocity and focal depth.

1. Introduction

Femtosecond laser micromachining has attracted much attention due to its ability to create three-dimensional (3D) micromachining inside transparent materials [1–4]. Many researchers have studied machining microchannels in transparent materials using femtosecond laser pulses [5–7]. However, there are few reports on fabrication of 3D microchannels inside absorptive materials, such as silicon, using femtosecond laser pulses. Silicon is a strong absorber with optical opacity in the near-infrared and visible light regions, which makes it difficult to create and observe microstructures in the interior of silicon. Nejadmalayeri *et al* (2005) reported a buried waveguide in silicon using a femtosecond laser at 2.4 μm, which extended the ultrafast 3D modification technique to silicon [8]. Recently, we demonstrated photo-induced microstructures in silicon using an 800 nm femtosecond laser, which showed the possibility of 3D fabrication inside silicon using this technique [9].

In this paper, we present experimental fabrication of microchannels inside silicon using an 800 nm femtosecond laser. Using a high-numerical aperture (NA) microscope objective, multilayer microchannels were fabricated, and no damage was observed on the silicon surface and around the buried microchannels. The microchannels were fabricated using transverse scanning and longitudinal scanning, which were perpendicular and parallel to the laser beam, respectively. Our experimental results show that true 3D microchannels can be fabricated inside silicon samples by using a femtosecond laser and a high-NA microscope objective. We also investigated the dependence of the diameter of microchannels on the laser power, scan velocity and laser focal depth.

2. Experiments

The thickness of silicon samples used in the experiment is 300 μm. A regeneratively amplified Ti: sapphire laser system was used, which delivered pulses with a duration of 30 fs, center wavelength at 800 nm, repetition rate of 1 kHz and pulse energy of 1 mJ. The laser beam was focused inside the silicon sample using microscope objectives with NA of 0.3, 0.45 and 0.9. The energy of the incident pulses could be continuously varied using a variable attenuator. A mechanical shutter was employed to blank the pulsed laser beam. The silicon sample was mounted on a computer controlled 3D translation stage with a step resolution of 0.04 μm in x, y and z.

Figure 1 shows the schematic setup for the fabrication of microchannels inside silicon. The femtosecond laser was focused inside the silicon sample with one of the high-NA microscope objectives. The microchannels were fabricated with either transverse scanning or longitudinal scanning, which were perpendicular and parallel to the laser beam, respectively. The silicon was then cross-sectioned by cleaving and polishing in the zy plane to expose the buried channels,

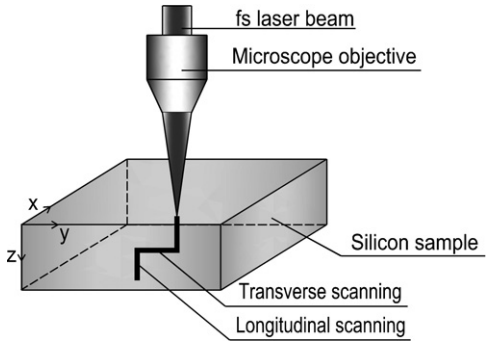

Figure 1. Schematic of the setup for fabrication of microchannels inside silicon sample.

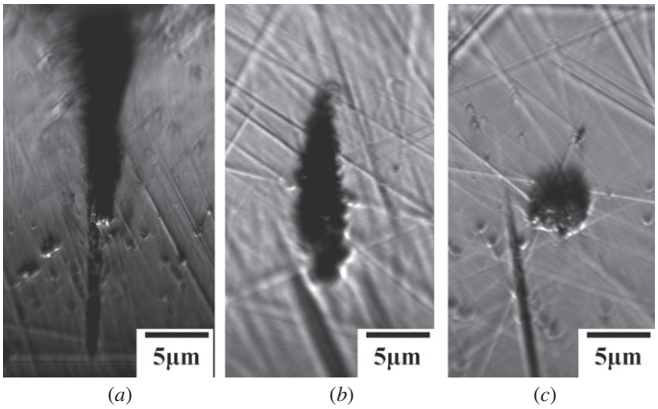

Figure 2. Cross-sectioned views of microchannels fabricated using transverse scanning. The NA of the microscope objectives were (*a*) 0.3, (*b*) 0.45 and (*c*) 0.9, respectively. Laser average power was set at 4 mW and laser scan velocity was set at 25 μm s^{-1}. The laser focal position was set at 100 μm below the silicon surface.

and then cleaned with alcohol. We observed the exposed microchannels on the polished surface through an optical microscope with a 50× microscope objective using a CCD camera.

3. Results and discussions

First, we fabricated microchannels inside the silicon sample by employing the three different NA microscope objectives with a laser power of 4.0 mW and a scan velocity of 25 μm s^{-1}. The laser beam was focused at a depth of 100 μm beneath the silicon surface. Figures 2(*a*), (*b*) and (*c*) show optical micrographs of the resulting microstructures inside the silicon sample after exposure by polishing. From figure 2, we observed a transition with increasing NA from damage in a wide area inside silicon at NA = 0.3 to a microchannel with circular cross section at NA = 0.9. For NA = 0.3, damage on the original surface of the silicon sample was observed and the microchannel had triangular cross section, as shown in figure 2(*a*). For NA = 0.45, an elliptic microchannel was obtained, as shown in figure 2(*b*). For NA = 0.9, the microchannel showed a nearly circular cross section as in figure 2(*c*), and no damage was observed on the original silicon surface or around the cross-sectioned microchannel.

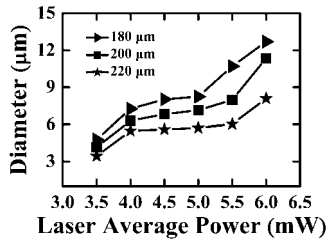

Figure 3. Microchannel diameter versus laser average power. The laser focal depth was set at 180 μm, 200 μm and 220 μm, respectively.

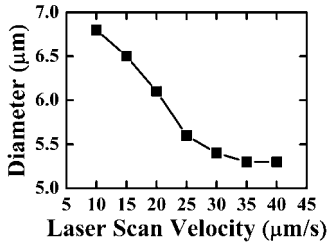

Figure 4. Microchannel diameter versus laser scan velocity.

The changes in the cross-sectional microchannel shape with increasing NA can be attributed to the distribution versus depth of the spatial intensity of the femtosecond laser beam focused by microscope objectives with different NA. It is clear that using a higher NA microscope objective can improve the circularity of the microchannel, which is consistent with the results for photo-induced machining of the transparent glass material [10, 11].

Next, we investigated the dependence of the diameter of the microchannels on the laser power at different focal depths, which is the distance of the laser focal point beneath the silicon surface. As shown in figure 3, the diameter of microchannels increased with increasing laser power, and decreased with increasing laser focal depth. Here, the laser focal depth was set at 180 μm, 200 μm and 220 μm, respectively, and the laser scan velocity was set at 25 μm s^{-1}. The 0.9 NA microscope objective was used. The dependence of the microchannel diameter on focal depth is attributed to light absorption by silicon at the 800 nm wavelength. When the focal depth increases, the laser path length increases and more energy is absorbed before the focal depth is reached, so that energy deposited at the focal depth decreases.

In addition, we studied the formation of microchannels by changing the laser scan velocity when a 0.9 NA microscope objective was used. As shown in figure 4, the diameter of microchannels decreased with increasing scan velocity from 10 μm s^{-1} to 40 μm s^{-1} when the laser focal depth and the average power were set at 200 μm and 4.0 mW, respectively. This makes intuitive sense because slower scan velocities cause higher power deposition per unit volume, which should cause channel diameter to increase.

Starting from the experimental results described above, we also fabricated multilayer microchannels using transverse scanning. We first focused the laser beam using a 0.9 NA microscope objective at the depth of 220 μm away from the

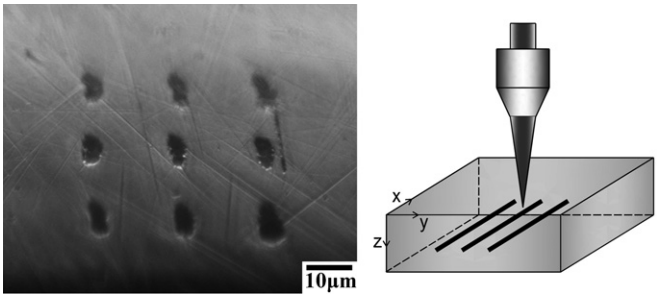

Figure 5. Cross-section view of three layers of microchannels fabricated using transverse scanning. The depth difference between adjacent layers is 20 μm.

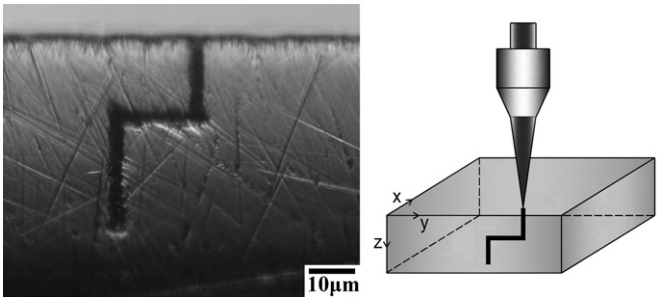

Figure 6. Cross-section view of microchannels fabricated using combined longitudinal scanning and transverse scanning. The laser average power was set at 4.0 mW and the laser scan velocity was 25 μm s^{-1}.

silicon surface and moved the sample perpendicularly to the laser beam to fabricate a first layer of microchannels, and then we decreased the laser power and the laser focal depth to fabricate a second and a third layer of microchannels also using transverse scanning. The three layers of microchannels were fabricated at depths of 220, 200 and 180 μm beneath the silicon surface, when the laser power was set at 4.0 mW, 3.8 mW and 3.6 mW, respectively, and the laser scan velocity was kept at 25 μm s^{-1}. The selection of laser power for the three different focal depths was based on figure 3. Figure 5 shows a cross section micrograph through the resulting microchannels obtained by polishing. From figure 5, we can see that the diameters of the microchannels are about 5 μm, and the cross sections of the microchannels are close to a circular shape. Except for the microchannels themselves, no photo-induced damage appeared between layers.

Finally, we fabricated microchannels by combining longitudinal scanning and transverse scanning. We first focused the laser beam inside the silicon sample using the 0.9-NA microscope objective and translated the silicon sample along the z direction step by step. By scanning the focal point at a constant speed toward the entrance surface, a first microchannel was fabricated by longitudinal scanning. After that, the sample was moved along the y direction to form a second microchannel by transverse scanning. Then, we repeated the longitudinal scanning process until the focal point reached the silicon surface, forming a third microchannel. Figure 6 shows a cross section micrograph through the three resulting microchannels. From figure 6, we can see that the three microchannels have good continuity where they join one another and along their lengths.

According to the results described above, using combining longitudinal scanning and transverse scanning, we can fabricate arbitrary 3D microchannels in the interior of silicon using an 800 nm femtosecond pulsed laser. It should be noted that 3D microchannels can only be fabricated to a depth of several hundred micrometers from the silicon surface because of the strong absorption of silicon at 800 nm wavelength. In our experiments, the maximum depth to which a microchannel can be fabricated in silicon was about 300 μm by choosing suitable laser power and laser scan velocity. To fabricate deeper 3D microchannels inside silicon, an infrared femtosecond laser of longer wavelength, at which silicon is transparent, should be used [8].

The formation of the microchannels is believed to be the result of micro-explosions [12–14]. The laser pulses create a high-density electronic plasma in the focal volume, which transfers its excess energy to the silicon lattice. The focal volume is thus heated to a high temperature. The rise in temperature at a constant volume causes immense pressures which force material from the center of the explosion outward. During cooling, the material does not anneal and a denser phase is frozen into the microchannel walls, forming a cavity surrounded by a higher density layer and leaving some debris in the microchannels.

4. Conclusion

Multilayer microchannels were fabricated inside silicon samples using an 800 nm femtosecond pulsed laser, the wavelength of which is in the absorption region of silicon. Using combined transverse scanning and longitudinal scanning, we can fabricate arbitrary 3D microchannels in the interior of silicon to a depth of several hundred micrometers. We expect that this femtosecond laser micromachining technique can be used for the fabrication of silicon microchannel plates [15] and silicon microchannel heat exchangers [16, 17].

Acknowledgments

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References

[1] Matsuo S, Kiyama S, Shichijo Y, Tomita T, Hashimoto S, Hosokawa Y and Masuhara H 2008 Laser microfabrication and rotation of ship-in-a-bottle optical rotators *Appl. Phys. Lett.* **93** 051107

[2] Kanehira S, Si J, Qiu J, Fujita K and Hirao K 2005 Periodic nanovoid structures via femtosecond laser irradiation *Nano Lett.* **5** 1591–5

[3] Saliminia A, Nguyen N T, Chin S L and Vallée R 2006 Densification of silica glass induced by 0.8 and 1.5 μm intense femtosecond laser pulses *J. Appl. Phys.* **99** 093104

[4] Dai Y, Zhu B, Qiu J, Ma H, Lu B, Cao S and Yu B 2007 Direct writing three-dimensional $Ba_2TiSi_2O_8$ crystalline pattern in glass with ultrashort pulse laser *Appl. Phys. Lett.* **90** 181109

[5] Marcinkevičius A, Juodkazis S, Watanabe M, Miwa M, Matsuo S, Misawa H and Nishii J 2001 Femtosecond laser-assisted three-dimensional microfabrication in silica *Opt. Lett.* **26** 277–9

[6] Masuda M, Sugioka K, Cheng Y, Aoki N, Kawachi M, Shihoyama K, Toyoda K, Helvajian H and Midorikawa K 2003 3-D microstructuring inside photosensitive glass by femtosecond laser excitation *Appl. Phys* A **76** 857–60

[7] Li Y, Itoh K, Watanabe W, Yamada K, Kuroda D, Nishii J and Jiang Y 2001 Three-dimensional hole drilling of silica glass from the rear surface with femtosecond laser pulses *Opt. Lett.* **26** 1912–4

[8] Nejadmalayeri A H, Herman P R, Burghoff J, Will M, Nolte S and Tünnermann A 2005 Inscription of optical waveguides in crystalline silicon by mid-infrared femtosecond laser pulses *Opt. Lett.* **30** 964–6

[9] Chen T, Si J, Hou X, Kanehira S, Miura K and Hirao K 2008 Photoinduced microchannels inside silicon by femtosecond pulses *Appl. Phys. Lett.* **93** 051112

[10] Cheng Y, Sugioka K, Midorikawa K, Masuda M, Toyoda K, Kawachi M and Shihoyama K 2003 Control of the cross-sectional shape of a hollow microchannel embedded in photostructurable glass by use of a femtosecond laser *Opt. Lett.* **28** 55–7

[11] Maselli V, Osellame R, Cerullo G, Ramponi R, Laporta P, Magagnin L and Cavallotti P L 2006 Fabrication of long microchannels with circular cross section using astigmatically shaped femtosecond laser pulses and chemical etching *Appl. Phys. Lett.* **88** 191107

[12] Glezer E N and Mazur E 1997 Ultrafast-laser driven micro-explosions in transparent materials *Appl. Phys. Lett.* **71** 882–4

[13] Juodkazis S, Nishimura K, Tanaka S, Misawa H, Gamaly E G, Luther-Davies B, Hallo L, Nicolai P and Tikhonchuk V T 2006 Laser-induced microexplosion confined in the bulk of a sapphire crystal: evidence of multimegabar pressures *Phys. Rev. Lett.* **96** 166101

[14] Juodkazis S, Misawa H, Hashimoto T, Gamaly E G and Luther-Davies B 2006 Laser-induced microexplosion confined in a bulk of silica: formation of nanovoids *Appl. Phys. Lett.* **88** 201909

[15] Chen X, Lin J, Yuan D, Ci P, Xin P, Xu S and Wang L 2008 Obtaining a high area ratio free-standing silicon microchannel plate via a modified electrochemical procedure *J. Micromech. Microeng.* **18** 037003

[16] Colgan E G, Furman B, Gaynes M, LaBianca N, Magerlein J H, Polastre R, Bezama R, Marston K and Schmidt R 2007 High performance and subambient silicon microchannel cooling *J. Heat Transfer* **129** 1046–51

[17] Agostini B, Fabbri M, Park J E, Wojtan L, Thome J R and Michel B 2007 State of the art of high heat flux cooling technologies *Heat Transfer Eng.* **28** 258–81