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A study on separating of a silicon wafer with moving laser beam by using thermal stress cleaving technique

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ABSTRACT

This study describes the characteristics of separating a silicon wafer with a moving Nd:YAG laser beam by using a thermal stress cleaving technique. The applied laser energy produces a thermal stress that causes the wafer to split along the irradiation path. The wafer separation is similar to crack extension. In this study, the micro-groove was prepared at the leading edge of the silicon wafer to facilitate the fracture. In order to study the thermal effect in the separating process, the temperature at the laser spot was measured by using a two-color pyrometer with an optical fiber, and the mechanism of crack propagation was observed by using an acoustic emission (AE) sensor. The influence of the micro-groove length and depth was also examined. Thermal stress distribution was calculated using the finite-element method (FEM) by considering the temperature from the experimental result. The result indicates that the wafer separation occurred in two stages, fracture initiation and intermittent crack propagation. A higher temperature resulted in faster fracture initiation and higher repetition of the crack propagation signal. The wave mark on the cleaved surface was consistent with the AE signal. The influences of laser power, temperature and the groove parameters to the fracture initiation, crack propagation and cleaved surface features are explained based on the experimental results, while the thermal stress condition is clarified with FEM analysis.

1. Introduction

Laser cutting is today the most common industrial application of laser material processing. Besides the need for additional investment in a tough industry, laser cutting happens to be able to cut faster with higher quality than the other processes (Steen and Mazumder, 2010). Laser cutting is becoming an upcoming potential process substitution into an established market. One of the latest technologies that has been evolving rapidly is thermal stress cleaving using a laser beam, which is used in separating the substrates from brittle material such as silicon wafer, ceramic and glass (Wang and Lin, 2007).

Thermal stress cleaving is a process used for separating a brittle material by irradiating a laser beam onto a small area of the substrate. The laser energy absorbed generates the thermal gradient that creates a compressive stress at the laser spot area and tensile stress around it. A fracture on the wafer that is caused by circumferential tensile stress will propagate toward the laser spot. By introducing a flaw, such as a groove on the material, the crack is started from the groove tip, and the fracture can be controlled. By moving the laser beam, the crack will propagate along the laser path, causing separation of wafer. The material separation process is similar to crack extension. This process is preferred over the conventional mechanical dicing process due to its non-contact cutting process. The process does not need a coolant and production of chips is eliminated. Furthermore, this method is capable of producing a good surface finish.

Garibotti (1963) first proposed the application of a laser in separating brittle material. A laser was used to scribe the grooves along the desired line before broken by ultrasonic energy. Lumley (1969) proposed an important laser cutting process that has high potential for separating brittle materials such as alumina ceramic and glass by using a controlled fracture technique. This procedure uses less laser power and enables high cutting speeds compared to

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conventional laser cutting methods. Lambert et al. (1976) developed the laser cutting process to separate glass by using two lasers. The first laser beam was used to create a shallow groove via heating and vaporizing procedures. The second laser beam generated thermal stress at the groove tip to separate the material. Tsai and Liou (2003) investigated the fracture mechanism of laser cutting of alumina by using a single laser. A shallow groove was created by using an evaporative procedure, and heat produced from the laser beam generated a time-dependent thermal stress along the moving path. Tsai and Huang (2008) reported on diamond scribing and laser breaking for LCD glass substrate. A groove-crack was created along the cutting path using a scoring tool, before separated by applying a defocused CO_2 laser beam.

Several studies have been performed on the thermal cleaving process of a silicon wafer. Ueda et al. (2002) found that the temperature at the area irradiated with a pulsed laser is an important factor in controlling the propagation of the crack and in achieving high cleaving accuracy with low thermal damage. Yamada et al. (2006) recommended a cleaving process with a pulsed laser and the use of refrigerating chuck for cleaving with a continuous wave (CW) laser to reduce thermal damage during the cleaving processes. Takeda et al. (2009) reported that separation in the same direction of the wafer cleavage plane can be achieved by lower laser energy, furthermore improving the cleaving surface. Both researchers conducted their experiments on thermal stress cleaving of a silicon wafer with the preparation of the initial crack by using the Vickers indenter impressions. However, the impressions created damage to the indentation area and a lateral crack in the direction perpendicular to the cleaving path. Ishikawa et al. (2012) introduced the use of a micro-groove to facilitate the fracture initiation during the thermal stress cleaving process. The unnecessary crack and damage were eliminated during the initial crack preparation, subsequently improving the quality of the material specimen.

Previous studies on the thermal stress cleaving process of a silicon wafer were focused on the cleaving temperature, thermal damage and surface finish of the material's separated surface. However, the mechanism of the thermal stress cleaving process of a silicon wafer had not been analyzed in detail, and the relation between laser condition and cleaving performance is not fully understood.

In this paper, the separating characteristics of a silicon wafer with a moving laser beam by using the thermal stress cleaving process is investigated experimentally and computationally. The micro-groove was prepared at the leading edge of the silicon wafer to facilitate the fracture. The effect of laser energy on the cleaving mechanism was analyzed, and the influence of the groove parameters such as groove length and depth were also studied. The temperature of the moving laser spot was measured by using a two-color pyrometer with an optical fiber, and the AE signal was assessed to observe the mechanism of propagations. The cleaved surface was observed using scanning electron microscope (SEM). Further, the influences of laser power, temperature and the groove parameters to the fracture initiation, crack propagation and cleaved surface features are explained based on the experimental results. In order to explain the three-dimensional thermal stress distribution, the finite-element method (FEM) software, ANSYS, is applied by considering the temperature ascertained from the experimental result.

2. Experimental method

2.1. Silicon wafer specimen

The specimen used in the experiments was a silicon wafer of ⟨1 0 0⟩ crystal orientation and with a thickness of 0.5 mm. The schematic illustration of the silicon wafer specimen with a size of 20 mm × 10 mm × 0.5 mm is shown in Fig. 1. The micro-groove was created initially by focusing the pulsed laser beam through the micro-lens at the edge of the silicon wafer (Ishikawa et al., 2012). A second harmonic generation (SHG) Nd:YAG laser with a wavelength of 532 nm, frequency of 10 Hz and pulse width of 5 ns was used in the specimen preparation. The laser energy was focused onto the specimen resulting in material heating and evaporating, thus forming the groove. By using this technique, the groove size can be controlled, and the area of damage can be minimized. In contrast with the initial crack created by the indenter, the unnecessary crack was eliminated; consequently improved the quality of the separated surface.

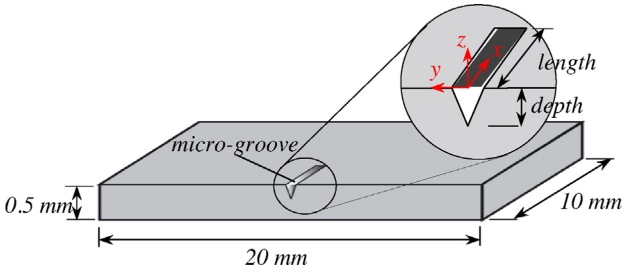


Fig. 1. Schematic illustration of silicon wafer specimen with the micro-groove and references axis.

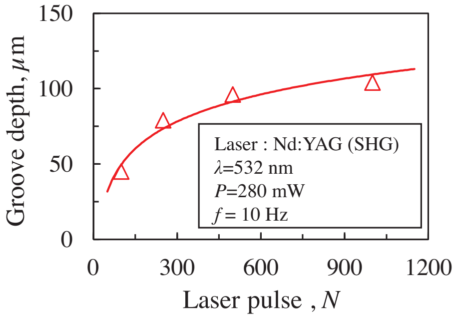
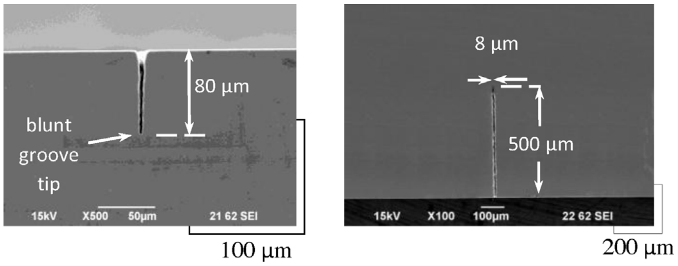


Fig. 2. Relationship between laser pulse number and groove depth.



(a) Micro-groove depth (front view)

(b) Micro-groove length (top view)

Fig. 3. Images of micro-groove with dimensions.

The depth of the groove was adjusted by varying the laser pulse number while the groove length was controlled by focusing the laser beam only onto the required exposed area. Fig. 2 shows the relationship between the groove depth and laser pulse number. The images of the pre-prepared micro-groove are shown in Fig. 3.

2.2. Temperature measurement

The temperature gradient produced from the laser beam generates thermal stress in the material substrate. Therefore, it is