Laser Micro-machining of Three-Dimensional Microstructures in Optical Materials

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ABSTRACT

We demostrate an advanced precision cutting tool using a 349 nm nanosecond-pulsed UV laser micromachining setup. After expansion and collimation, the laser beam is directed vertically and focused with a high performance triplet lens. With an Al mirror inserted in the path of the convergent beam, the beam can be focused on a horizontal machining plane at any desired tilting angles. Microstructures of a wide range of geometries on hard materials can be formed using this custom machining method. Conventional linear and rotary machining on sapphire materials have been demonstrated.

INTRODUCTION

A variety of laser processes, including laser lithography, laser reinforcement and selective laser sintering are considered as emerging technologies for rapid prototyping [1]. However, the development and application of finely focused laser beams has stagnated since the widespread adoption of wafer dicing in the semiconductor industry [2,3]. The rapid progress and advancement of photonics devices, such as light-emitting diodes (LEDs) and laser diodes (LDs) calls for the rapid development of 3-dimensional fabrication technologies to enable the formation and assembly of micro-scale solid components. Focused laser beam micromachining is a promising candidate for this purpose.

EXPERIMENTAL DETAILS

Focused laser beam has widely been recognized as a tool suitable for in-depth fabrication or precise cutting and has been widely applied in wafer dicing. The physical process is that of ablation, due to the extremely high power density incident on the target material. This is realized by passing the laser beam through a high optical quality UV objective lens as shown in figure 1. In our experiments, a third harmonic ND:YLF diode-pumped solid state (DPSS) laser at 349 nm was used as the source, operating at 1000 Hz pulse repetition rate. After beam expansion and collimation, the laser beam is turned 90° by a laser line mirror and focused on the horizontal machining plane to a very tiny spot several micrometers in diameter. The added feature of the present set-up, as illustrated in the schematic diagram of figure 1, is the placement of a tilting mirror within the optical path, which serves to deflect the convergent beam to strike the sample at an oblique angle to the horizontal working plane. The size of the beam waist at the focusing point is not only limited by the capability of UV objective lens but also sensitive to the coaxiality of the optics. Using this modified set-up, it is relatively easy to optimize and monitor the location of the beam from the upper optical pathway through a tube lens together with a CCD camera. Once the optical setup is optimized before insertion of the tilting mirror,

the mirror can be inserted without affecting the coaxiality of the laser beam, so that the dimension of the beam spot remains unaffected. The focal length of the UV objective lens is 75 mm, which allows for the introduction of the tilting mirror and provides appropriated penetration depth of the laser beam into optical materials.

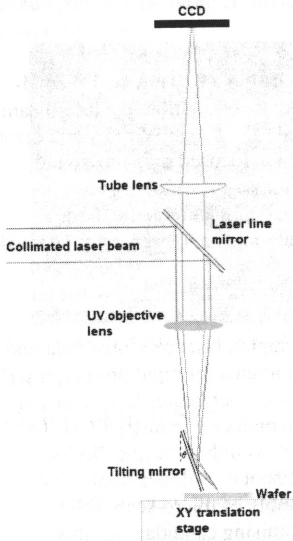

Figure 1. Setup diagram of tilting laser beam machining.

DISCUSSION

This tilted and focused laser beam can be effectively applied for cutting microstructures with desired angle profiles. The sample is mounted onto a precision motorized stage. The deflection of the laser beam or the incident angle to the wafer is 2θ, where θ is denoted in Fig.1 as the angle from the mirror plane to the vertical line. This angle can be controlled by mounting the mirror on a rotation stage. Figure 2 shows the result of two cuttings on a 415 μm thick sapphire wafer at 45° and 15° incident angles respectively. Both of the optical images are taken after 10 scan cycles. Obviously, it takes more scan cycles or requires higher diode pump current to penetrate through the wafer in an inclined manner. For custom wafer dicing, whether mechanically or through laser micromachining, the separation is completed by applying a mechanical bending stress. However, micromachining of inclined profiles makes it difficult to separate the tiny target structure from the matrix because of the fragile nature of the keen-edged profiles and the prolonged machining length to go through the wafer. Multiple scan cycles is performed to achieve deeper machining otherwise a thin-down polish process is needed

to separate the parts intact. In our experiments, self-break of the 415 μm sapphire wafer is observed after 10 cycles of laser scan at 15° incident angle.

Figure 2. Cross section views of sapphire wafers after straight line tilted cutting at incident angle of (a) 45° and (b) 15° respectively.

Apart from linear micromachining to fabricate cuboids, the setup is also capable of creating three-dimensional microstructures using a motorized rotary stage. The beam is focused at a controlled distance R from the rotary axis. While the stage is rotated the beam is cutting vertically or tilted, as the result a disk or conical structure is drilled through the sapphire substrate. The inverted conic structure is realized when the beam propagation axis intersect with the rotary axis at a point below the wafer surface; in the other case, when beam crosses the rotary axis over the wafer, a truncated conic structure is drilled out of the wafer. Some optical images of typical 3-D structures machined via laser micromachining are shown in figure 3. The side walls of the truncated cone and the truncated pyramid have a 50° internal angle with the base plane as the laser beam is accurately deflected by 2θ or 40°. The image of the truncated pyramid structure is taken with field-emission scanning-electron microscope (FE-SEM).

Figure 3. Optical 3-D images of the fabricated structures in the shape of cuboid (a) disk (b), inverted truncate cone (c), and a SEM image of a truncated pyramid structure (d). The samples are cleaned with HCl solution and sonication process except the disk.

Penetration depth

The beam power density reach maximum at the beam waist and drops sharply along the propagation axis. The ablation process is limited within the range where the beam power density is above the threshold. For vertical cutting without the tilting mirror, the laser beam can penetrate a 420 μm sapphire wafer after 10 scanning cycles at 2.86 A pump current and 50 μm/sec scanning speed. If a wafer is thin down to below 325 μm, tilted laser machining of a 50° inclined side wall as shown in figure 3 (c) and (d) is available with a 10-cycle micromachining at 3.16 A diode pump current and the same scan speed.

The capability of penetration depth and aspect ratio in the current setup mainly lies on the focal length of the objective lens [4], although the hardness and absorption coefficient of the material may also affects the profiles after machining, such as surface roughness, aspect ratio and heat affected zone (HAZ). In order to achieve in-depth machining as deep as a few hundreds micrometers, a 75 mm focal length of the objective lens is adopted in this experiment.

Debris remove and surface examination

Debris arising from laser ablation in the form of metal oxide and nitride can be removed by soaking in diluted (18%) HCl solution for 5 min, followed by sonication in deionized water. Figure 4 shows the FE-SEM view of a GaN/Sapphire wafer after tilting laser micromachining of 60° angle with 5 scan cycles highlighting the surface of the exposed sidewall after separation. The interface between the sapphire substrate and the GaN layer is clear and no heat affected zone (HAZ) is observed except for some resolidified melt clung on the surface of sapphire section. The thickness of GaN estimated from the image is 4.5 μm. Sedimentary by-product is largely removed after acid treatment and sonication, also seen in figure 3.

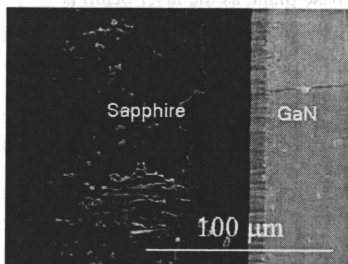

Figure 4. FE-SEM image of a GaN/Sapphire wafer after laser micromachining (the GaN thickness is about 4.5 μm)

CONCLUSIONS

Laser micromachining of inclined micro-structures are demonstrated using a tilting mirror as the angle controller. The parameters can be controlled to produce a wide range of microstructures, including conventional cubes, truncated pyramids, disks and even conic sections. The process was demonstrated on sapphire substrates, and thus can readily be adopted for InGaN/GaN LEDs.

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