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TECHNICAL PAPER

Femtosecond laser-induced silicon surface morphology in water confinement

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Abstract This article investigates the use of femtosecond laser induced surface morphology on silicon wafer surface in water confinement. Unlike irradiation of silicon surfaces in the air, there are no laser induced periodic structures, but irregular roughness is formed when the silicon wafer is ablated under water. The unique discovery of a smoothly processed silicon surface in water confinement under certain laser parameter combinations may help improve laser direct micromachining surface quality in industrial applications.

1 Introduction

Micro-structuring induced by using femtosecond (fs) laser has been widely discussed as a promising technique for total analysis system (μ-TAS) fabrication. The femtosecond laser direct-write process is controllable by programming and is highly efficient. Quite a few research groups have been investigating interesting phenomena-micro/nano scale periodic structures on some semiconductor materials. However, femtosecond induced micro/nano-scale periodic structures make the product surface too rough to be acceptable in the industrial world. Femtosecond laser direct-write sub-micron structures such as channels and resonators have been reported on transparent material like glass (Dong and Molian 2003; Hwang et al. 2004). Because these surfaces were still not acceptable, chemical etching was suggested as a methodology to decrease surface roughness (Dong et al. 2003). Although it works for specific kinds of materials in special solutions, it is not effective in every single case. Etching also lowers the fabrication efficiency. Thus, it is still worthwhile to look for a proper set of parameters for fabricating a smooth surface with a femtosecond laser. Especially for silicon, the most common dielectric material in use, the ultra-fast pulsed laser induced periodic structure is phenomenal, which makes it difficult to achieve a satisfactory surface after laser irradiation.

We will discuss some unique results of a laser direct-write experiment, which hold promise in the field of femtosecond laser application in silicon micro/nano-machining. With specific machining parameters, the machined surface on the silicon wafer has been smoothened strongly.

2 Experiment

The experiments were carried out at a home-integrated fs laser 3D micromachining system (Fig. 1). The maximum repetition rate, center wavelength and pulse width of the fs laser (Legend-F, Coherent, Inc.) were 1 kHz, 800 nm and 80 fs, respectively. The maximum output power of the fs laser was approximately 1 W; however, we used a combination of a half-wave plate and a polarizer to first reduce the laser power to 20 mW, and then used several neutral density (ND) filters to further reduce the laser power to desirable values based on different experimental conditions. The attenuated laser beam was directed into objective lenses (Olympus UMPLFL 10X, 20X) with different numerical apertures (NA) and finally focused into the

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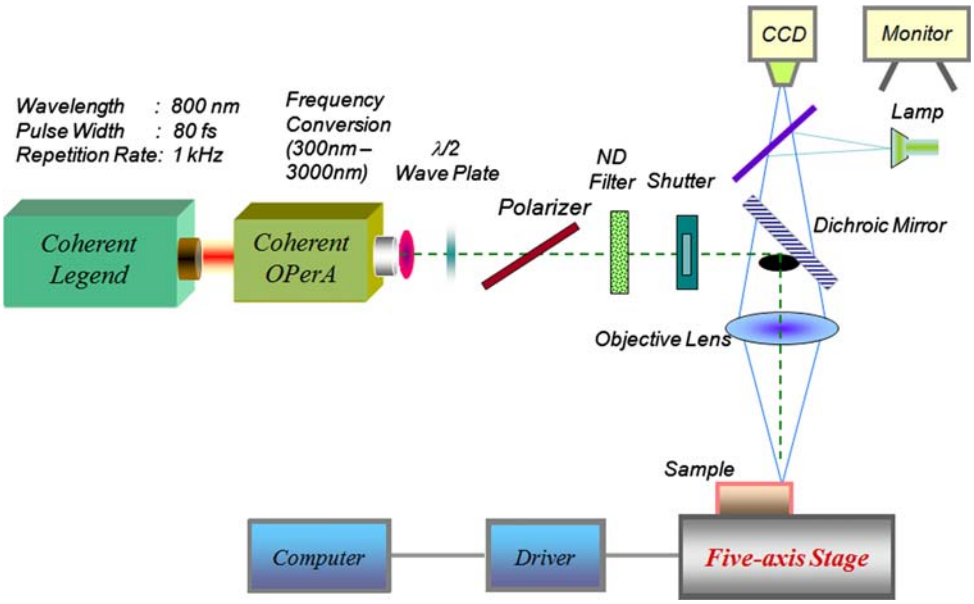

Fig. 1 Schematic diagram of the experimental setup

silicon samples. For fabrication of 3D microstructures, silicon samples were translated by a five-axis motion stage (Aerotech, Inc.) with a resolution of 1 µm.

The fs laser was adjusted to focus on the silicon wafer sample. Trenches were fabricated layer by layer from the surface of the sample to inside of the sample. A 10X objective lens with NA = 0.30 was used in the processing.

As shown in Fig. 2, an empty liquid container is preloaded to the stage. The specimen was fixed to the bottom of the container so as to make it stable relative to the stage. Then, de-ionized water was added to the container to cover the surface of the specimen. Concerning the working distance of the objective lens, the depth of water should be less than 5 mm.

3 Results and discussions

We study on the effect of laser repetition rate on the ablated silicon surface quality. The repetition rate is adjustable from 1 to 1,000 Hz. Six typical frequencies were selected in this experiment so as to fully elucidate the evolution of the surface patterns with the repetition rate, 500, 333, 250, 167, 100, and 10 Hz respectively. The traveling speed of the stage was set as 3 mm/min and the pulse energy was fixed as of 0.2 µJ. The laser power is just above the ablation threshold. First, the experiments were taken in water confinement.

The machined surfaces after femtosecond laser scanning with different frequencies are shown in Fig. 3. All the images were taken at the same scale. The surface pattern after irradiation was found to vary significantly with the repetition rate when the scanning speed was fixed.

Fig. 2 Specimen setup in water confinement

According to the above laser scanning results, a repetition rate of around 100 Hz, with pulse energy of 0.2 µJ, are good parameters for obtaining a smooth surface for application requirement. As the laser repetition rates increased, the surface became rougher. The roughness is due to big laser overlapping.

Next, by way of contrast, identical experiments were conducted in the air with the same series of parameters. It was found that the ablation threshold in air is the same as the ablation threshold in water. The phenomenal laser-induced periodic cones came into being, as shown in Fig. 4.

The potential mechanism of laser induced periodic structure formation in the air has been widely discussed. Some researchers indicated that oxidation might be a reason for the formation of nano-particles on the

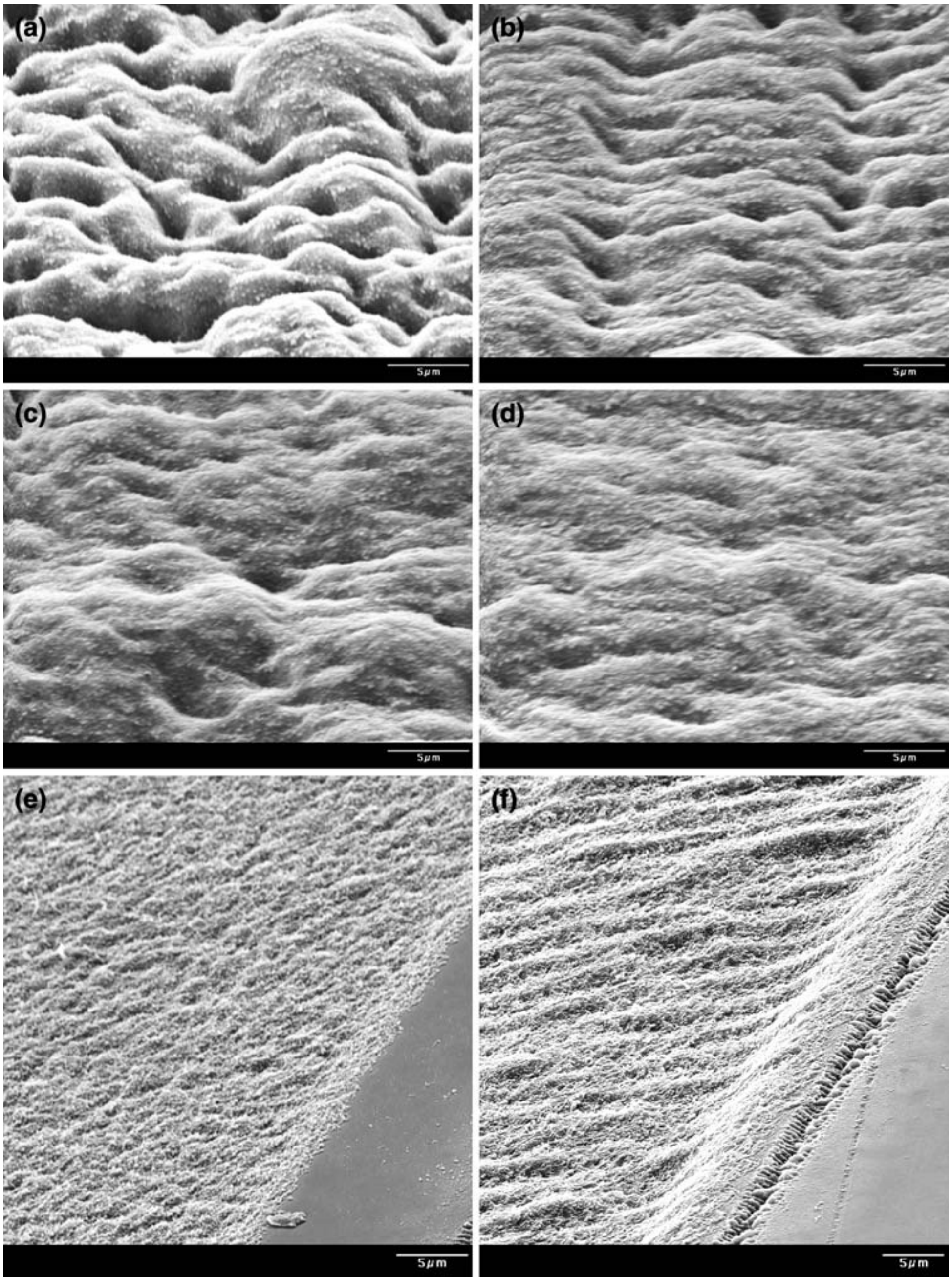

Fig. 3 SEM images of femtosecond laser-induced surface morphology in water at (**a**) 500 Hz, (**b**) 333 Hz, (**c**) 250 Hz, (**d**) 167 Hz, (**e**) 100 Hz and (**f**) 10 Hz

columnar spikes (Seifert et al. 2005), since the content of dissociated oxygen is much higher than that in the water. The most widely accepted explanation takes into account the interaction of an electromagnetic wave with the microscopically rough selvedge of the surface. As the laser light hits onto the surface, the light may be refracted by the material, as well as scattered by the selvedge. The incoming laser light then interferes with the surface waves, leading to periodic electromagnetic field distribution. Hence, periodic structures form on the material surface (Georgescu 2003).

The formation mechanism of surface pattern by laser direct writing in the water has seldom been studied. For underwater laser scanning, incident laser light interference with the surface waves is a possible reason for the boulder-furrow-like structure formation at frequencies of 167–500 Hz. However, the morphology is not as regularly periodic as that obtained in the air. The water layer plays the role of shielding source from laser energy.

There are two possible causes of the special surface patterning phenomenon in water. First, as discussed

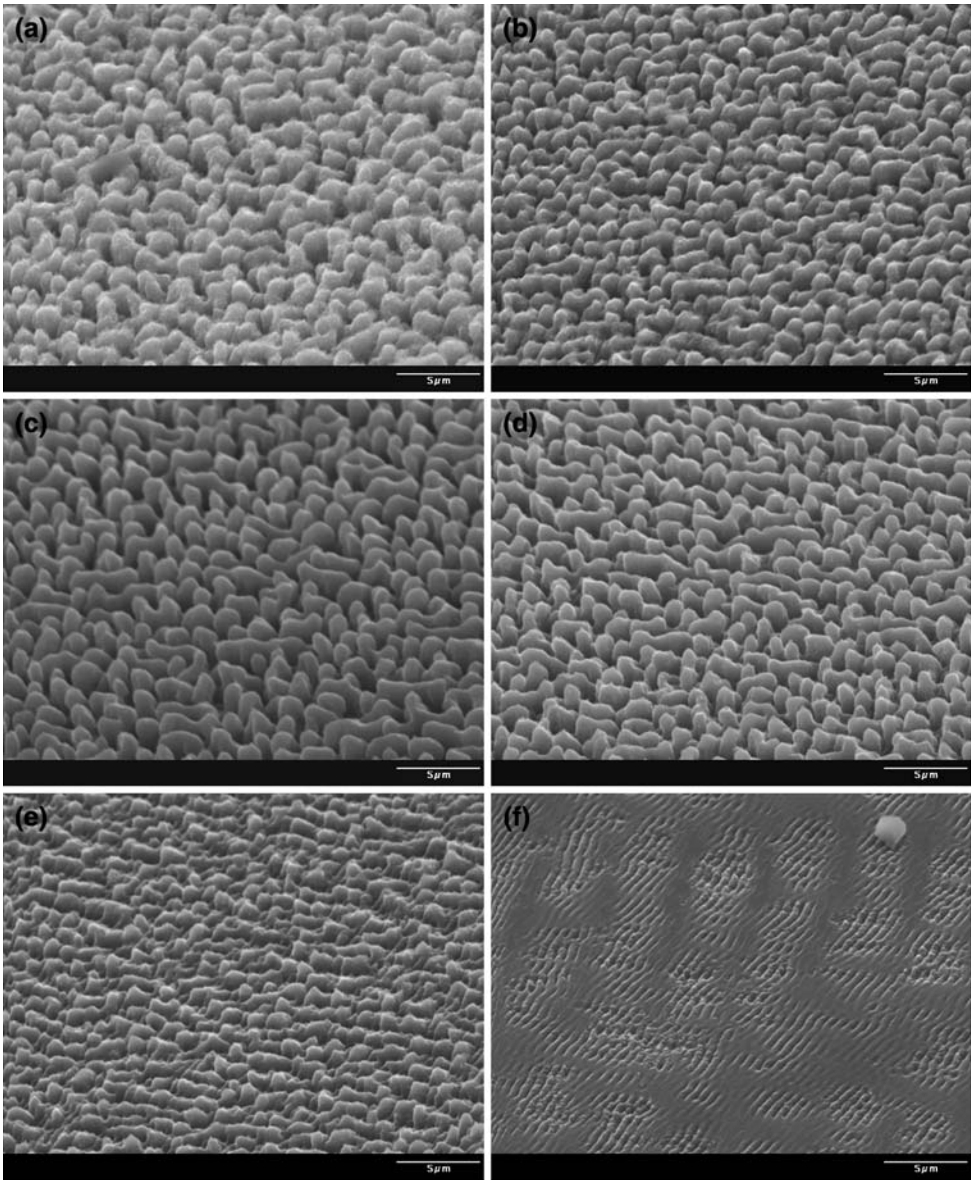

Fig. 4 SEM images of femtosecond laser-induced surface morphology in the air at (**a**) 500 Hz, (**b**) 333 Hz, (**c**) 250 Hz, (**d**) 167 Hz, (**e**) 100 Hz and (**f**) 10 Hz

previously, the cavitation bubbles caused by plasma formation and water evaporation significantly impact the interference processes. This might be a reasonable explanation for why the surface is corrugated, but not as regular as that in the air. Another reason is that H_2O molecules are strongly polarized due to the high electronegativity of the oxygen atoms. During the scanning process, the laser beam can be considered as a moving electromagnetic field on the sample surface. This moving electromagnetic field will affect the energy status of H_2O molecule because of its polarization. Then it influences the electromagnetic field itself in return. At an appropriate laser pulse overlapping rate (changing with the change of the repetition rate), for instance, at 100 Hz, the surface quality will be improved a lot.

Then, we fabricate some structures on the silicon in water with the appropriate machining parameters we achieved to get a high quality machined surface. The results are shown in Fig. 5. Compared with the same structures machined in the air, the structure surface quality has been improved a lot. The periodic formation did not appear. The surface became much smoother.

4 Conclusion

In summary, we stated a femtosecond laser machining method to achieve clean, high quality surface on the silicon wafer under some specific laser machining parameters in the water confinement. It is unique way to avoid periodic

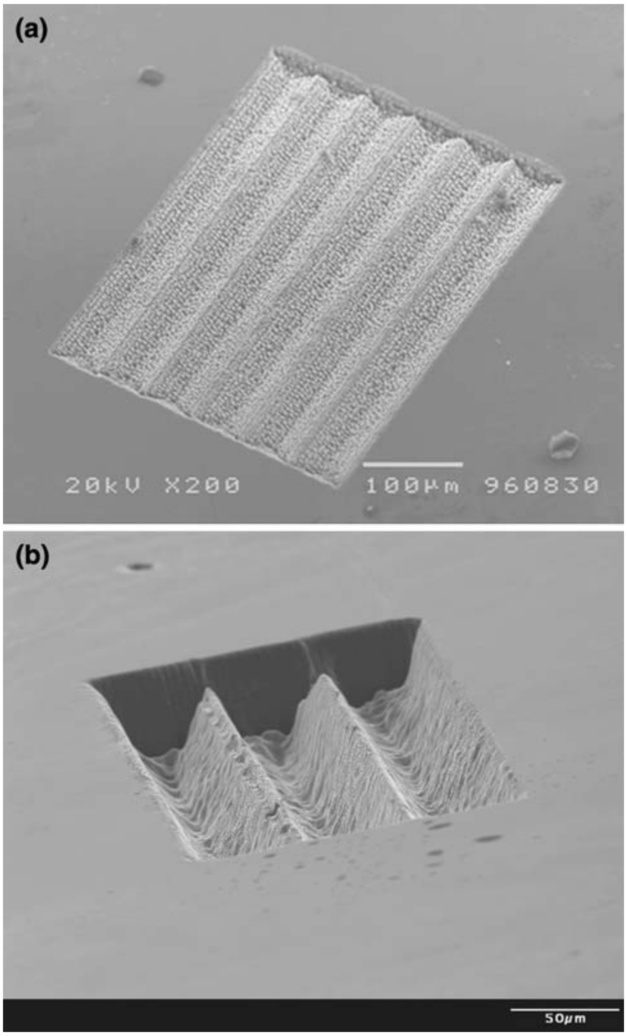

Fig. 5 V-shape grooves fabricated by fs laser direct writing in (**a**) air, and (**b**) water

structures that is induced by the femtosecond laser machining in the air on the machined silicon surface. It can help improve the silicon machining quality in many applications.

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