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Machining on Rear Surface of a Silicon Substrate by an Infrared Femtosecond Laser via Non-linear Absorption Processes

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Abstract

Silicon (Si) is a semiconductor material widely used in modern technologies such as microelectronics, MEMS, and photonics. Si is an opaque material in visible to near-infrared wavelength region but it transmits any light longer than 1127 nm, which corresponds to its band gap energy of 1.12 eV. Therefore, Si can be considered as transparent material for radiations longer than 1127 nm. Here we have proposed a new laser microprocessing method of Si, which increases the efficiency, accuracy and flexibility in machining. The thickness of the Si substrate used was 320 μm and a femtosecond laser at 1552 nm was focused by a 100x infrared objective lens on the rear surface of the substrate. However, only a shallow groove was formed: its depth was approximately 170 nm or less. It is expected that when the laser is focused on the Si rear surface, where it is contacting with an etchant, wet etching will occur due to the temperature rise caused by the laser irradiation. Therefore, to increase the machining rate, we tried laser-assisted backside wet-etching using KOH solution as the etchant. The maximum groove depth was increased to more than 3 μm. The effects of laser irradiation conditions on machined grooves were examined. The results achieved showed rather scattered values and indicated that the maximum groove depth was not always produced at high energy deposition conditions. One of the reasons might be the formation of hydrogen bubbles from the chemical reaction between Si and KOH, which block the contact of Si and KOH.

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Keywords: Silicon, processing, rear surface, KOH etching, femtosecond laser, infrared laser.

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1. Introduction

Silicon (Si) is an important semiconductor material underlying the modern technological society [1]. The most of currently used Si processing techniques are based on lithography technique, which has been used widely in manufacturing IC or LSI electronic devices. However, lithography is basically a 2D processing method which uses projection and selective etching processes. Thus these techniques require sophisticated multiple steps demanding many kinds of chemicals in developing, etching and cleaning steps and cause heavy environmental loads. Nowadays, there are large demands to find a machining method of Si that can produce real three-dimensional microstructures with high accuracy, low cost and low environmental impact. In order to provide a cost-effective, efficient and reliable Si machining technique, many technologies have been proposed, such as electrical discharge machining and laser machining [2, 3]. These methods are, however, essentially surface machining methods. Here we propose a new laser processing method, which machines on rear surface, to increase the efficiency, accuracy and flexibility of Si micro processing.

Silicon is a semiconductor with band gap energy of 1.12 eV, which corresponds to a wavelength of 1127 nm [4]. Therefore, Si is considered as a transparent material for radiations longer than this wavelength. We have demonstrated that micromachining through a Si substrate by a femtosecond laser at 1552 nm is possible [5, 6]. However, only a shallow groove was formed when we focused the laser on the rear surface of Si substrate: its depth was approximately 170 nm or less. Therefore, to increase the machining rate, we tried laser-assisted wet etching using KOH solution. KOH solution is less toxic than other etchants used in Si lithography, and hence is easy to handle. It is expected that when the laser is focused to the Si rear surface where it is contacting with KOH solution, the temperature will rise locally due to the laser energy absorption through non-linear absorption and the selective wet etching of Si can be achieved. The aim of present work is to

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investigate the effect of laser pulse energy, repetition rate and scanning speed in groove machining on the Si rear surface by irradiating infrared femtosecond laser pulses through the Si substrate. A laser microscope was employed for measurement of the groove depth. A scanning electron microscope (SEM) was used to observe surface structures.

2. Experimental set up

In this study, the irradiation was performed by using an infrared femtosecond laser system. This system was operated at adjustable repetition rate from 1 Hz to 500 kHz and adjustable pulse energy from 1 µJ to 5 µJ with pulse duration 900 fs at 1552.5 nm. The schematic diagram of the laser irradiation system is shown in Fig.1 [7]. The laser was steered by two mirrors, and then introduced to the microscope from the side. Inside the microscope, dichroic mirror, which reflected processing laser light wavelength of 1552.5 nm and transmitted observing light wavelength of 1100 ~ 1300 nm, was installed. The laser was inserted coaxially with the observation optical system. By this system, it was possible to irradiate the laser while observing the rear surface of Si by an infrared camera. In addition, an infrared objective lens of x100 equipped with correction collar was used in order to compensate the aberrations due to the high refractive index of Si, 3.54 at 1100 nm [8]. P-type Si substrates of 20 x 20 mm square, 320 µm thick with polished surfaces were used. In this study, focus point position defined ± 0 µm was the condition where a marker on the Si rear surface was observed clearly. Moving the focus position towards the front surface of the substrate was indicated as positive value and vice versa. The KOH solution concentration used in the experiment was 40%.

A pair of electric micro-stages controlled the sample movement. After irradiation, the front and rear surface of the sample was observed with an infrared microscope, a laser microscope and a scanning electron microscope (SEM).

3. Results and discussions

Using the laser irradiation system, laser-assisted etching of the rear surface by aqueous KOH solution has been carried out. Fig.2 shows optical microscope image of the rear surface of the Si substrate observed at 1100 nm after scanning the sample at the speed 400 µm/s under laser irradiation with 4 µJ pulse energy and 500 kHz repetition rate. Each vertical line was a trace obtained at focus positions indicated at the bottom of the figure: the focus position moves from -20 to 0 µm from left to right with 1 µm increments. The traces have parts with dark color and faint color. Deeper groove was observed in the dark part. The difference in color is thought to be in the difference in structural change on the rear surface. Grooves deeper than the dry etching [3] were realized.

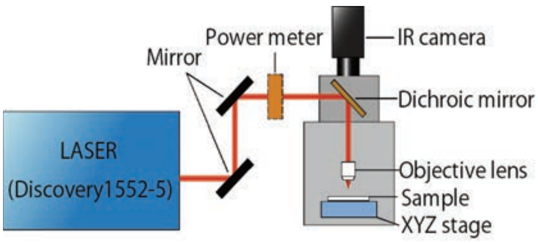

Fig.1: Schematic diagram of experimental set up [7].

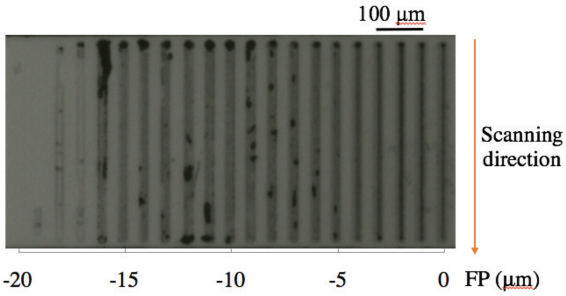

Fig.2: Observation of the rear surface of 320 µm thick Si substrate wet etched by 4 µJ, 500 kHz laser at 1552 nm. Each vertical line was a trace obtained at focus position indicated at the bottom of the figure.

Fig.3 shows the processing line width in 2 cases: one is dry etching in the air and the other is wet etching where KOH solution is in contact with the Si rear surface. It seemed that at the focus positions where the rear surface processing can be observed, the width of the processing lines was nearly the same for both cases. The maximum line width in dry etching was 24.8 µm at -12 µm focus position while in wet etching it was 25.0 µm at -11 µm. When the focus position moved towards the positive direction, the line width reduced significantly. It can be seen that KOH did not affect the laser spot size.

3.1. Effect of laser pulse energy on groove depth

Fig.4 shows the effect of laser pulse energy on groove depth at different focus positions for wet etching. A laser microscope was used to measure the groove depth of 140 µm part at the center of each processing line and the results presented in the figure were the average of five different positions along the groove with standard deviation. The scanning speed was 400 µm/s and the laser repetition rate was 500 kHz. Generally, the deeper groove depth can be achieved at the focus position of -10 µm or lower. It can be seen that the maximum depth of the groove reaches approximately 1.5 µm. At almost all of the focus positions, the groove depth became

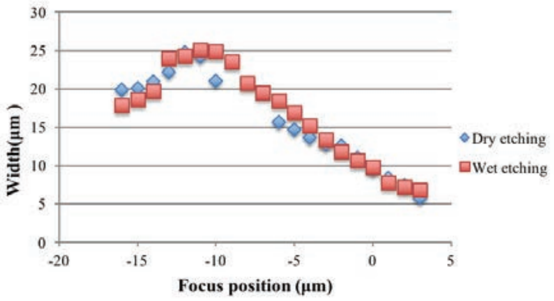

Fig.3: Comparison of processing line width in 2 cases: dry etching in air and wet etching when scanning the sample at the speed 400 µm/s under laser irradiation with 4 µJ pulse energy and 500 kHz repetition rate.

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