LidroCUT – Ultrashort-pulsed laser processing in liquids for clean dicing in one process step

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Abstract

Ultrashort-pulsed laser dicing in liquids, a combination of laser cutting and flowing liquids is a new technology for wafer dicing. This technology can cut any material at very high quality with virtually zero yield loss. This makes it possible to cut even complex material stacks with a single machine in one process. In detail, an ultra-short pulsed laser effectively cuts the material, while the liquid prevents heating of the substrate and adjacent structures, in addition to effectively flushing debris away from the kerf, keeping the sidewall and device clean. In this paper, the features of cleanliness, sidewall quality and thermal impact for silicon, copper on silicon and mold compound are presented.

Key words

Dicing, laser ablation in liquids, advanced packaging, cleanliness

I. Introduction

The semiconductor industry has long relied on the saw blade as the standard technology for wafer dicing. While effective, this method introduces significant mechanical forces that pose a high risk of damaging chips, particularly as wafers become thinner in the shift towards advanced packaging technologies, for example the use of chiplets [1]. Other singulation technologies such as Stealth Dicing [2], LaserMicroJet Dicing [3], TLS Dicing[4], plasma dicing [5], and conventional laser dicing [6] have been developed. However, these methods are not without their own limitations [7,8]; laser technologies, for instance, can generate excessive heat even with ultrashort laser pulses, potentially damaging the delicate wafer structures, and debris from these processes can contaminate the wafer surface, compromising the integrity of the final product [9].

As the semiconductor industry transitions from 2D to 3D packaging and thereby strongly relies on thinner wafers, there is a growing demand for innovative separation methods that can meet the stringent requirements of these advanced applications. Thinner packages necessitate cleaner processing techniques to ensure reliability and performance [7].

LidroCUT – laser dicing in liquids circumvents the issues associated with mechanical pressure as it is a non-contact method. This technology not only eliminates the risk of mechanical damage but also addresses thermal concerns through the use of a flushing liquid when compared to other laser technologies. The liquid cools down the wafer surface during laser processing, effectively dissipating heat and preventing thermal damage [10]. Furthermore, the flushing liquid plays a crucial role in managing debris; it cools ejected particles and stabilizes them within the liquid, preventing re-adhesion to the wafer surface.

In this paper, we present evidence that laser cutting in liquids using ultrashort-pulsed lasers, achieves exceptionally clean results. The effectiveness of this technology is such that cleaning steps after dicing may become redundant. The findings outlined herein demonstrate the technologies' potential to meet the evolving needs of the semiconductor industry, ensuring high-quality, damage-free dicing for advanced, thinner wafers.

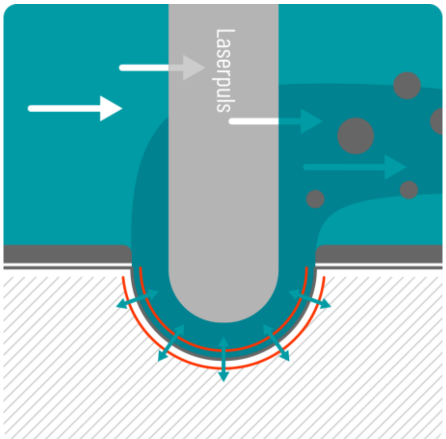

Figure 1: Schematic of laser cutting in liquids. A liquid is flowing over the surface of the wafer. A laser beam is guided through the liquid onto the substrate. At the substrate's surface, the high intensity of the laser beam ablates the material while the processing zone is cooled and rinsed by the liquid.

II. LidroCUT – ultrashort-pulsed laser dicing in liquids

The LidroCUT technology combines the advantages of conventional laser dicing to cut contactless and free-forms with high flexibility with the advantages of a wet processing which allows to cool the substrate material during processing and flushing away debris and therefore, cleaning the substrate during processing.

At the core of LidroCUT, it is a laser process cutting in a liquid (compare Figure 1) where the liquid is flowing over the substrate while a laser beam is transmitted through the liquid onto the substrates surface. On the surface, the laser energy is deposited leading to the ablation of the surface area.

Besides the technological advantages of having a cooled and clean process, the process does not require any adjustment in the standard dicing procedures. It can be used with standard dicing tapes or other wafer carriers. No additional processes, as for example coating or cleaning steps, are required.

III. Methodology

In this paper, three different substrates are presented. Silicon (Si), Copper deposited on Silicon (Cu-on-Si) and Mold Compound (MC). These materials represent the most used materials. These materials are exemplary for materials used in the sector of advanced packaging.
The silicon was 200 µm thick with an <100> crystal orientation. The processed side was polished. For the copper on silicon interface, a ten µm thick layer of copper was deposited onto the Si. The mold compound was 370 µm thick with SiO_2 filler.

The samples were processed in two ways in order to demonstrate the cleanliness of laser cutting in liquids. On the one hand, the samples were processed in the liquid. On the other hand, the samples were processed with the same system but in a conventional manner without a liquid flowing over the substrate in air.
For the sake of simplicity, several simplifications must be taken into account:
i) Samples were treated in a non-clean room environment. Therefore, contamination from the environment is possible and visible here. However, debris from the process can be well identified.
ii) Samples under liquid flow as well as in air were processed with the same set of parameters.
While this approach simplifies the investigation, it is important to note that in practical applications, process parameters are typically fine-tuned to meet specific requirements. Despite this simplification, fundamental differences between the two processes can still be demonstrated, as the underlying physics remain consistent. Therefore, any variations observed in the output can be attributed to the differing environments, providing valuable insights into the performance and efficacy of each method.
Furthermore, laser power and effective cutting speeds are in the same order of magnitude as use-cases with real applications. The parameters reach effective cutting speeds in the order of several wafer per hour, depending on the thickness and use case, comparable to dicing speeds with established methods.
The samples were investigated by optical microscopy (OM) and scanning electron microscopy (SEM). Microscopy images are typically shown in the dark field mode to show the impact of small particles and surface deviations due to the laser processing.
First, the results regarding the surface quality are shown. Second, the data on the sidewall quality will be discussed.
Furthermore, it should be noted that the conventional laser cutting could not cut through the materials with the same parameters whereas it was fully cut within the liquid.

IV. Surface quality results

In this paragraph, the surface quality of the conventional laser process in air and in liquid will be presented and discussed.

A. Silicon substrate

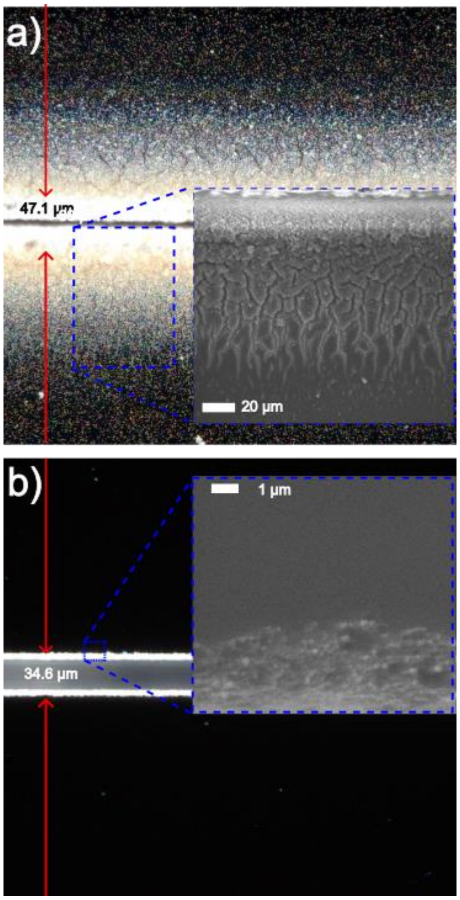

Figure 2: a) Sample cut of a 200 µm thick Silicon wafer diced in air. b) Sample cut of a 200 µm thick Silicon wafer diced in liquid.

Figure 2 a) shows a dark field microscopy result with an SEM image inlet when the sample was processed conventionally in air while Figure 2 b) shows the result of a full cut when it was processed in liquid. It should be noted that the sample processed in air was not cut through.

Figure 2 a) shows that the conventional laser processing leads to a strong distribution of debris around the processed area. Moreover, the debris structure shows channels and a color change which indicates that the debris was still molten when reaching the substrate leading to the formation of these channels. A further indication of excessive heat impact is the appearance of the rainbow colors, which can be slightly seen in the dark field image, that indicates the formation of an oxidized layer at the surface where the interference leads to the formation of the rainbow effect within the microscope image.

Comparing the results, Figure 2 b) shows a very clean kerf without debris observed around the processed area. The kerf is enclosed by a small region inducing a rounded edge into the silicon with a width of approximately 4 µm. This region occurs due to the low energy in the flank of the gaussian beam profile. It should be noted that the height of this region is below the level of the polished silicon substrate. As visible in the SEM image inlet, no debris could be observed outside of the rounded edge area.

Furthermore, the kerf performed in liquid seems to be larger than the kerf performed in air. However, this may be attributed to re-deposition of Si at the sidewalls as it cannot be carried away effectively in air.

This result highlights the cleanliness of laser cutting in liquids for silicon performed with only one process step. It emphasizes that the technology can be used in particle sensitive packaging applications like hybrid bonding.

B. Copper on Silicon

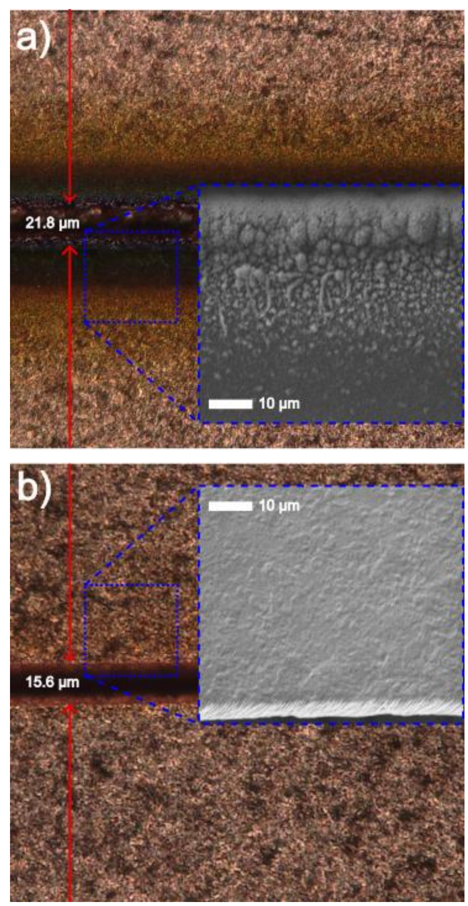

Figure 3: a) Sample cut of copper deposited on silicon diced in air. b) Sample cut of copper deposited on silicon diced in liquid.

Figure 3a) shows the Cu-on-Si system processed in air. A strong formation of debris and burr can be observed. Furthermore, the microscopy image seems to indicate a change of color in the copper which could occur due to the heating and oxidation of the copper. The SEM-inlet in Figure 3a) shows the well defined burr and debris structure close to the kerf as well as dispersed particles at increasing distances from the kerf.

In comparison, Figure 3b) shows the sample processed in liquid. Besides the rounded edge, no further debris or influence can be observed neither in the optical nor in the electron microscopy image.

This result shows not only the cleanliness of the laser cutting in liquids approach but also that the metal deposited onto the Si does not affect the cut in a negative manner, e.g. the formation of burr or melt drops. Thus, laser cutting in liquids shows the ability to not only cut single materials but also material stacks including metals and semiconductor materials.

C. Mold Compound

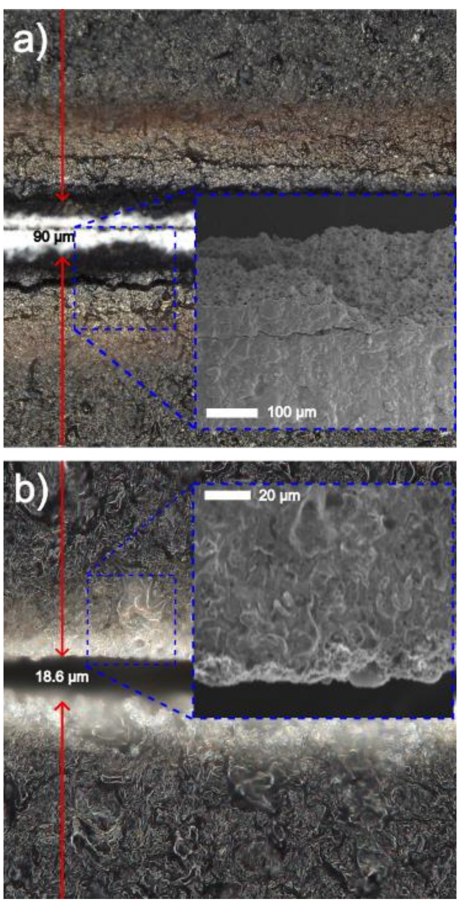

Figure 4: a) Sample cut of mold compound diced in air. b) Sample cut of mold compound diced in liquid.

For the analysis of the mold compound material, it should be noted that an equal laser power comparison between the conventional process and liquid process could not be performed as the mold compound material started burning using 5x less power compared to when using a liquid. This fact already confirms that the cooling by the liquid is very effective.

This is further emphasized by the comparison of Figure 5a) and b). It is obvious that the area affected by the laser beam is much larger when processing in air compared to processing in liquid.

Furthermore, the high amount of heat stored in the substrate leads to severe cracking of the surface as can be observed in the optical microscopy image as well as in the SEM image. This is most probably due to the reason that mold compound is an organic material with a low heat conductivity (1-10 W/mK [11]) compared to silicon (139 W/mK [12]) and copper (401 W/mk [13]). However, these effects are not observed in Figure 5 b) where a clean cut resulted when cutting in liquid without cracking.

However, it has to be stated that debris does not seem to be an issue of concern here. This occurs most likely due to the fact, that the organic material almost instantaneously evaporates and does not re-condensate on the surface. This is in accordance with the work done by reference [14] who were able to cut thick mold compound by conventional laser processing in air.

V. Sidewall quality results

In this paragraph, the sidewall quality regarding cleanliness, so the upper part of the kerf, will be presented and discussed.

A. Silicon substrate

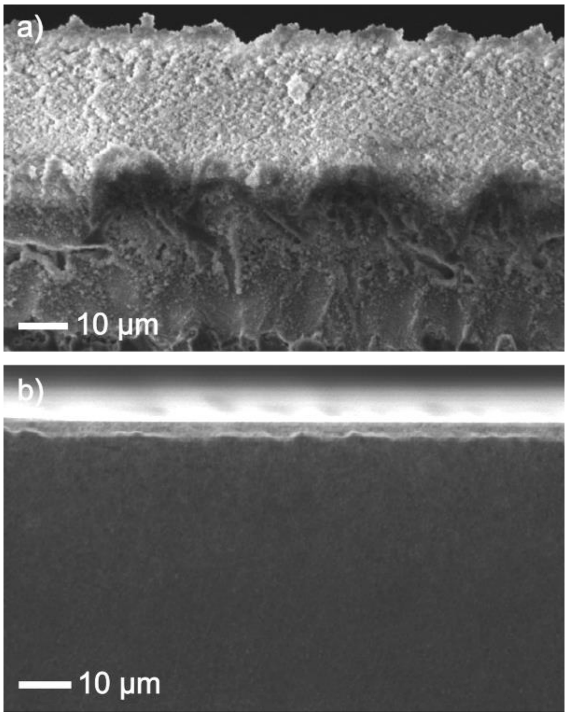

Figure 5: a) Sidewall of the sample cut of silicon diced in air. b) Sidewll of the sample cut of silicon diced in liquid.

Figure 5a) shows a high amount of debris above the kerf as well as melt traces on the sidewall. In contrast, Figure 5b) shows a very clean cut and no debris or burr remaining on the surface. The transition from the small curved or tapered region at the surface to the steep sidewall can be observed as discussed previously.

This result shows how exceptionally clean the laser cutting in liquid is without any melt traces or burr at the sidewall.

B. Copper on Silicon

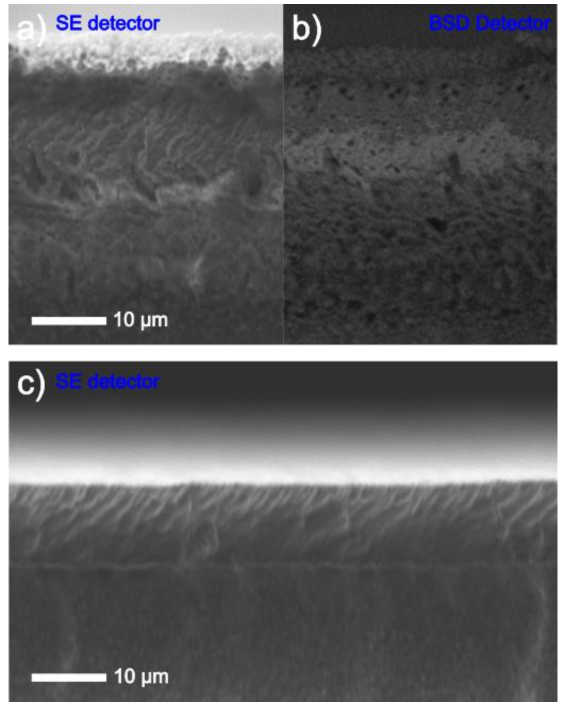

Figure 6: a) Sidewall of the sample cut of copper deposited on silicon diced in air. b) Sidewall of the sample cut of copper deposited on silicon diced in liquid.

In Figure 6 a), the side wall result of the kerf edge shows a rich amount of physics. To make the findings more evident, we performed an additional measurement with a backscatter detector in the SEM. Figure 6 a) shows that the copper layer was remolten and deformed, similar to reference [15], and is enclosed into a sandwich structure of silicon. Thus, silicon and copper debris moved on top of the pure copper layer. Furthermore, on the lower side, the copper also was fused into the silicon.

In contrast, Figure 6 b) shows a very clean cut, where the copper layer and the silicon wafer can be clearly identified within the SEM image.

This highlights that the low heat impact and the clean process are suitable to cut complicated material stacks without any damage to the adjacent material layers and no contamination of the sidewall or change of the integrity of the adjacent materials.

C. Mold Compound

As previously seen in the surface area images, Figure 7 a) shows that the heat load leads to a rupture of the mold compound structure and a very rough surface structure. Figure 7 b) shows that there was a clean cut with no debris or burr on the sidewall when cutting in liquids. The rough impression of the sidewall is created by the exposed glass beads, which are embedded in the polymer matrix of the mold compound and are exposed by the dicing step. Thus, the roughness of the surface wall is determined by the size of the filler material similar to reference [14].

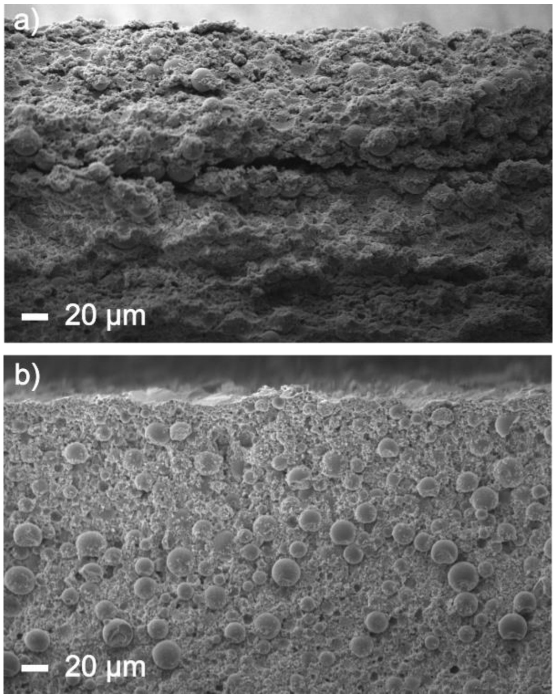

Figure 7: a) Sidewall of the sample cut of mold compound diced in air. b) Sidewall of the sample cut of mold compound diced in liquid.

VI. Conclusion

In conclusion we showed that laser cutting in liquids performs very clean cutting results and further prevents heating of the substrate while performing at the same throughput levels as established technologies.

These three features, cleanliness, high quality due to almost no heat impact and throughput, which was not discussed here, make laser cutting in liquids of wafers a viable technology for high quality cutting of advanced packaging materials within one process step.

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