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Developments in Silicon Wafer Micromachining

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Abstract—Most electronic components are based on monocrystalline silicon, with only a small percentage of them made of polycrystalline and amorphous silicon. Micromechanical components such as acceleration sensors in car safety systems and micro-fluidic circuits are also made of monocrystalline silicon. The machining of complex shapes from hard and brittle materials such as monocrystalline silicon still remains a critical area of research.

This paper explores the current status of research and developments in micromachining of silicon. Special focus is paid on the cutting methods employed in slicing and dicing of the silicon. Areas of concern that call for further research and development in micromachining of silicon are also discussed. It is expected that this paper will expose the challenging issues of silicon micromaching and wafer slicing and dicing, and also stimulate research interests in this area.

Keywords—laser, monocrystalline silicon, silicon wafers, slicing, dicing.

I. INTRODUCTION

EFFICIENT micromachining of monocrystalline silicon is essential for high production and high quality of products. In the recent past, silicon micromachining using lasers has generated a lot of interest. There are few manufacturing methods available for the precision processing of silicon i.e, grinding, lapping, electro discharge machining and chemomechanical polishing, but they are not suitable for very small and complex structures. Laser cutting offers new possibilities by selective processing of all kinds of silicon since it does not require any mechanical cutting force and does not result to any form of tool wear. However, during laser cutting, different kinds of defects can arise depending on the beam-material interaction phenomena. The defects include: brittle cracking, bulge formation and change in microstructural propeties of the heat affected zone (HAZ) [1].

A good understanding of the process and the various cutting parameters are essential to the successful application of the laser cutting process. Achieving a quality cut by laser depends on many factors such as laser characteristics, material properties of the specimen and manufacturing parameters. Laser process parameters include: pulse repetition rate, pulse duration and scan speed. Laser beam parameters include: laser power, spot size and depth of focus.

Silicon wafers are conventionally diced off by a thin diamond blade into individual IC chip, before they are packaged. The problems encountered in blade dicing include chipping, kerf loss and low productivity [2], [3]. Currently green wavelength (frequency doubled) and microjet are being used, but both of these processes are slow and expensive to operate [4]. Milliseconds low power pulsed Neodymium doped Yttrium Aluminium Garnet (Nd:YAG) lasers and high beam quality continuous wave fiber lasers have been used to cut brittle materials. However, the cut quality is poor i.e, microcracking due to excessive heat input, which can lead to failure of some components during process steps and associated reduction in yields [5]. The length of microcracks can range from 15 - 100 nm depending on the laser source [6].

II. SILICON WAFER DICING

A. Introduction

Wafer dicing is the process by which dies are separated from a wafer of semiconductor following the processing of the wafer. The dicing process can be accomplished by scribing and breaking, by mechanical sawing (normally with a machine called a wire saw), or by laser cutting [3]. Following the dicing process the individual silicon chips are encapsulated into chip carriers which are then suitable for use in building electronic devices such as computers, calculators and mobile phones. During dicing, wafers are typically mounted on dicing tape which has a sticky backing that holds the wafer on a thin sheet metal frame. Once a wafer has been diced, the pieces left on the dicing tape are referred to as dice or dies. These are packaged in a suitable package or placed directly on a printed circuit board substrate. The areas that have been cut away are called die streets, which are, typically about 75 μm wide. Once a wafer has been diced, the dies will stay on the dicing tape until they are extracted by die handling equipment, such as a die bonder or die sorter, further in the electronics assembly process.

The size of the die left on the tape may range from 35 mm^2 (very large) to 0.5 mm^2(very small). The dies created may be of any shape generated by straight lines, but they are typically rectangular or square shaped.

B. Chipping by diamond indentor.

Several studies have been performed to investigate the chipping modes produced in the die edges of diced silicon wafer using the thin diamond blades. The effects of dicing directions and different wafer types on the chipping size have been studied [3]. Scratch tests have been used to assist in analysis of the chipping conditions of the silicon wafer. The experimental results showed that the trace behaviors produced

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by the diamond indenter in the scratching test of silicon wafer can be divided into the three stages:

- rubbing
- plastic deformation
- cracking

The plastic pile up and the cracks of the scratching traces on the wafer mainly propagate along the slip direction family $< 110 >$. The chipping modes produced in dicing silicon wafer can be broadly classified as four types:

1) 30^ochipping
2) 60^o chipping
3) 90^o chipping
4) irregular chipping

C. Single and dual pass sawing

The drive for package thickness reduction has created new processing challenges with regards to thin wafer handling. While back-grinding and die attach film (DAF) lamination are now established procedures, sawing DAF laminated wafers with wafer thickness 3mm and below is still a significant challenge. There is need for a suitable saw process that meets the following criteria: less than 1mm wafer chipping, low cost and high throughput. Paydenkar *et al* [3] analyzed both single and dual pass saw processes. The effects of saw parameters: feed, speed, RPM and blade types were also elaborated. The results showed that for a thin die, a dual pass saw process gave better results than a conventional single pass process. The results also showed that application of non-optimized saw process parameters for a given DAF material set combination could adversely affect the yield consequent assembly processes like die attach and wire bond.

III. STEALTH DICING

A. Introduction

Dicing of silicon wafers may also be performed by a laser based technique, the so-called stealth dicing process. It works as a two stage process in which defect regions are firstly introduced into the wafer by scanning the beam along intended cutting lines, and secondly, an underlying carrier membrane is expanded to induce fracture.

The first step operates with a pulsed Nd:YAG laser, the wavelength of 1064 nm is well adopted to the electronic band gap of silicon (1.11 eV or 1117 nm), so that maximum absorption may well be adjusted by optical focusing [7]. Defect regions of about 10 μm width are inscribed by multiple scans of the laser along the intended dicing lanes, where the beam is focused at different depths of the wafer. Fig. 1 displays an optical micrograph of a cleavage plane of a separated chip of 150 μm thickness that was subjected to four laser scans. The topmost defects were the best resolved and it was realized that a single laser pulse caused a defected crystal region that resembled the shape of a candle flame. This shape was caused by the rapid melting and solidification of the irradiated region in the laser beam focus, where the temperature of only some small volumes suddenly rose to some 1000 K within nanoseconds and fell to ambient temperature again [8]. The laser is typically pulsed by a frequency of about 100 kHz, while the wafer is moved with a velocity of about 1 m/s. A defected region of about 10 μm width is finally inscribed in the wafer, along which preferential fracture occurs under mechanical loading. The fracture is performed in the second step and operates by radially expanding the carrier membrane to which the wafer is attached [1]. The cleavage initiates at the bottom and advances to the surface, and a high distortion density must be introduced at the bottom.

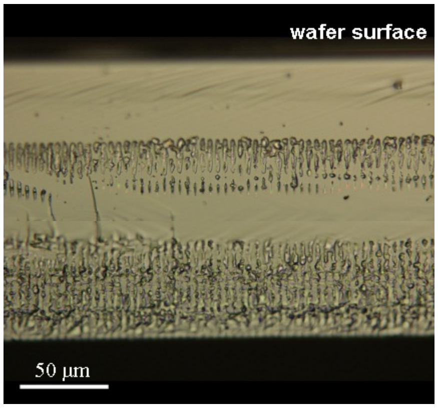

Fig. 1. Stealth diced wafer [8].

An advantage of the stealth dicing process that it does not require a cooling liquid. Dry dicing methods have been applied for the preparation of certain micro-electromechanical systems (MEMS), in particular, when these are intended for bio-electronic applications [8]. In addition, stealth dicing hardly generates debris and allows for improved exploitation of the wafer surface due to smaller kerf loss compared to wafer sawing.

B. High speed laser dicing of thin silicon wafers using line focus

For pulsed lasers with the same average power and repetition rate, the speed and quality of a dicing process can vary widely due to the strong influence of other laser characteristics such as pulse duration and wavelength [9]. For example, while longer pulse widths and longer wavelengths will generally cut faster, they are also more likely to cause excessive melting and cracking. Alternatively, shorter pulse widths (picoseconds and femtoseconds) and shorter wavelengths (ultraviolet) will offer the best quality results with minimal HAZ and high die strength. However, that was at a much higher cost and with lower system throughput. Richerzhagen *et al* [10] experimentally examined the efficiency advantage of line focus fluence optimization for thin silicon dicing. The results showed that even with the high quality of short pulse and short wavelength processing, exceptionally high cutting speeds are still possible. The low ablation threshold, which is a result of the short pulse width coupled with line focus fluence optimization, offers the best of both worlds: high quality of short wavelength machining with industrial scale process speeds. The longer beam spot produces a very high pulse overlap on the material and therefore a heavy averaging effect, resulting in the formation of smooth, laser precision cut sidewalls. Fig. 2 shows a single pulse ablation spot in silicon using pulsed laser with high aspect ratio elliptical line focus beam spot.

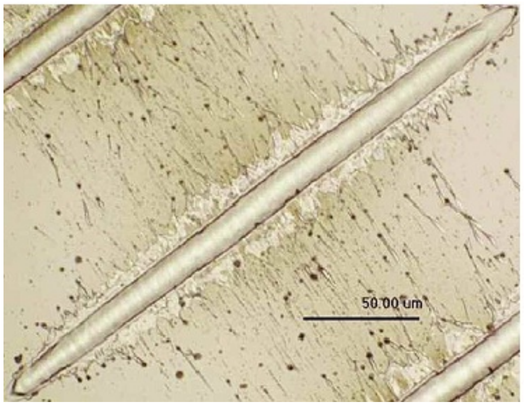

Fig. 2. Single pulse ablation spot in silicon using pulsed laser with high aspect ratio elliptical line focus beam spot [9].

C. Thin silicon wafer dicing with a dual focused laser beam

Dual focus has been proved to be able to improve the machining throughput and quality. Currently, the only way to generate two focal spots from a single laser source is to use a dual-focus lens. Fig. 3 shows the schematics of the setup for the dual focus dicing. Dual focus can be used for all laser ablation processes such as cutting, drilling, scribing to improve the machining efficiency and the quality. But a dual focus lens is not suitable for semiconductor wafer dicing due to the long separation distance between the two focal points (separation in the range of tens or hundreds of microns). Another factor that holds back the dual focus lens for semiconductor micromachining is that it is not telecentric. Therefore, using a translation stage is the only method of positioning the laser beam. This imposes a serious throughput limitation on the application of semiconductor wafer dicing processing. Krishnan *et al* [11] developed a technique to generate dual focus from a single laser beam. results of the investigation revealed that dual focus greatly improved the process of dicing thin silicon wafers

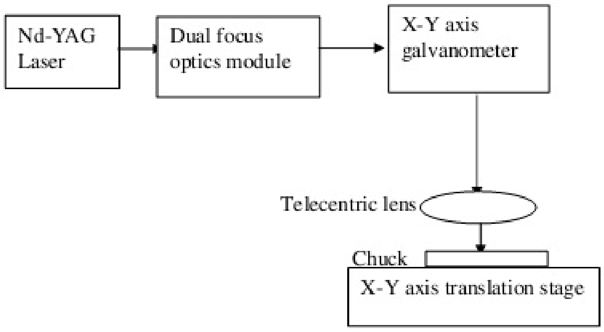

Fig. 3. Schematics of dual focus dicing setup [11].

D. Water jet guided laser cutting of silicon

The principle of the water jet guided laser technology entails coupling of a high power pulsed laser beam into a hair thin, low-pressure water jet [12]. Fig. 4 shows a schematic of the principle. The water jet guided laser technology offers several advantages over the conventional dry laser cutting process. First, because the water jet is cylindrical and the guided laser beam is parallel, kerf walls are highly parallel. The jet stable length and hence the working distance can be several centimeters long, depending on the jet diameter. There is thus no need for expensive focus control optics. The largest nozzle diameters used with the laser microjet process can yield working distances in excess of 15 cm. Secondly, the water jet prevents heat damage to the material by cooling the cutting edges in between the laser pulses. Thirdly, contamination is greatly reduced, as the water jet develops a high kinetic energy that efficiently removes the molten material generated by the laser ablation [10].

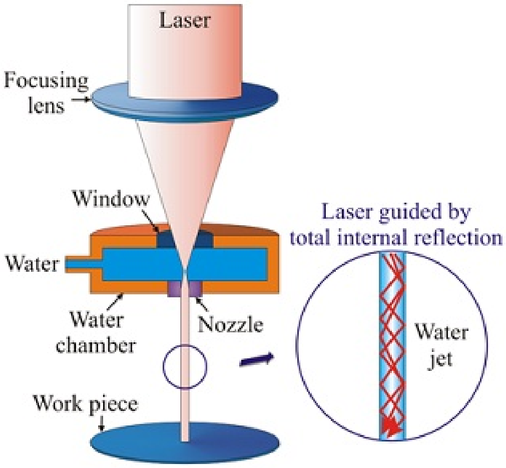

Fig. 4. Basic principle of the water jet-guided laser technology [10].

IV. DETERMINATION OF A GOOD WAFER

The main requirements for cutting of silicon wafers are dross free and crack free cut edges in a range of thicknesses.

A. Quantifying surface damage by measuring mechanical strength of silicon wafers

Colleti *et al* [13] performed the ring on ring test geometry. The investigations revealed the great importance of the saw damage on the mechanical stability of textured wafers. The initial surface defects made big and unexpected differences in the strength after a standard industrial acid etch. The measuring technique was very sensitive to the surface of the wafers rather than the edge. The influence of bulk defects was excluded too, as the strength of wafers from different manufacturers was analyzed. It permitted to focus on the modification of mechanical stability by adaptations of wafering or chemical treatment. The apparent critical crack length was introduced as an intuitive parameter to quantify the surface damage.

B. Mechanical strength of silicon wafers depending on wafer thickness and surface treatment

Colleti *et al* [6] investigated the mechanical stability of wafers with thickness ranging between 120 μm and 320 μm by means of tests with the ring on ring breakage tester. A linear relationship between breakage force and thickness was found. The results showed that thinner wafers tolerated a higher force than expected. The thinner wafers bent and stretched due to the increased flexibility, and redistributed the stress inside the wafer.

V. CONCLUSION

There are a number of application areas which might drive diamond indenting, sawing and stealth dicing into mainstream, mass-market industrial use. Some of the applications sectors include:
Biomedical devices: the need for smaller biomedical devices made from silicon.
Micro-optics: machining of micro-lenses or diffractive optical elements in optical materials with a high surface finish.
Photonics devices : machining of optical waveguides in bulk glasses or silica for photonic lightwave circuits and other telecommunications devices.
It is not clear which of the above applications, if any, will mature sufficiently in the future or whether other applications may emerge. There is no doubt that the range of applications being addressed with the micromachining methods is increasing.

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