Study of fast laser induced cutting of silicon materials

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ABSTRACT

We report on a fast machining process for cutting silicon wafers using laser radiation without melting or ablating and without additional pretreatment.

For the laser induced cutting of silicon materials a defocused Gaussian laser beam has been guided over the wafer surface. In the course of this, the laser radiation caused a thermal induced area of tension without affecting the material in any other way. With the beginning of the tension cracking process in the laser induced area of tension emerged a crack, which could be guided by the laser radiation along any direction over the wafer surface. The achieved cutting speed was greater than 1 m/s. We present results for different material modifications and wafer thicknesses. The qualitative assessment is based on SEM images of the cutting edges.

With this method it is possible to cut mono- and polycrystalline silicon wafers in a very fast and clean way, without having any waste products. Because the generated cracking edge is also very planar and has only a small roughness, with laser induced tension cracking high quality processing results are easily accessible.

1. INTRODUCTION

Separation of silicon wafer material is one of the essential processes in the semiconductor industry, including MEMS production and photovoltaic manufacturing. Presently, mechanical separation methods such as saw dicing and grinding have reached their technological limits that will hinder both the ongoing trend of product miniaturization and the increase of the productivity in photovoltaic production. The major concerns and limitations of these separation technologies can be addressed, among others, as follows: mechanical stresses, dicing street contamination with material inherent debris or/and external material, limited machining speed (up to 200 mm/s) and throughput, as well as imperfect edge quality. Alternatively to conventional separation, different laser-based silicon cutting technologies have been introduced recently: laser ablation dicing, laser microjet separation, thermal laser separation, and laser-induced subsurface modification.

In recent work, laser ablation dicing has been proposed as preferable for thin and brittle materials compared to saw dicing. [1] However, debris deposition due to material ablation and reduced machining speed (in the range of 50 mm/s) are still problems by using this technology. For clean and dry separation of silicon wafers, by contrast, thermal laser separation with dry cooling as well as laser induced subsurface separation have been suggested in [2] as the most promising technology for MEMS dicing. From industrial point of view, slow processing speeds between 25 mm/s and 300 mm/s [3] as well as the limited geometric shapes can be pointed out as major disadvantages for these technologies.

In addition, laser cutting based on thermal stresses to silicon wafer material by using a Gaussian single mode fiber laser was reported [4]. In this work, thermal gradients inducing compressive stress inside and tensile stress outside the laser spot have been used to separate silicon in defined geometries. For this, an initial crack (seed crack) was created at the outer area of the wafer, subsequently following the laser beam along its path across the wafer. By using this method, the maximum processing speeds were 0.55 m/s and 1.0 m/s obtained at 220 µm and 60 µm thick silicon wafers, respectively. Moreover, high machining qualities, vertical cutting edges, and completely flat cutting surface without any material losses or damage to the wafer surface have been demonstrated.

Another technology called “water assisted thermally driven separation mechanism” has been introduced in [5]. This method works without a seed crack and silicon wafers with a thickness of 200 µm were separated with a maximum cutting speed of 180 mm/s.

Our paper reports on studying fast laser-induced cutting of silicon material. A high-power continuous wave single mode fibre laser was used in combination with a galvanometer scan system for fast laser beam deflection. The main goal of our study was to significantly increase the cutting speed for silicon wafer separation with neither any material ablation nor damage to the wafer substrate.
2. EXPERIMENTAL

The experimental setup used in our study to investigate fast laser induced cutting of silicon materials is schematically shown in Figure 1. The single mode continuous wave fiber laser emits a maximum laser power of 3.3 kW. The wavelength of the laser beam was 1070 nm with a beam quality of $M^2 < 1.25$. To deflect the laser beam across the wafer surface a galvanometer scanner was applied. The focus spot diameter was 62 µm, achieved with a focusing optic of 500 mm focal length. The specimens were placed on a wafer holder on top of the processing table. There was a free space underneath the wafer to cut through. The distance between the scanner system and the wafer surface was adjustable. By this way, the irradiated laser beam diameter was varied in the study by defocusing in a range between 0.75 mm and 3.0 mm.

The investigation was carried out by using two different wafer materials: mono crystalline silicon with a thickness of 220 µm and poly crystalline silicon with a thickness of 200 µm.

Figure 1: Experimental setup.

Figure 2: Schematic of fast laser induced cutting of silicon wafers.

A schematic of the functional principle of the investigated laser induced silicon wafer cutting process is presented in Figure 2. In a first step, a seed crack was set at the starting point of the cutting path. The need of this initial crack in order to cut silicon wafers has been already reported in [4]. In our work, the seed crack was produced with the focused laser beam. After this, the laser beam was defocused in the range between 0.75 and to 3.0 mm. In a second step, this defocused laser beam was deflected across the wafer surface with a scan speed in the range of 0.7 up to 15 m/s. The laser power impinging on the wafer surface was varied between 150 W and 3,000 W.

The complete separation of silicon wafers has been considered as the main evaluation criterion in our study. In addition, both optical and SEM microscope photographs taken from the intersection areas of the separated wafers give a first impression about the process quality of the investigated technology in terms of edge bulging and roughness. Optical microscope surface evaluation has been done by positioning the specimens in side view under an angle of 10° to the vertical line. By doing so, more information about the surface characteristics can be obtained, as can be seen in Figure 3. Side views of the cutting edges are presented, placed either horizontally (left) or tilted by an angle of 10° under the optical microscope. While the cutting surface appeared to be very flat in horizontal view, an inhomogeneous surface characteristic can be seen by tilting the sample. This wafer was separated by irradiating a laser beam of 2 mm diameter, 2.5 m/s scan speed, and 600 W laser power.

Figure 3: Optical microscope photographs of laser separated silicon wafers in side view; the samples were placed horizontally (left) and tilted by an angle of 10° (right) under the microscope.
3. RESULTS AND DISCUSSION

3.1 Study of laser parameters for laser induced separation of silicon wafers

Figure 4 shows the impact of the laser power and the dimension of the impinging laser spot on the maximum feasible cutting speed per irradiated laser power to separate 200 µm poly crystalline silicon wafers. No significant effect of the laser spot diameter on the cutting process can be observed for cutting speeds up to 5 m/s. In the investigated laser spot diameter range, excluding the 0.75 mm spot diameter, the cutting speed increased linearly with the higher irradiated laser power. For the higher laser power it can be seen that the laser spot diameter affected the maximum achievable cutting speed. The highest cutting speed of 15.0 m/s was obtained by irradiating a laser beam of 3.0 kW power and 2.0 mm spot size (impinging the wafer surface). In contrast, by using the 3.0 kW laser beam and either 1.5 mm or 3.0 mm spot size, maximum cutting speeds have been achieved of 13.0 m/s and 12.5 m/s, respectively. From this, it can be concluded that laser induced cutting of the investigated poly crystalline silicon wafer material is most efficient when irradiating a laser beam of 2 mm spot size.

A similar processing behavior has been observed for laser induced cutting of mono crystalline silicon wafers of 220 µm thickness. As shown in Figure 5, with lower laser power in the range up to 1.2 kW, the cutting speed increased linearly to a maximum of 5.0 m/s, almost unaffected by the laser beam diameter. Only for the smaller laser beams of 0.75 and 1.0 mm, the maximum feasible cutting speed was limited of 0.7 m/s and 3.75 mm/s, obtained with respective irradiated 0.16 kW and 1.1 kW laser power. It is worth mentioning, that irradiation of these both small laser beams with higher laser power levels caused damage to the material due to high thermal stresses. However, for irradiated laser power higher than 1.2 kW it can be seen in the figure, that the laser beam diameter considerably affect the maximum cutting speed. The highest feasible speed to cut the 220 µm thick mono crystalline wafer was 14.0 m/s, obtained by irradiating the 3.0 kW laser beam at 2.0 mm spot size. By contrast, considerably lower cutting speeds of 10.0 m/s and 11.0 m/s have been obtained by irradiating laser beams of 3.0 kW and different laser spot diameters of 3.0 mm and 1.5 mm, respectively. As a result, laser cutting by using laser beams of 2.0 mm can be suggested as most efficient that is conclusive to the results reported above for poly crystalline silicon. Moreover, a further increase of the cutting speed can be proposed for single mode laser beam of higher laser power. This might be due because of no damage to the material has been observed by using the highest available laser power of 3.0 kW and beam diameters larger than 1.5 mm.
Figure 5: Maximum cutting speed versus laser beam power to separate 220 µm mono crystalline silicon wafers, the laser beam diameter was varied in a range between 0.75 mm and 3.0 mm.

The plot given in Figure 6 shows the minimum required energy per unit length versus the maximum feasible cutting speed to separate the 220 µm thick mono crystalline wafer. The energy per unit length was calculated by the laser power divided by the processing speed. For this, the data given in Figure 4 were taken into account. The figure points out that particularly for higher cutting speeds the lowest amount of energy per unit length was needed with the 2 mm laser beam, compared to other beam diameters and identical nominal cutting speeds. Considering the maximum feasible cutting speed of 14 m/s, an energy need per unit length of 200 W/m was needed here. For the other investigated laser beam diameters, a minimum energy per unit length demand ranging between 180 W/m and 340 W/m has been experimentally determined to separate the wafers.

Figure 6: Demand on energy per unit length versus cutting speed to separate 220 µm mono crystalline silicon wafers, the laser beam diameter was varied in a range between 1 mm and 3.0 mm.
Moreover, a significant fluctuation in the curves of figure 6 can be seen for all investigated beam diameters. Initially, the energy need per unit length decreased with increasing cutting speed, followed by an increased energy need for a little higher cutting speed. This fluctuation is repeated in the further curve progression. This phenomenon has not been fully clarified during the study, but the fluctuating curve progression was confirmed by a number of experiments. Until now only the lower process limit was considered, given by the minimum laser power that has to be irradiated to reach a nominal cutting speed. However, it is not hard to imagine that a higher laser power can be applied to cut the wafers by using this nominal cutting speed. The minimum cutting speed applicable with no damage to the wafer material per laser power determines the upper limit of the cutting process. These both limits determine the process window indicating the range of appropriate processing conditions for laser induced wafer separation. Figure 7 presents the process window for laser induced wafer separation as experimentally determined in our study for the 2 mm laser beam. Results obtained for both wafer materials of interest, the mono crystalline and the polycrystalline silicon, have been included. For example, the figure points out that cutting speed ranging from 3 m/s to 9 m/s can be achieved by irradiating 2 kW laser power. For a laser beam of 3 kW power, by contrast, increased cutting speeds in the range between 4 m/s and 14 m/s can be applied.

3.2 Qualitative view on laser induced separated silicon wafer

An initial view on the cutting quality which can be obtained by using this laser induced wafer separation technology is given following by means of optical and SEM microscope photographs. Side views of laser separation wafers are presented in Figure 8 (mono crystalline silicon) and Figure 9 (poly crystalline). It can be seen that laser cutting by irradiating the 2 mm laser beam of 2.8 kW power and 14.0 m/s cutting speed potentially induce sharp cutting edges. In addition, it can be suggested that the cutting surface obtained on mono crystalline silicon appeared smoother, compared to polycrystalline silicon.

Figure 7: Process window to cut silicon wafer materials using a laser beam of 2 mm diameter.

Figure 8: Side view on a cut surface obtained on 220 µm mono crystalline silicon wafer, a laser beam of 2 mm diameter, 2.8 kW laser power, and 14 m/s cutting speed was irradiated.

Figure 9: Side view on a cut surface obtained on 200 µm poly crystalline silicon wafer, a laser beam of 2 mm diameter, 2.8 kW laser power, and 14 m/s cutting speed was irradiated.
The Figures 10 and 11 present a closer view on the laser induced separated silicon wafers by means of side-view SEM images. No evidence of melting or ablation of the silicon wafer material can be observed. A higher degree of non-uniformity with respect to the quality of the cutting edges can be estimated for mono crystalline silicon. By taking into account Figure 13, erosion artefacts have been measured along the laser cut edges in the range of 2 µm for poly crystalline silicon. This is notably smaller than 4 µm that have been observed for mono crystalline silicon in Figure 12. However, further work is needed to determine optimized processing conditions in terms of surface roughness and edge quality.

4. CONCLUSION

In this work, we introduced a new method for fast laser induced separation of silicon wafer materials (mono crystalline and poly crystalline silicon). We investigated the impact of both the laser beam power and the laser beam diameter on the cutting speed. With the maximum available laser power of 3.0 kW a maximum cutting speed of 15 m/s was demonstrated to separate 200 µm thick poly crystalline silicon wafers. A little lower cutting speed of 14 m/s was reached to cut 220 µm thick mono crystalline silicon wafers. This is more than two orders of magnitude faster than cutting speeds reported elsewhere to separate silicon wafers. In addition, we found a laser beam diameter of 2 mm as most efficient to cut the wafer material. Sharp cutting edges and smooth cutting surfaces have been obtained by using this technology without material cracking, melting or ablation. Moreover, it was detected that the cutting process is stable within a large processing window. These advantages might be beneficial for industrial applications of the technology, potentially in photovoltaic and electronics.
Our future work is focused to investigate the spatial resolution of laser induced wafer separation as well as the feasible wafer thickness. In addition, separation of the silicon wafers in pieces of any desired geometries is of interest. Further work is required to study the mechanism causing the fluctuation in the laser beam power versus cutting speed - curve detected for mono crystalline silicon.

ACKNOWLEDGEMENT

The presented results have been conducted in the course of the project “SONNE” funded by the German “Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit” following a resolution of the German “Bundestag”, grant agreement number 0325277B. The authors are responsible for the content of this paper.

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