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Research paper



Evaluation of Separating Process for Different Materials by Thermal Stress Cleaving Technique

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Abstract

This paper aims to evaluate the separating process of brittle materials by thermal stress cleaving technique. This process is suitable for separating thin brittle materials such as sapphire and silicon wafer, which are sensitive to force. Both materials were used largely in microelectronics, solar cells and micro-mechanical industries that require precise machining. Finite element method was used to evaluate a steady state thermal stress by considering the temperature transient during laser irradiation process. The heat source was assigned according to the laser energy absorption characteristics of the materials. Stress intensity factor was analyzed to determine the starts of separation process. The results show that CO_2 laser energy was absorbed on the surface of the sapphire material as compared proportionated absorption of Nd:YAG laser energy on silicon material. Due to thermal stress generated by the laser beam, material separation was start. Fracture begins at the bottom surface of sapphire wafer compared to fracture initiation at the prepared groove for silicon wafer. The material separation can be controlled when it begins at the groove. Hence, better surface finished can be achieved.

Keywords: *Thermal stress cleaving, stress intensity factor, sapphire, silicon.*

1. Introduction

Separating of brittle materials such as sapphire and silicon wafers by using thermal stress technique has a huge prospective. This non-contact technique gives an advantage for separating wafers especially at micro-thickness, which is vulnerable to physical energy from the cutting disc, clamping jigs and fixtures.

Currently, sapphire is largely used for watches display covers and consumer electronic devices, as well as in LED manufacturing of display illumination in mobile phones, headlights and interior illumination in the automotive industry [1]. Silicon wafers, on the other hand uses mainly in integrated circuits of common devices today, such as computers and smartphones. Other applications include sensors and solar cells.

Thermal stress cleaving technique by using a laser beam has been introduced for brittle materials processing [2]. The material is separated by crack extension via thermal stress imposed by a laser beam. Thermal stress cleaving produces a good surface finish without making machining chips and eliminate the need of machining liquid.

Numbers of studies in thermal stress cleaving technique using laser beam have been performed on sapphire and silicon wafers. Heat damages can be controlled by using appropriate processing parameters. The effects of laser power, temperature and the groove parameters on cleaving silicon wafer were explained based on the experimental and computational results [3]. Mechanism of material separation was investigated by assessing the temperature and crack propagation by using a two-color pyrometer with an optical fiber and AE signal respectively [4]. Wafers were successfully separated by laser irradiation along a pre-made shallow groove [5].

In this paper, thermal stress conditions during laser beam irradiations on sapphire and silicon wafer were analyzed by computational analysis. CO_2 laser and Nd-YAG laser were used for separating sapphire and silicon wafers, respectively. Material properties and laser energy absorption of sapphire and silicon are discussed. Temperature transient analyses were performed by simulating the laser irradiation on the wafers. Thermal stress distributions were analyzed and compared. Then, the material separation is anticipated by stress intensity value.

2. Methodology

In this study, commercial computational analysis software, ANSYS, was used to analyze the behavior of thermal stress during the laser cleaving process. The analyses were divided into two stages. Stage one starts with temperature analysis. In stage two, the analysis was done to simulate thermal stress generated by the laser beams. Results from the temperature analysis were used in thermal stress simulation. Later, stress intensity factor will be evaluated to determine the successful of material separation.

During laser cleaving process, temperature and thermal stress deviated into the material. 3D finite-element model was used to represent the process.

Fig. 1 shows the finite-element (FE) model with a coordinate system. The FE model size used was 6mm x 6mm x 0.15mm. Pre-groove was prepared (15µm in depth and 5µm in width) along the x-axis to facilitate the fracture initiation. CO_2 (6W) and ND-YAG (20W) lasers were used to irradiated the sapphire and silicon wafers respectively. Beam diameter and travel speed are made constant at 0.3mm and 5mm/s.

Following assumptions were considered during laser irradiation process. Material properties of sapphire and silicon are assumed

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to be uniform. The stress-strain relationship is considered to be elastic. Heat convection was occurred on all surfaces at $8Wm^{-2}K^{-1}$. Initial temperature was set to 20 °C. In thermal stress analysis, the calculation was made at steady state condition. All surfaces were set to be traction-force free.

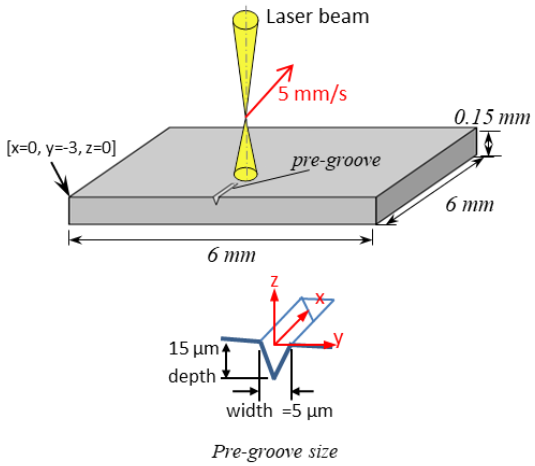

Fig. 1: Finite-element model with a coordinate system

2.1. Absorption spectrum

Material's absorption spectrum is a division of laser radiation absorbed by the material over a range of wavelength. The absorption characteristic is explained by Beer Lambert's Equation (1), where T is the spectral transmittance, β is the absorption coefficient and x is the thickness of the material [7]. Laser intensity varies exponentially as it propagates in the medium.

$$\beta = \frac{-\ln T}{x} \quad (1)$$

Spectral transmittance was measured by using Perkin Elmer Corp.: Spectrum One NTS (λ-0.68 to 4.3 µm) and Varian 3100 FT-IR (λ-2.5 to 25 µm). The measurement was performed on the polished surface of sapphire and silicon wafers.

Fig. 2 illustrates the transmittance characteristic of laser energy. Full transmittance signifies all the energy has passed through the material and none was absorbed. Zero transmittance indicates that no energy passed through the material and absorbed fully into the material. Therefore, the lower transmittance is favourable in selecting suitable laser type for thermal cleaving process.

Fig.3 shows the comparison of spectral transmittance for sapphire wafer and silicon wafers with 150 µm of thickness. CO_2 laser (λ=10.64µm) was used for cleaving the sapphire material due to high absorption characteristic. While, Nd:YAG laser (λ=1.064 µm) is used to irradiate the silicon wafer, with transmittance value of 23%.

Based on the Beer Lambert's Equation, laser energy absorption in relative to the material thickness is summarized in Fig. 4. The material was divided into 10 layers and the absorbed energy was calculated for each later. Over than 93 percent of the laser energy was absorbed on the first two upper layer of sapphire material. In comparison, laser energy was absorbed proportionately through the silicon material. This absorption characteristic was considered during temperature analysis.

2.2 Mechanical and Thermal Properties

Comparison of mechanical and thermal properties between sapphire and silicon wafers is shown in Table 1. Sapphire is a superior material compared to silicon with larger value of hardness and fracture toughness number. Moreover, Young's modulus and density of sapphire are much higher than silicon. The expansion coefficient value of sapphire is also greater. Sapphire also a tougher material compared to silicon.

However, thermal conductivity and thermal diffusivity of silicon were found superior. This indicates that heat was disseminated well in silicon compared to sapphire wafer. Expansion on silicon due to the heat absorption is lower in contrasted with sapphire material.

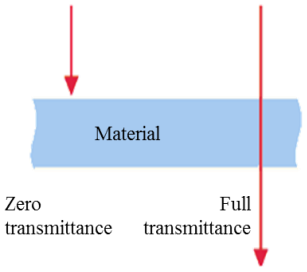

Fig. 2: Absorption characteristic of laser energy in material

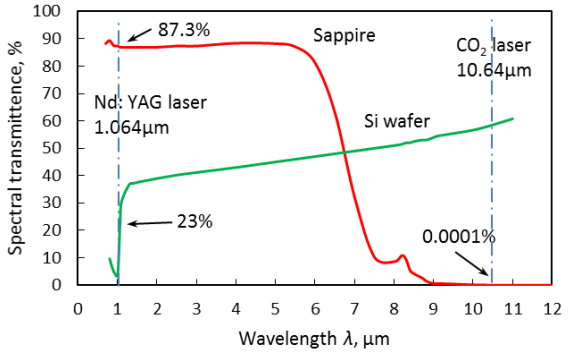

Fig. 3: Spectral transmittances for sapphire (0 0 0 1) and silicon wafers (1 0 0)

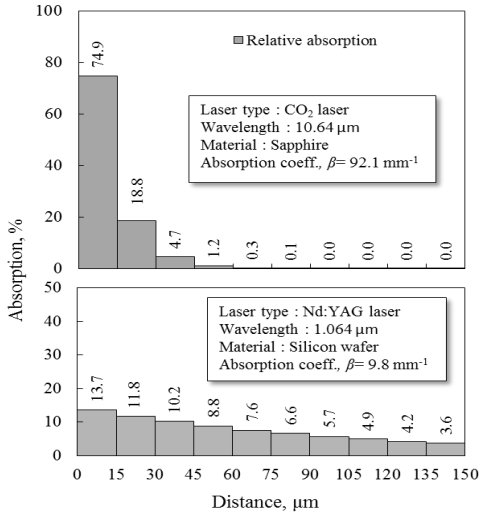

Fig. 4: Laser energy absorption for sapphire and silicon wafers

Table 1: Mechanical and thermal properties of sapphire and silicon

Mechanical properties	Sapphire	Silicon
Density, ρ (kg/m^3) ($x10^3$)	3.97	2.34
Young modulus, E	470	169
Vickers hardness, H_v	19	8.9
Fracture toughness, K_{IC}	1.96	0.7
Poisson ratio, υ	0.3	0.26
Thermal properties		
Thermal expansion coef., α ($x10^{-6}$)	5.3	2.6
Thermal conductivity, K	42	156
Thermal diffusivity, k ($x10^{-7}$)	141	800
Specific heat, C	0.75	0.76

3. Result and Discussion

3.1. Temperature Distribution Results

The temperature analysis was done during laser irradiation along the x-axis, started at position x,y,z=0 (t=0s). Fig. 5 shows the transient temperature on the laser spot recorded along the irradiation path. The temperature was increased rapidly at the beginning of laser movement and decreased to the uniform temperature.
Fig. 6 shows the comparison of temperature conditions for sapphire and silicon wafers at position x=0.45mm. Due to the laser energy absorption characteristics, higher temperature was accumulated at the sapphire wafer surface. However, for silicon wafer, the temperature was distributed across the material thickness.

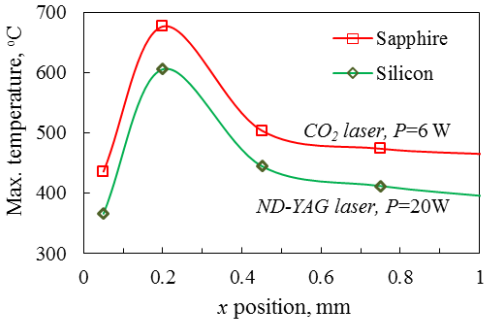

Fig. 5: Maximum temperature on the laser spot along the irradiation path

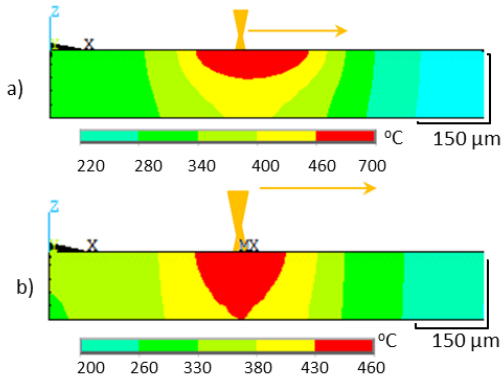

Fig. 6: Comparison of temperature conditions at position x=0.45mm (a) sapphire (b) silicon wafer

3.2. Thermal Stress Results

Thermal stress analyses were performed based on the temperature data gained from previous analysis. Fig.7 shows the comparison of thermal stress conditions for sapphire and silicon wafers at the positions of x=0.45mm, respectively. Compressive conditions were shown at surrounding area of laser beam positions. High compressive stress resulted at the surface area of sapphire wafer while uniform compressive stress through the material thickness showed for silicon.
These situations occurred due to the laser absorption characteristics of the materials. Tensile stress was accumulated at edge of the FE model, where x=0. Two critical point for material separation to begin at pre-groove edge, where z=-0.015 and at bottom edge of FE model, z=-0.15. When the tensile stress is high enough, material separation will occur.
Fig. 8 and Fig. 9 show the records of maximum thermal stress at the edge of FE model, where z=-0.15 (bottom surface) and z=-0.015 (pre-groove), respectively. High stress value was developed at sapphire wafer. The thermal stress resulted at (x=0, z=-0.15) ranges from 95 to 415MPa for Sapphire and 15 to 70MPa for silicon wafer. Greater thermal stress was resulted at the pre-groove indicate that the stress concentrates in one area, makes the area become weak, and fracture may happen.
Pre-groove was prepared on the top of the wafer material to facilitate the separation process. To control the material fracture, the crack shall propagate from this point. The stress concentrated at the pre-groove ranges from -150 to 1109MPa for sapphire, and 15 to 165MPa for silicon. Negative value denotes that compressive stress happened at the beginning of laser path. At this point, the laser beam is on the pre-groove itself.

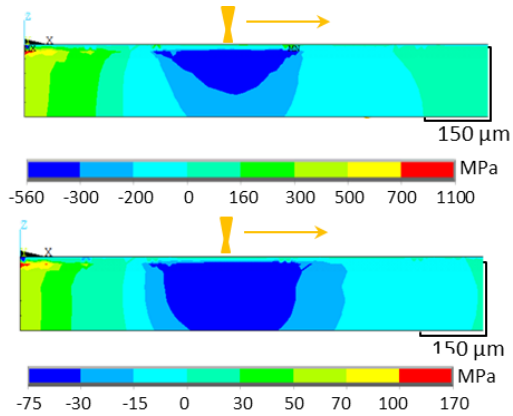

Fig. 7: Comparison of thermal stress conditions at position x=0.45mm (a) sapphire (b) silicon wafer

3.3. Stress Intensity Factor, K_I

Thermal stress condition the interest area can be predicted by stress intensity factor, K_I. The material will able to resist fracture as long as the stress intensity factor, K_I no reaching the fracture toughness property of the material.
In this study, material separation was assumed occurs according to Mode 1 and in one direction. σ_{yy} was determined by as the value of thermal stress from section 3.2. Stress intensity factor, K_I was calculated by considering the σ_{yy} at a constant distance, r=0.15µm by using Equation 2[8].

$$K_I = \sigma_{yy}\sqrt{2\pi r} \quad (2)$$

Fig.10 illustrates the stress intensity factor, K_I at bottom surface position (0, 0,-0.15) for sapphire and silicon wafer. It is shown that, calculated value for sapphire was reached beyond the critical fracture toughness K_{IC} (2MPa.m$^{0.5}$). The fracture may start from this position and could cause uncontrolled fracture and poor resultant surface. However the fracture was not happened at silicon wafer as the stress intensity value, K_I not reached the K_{IC} (0.7 MPa.m$^{0.5}$). Maximum K_I value reached at sapphire wafer was 4.05 MPa.m$^{0.5}$ and maximum of 0.64 MPa.m$^{0.5}$ was recorded for silicon wafer.

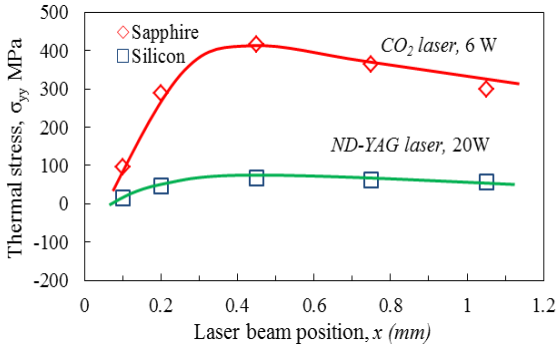

Fig. 8: Records of maximum thermal stress at position (0, 0,-0.15) (bottom surface)

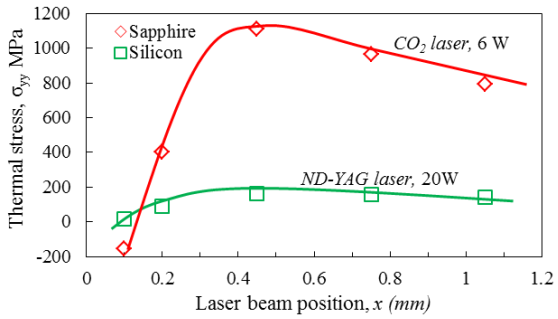

Fig. 9: Records of maximum thermal stress at position (0, 0,-0.015) (pre-groove)

Fig.11 illustrates the stress intensity factor, K_I at pre-groove position (0, 0,-0.15) for sapphire and silicon wafer. As laser beam move forward along x-axis, stress intensity K_I crossed the critical toughness, K_{IC} value and reached to the maximum of 7.72 MPa.m$^{0.5}$. However, K_{IC} was achieved earlier at the position z=-0.15 as shown in Fig. 11.

Meanwhile, stress intensity factor, K_I for silicon wafer was reached the K_{IC} value and raised up to 1.16 MPa.m$^{0.5}$. Material separation was success to be initiated at the pre-groove. Fracture of material was controllable and better surface finish can be attained.

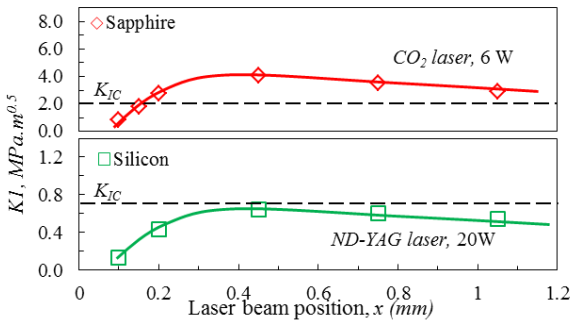

Fig. 10: Stress intensity factor, K_I at position (0, 0,-0.15) (bottom surface)

Based on the analysis results achieved, it is recognized that laser energy absorption characteristic plays an important role fracture initiation. Fracture can be controlled when starts at designate groove. However, when the fracture begins at other position, undesirable surface finish will be achieved. In order to achieve the control fracture condition when cleaving the sapphire wafer with CO_2 laser, pre-groove shall be located on opposite to the irradiating surface.

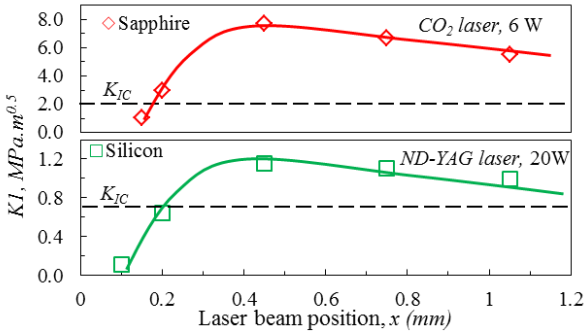

Fig.11: Stress intensity factor, K_I at position (0, 0,-0.015) (pre-groove)

4. Conclusion

In this paper, separating process by thermal stress cleaving technique for sapphire and silicon wafer were compared and discussed. CO_2 and ND-YAG lasers were used to irradiate the sapphire and silicon wafers respectively. The selection of laser type was based on the spectral transmittance performance. Laser type which having better absorption was preferred as optimum power can be utilized in cleaving process.

The temperature analysis results shows heat distribution was depending on laser power absorption characteristics. Heat was concentrated at the surface of sapphire wafer during laser irradiation in contrast with proportion heat distribution in depth of silicon material. As an outcome, higher tensile stress was resulted at bottom surface of sapphire wafer and not concentrated at pre-groove as shown for thermal stress result for silicon wafer.

Investigation on the stress intensity shows that material separation was successful as desired for silicon wafer. The stress intensity factor was reached at pro-groove position, so the material separation started at pre-groove that formed on the wafer surface; therefore controlled fracture mechanism can be expected during real thermal cleaving process. However, the designated pre-groove position was not effective in sapphire cleaving. Due to the laser energy absorption characteristic, greater tensile stress generated at bottom position sapphire wafer. Stress intensity factor was higher at that position and reached the critical fracture toughness value of sapphire earlier than pre-groove. When this condition happened, uncontrolled fracture will be resulted. Good machining surface is difficult to be achieved.

Thermal stress cleaving process succeeds by fracture extension technique. Hence, pre-groove preparation is very important to ensure the advantages of this cleaving technique can be profited. The decision of pre-groove arrangement must be done with consideration of material type, laser used and energy absorption characteristic.

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