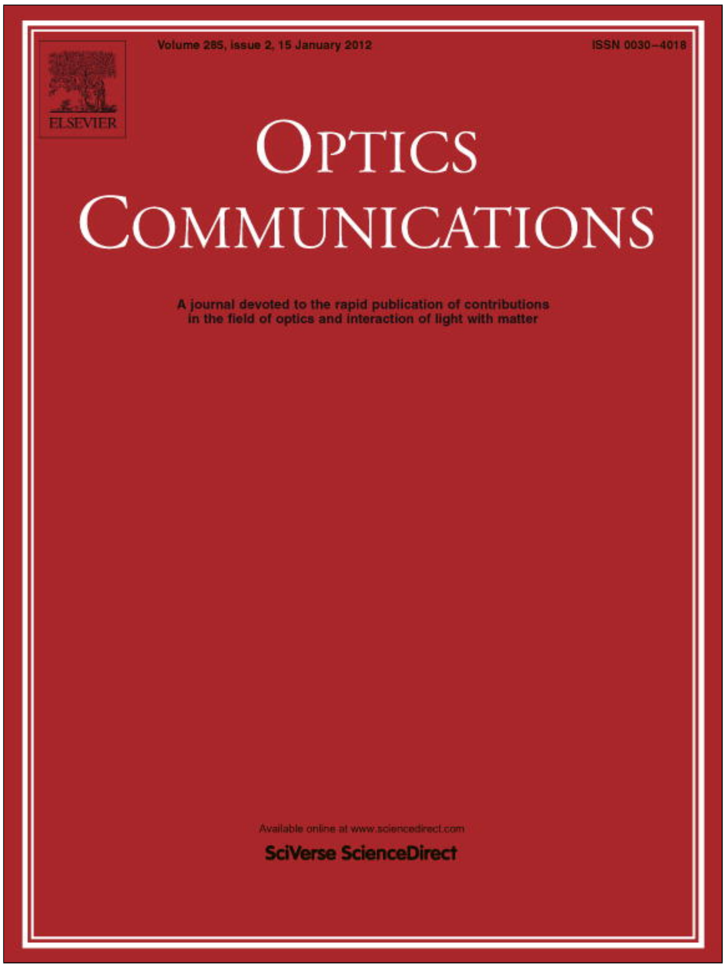

Volume 285, issue 2, 15 January 2012
ISSN 0030-4018

OPTICS COMMUNICATIONS

A journal devoted to the rapid publication of contributions
in the field of optics and interaction of light with matter

Optics Communications 285 (2012) 140–142

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Photoinduced microchannels and element change inside silicon by femtosecond laser pulses

Yuncan Ma, Haitao Shi, Jinhai Si *, Tao Chen, Fei Yan, Feng Chen, Xun Hou

Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Shaanxi Key Laboratory of Information Photonic Technique, School of Electronics and Information Engineering, Xi'an Jiaotong University, Xianning West Road 28, Xi'an 710049, PR China

ARTICLE INFO

Article history:
Received 17 May 2011
Received in revised form 4 August 2011
Accepted 10 September 2011
Available online 23 September 2011

Keywords:
Microchannels
Element change
Silicon
Femtosecond laser

ABSTRACT

Microchannels are fabricated inside silicon along the direction of laser beam by a femtosecond laser at 800 nm, which is located at the absorption region of silicon. Formation mechanism of the microchannels is attributed to spherical aberration. The element change in surrounding of the microchannel is characterized, and results show that oxygen is incorporated into silicon after irradiation. The origin of the oxygen incorporation and the laser intensity dependence of the amount of oxygen are discussed, respectively.

1. Introduction

Silicon, which plays important roles in the semiconductor industry, has a large amount of potential applications in silicon-based optoelectronic devices and micro-electromechanical systems. As a powerful technique of material processing, the interaction of femtosecond laser pulses with materials has attracted increasingly more attention during recent years [1–4]. Femtosecond laser induced microstructures on silicon surface have been widely investigated in different environments, such as water, alcohol, vacuum and various kinds of gases [5–10]. Researchers also produced surface wave structures on flat silicon surface using a single-shot femtosecond laser pulse [11]. However, the majority of studies on the microfabrication of silicon using femtosecond laser were conducted on the surface, there have been few reports on the microstructures fabricated in the interior of silicon, which is probably because silicon is opaque to the 800 nm laser light provided by most femtosecond laser amplifiers, or the microstructures produced inside silicon could not be easily observed as those in transparent materials. Recently, we presented the fabrication of single and periodically aligned microchannels in the interior of silicon using 800 nm femtosecond laser pulses [12,13]. However, up to now, we have no knowledge of the chemical elements in surrounding of the microchannels fabricated inside silicon.

In this paper, we demonstrate the fabrication of microchannels in the interior of silicon with a femtosecond laser at the wavelength of 800 nm, which is located at the absorption region of silicon. The formation of microchannels inside silicon could be attributed to the spherical aberration which resulted from the mismatch of refractive-index when a tightly focused femtosecond laser propagated through the interface of two different materials. According to the energy dispersive X-ray spectroscopy (EDS) analysis, oxygen was found in the irradiated regions inside the silicon wafer besides silicon. We propose that oxygen was trapped by the dangling bonds which formed in the process of femtosecond laser pulses irradiating the silicon wafer. Furthermore, the atomic percentage of the oxygen decreased with the increase of the distance between the irradiated regions and the entrance surface in the longitudinal direction, and in the transverse direction the atomic percentage of oxygen reached to its maximum value at the center of the irradiating beam.

2. Experiments

The experiment was carried out by using a Ti:sapphire amplifier system (FEMTOPOWER Compact Pro, Austria), which delivered femtosecond laser pulses at the central wavelength of 800 nm, the duration time of 30 fs, with the repetition rate of 1 kHz. The average power of the incident laser pulses could be continuously changed by rotating a variable neutral density filter, and the access of the laser pulses was controlled via a mechanical shutter. Fig. 1 shows the schematic illustration for the fabrication of the microchannels. The silicon wafer with a thickness of 300 μm, was primarily rinsed with absolute alcohol in an ultrasonic cleaner for about 15 min, then mounted horizontally on a computer-controlled three-dimensional translating stage with a resolution of 40 nm at *x*, *y* and *z* axis. A 20× microscope objective with the numerical aperture (NA) of 0.45 was employed to focus the

---

* Corresponding author. Tel.: +86 29 82663485.
E-mail address: jinhaisi@mail.xjtu.edu.cn (J. Si).

0030-4018/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2011.09.024

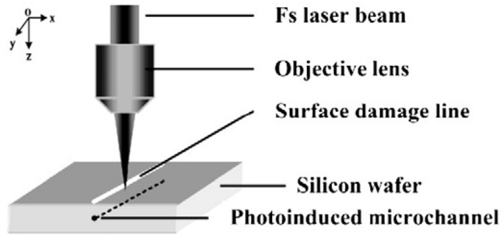

Fig. 1. Schematic illustration for the fabrication of the microchannel.

femtosecond laser beam below the surface of the silicon wafer. The scanning direction was set parallel to *y* axis.

After irradiating with the femtosecond laser pulses, surface damage lines could be observed clearly on the surface of the silicon wafer via a CCD camera. The irradiated silicon wafer was polished with waterproof abrasive paper along the cross section (means the *xoz* plane) which was perpendicular to the scanning direction (means the *y* axis direction) to a random position. After that, the wafer was rinsed with absolute alcohol and de-ionized water for about 15 min, respectively. Finally, the induced microchannels and element change were characterized by SEM equipped with EDS (JEOL JSM-6390A series).

3. Results and discussion

The laser power and the scanning velocity were selected appropriately not to cause vaporization or splash of the molten silicon, after a few trials, the former was set at 4.50 mW, while the latter was set at 15 μm/s. The fluence of the incident laser was estimated to 5.73 J/cm^2, which exceeded the reported melting threshold [14]. The silicon wafer was polished along the cross section to a random position to observe the induced microchannels, which means the continuity of the microchannels is well.

Fig. 2 illustrates the SEM morphology of the induced microchannel inside the silicon wafer. We can see from Fig. 2 that a microchannel with the diameter of about 1 μm was fabricated at the depth of about 40 μm below the entrance surface. Moreover, there is a gray area between the microchannel and the entrance surface, indicating that there may be some changes in these regions. We contribute the formation of the microchannels to the spherical aberration which resulted from the mismatch of refractive-index when a tightly focused laser beam propagated through the interface of two different materials [12,15]. In our experiment, the laser was focused by a microscope objective through the air-silicon interface into the silicon sample, due to the refractive-index mismatch of these two different materials, the spherical aberration made very elongated shape even inside strongly absorbing substance. According to the exited calculated axial intensity distribution of the laser irradiation through an interface of two different materials [15], there were several hot spots in the sub-surface regions of the sample, the energy at one of the hot spots exceeded the melting threshold of the silicon material. The instantaneous rise of energy at a constant region caused immense pressures, and the pressures pushed the material from the center to the peripheral regions, leaving the area of the hot spot to form a microchannel surrounding with some denser materials. In addition, when femtosecond laser irradiated the silicon wafer, self-focusing due to the nonlinear Kerr effect may occur, which may play a role in the formation of the microchannel [4, 12].

To investigate whether the element of the irradiated silicon changed or not, we measured the elements of the irradiated regions with EDS. The polished silicon wafer was immersed in an ultrasonic cleaner with absolute alcohol and de-ionized water for about 15 min respectively, for removing the influence of the residual debris. The EDS analysis was conducted at three different positions as marked out in Fig. 2: (1) the laser propagation direction along the longitudinal direction, as shown in Fig. 2(a); (2) the surrounding area of the microchannel along the transverse direction, as shown in Fig. 2(b); (3) the half depth of the microchannel along the transverse direction, as shown in Fig. 2(c). Meanwhile, the depth of the EDS analysis in (1) was about 40 μm below the entrance surface, while the width of that in (2) and (3) was about 4 μm and 16 μm from the center of the irradiated regions to the periphery, respectively.

In the process of the EDS analysis, the element of the polished regions which were not irradiated by the laser was primarily measured, results showed that the element was silicon only. As for the polished irradiated regions, the element was not just silicon any longer, additional oxygen was observed. Oxygen was not observed in the cross section besides the irradiated regions, which confirmed that the SiO$_2$ micro-grain in the abrasive paper did not influence the results of the measurement. We speculate that the oxygen was incorporated into the interior of silicon wafer under the irradiation of the laser. When the silicon wafer was irradiated by the laser, there would be some defects formed inside silicon, the crystalline silicon would transform to amorphous silicon [16–18]. The dangling bonds in the laser induced amorphous silicon have the capacity of trapping oxygen. What's more, the wavelength of 800 nm was located in the absorption region of silicon, under the irradiation of the laser pulses, the instantaneous accumulation of the laser energy made the local temperature of silicon rise, which consequently enhanced the diffusion of oxygen into silicon.

Furthermore, the atomic percentage of the oxygen at the three positions are illustrated in Figs. 3 and 4 respectively. We can see from Fig. 3 (the measured points are point A to point F, as shown in Fig. 2 (a)) that the atomic percentage of the oxygen decreases with the increase of the propagating depth in the longitudinal direction, which is parallel to the *z* axis. As discussed above, the dangling bonds in the laser induced amorphous silicon have the capacity of trapping oxygen species, therefore, the density of the dangling bonds and the diffused

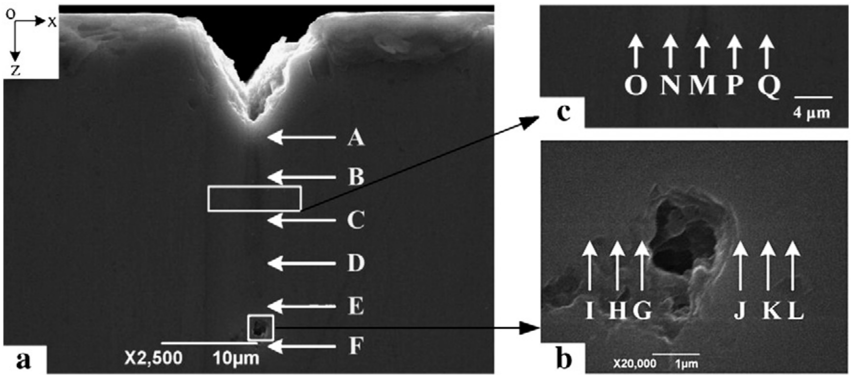

Fig. 2. SEM morphology of the induced microchannel inside the silicon wafer. The points marked out in the three pictures were the regions which we analyzed the element of the irradiated silicon. The laser power and the scanning velocity were set at 4.50 mW and 15 μm/s, respectively.

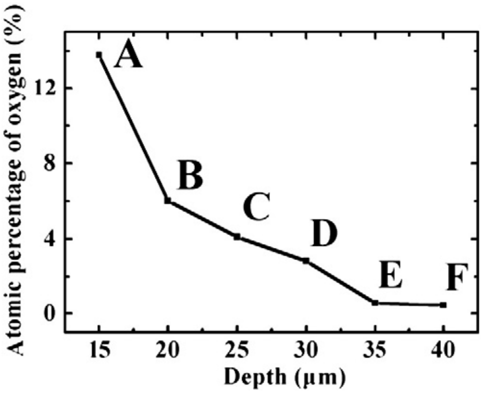

Fig. 3. Atomic percentage of the oxygen species in different regions of the irradiated silicon in the longitudinal direction, which is parallel to the propagating direction of the laser beam.

oxygen directly influence the atomic percentage of the oxygen incorporated into the interior of the silicon wafer. The density of the defects and the laser induced amorphous silicon in the crystalline silicon may be proportional to the laser energy density delivered inside the silicon material, meanwhile, as the laser we used is located at the absorption of silicon, the laser energy density and the laser induced temperature rise will decrease with the increase of the propagation depth. Therefore, the density of the dangling bonds and the amount of the diffused oxygen decrease as the depth increases. On the basis of the reasons described above, the atomic percentage of the oxygen decreases with the increasing of propagation depth.

We also measured the atomic percentage of oxygen at these regions (point G to point L) along the transverse direction as shown in Fig. 2(b). Fig. 4(a) shows the element change of oxygen, which crossed the center of the photoinduced microchannel along the transverse direction. We can see that the atomic percentage of oxygen decreases from the edge of the induced microchannel to the periphery regions in the transverse direction. Furthermore, we also measured the elements of the irradiated silicon at the half depth of the microchannel along the transverse direction (which is parallel to the *x* axis) as shown in Fig. 2(c) (point M to point Q), the results are shown in Fig. 4(b), which shows the same tendency with that in Fig. 4(a) and the atomic percentage of oxygen reaches to its maximum value at the center of the irradiated regions in the transverse direction. These atomic percentage distributions could also be attributed to the speculation that the laser induced dangling bonds and the amount of the diffused oxygen depend on the intensity of the incident laser. As the intensity of the laser decreases from the center to the periphery region, the amount of the dangling bonds and the diffused oxygen decreases consequently, and the oxygen incorporated into silicon decreases.

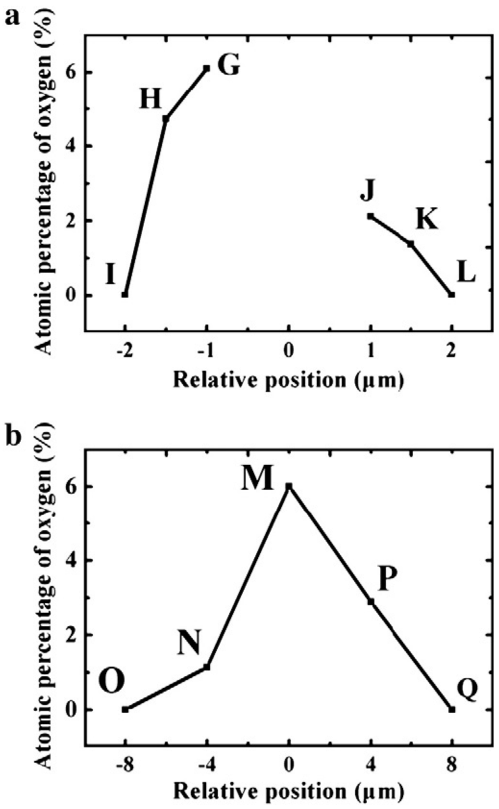

Fig. 4. Atomic percentage of the oxygen species in the transverse direction: (a) in surrounding of the induced microchannel and (b) at half depth of the microchannel.

4. Conclusions

As conclusion, microchannels were fabricated inside the silicon wafer, the depth and diameter of which were about 40 μm and 1 μm, respectively. The formation of the microchannels could be attributed to the spherical aberration results from the mismatch of the refractive index. Furthermore, the element of silicon wafer changed after the irradiation of the femtosecond laser pulses. The incorporation of oxygen into silicon probably resulted from the trapping of laser induced dangling bonds. And the atomic percentage of the oxygen decreases with the increase of the distance between the irradiated regions and the entrance surface in the longitudinal direction, and also decreases from the center to the surrounding area in the transverse direction. This could be attributed to the speculation that the amount of the dangling bonds and the diffused oxygen depend on the intensity of the laser.

Acknowledgements

The authors gratefully acknowledge the financial support for this work provided by the National Science Foundation of China under the Grant Nos. 11074197 and 91123028, and the National Key Scientific Research Foundation of China under the Grant No. 2012CB921800.

References

[1] S. Juodkazis, H. Misawa, T. Hashimoto, E.G. Gamaly, B. Luther-Davies, Appl. Phys. Lett. 88 (2006) 201909.
[2] T. Kondo, S. Matsuo, S. Juodkazis, V. Mizeikis, H. Misawa, Appl. Phys. Lett. 82 (2003) 17.
[3] S. Juodkazis, K. Nishimura, S. Tanaka, H. Misawa, E.G. Gamaly, B. Luther-Davies, L. Hallo, P. Nicolai, V.T. Tikhonchuk, Phys. Rev. Lett. 96 (2006) 166101.
[4] M. Malinauskas, A. Zukauskas, G. Bickauskaite, R. Gadonas, S. Juodkazis, Opt. Express 18 (2010) 10.
[5] M.Y. Shen, C.H. Crouch, J.E. Carey, E. Mazur, Appl. Phys. Lett. 85 (2004) 5694.
[6] S. Amoruso, R. Bruzzese, N. Spinelli, R. Velotta, M. Vitiello, X. Wang, Appl. Phys. Lett. 84 (2004) 4502.
[7] A. Djemaa, N. Gabouze, C. Yaddadene, Y. Belaroussi, T. Kerdja, M. Kechouanec, H. Menari, A.Y. Khereddine, Surf. Interface Anal. 42 (2010) 1295.
[8] C. Wu, C.H. Crouch, L. Zhao, E. Mazur, Appl. Phys. Lett. 81 (2002) 1999.
[9] H. Liu, F. Chen, X. Wang, Q. Yang, H. Bian, J. Si, X. Hou, Thin Solid Films 518 (2010) 5188.
[10] T. Her, R.J. Finlay, C. Wu, S. Deliwala, E. Mazur, Appl. Phys. Lett. 73 (1998) 1673.
[11] T. Tomita, Y. Fukumori, K. Kinoshita, S. Matsuo, S. Hashimoto, Appl. Phys. Lett. 92 (2008) 013104.
[12] C. Li, X. Shi, J. Si, F. Chen, T. Chen, Y. Zhang, X. Hou, Appl. Phys. B 98 (2010) 377.
[13] T. Chen, J. Si, X. Hou, S. Kanehira, K. Miura, K. Hirao, Appl. Phys. Lett. 93 (2008) 051112.
[14] J. Bonse, S. Baudach, J. Krüger, W. Kautek, M. Lenzner, Appl. Phys. A 74 (2002) 19.
[15] A. Marcinkevičius, V. Mizeikis, S. Juodkazis, S. Matsuo, H. Misawa, Appl. Phys. A 76 (2003) 257.
[16] T. Kudrius, G. Slekys, S. Juodkazis, J. Phys. D: Appl. Phys. 43 (2010) 145501.
[17] Y. Izawa, Y. Izawa, Y. Setsuhara, M. Hashida, M. Fujita, R. Sasaki, H. Nagai, M. Yoshida, Appl. Phys. Lett. 90 (2007) 044107.
[18] T.H.R. Crawford, J. Yamanaka, G.A. Botton, H.K. Haugen, J. Appl. Phys. 103 (2008) 053104.