Laser Grooving of Copper for Microelectronics

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Copper has emerged as a critical material in the semiconductor industry due to its superior electrical and thermal conductivity. For the classical wafer separation process using a blade, the presences of copper in the dicing lane is challenging and often the copper layer needs to be removed by laser grooving to achieve a high quality blade cut. The goal of this study is to investigate the influence of the applied average power from the laser head, the feed speed of the linear stages and beam splitting using an elliptical beam on the grooving dynamics of copper. The commercially available short pulse laser system DFL7262 from DISCO, which operates at wavelength of 355 nm was used to optimize the grooving process towards highest efficiency. Different multi beam configurations were characterized in terms of grooving depth as a function of fluence, feed speed and number of overscans. In addition the average roughness is investigated for selected settings.
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1. Introduction

The semiconductor industry is one of the most advanced and sophisticated industries in the world. Stable operations and fine-tuned process steps are key for 24/7 high quality mass production on a micro- and nanometer scale. One important material for semiconductor device manufacturing is copper. Its' exceptional electrical conductivity enables efficient electron flow and the low resistance translates to reduced power dissipation and heat generation compared to other materials. Despite its` advantages for the device functionality, copper introduces challenges to one of the most critical manufacturing steps along the process chain, the wafer separation into single dies. From frontend point of view, no additional value is added to the wafer itself, and for backend high quality incoming dies are a key for a stable yield. Therefore a lot of effort is spent to provide best in class separation techniques and high efficient process steps. Fig. 1 shows the evolution of dicing equipment from blade dicer to the laser saw.

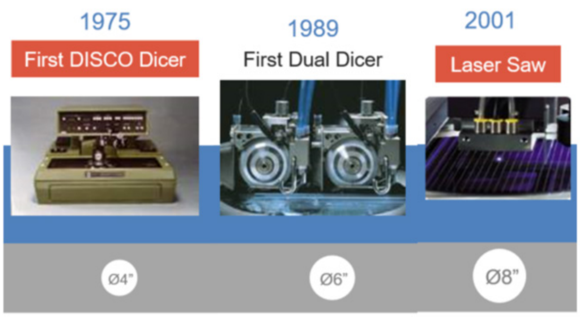

Fig.1 Evolution of wafer separation equipment: First DISCO blade dicer was introduced 1975, since 2001 laser saws are introduced to the market.

DISCO is a semiconductor equipment manufacturer providing precision processing equipment, including dicing saws and grinders, and precision processing tools (blades and wheels) used for manufacturing semiconductors and electrical components. The classical workhorse of the semiconductor industry is mechanical sawing. For decades, processes and tools where optimized and most of the silicon wafer are diced using a sawing blade. Nevertheless the need to add other materials like copper inside the dicing lane can cause blade clogging, sidewall chipping and surface damages during blade dicing [1]. The solution was the introduction of laser grooving for certain products with challenging kerf conditions. Fig. 2 displays the typical process flow for laser grooving followed by blade dicing on tape and frame.

Fig. 2 Process flow of laser grooving followed by blade dicing.

In the past, mainly ns-laser grooving was used to pre-condition the dicing kerf for a high quality blade cut. The downside is the reduced die strength for long pulse laser grooving due to the thermal damage introduced by energy release over a relatively large time scale. This leads to a Heat Affected Zone (HAZ), where remaining Silicon is not in single crystal orientation anymore, but remolten into poly-crystalline Silicon, containing small voids and dislocations. [2, 3, 4] This is weakening the mechanical stability of the device and can reduce the overall separation yield. Compared to long pulse laser grooving an increased robustness can be achieved using short pulses and therefore reducing the material damage from thermal to optical penetration depth. (Fig. 3) The main drawback using short pulse laser at the beginning was the reduced throughput and therefore relatively high cost of ownership to reach a desired quality. But over the last years new system architectures and reliable high average power laser heads combined with a high repetition rate allowed to meet the throughput requirements of the Industry.

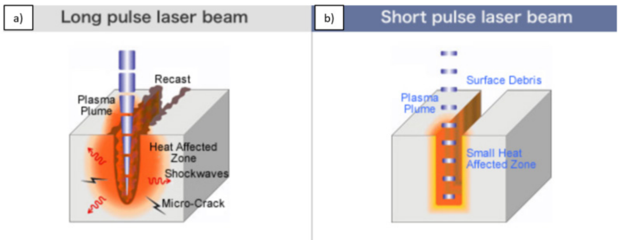

Fig. 3 Schematic drawing of the HAZ for laser grooving with (a) long pulse and (b) short pulse laser beam.

The laser parameter and optical setup for grooving needs to be optimized to introduce as little damage as possible and minimize the thermal impact on the remaining grooved surface. Reducing the HAZ to minimum is significantly improving the mechanical integrity of the chip which can be measured via 3 point bending strength after mechanical blade cut, like it is shown in Fig. 4. [5] The main goal is to keep the mechanical robustness compared to a single blade cut without laser grooving upfront, which is not possible for real production due to the above mentioned problems.

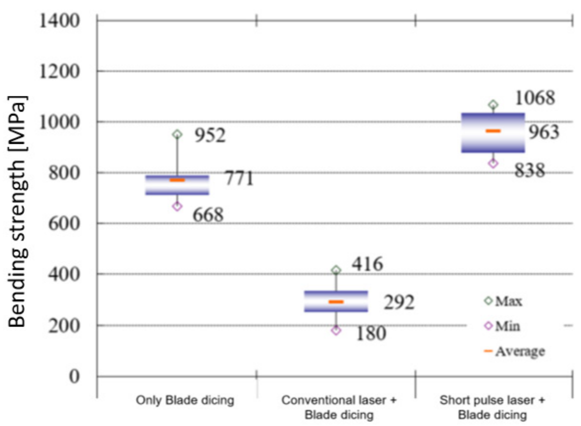

Fig. 4 Comparison of bending strength for Si wafer. Only blade cut (left) Laser grooving with long pulse (middle) and short pulse laser (right) followed by blade dicing. [6]

2. Equipment

All experiments were performed on the commercially available laser platform DFL7262 from DISCO (Fig. 5). The latest laser dicing platform achieves a high throughput due to a high speed axis system and provides excellent machine up-time. A variety of built-in diagnostic functions are continuously monitoring the process and machine conditions like temperature and laser power stability. A beam profiler was used to setup the beam configuration for the experimental investigations. The new optical beam shaping system gives a wide flexibility for micromachining of different materials. One attractive version of beam manipulation for grooving is an elliptical configuration perpendicular to grooving direction. This allows a wide flexibility of processing due to the possibility to adapt the length of the elongated axis within in the focal point directly to the requested grooving width.

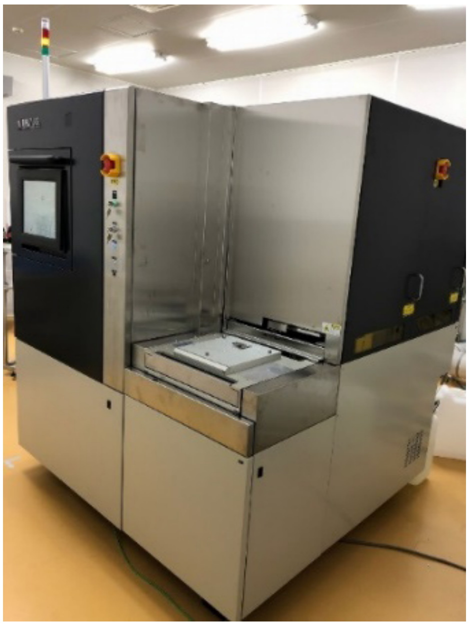

Fig. 5 DISCO fully automated laser dicing platform DFL7262.

3. Materials and Experimental Methods

The used base material for all experiments are prime grade Silicon wafers with (100) crystal orientation. A 5 µm thick copper layer was applied on the surface by Ion sputtering. For all experiments a short pulse solid-state laser with a wavelength of 355 nm was used. To protect the surrounding surface area of the laser processed lanes from debris during machining a water-soluble protective coating HOGOMAX103 was spin-coated prior to laser grooving. The coating was washed away after processing together with the debris particles using standard pressurized water cleaning. Three different arrays of beam splitting configurations (Single beam, split 4 and split 8) for a fixed beam width of 45 µm were investigated, One pass laser grooving was performed by varying the laser power (P_{avg} = [2 W; 12 W], Δ = 2 W) and feed speed of the linear stages (v_{feed} = [200 mm/s; 1000 mm/s], Δ = 200 mm/s) to generate a characterization matrix of 36 measurement points for each setting.

The profile of the laser grooves and the roughness was measured using a laser scanning microscope VK-X3000 from Keyence.

4. Results and Discussion

For reliable and high quality grooving of Copper the used laser parameter needs to be set close to the optimal working point with respect to the applied fluence. In general laser grooving has clear 3-dimesional targets in terms of grooving width, length and depth. Laser grooving of a media with strong linear absorption is following the concept of exponential attenuation of energy distribution into the material. This leads to a logarithmic dependence of grooving depth on the peak fluence [6].

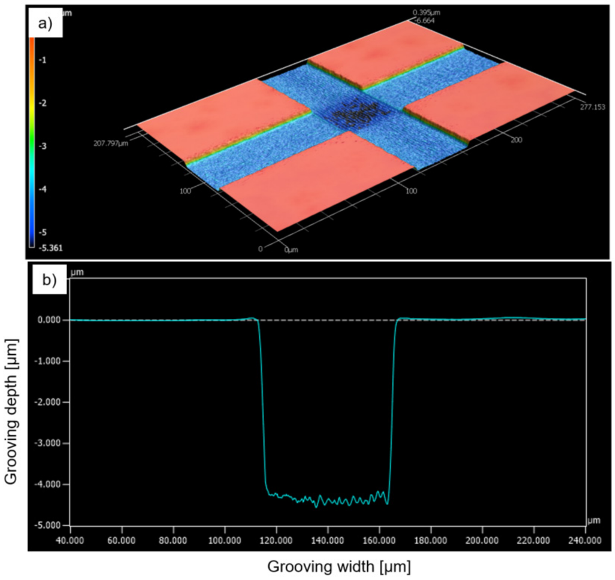

Fig. 6 Example of a short pulse laser grooving application with zero burr and homogenous depth control over the whole grooving lane. (a) Displays a 3D view of intersection after laser grooving and (b) is the corresponding shape profile measurement.

The idea of the elliptical beam is to use the available average power in the most efficient way, by elongating the spot size perpendicular to the grooving direction with respect to the required grooving width and therefore shifting the process point net fluence closer to optimal conditions (Fig. 6). The grooving depth d with respect to the applied fluence F_0 for a single line groove is following Eq. (1) [7]:

$$d = d_0 * \ln\left(\frac{F_0}{F_{th,gr}}\right), \tag{1}$$

The parameters d_0 and $F_{th,gr}$ can be determined by curve fitting, as shown in Fig. 7. Within the investigated parameter range, a good correlation between experimental and theoretical results is visible.

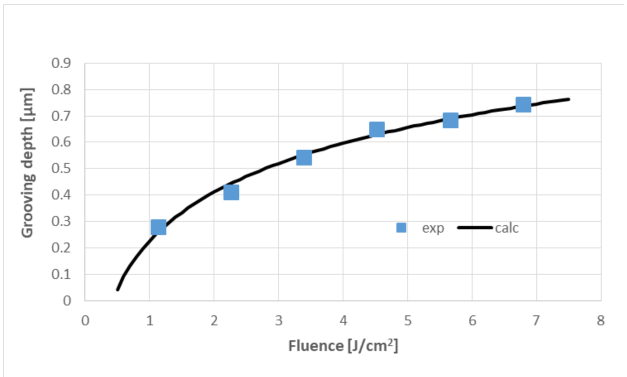

Fig. 7 Grooving depth as a function of the applied fluence.

The value d_0 is a linear function of the number of pulses N_{eff} incident on the wafer at a certain position. The slope d_{SP} presents the ablation depth of a single spot at a fluence of e x $F_{th,gr}$, as shown in Eq. (2).

$$d_0 = d_{SP} * N_{eff}, \tag{2}$$

Adding up all single shot fluences that contributes to the ablation within a certain distance ω_{minor}, is leading to the net fluence. N_{eff} can be interpreted as the equivalent number of accumulated individual fluences to reach the same peak and can be calculated by Eq. (3) [7, 8].

$$N_{eff} = \sqrt{\frac{\pi}{2}} \frac{\omega_{minor} * frep}{v_{stage}}, \tag{3}$$

For a grooving width of 45µm and therefore an elongation of the major axis to the same value, a threshold fluence for Copper of $F_{th,\,gr}$ = 0.49 ± 0.02 J/cm^2 was determined. Only for a feed speed of 200 mm/s the threshold value is slightly lower, which is most likely a result of heat accumulation due to increased pulse overlap. Additional the ablation depth of a single pulse with 174.39 nm is reduced by 12.5 % compared to the investigated higher feed speeds, indicating a reduced grooving efficiency.

Table 1 Fitting parameter for 45 µm elongated line focus showing a constant grooving threshold and single spot ablation depth over the investigated feed speed range from 200-1000 mm/s.

v_{feed} [mm/s]	N_{eff} [shot]	d_0 [µm]	F_{th} [J/cm^2]	d_{sp} [nm]
200	15.67	2.73	0.45	174.39
400	7.83	1.55	0.51	198.37
600	5.22	1.03	0.49	197.67
800	3.92	0.80	0.51	203.34
1000	3.13	0.63	0.50	199.70

Another known correlation is the dependence of the resulting grooving depth from the feed speed v_{feed} as shown in Eq. (4) for a given laser fluence. The fitting parameter A can be used to adjust the speed with respect to the requested grooving depth (Fig. 8) and also can help to determine if lowering the feed speed or doing more overpasses at a higher speed is leading to a faster overall throughput.

$$d_{groove}(v) = \frac{A}{v_{feed}}, \tag{4}$$

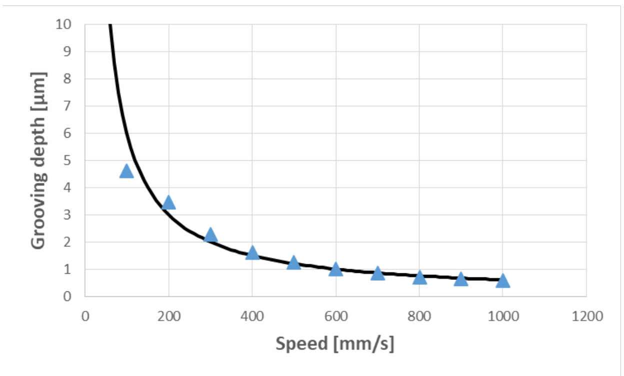

Fig. 8 Grooving depth as a function of the applied feed speed.

To further improve the process efficiency a widely used approach is the implementation of diffractive optical elements (DOE) inside the optical path. A DOE consists of a glass plate with special etched micro structures, which are altering the phase of the light propagated through and thus generate beam patterns in almost any configuration. The main goal is usually to increase the area over which the pulse energy is released and therefore allow the shifting of the processing point closer to the optimal fluence conditions without sacrificing available average power.

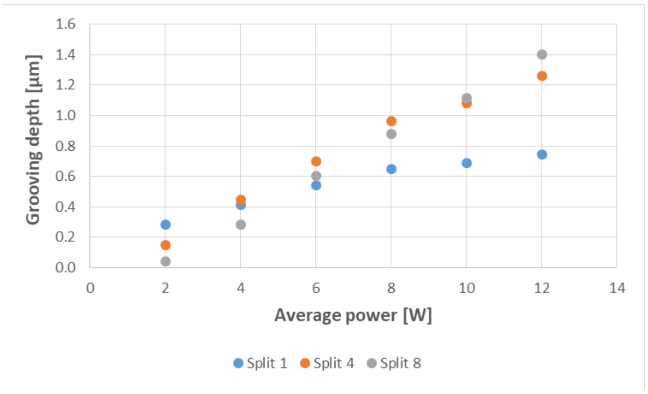

Fig. 9 Grooving depth as a function of the average power for single beam, Split 4 and Split 8.

In Fig. 9 the grooving depth for a fixed feed speed is plotted as a function of the applied power for a single beam and multi beam configuration (spilt 4 and split 8). Whereas the single beam is already reaching saturation of the grooving depth at a power of around 8 W, the multi beam approaches did not saturate in the investigated power regime and shows for 12 W a grooving depth improvement of 45 % compared to the single beam. Fig. 10 is showing the efficiency plotted as a function of fluence and is giving an explanation of the improved performance using DOEs. Due to increased area the fluence is shifted towards lower values in each beam of the multi beam array and the energy incoupling of the laser light is improved, which leads to a deeper groove for the same applied average power.

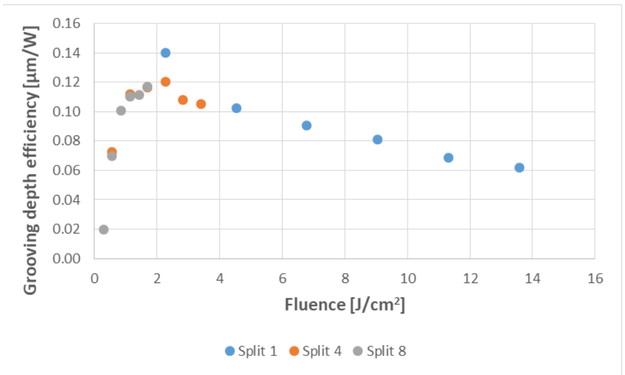

Fig. 10 Grooving depth efficiency as a function of the peak fluence for single beam, Split 4 and Split 8.

Additionally the quality of the ablation process is improved, due to less thermal damage. For a fixed speed and average power of 12 W, the measured roughness R_a at the bottom of the grooved traces decreases from 128 nm for single beam, to 86 nm for a split 4 and 54 nm by applying an 8 split configuration (Fig. 11).

Fig. 11 Microscope images for a fixed feed speed and average power of 12W. Improved optical quality visible for higher amount of splitting.

5. Conclusion

Latest grooving equipment DFL7262 from DISCO can be used to micro machine copper with superior quality in terms of depth control, zero burr and low average roughness of the remaining material. The benefits of increased spot area due to working close to optimal processing conditions using an elliptical beam perpendicular to grooving direction could be nicely demonstrated and matches well with theoretical assumptions. Additionally it was presented that the multi beam approach is suitable to use the available average power more efficient due to lowering the processing fluence,

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