Journal of Materials Processing Technology 227 (2016) 200–215

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

A study on co-axial water-jet assisted fiber laser grooving of silicon

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ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 5 August 2015
Accepted 13 August 2015
Available online 18 August 2015

Keywords:
Fiber laser
Grooving
Micro-machining
Silicon
Water-jet assisted

ABSTRACT

Potential of fiber laser grooving in silicon has been investigated with continuous wave beam and modulated beam of micro-second durations. Though silicon shows considerably high transparency for the utilized laser wavelength (1.07 μm), due to the increase of absorption coefficient with temperature its micro-machining is feasible with good precision by laser. A co-axial water-jet has been employed for ejecting out the molten silicon effectively and simultaneously for rapid cooling. This in turn, overcomes the limitation of micro-machining of silicon with laser pulses of relatively longer durations and alleviates the oxidation problem also. It has been observed that with increasing water-jet speed at constant laser parameters, spatter and recast are reduced. Grooves of controlled depth in 14–520 μm range, free from micro-cracks and thermal damage could be obtained by controlling the laser and process parameters. Compared to argon-jet assisted laser grooving this technique produced grooves of relatively better quality in terms of lesser micro-cracks, spatter and thermal damage.

1. Introduction

Silicon, a brittle semiconductor material has always been in the interest of researchers due to its many applications in various fields, such as in electronics instruments (Scotti et al., 2013), medical devices (Miller et al., 2009), micro-fluidics (Malek 2006), solar cells (Dobrzanski et al., 2008) etc. This needs to be machined, viz., cut, polished, scribed, drilled, and grooved for its various usages. Though micromachining of silicon has been investigated extensively, it has remained as a technological challenge because of its brittle nature. The conventional methods of micromachining such as reactive ion etching (Fukui et al., 1997), wet chemical etching using acids (Panek et al., 2005), and mechanical processes (Fath et al., 1995) are difficult to control. First two processes are difficult to use because of its dependency on crystallographic orientation, non-uniform material removal, long processing time and requirement of hazardous chemical etchants. Mechanical machining process too suffers from many disadvantages like non-uniform material removal and generation of micro-cracks due to brittle fracture.

The laser micromachining is a very promising technique for machining silicon. Various approaches of using lasers to get damage-free micromachining of silicon have been reported in literatures in last four decades. The types of laser employed by various researchers, mode of their operation and additional processes employed during or after lasing are presented in Table 1. This also contains a broad range of recommended applications. It is seen that the required depth, width and shape of grooves change according to applications. However, many of these applications cannot accept common defects like micro-cracks, spatter and recast of ejected/molten silicon in and around grooves. With the development of ultraviolet (UV) wavelength lasers and owing to their high absorption in silicon, their application in micromachining of silicon has become popular. More recently, short pulse duration lasers are proving to be very effective even at near infrared (NIR) wavelengths region. At high intensities, typically produced by short duration laser pulses the laser energy is efficiently absorbed in a small volume through the nonlinear absorption process. This causes high temperature rise in a very short duration causing fast ablation of material. This in turn, enhances the recoil pressure, and the material removal mechanism may become completely mechanical (Steen and Mazumder, 2010). However, material damage can not be completely avoided and often some additional processes during or after laser machining are needed to be employed for minimizing/eliminating the damage, Table 1.

Laser ablation is a mask-less micro fabrication process for scribing, grooving and direct writing patterns. The multiple scans are often required to scribe up to a desired depth in silicon. Re-deposition of ablated silicon near the sidewalls can not be usually eliminated completely, and this could be a serious drawback for applications where a rigid material is bonded (Scotti et al., 2013).

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http://dx.doi.org/10.1016/j.jmatprotec.2015.08.013
0924-0136/

Table 1
Laser grooving and texturing of silicon, recommended applications, and depth requirements reported in literature.

S. no.	Laser used & lasing parameters	Silicon used	Additional approach (During or after laser irradiation)	Remarks & recommended applications	Ref.
1.	Diode pumped 3rd harmonic pulsed Nd:YAG laser, λ-355 nm, nanosecond pulses RR-10–50 kHz	<100> wafer t-533 μm	After laser machining etching in 20% KOH solution at 70 °C	Ablation depth ~5–90 μm; Micro-fluidics, semiconductor electro-tumescent devices	Chen and Darling (2005)
2.	Picoseconds laser, λ-355 nm, pw-15 ps RR-400 kHz & 1 MHz	Highly conductive silicon wafer t-400 μm	After laser machining deep reactive ion etching in a buffered HF solution	Depth achieved 50-80 μm; Micro fuel cells (MFCs)	Scotti et al. (2013)
3.	ArF^* excimer laser λ-193 nm	<111> silicon wafer	Employing aperture to vary spot size and locations;	Ablation depth ~10–275 μm, Width ~30–110 μm; cell alignment, variety of medical devices	Miller et al. (2009)
4.	Frequency tripled Nd: YVO_4 laser, λ-355 nm, pw-30–50 ns & femtosecond laser λ-775 nm pw-150 fs	<111> single crystal silicon wafer	Employed temporal and special distribution of laser energy in fs and ns laser pulses and single pass laser scan for grooving	For Semiconductor, ceramic and various composites industrial applications	Amera et al. (2005)
5.	Ti:sapphire laser λ-800 nm pw~150 fs RR-1 kHz	<100> oriented P-doped silicon	Laser processing in vacuum ~0.1 mbar,	Groove depth ~0.1–60 μm; semiconductor technological uses	Crawford et al. (2005)
6.	Ti:sapphire laser λ-800 nm pw-50 fs RR-1 kHz	<100> p-Type wafer t-500 μm	After lasing ultrasonic cleaning in acetone alcohol and deionized water for 15 min respectively, followed by HF (20%) etching for 45 min	MEMS, silicon trench capacitors, micro-fluidic devices of biochemistry	Pan et al. (2013)
7.	Q- Switched Nd:YAG laser, λ-1064 nm RR-15 kHz Beam translation-20 mm/s	p-Type, boron doped multi-crystalline silicon t-330 μm	Wet etching treatment after laser texturisation in 20% KOH at 80 °C for 10 and 20 min	In solar cells for reducing reflection	Dobrzanski et al. (2008)
8.	Pulsed Nd:YAG laser λ-1.06 μm pw-2.5 ms	<110> & <111> wafer t-380 μm covered with 1.5 μm SiO_2	After laser machining anisotropically etching in a KOH solution at elevated temperature for several hours	Micro-channel depth ~150 μm; cooling devices on the back of ICs and micro-systems	Alavi et al. (1991)
9.	Fiber laser λ-1090 nm Dwell time-40 ms	<100> n-Type wafer t - 300 μm	Before lasing ultrasonic cleaning, shrouding gases- O_2 and Ar during laser processing	Bump height 660–850 nm; flexible, selective and fast local rapid thermal oxidation, debris-free wafer marking and SiO_2 structures for optical uses, and surface textures for new surface functionality	Farrokhi et al. (2012)
10.	Yb:fiber laser, λ-1070 nm, pw-6.7–48 μs, RR-5 kHz	<111> single crystal n-doped silicon t-275 μm	After laser irradiation ultrasonic cleaning	Hole depth per pulse 1–20 μm; silicon photovoltaic's and integrated circuit	Yu et al. (2013)
11.	Pulsed fiber laser, λ-1064 nm, pw-10–250 ns, RR-100 kHz, Scanning speed 1 mm/s, 66% overlap	Single & multi-crystalline silicon wafer t-200 μm	Analytical model to predict ablation depth for a range of process parameters	Ablation depth ~2–17.5 μm	Hendow and Shakir (2010)
12.	Argon-ion laser, Laser power-15 W, Scanning speed-3 mm/min, Pulsed mode	<111> Wafer	Slotting in air, in water and KOH environment	Slot depth in KOH ~100 μm; micromachining of a variety of electronic parts	Gutfeld and Hodgson (1982)
13.	KrF^* excimer laser, λ-248 nm, pw-25 ns, RR-5 Hz	Silicon wafer	Machining in air and water	Depth per pulse ~0.006–0.016 μm; micro-electromechanical system (MEMS), actuators and electronic components	Das et al. (2010)
14.	Ti: sapphire laser, λ-800 nm, pw-30 fs, RR-1 kHz	<100> single-crystal silicon wafer t-400 μm	Before lasing ultrasonic treatment for 15 min in acetone and rinsed in alcohol, lasing in air, water and alcohol medium	Depth in air-0.5–4.5 μm, in water-0.5–7 μm, in alcohol-0.3–6.3 μm; micro-electro-mechanism system devices and silicon-based optoelectronic devices	Liu et al. (2010)