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Controllable laser thermal cleavage of sapphire wafers

Jiayu Xu[a], Hong Hu[a,*], Changhui Zhuang[b], Guodong Ma[b], Junlong Han[a], Yulin Lei[a]

[a] School of Mechanical Engineering and Automation, Harbin Institute of Technology Shenzhen Graduate School, D-buiding 202H, Shenzhen Guangdong 518055 China
[b] Measurement & Micromachining Department, Han's Laser Technology Industry Group Co., Ltd, Shenzhen, Guangdong, China

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ABSTRACT

Laser processing of substrates for light-emitting diodes (LEDs) offers advantages over other processing techniques and is therefore an active research area in both industrial and academic sectors. The processing of sapphire wafers is problematic because sapphire is a hard and brittle material. Semiconductor laser scribing processing suffers certain disadvantages that have yet to be overcome, thereby necessitating further investigation. In this work, a platform for controllable laser thermal cleavage was constructed. A sapphire LED wafer was modeled using the finite element method to simulate the thermal and stress distributions under different conditions. A guide groove cut by laser ablation before the cleavage process was observed to guide the crack extension and avoid deviation. The surface and cross section of sapphire wafers processed using controllable laser thermal cleavage were characterized by scanning electron microscopy and optical microscopy, and their morphology was compared to that of wafers processed using stealth dicing. The differences in luminous efficiency between substrates prepared using these two processing methods are explained.

1. Introduction

Light-emitting diodes (LEDs) are being used in an increasing number of applications because of their high brightness, low power consumption, and long life. Sapphire is widely used as an LED substrate material. The Mohs hardness of sapphire is 9, making it difficult to cut using traditional methods [1]. In addition, sapphire wafers are brittle and chips may be generated during sapphire processing. The processing of sapphire wafers has therefore attracted extensive attention from researchers.

At present, three methods are widely used to cut sapphire: mechanical cutting, laser ablation dicing, and stealth dicing. Because of the high speed of the diamond blades used in mechanical cutting, chips can be produced during processing. Furthermore, the diamond blade can be damaged because of the hardness of sapphire [2], resulting in decreased efficiency and productivity of dicing. Laser ablation cutting involves the absorption of photon energy by the surface of the material being cut [3]. The surface temperature increases rapidly, resulting in melting, vaporization, and, ultimately, cleavage. However, it may also result in thermal damage at the surface, which would result in reduced luminous efficiency and service life of an LED. Stealth dicing is widely used in LED wafer processing [4]. In stealth dicing, a laser is focused on the middle of a wafer to generate an internally modified layer. Expanding blue tape is then used to cleave the wafer. However, in the case of a sapphire LED, this processing method would also result in loss of luminous efficiency. The present work aims at the development of a processing method that results in improved luminous efficiency of sapphire LEDs.

There is a relatively new technology called controllable laser thermal cleavage (also known as thermal cleaving, laser-induced cleavage, or thermal laser separation) in which a laser is used to heat a material's surface, resulting in an increase in the material's surface temperature [5,6]. The uneven heat distribution generates thermal stress that in turn results in separation along the designed direction. The temperatures generated during controllable laser thermal cleavage are low meaning that the material's surface does not melt during processing. The area of the heat-affected zone is smaller than that generated during other sapphire cutting methods.

Many researchers have studied controllable laser thermal cleavage. Zuhlke et al. used it to separate silicon wafers [7] and observed that controllable laser thermal cleavage provided a higher quality of cut surfaces compared to other cutting methods; they also noted that the process is free of vibration and results in a clean surface. Yang et al. researched laser-cutting technology based on the controlled fracture method with graphite coatings [8] and observed that this technology provides better quality cuts compared to traditional machining methods, without forming micro-cracks or burns on the surface. In addition, the graphite-coated ceramic exhibited an improved laser absorption rate compared to the uncoated ceramic. Lewke et al. separated SiC-based electron devices

* Corresponding author.
E-mail addresses: 420249001@qq.com (J. Xu), honghu@hit.edu.cn (H. Hu), zhuangch106445@hanslaser.com (C. Zhuang), magd@hanslaser.com (G. Ma), hanjunlongxf@qq.com (J. Han), 849924979@qq.com (Y. Lei).

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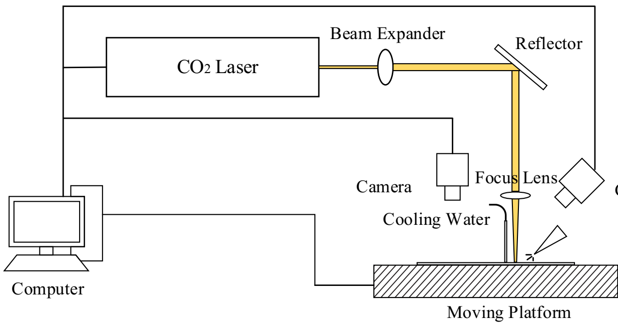

Fig. 1. Schematic of the controllable laser thermal cleavage process.

using the controllable laser thermal cleavage technique [9] with an ablation laser instead of a diamond tip for the initial scribe. Tsai and Chen found crack tips left behind by the laser and that when an asymmetrical straight line or a curve is being cut, the crack extension trajectory deviates from the desired cutting path [10]. Tsai and Liou established an off-line and on-line learning control system of laser cutting that reduced the deviation between the desired cutting path and the actual fracture trajectory [11]. Kubota et al. increased the laser cleaving velocity using two methods: a mist cooling method in which water is sprayed on the material surface, and a preheating method in which the specimen is preheated before the usual CO_2 laser heating step [12].

Although researchers have studied the controllable laser thermal cleavage of various materials, including silicon, alumina ceramics, and glass, the literature contains no study focusing on the application of this method to sapphire substrate wafers. The thickness of an LED wafer is only approximately 100 μm but in the case of thicker wafers, the heat-affected zone will affect the LED luminous efficiency. LED wafer controllable laser thermal cleavage is thus worthy of investigation. In this work, we model controllable laser thermal cleavage using finite element technology to simulate the effect of different cooling conditions and different lasers; the process is then optimized on the basis of the simulation results. In the experiment, controllable laser thermal cleavage is applied to a sapphire substrate wafer, and the cross section and surface of the resulting laser cut are characterized using scanning electron microscopy (SEM) and optical microscopy. The differences between sapphire substrates processed using controllable laser thermal cleavage and stealth dicing are then analyzed.

2. Experimental procedure

The experiment platform used in controllable laser thermal cleavage is very complex, comprising a laser system, a control system, a movement system, and a water cooling system, as shown in Fig. 1. The laser used in this work was a coherent CO_2 laser with a wavelength of 10.6 μm, a maximum power of 70 W, and a beam size of 3.6 mm; it could be operated in either continuous or pulse mode. A mirror positioned after the expander controlled the direction of the laser. The laser was then focused on the surface through a focusing lens with an experiment power of 15 W in Gaussian distribution. The shape of the laser spot could be changed from round to elliptical by adjusting the lens angle, while the size of the laser spot could be adjusted via rotation of the focusing lens. The speed of the controllable laser thermal cleavage was 100 mm/s.

Deionized water was used for cooling, thereby avoiding contamination of the semiconductor wafer by water impurities. The cooling water exited from the needle mouth, and replacing the needle could change the water beam diameter. The diameter of water-cooling nozzle was 0.1 mm and the pressure of cooling water was 0.8 MPa. The temperature of the water was 25 °C. An air nozzle was positioned in front of the laser spot to blow away the water and avoid the effects of laser heating. Because of the high precision demand, two industrial cameras were used for aligning the system. System alignment is important because a misaligned system results in an asymmetric thermal stress distribution; thus, the crack extension trajectory deviates from the desired cutting path.

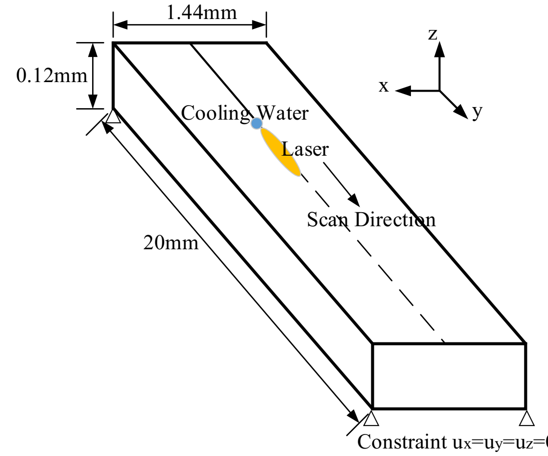

Fig. 2. Model of controllable laser thermal cleavage.

The semiconductor wafer was placed on the vacuum platform, which could move along an *x*–*y*–*θ* triple axis. An industrial computer controlled the laser system, water system, industrial camera, and motion systems. At the beginning of cleavage, the water needle and air nozzle were opened and the laser system was turned on. When the cleavage was complete, the water needle and air nozzle were closed and the laser system was switched off; the motion system then moved to the next cutting path.

LED sapphire wafers were used in the experiments. The sapphire substrate was covered with a 5-μm-thick gallium nitride film. The wafer dimensions were 15 mm × 15 mm, with a thickness of 120 μm. A scanning electron microscope (FEI Quanta 650) and an optical microscope (West Park KE510A) were used to characterize the surface morphology of the prepared substrates.

The wafer was simulated using the ANSYS 14.0 software. To avoid a large computation and improve the accuracy, the size of the simulation model was 1.44 mm × 20 mm × 0.12 mm, which was divided into 432,000 elements as shown in Fig. 2.

In the thermal simulation, SOLID 70, an eight-node 3D thermal solid element was used. It conducts heat in three directions. During the structural stress analysis, SOLID 70 could be converted into the SOLID 45 3D element. The initial temperature of model was set as 25 °C. The model was fixed by surrounded constraints, ensured that no displacement occurred. The parameters for sapphire differ greatly under different crystal orientation and temperature shown in Tables 1 and 2 [13]. According to shock heat transfer model, heat transfer coefficient of cooling water after calculated is 30,000 W/(m^2·K). The heat generation rate of the material surface was obtained according to the laser power.

3. Results and discussion

3.1. Influence of different processing conditions

Laser spots can have either elliptical or circular shapes, and different laser shapes can result in different heat distributions, which will in turn result in different thermal stress distributions. Heat and stress distributions are obtained through finite element technology.

As shown in Fig. 2, the temperature field distribution at 0.02 s is similar to that at 0.08 s. Because of the shape of the laser spot, the heat distribution area is elliptical. With the passage of time, the heat spreads from the middle to the surrounding area. Because of the cooling water, the area after the laser spot cools faster. Moreover, because of the