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DEBRIS-FREE IN-AIR LASER DICING FOR MULTI-LAYER MEMS BY PERFORATED INTERNAL TRANSFORMATION AND THERMALLY-INDUCED CRACK PROPAGATION

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ABSTRACT

We have developed a novel debris-free in-air laser dicing technology, which gives more design freedoms in the structure, process and materials of MEMS as well as improves yields. Our technology combines two processes: dicing guide fabrication and wafer separation process. The first process is the internal transformation using a fundamental wavelength of a Ti:Sapphire laser or a Nd:YAG laser. The second process is non-contact separation by thermally-induced crack propagation using a CO_2 laser or mechanical separation by bending stress. The internal transformation fabricated in the first process worked well as the guide of separation, and the processed wafer was diced with low stress. The diced lines completely followed the internal transformation.

1. INTRODUCTION

Conventionally, MEMS wafers are diced into chips using a rotating blade. The blade dicing needs water to cool the blade and remove the particles of grinded material. This makes dicing a design-limiting and traumatic process, because water which enters fine or fragile MEMS structures (e.g. electrostatics gap of cantilevers and diaphragms) causes contamination and sticking. Therefore, MEMS wafers are generally protected before dicing by wafer-level packaging, temporary protection films etc., which often limits the structural, process and material design of MEMS. In addition, the blade dicing requires relatively-wide dicing lines corresponding to a blade width and tipping margin, which reduces the number of obtainable chips in a wafer.

To resolve the problems, a precise new dicing technology without chipping has been desired. Laser dicing based on ablation [1] is one of the candidates. However, it suffers from the deposition of a lot of debris and heat affected zones around the dicing lines. To decrease these undesirable effects, Laser MicroJet [2], which combines laser ablation and water jet guide, has been developed by Synova Inc., Switzerland. In this technology, water micro jet was used as an optical guide, not as a water cutter. Since the laser light transmits in the water guide, it can reach a deeper area of an ablated hole without energy loss. The deep groove can be formed faster than the normal laser ablation. In addition, the water sweeps away the debris and reduces the heat affected zone. This technology must use water, but the width of dicing lines is less than 50 µm.

As a non-ablation process, dicing based on the laser internal transformation of silicon, which is known as "Stealth Dicing" [3, 4], has been proposed by Hamamatsu Photonics K.K., Japan. Stealth Dicing is a powerful dicing tool for thin LSI and MEMS fabricated on a single silicon wafer, because it is a dry and debris-free process, and the dicing line is much smaller than that of blade dicing.

However, Stealth Dicing cannot be applied to multi-layered MEMS composed of glass and silicon wafers. The laser used in Stealth Dicing is a 150 ns pulse Nd:YAG laser with a wavelength of 1064 nm. This laser is slightly absorbed by silicon, and thus the internal transformation can be formed. However, glass does not absorb a light of this wavelength at all. Therefore, it is very difficult to form the internal transformation inside glass by this laser. The MEMS wafer is often composed of glass and silicon wafer. If the precise internal transformation of glass can be formed, it is expected that the dicing for multi-layered MEMS can be realized.

2. PROPOSAL OF NEW MEMS DICING METHOD

In this paper, we describe the novel debris-free in-air laser dicing technology for multi-layer MEMS wafer. Our laser dicing technology consists of two processes, as illustrated in Fig. 1. First, internal transformation is formed inside a wafer by a permeable pulsed laser. At the second step, the processed wafer was separated into individual chips along the internal transformed line by an external stress. As the external stress, thermal stress induced by a CO_2 laser or mechanical stress was used.

The mechanism of the internal transformation of silicon is based on a thermal effect by single photon absorption [4]. Contrarily, the internal transformation of glass is possible by multi-photon absorption. The multi-photon absorption occurs only in the region where the laser energy is highly concentrated. Thus, a shorter pulse laser with high peak intensity is suitable for the internal transformation of glass.

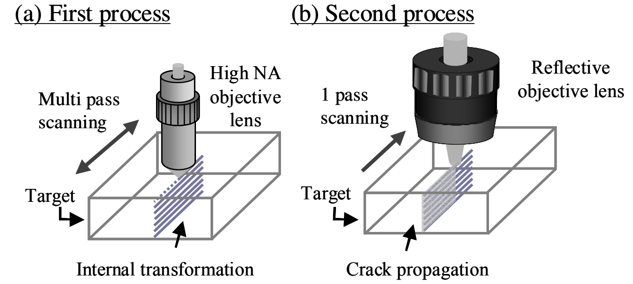

Figure 1: Process of debris-free in air laser dicing; (a) internal transformation by a transmittable pulsed laser, (b) thermally-induced crack propagation by CO_2 laser.

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In our experiments, we used a short pulse and an ultrashort pulse laser, whose pulse width was 10 ns and 100 fs, respectively.

Considering a fragile structure of MEMS, the low stress separation at the second process is desired. It is known the glass substrate can be separated by thermal stress. We investigated non-contact thermal stress separation for MEMS wafers. Depending on the wafer configuration, thickness and material of MEMS, simple mechanical separation is also available. For example, a tape expander, which is generally used for wafer separation after dicing, or similar equipments are useful for mechanical stress application in terms of throughput. Therefore, we measured the mechanical stress required for the separation of the internally-transformed wafers.

2. EXPERIMENTAL METHOD AND PROCEDURE

Internal transformation inside glass and silicon wafers induced by laser pulses

Figure 2 shows the configuration of laser processing setup used in this study. As an *in situ* monitoring system, a reflective polarization microscope and a near-infrared microscope were installed. The laser systems used in this setup are a commercially-available femtosecond Ti: Sapphire laser with a wavelength of 800 nm and a nanosecond Nd:YAG laser with a wavelength of 1064 nm. The pulse width of each laser is 100 fs and 10 ns, respectively. The targets are soda lime glass, Pyrex glass and an anodically-bonded Pyrex glass and silicon double layer wafer.

The Nd:YAG laser transmits in glass and silicon. Therefore, using the Nd:YAG laser, we can form the internal transformation in glass and silicon by multi-photon absorption. However, the Ti:Sapphire laser is absorbed on silicon surface [5]. It only can form the internal transformation in glass. In this process, the contrast of the laser energy density between a surface and a focal point is quite important. The objective lens must be selected to fulfill the following condition: The laser energy density on glass surface is below the ablation threshold, and that at the focal point is above the threshold of internal transformation. For these reasons, a high NA objective lens is suitable. In this study, the lenses with a NA of 0.7 were used.

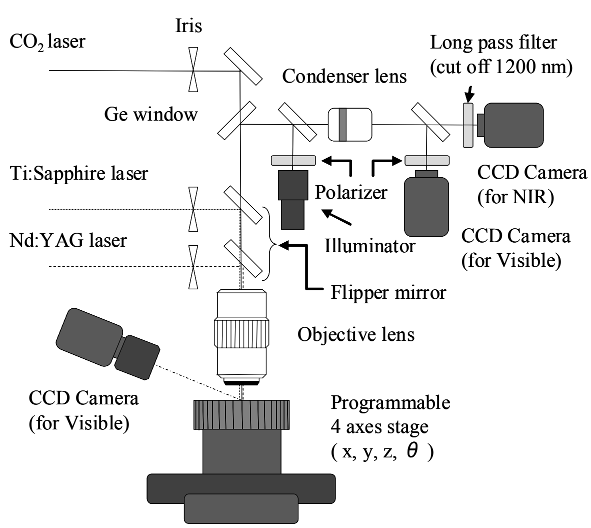

Figure 2: Configuration of laser processing setup.

The laser was scanned in several different depths inside the glass, as shown Fig. 1 (a). To avoid the laser energy scattering by the internal transformation, the laser scanning started from the bottom side and finished on the top side. Before the separation of the wafer, the internal transformation formed by the laser irradiation was observed using a laser scanning microscope.

Wafer separation by laser-induced thermal stress or mechanical stress

At the second step, the processed wafer was separated into individual chips by two methods: thermal crack propagation or mechanical stress application. For the thermal crack propagation, a 25 W CO_2 laser was used. Since the wavelength of the CO_2 laser (10.6 μm) is considerably absorbed by SiO_2, it is suitable for a local heat source in glass. The CO_2 laser was focused on the wafer by a Au-coated reflective objective lens. In this experiment, the laser spot was a ring-shaped with 2 mm external diameter and 0.5 mm internal diameter.

To apply and measure the mechanical stress for the wafer separation, an original instrument shown in Fig. 3 was developed, where three point bending force and tensile force can be applied. The distance of the two supporting points for three point bending is 10 mm, and a blade is pressed in-between by an air cylinder. By controlling the pressure supplied to the air cylinder, the bending and tensile forces are adjusted up to 40 N.

3. RESULTS AND DISCUSSIONS

Internal transformation inside glass and silicon wafers by laser pulses

Figure 4 shows the laser scanning microscope images of the internal transformation in Pyrex glass by a single shot Ti:Sapphire femtosecond and Nd:YAG nanosecond laser irradiation. The upper and lower images show the processed areas by a pulse energy near the process threshold and three times of that, respectively. The threshold laser energy for

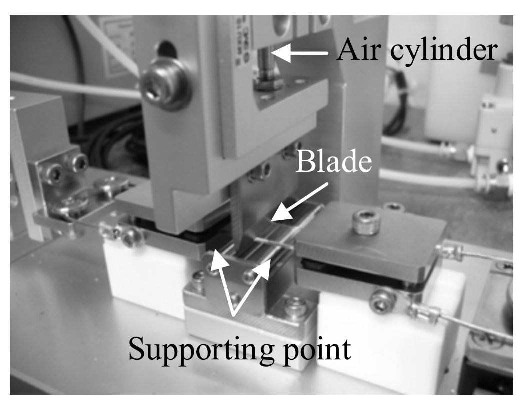

Figure 3: Instrument for mechanical stress application.

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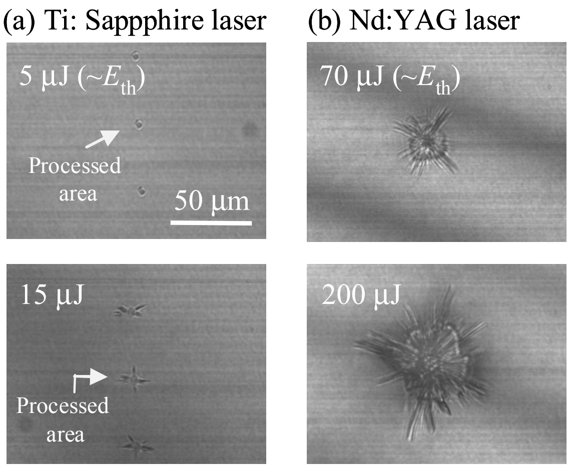

Figure 4: Laser scanning microscope images of the internal transformation in Pyrex glass by a single shot (a) Ti:Sapphire (b) Nd:YAG laser irradiation.

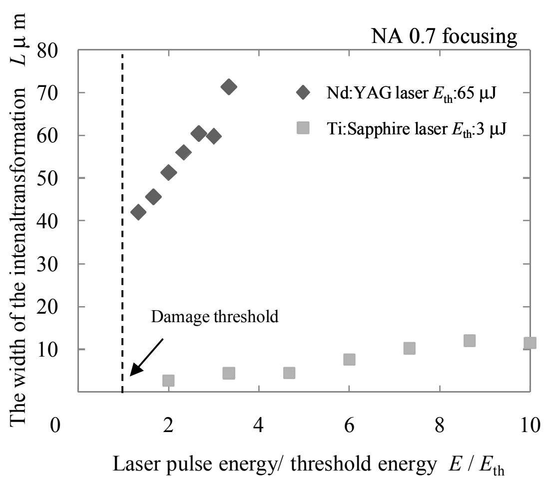

Figure 5: Width of the internal transformation as a function of the laser pulse energy. The threshold of Ti:Sapphire laser and Nd:YAG lasers is 3.0 µJ and 65 µJ, respectively.

internal transformation was 3 µJ with the Ti:Spphire femtosecond laser and 65 µJ with the Nd:YAG nanosecond laser. As the femtosecond laser has an extremely high intensity, multi-photon absorption occurs strongly. Therefore, the threshold energy of the Ti:Sapphire laser is much smaller than that of the Nd:YAG laser. The widths of the internal transformation by the Nd:YAG laser are several dozen µm even near the threshold. On the other hand, those by the Ti:Sapphire laser are one order of magnitude smaller.

Figure 5 shows the width of the internal transformation as a function of the laser energy. The definition of the width in this graph is the distance between the edges and center of the largest crack. The depth as well as the width of the internal transformation by the Nd:YAG laser was larger in comparison with that by the Ti:Sapphire laser. The depth of the crack induced by 1.5 times of the threshold energy of the Ti:Sapphire laser and the Nd:YAG laser was approximately

Table 1: Thresholds of laser energy for the internal transformation (0.7-NA focusing).

	Nd:YAG laser		**Ti:Sapphire laser**	
	Si	Pyrex glass	Si	Pyrex glass
Threshold of laser energy [µJ/pulse]	0.5	65	–	3.0

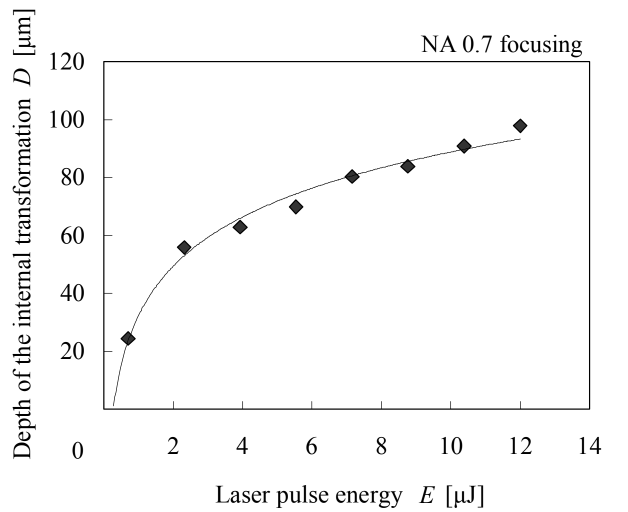

Figure 6: Depth of the internal transformation in silicon as a function of laser pulse energy.

10 µm and 80 µm, respectively.

The width of the internal transformation is smaller for the Ti:Sapphire femtosecond laser. In order to make the dicing line as narrow as possible, the Ti:Sapphire laser is preferable. However, the laser scanning speed is determined by a product between the size of the internal transformation and laser pulse repetition rate, and the Ti:Sapphire femtosecond laser needs a longer time to make the internal transformation enough for dicing than the Nd:YAG nanosecond laser. Especially for thick MEMS, the Nd:YAG nanosecond laser seems practical in terms of processing time. For example, the process speed per line of 4000 mm/s is possible using a 40 kHz pulse Nd:YAG laser with 20 W output. Although 10 pass is needed for the 1mm-thick glass wafer, this value is much faster than that of blade dicing.

The Nd:YAG laser is transparent for glass and silicon. It is expected that the Nd:YAG laser can also form the internal transformation in silicon. When the 0.7 NA objective lens was used, the internal transformation of silicon was formed. The threshold pulse energy is 0.5 µJ, which is much smaller than that for Pyrex glass. Table 1 summarizes the threshold energy of internal transformation in glass and silicon with NA 0.7 focusing. Figure 6 shows the depth of the internal transformation in silicon as a function of laser pulse energy. With increasing the laser pulse energy, the depth of the crack increases. On the other hand, the width was approximately constant at 10 µm. The aspect ratio of the cracks generated by the laser in silicon is much larger than that in Pyrex glass.

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Therefore, the precise internal transformation is easily formed in silicon.

Noncontact wafer separation by laser induced thermal stress

Conventional thermal cracking by a CO_2 laser [6-8] is used to cut large glass substrates for flat panel displays. However, it does not work for the small workpieces like MEMS because of difficulty in precisely controlling the direction of crack propagation.

In the conventional thermal stress cutting, the initial crack is formed by a blade only at the edge of a substrate, and then CO_2 laser scan above that. The crack by a thermal stress propagates from the initial crack, and then the glass is separated. However, if the gap between the parallel separation lines is narrow, the crack cannot run straight due to the asymmetry of the thermal stress. An appropriate guide is necessary for a thermal crack to run straight.

In our method, the laser induced internal transformation described above is used as the guide. First, the glass substrate was internally transformed along to-be-diced lines using the pulsed laser, and then a crack was propagated by the CO_2 laser.

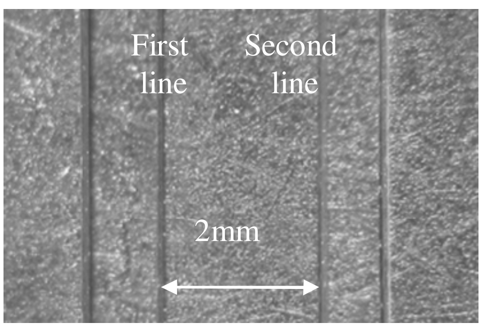

Figure 7: Soda lime glass substrate separated by thermally-induced crack propagation along the internal transformation (Substrate thickness: 1 mm, Gap of the dicing lines: 2 mm)

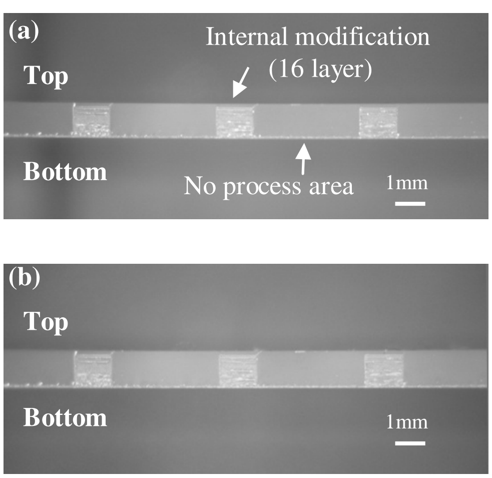

Figure 8: Cross-sectional view of the separated line along the perforated internal transformation: The duty ratio is (a) 0.5 and (b) 0.25.

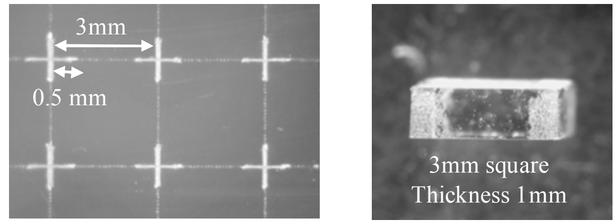

Figure 9: (a) Top view of the crossed internal transformation, (b) Side view of the diced Pyrex glass wafer by thermal crack propagation along the perforated internal transformation. The duty ratio of the internal transformation is 0.33.

The results for soda lime glass were shown in Fig. 7. In this case, the Ti:Sapphire laser was used to form the internal transformation. It shows that the two parallel dicing lines ran straight along the internal transformation, as expected.

We performed similar experiments using Pyrex glass. The thermal expansion coefficient of Pyrex glass (ca. 3.5 ppm/K) is smaller than that of soda lime glass (ca. 8.3 ppm/K). This suggests that the stress induced by CO_2 laser is smaller for Pyrex glass. For the thermal crack propagation in Pyrex glass, the internal transformation wider than 60 μm must be generated by the Nd:YAG laser.

To increase the throughput, we investigated the effect of perforated internal transformation. Figure 8 shows the microscope images of the separated section. The duty ratio of the processed area in Fig. 8 (a) and (b) is 0.5 and 0.25, respectively. The frosted areas are the internally-transformed area, showing that the thermally-induced crack completely ran along the perforated internal transformation. If we make a crossed internal transformation as shown in Fig. 9, we can separate a glass wafer into chips by the noncontact laser induced crack propagation.

Measurement of mechanical stress required for wafer separation

Considering the process throughput, the mechanical separation method like using a tape expander is preferable, if possible. Using the developed instrument, wafer separation by bending stress and tensile stress was tried, and the bending stress application was more reliable for samples prepared in this experiment. Therefore, we measured the bending stress required to separate the laser-transformed wafers by a three-point bending test. For practical uses, the bending stress can be applied to wafers e.g. using a special tape expander with a convex wafer stage.

In this experiment, a Pyrex glass substrate of 10 mm in width and 1 mm in thickness, and the anodically-bonded double layer sample consisting of a 300 μm thick silicon and a 300 μm thick Pyrex glass were used as samples. As shown in Fig. 4 and 5, the size of the internal transformation by the Nd:YAG laser is much larger than that by the Ti:Sapphire laser. Therefore, the bending stress required to separate the wafer processed by the Nd:YAG laser is expected to be small. Therefore, in this experiment, the Nd:YAG laser was used to form the internal transformation.

The bending stress for Pyrex glass with a 900 μm deep, 100 μm wide internal transformation line was 6.5 MPa, and

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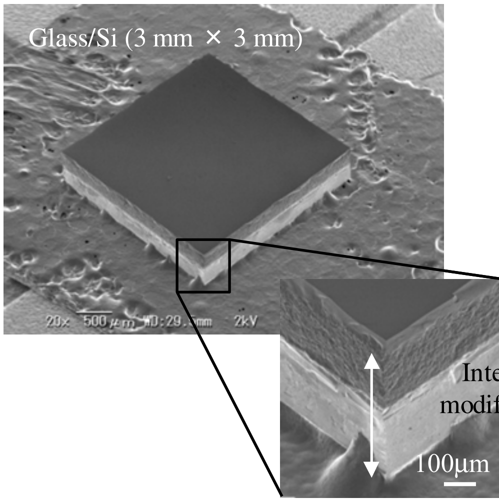
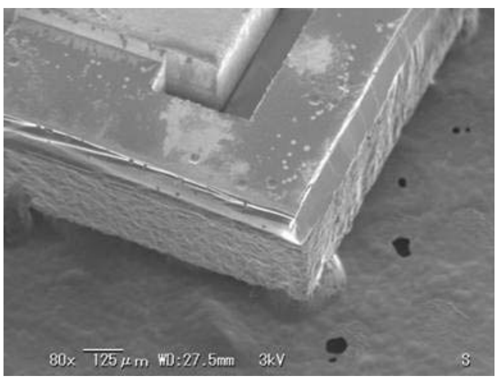


(a) Double layer sample consisting of a 300 μm thick silicon and a 300 μm thick Pyrex glass.



(b) MEMS consisting of a 100 μm thick silicon and a 500 μm thick Pyrex glass (The surface was contaminated in the MEMS fabrication process, not laser dicing.)

Figure 10: SEM images of laser-diced double layer MEMS sample.

that with a 900 μm deep, 100 μm wide perforated internal transformation line with 0.33 duty ratio was 15 MPa. The bending stress for the anodically-bonded Pyrex glass/silicon wafer was 38 MPa. In this target, the length of the internal transformation was 500 μm, and the width in Pyrex glass and silicon was 100 μm and 15 μm, respectively.

In Fig. 10, the laser-diced samples for multi-layer MEMS by this method are shown. Inset (a) shows a double layer sample consisting of a 300 μm thick silicon and a 300 μm thick Pyrex glass. Inset (b) shows a MEMS consisting of a 100 μm thick silicon and a 500 μm thick Pyrex glass. The dicing lines completely follow the internal transformation, and the diced cross-section is sharp and tipping-free. In addition, neither debris nor damages are found on the surface after laser dicing.

4. CONCLUSION

In this paper, we demonstrated the novel debris-free in-air laser dicing technology for multi-layer MEMS wafers which combines laser internal transformation and wafer separation process. As the first step, the internal transformation was formed by a Ti:Sapphire femtosecond laser or a Nd:YAG nanosecond laser. At the second step, the wafer with the internal transformation was separated into individual chips by CO_2 laser induced thermal stress or the mechanical bending stress.

The internal transformation by the Ti:Sapphire femtosecond laser works as a precise guide for dicing whose width is less than 20 μm. The size of the internal transformation by the Nd:YAG laser is larger than that by the Ti:Sapphire laser. Although the width of the dicing lines increases, the stress required separating the processed wafer becomes smaller. The laser scanning speed is determined by a product between the size of the internal transformation and laser repetition rate. The high speed internal transformation for dicing can be realized by the Nd:YAG laser. If a 40 kHz pulse Nd:YAG laser with 20 W output is used for 1 mm thick glass wafer, the effective processing speed is expected to be 400 mm/s.

At the second step, these internal transformed lines worked as a guide of the separation. The dicing line completely followed the internal transformation by both thermally induced crack propagation and bending stress application. The diced cross-section was sharp and free from chipping. The perforated internal transformation also worked as a guide for the crack propagation, which can increase the throughput. If a duty ration of the perforation is 0.25, the effective processing speed of internal transformation exceeds 1000 mm/s.

The 10 ns Nd:YAG laser can form the internal transformation in silicon. The double layer wafer consisting of glass and silicon can be diced in low stress by our technology. These successful demonstrations suggest that our debris-free laser dicing technology is promising for the multi-layer MEMS wafers.

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