Quality and Reliability Aspects in the Singulation of Complex Wafers Containing Low-k, Copper and TEGs in the Streets

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Abstract

A process is presented for the singulation of complex wafers containing low-k, copper and TEGs in the streets. The method is based upon a novel scribing process using a carbon dioxide laser in which a thin top layer of non-silicon elements is removed, followed by a mechanical dicing step that cuts completely through the remaining thickness of the wafer. The impact of laser scribing on cut quality and resulting die strength is discussed and is compared to that of a traditional two-step dicing process. The different alternatives available to the end-user are presented, and the relevant quality, reliability and cost considerations are discussed in depth. Two cases studies are presented in which the technology is applied to different wafer types.

Introduction

The more significant innovations in chip fabrication usually originate from research and development work conducted in the front-end of the industry. However, in addition to boosting IC performance, these developments may also influence the down-stream processes of the back-end of the semiconductor manufacturing cycle. One such development has had a particular impact on the process of dicing in which semiconductor wafers are singulated into individual die. We refer to the transition of metal interconnects from aluminum to copper, due to the higher electrical conductance of the latter. Singulation processes have also been affected by the consequential conversion from the use of traditional silicon dioxide dielectrics to low-k materials. Copper is considerably more ductile than aluminum resulting in premature clogging of the dicing blade, which in turn leads to increased loading and excessive chipping that deteriorates the cut quality. The porous organic and other materials that make up the group of low-k materials are more fragile than silicon dioxide and are hence much more susceptible to chipping and cracking during dicing. Lower levels of adhesion to the underlying substrate render them sensitive to layer peeling. In general, the interaction of these materials with the dicing blade used in traditional mechanical dicing results in issues of delamination, micro-cracking, top- and back-side chipping leading also to reduced die strength.

In addition to the challenges outlined above, the cut quality obtained during wafer singulation can also be complicated by the placement of test element groups (TEGs) in the wafer streets. These groups contain various non-silicon elements that significantly reduce dicing blade performance and diminish cut quality by the creation of metallic burrs, for example.

Figure 1 shows typical examples of problematic cut quality that can result when dicing complex wafers. Figure 1a exhibits an optical micrograph of severe back-side chipping. Figures 1b and 1c demonstrate the phenomenon of layer delamination, showing optical and SEM micrographs, respectively.

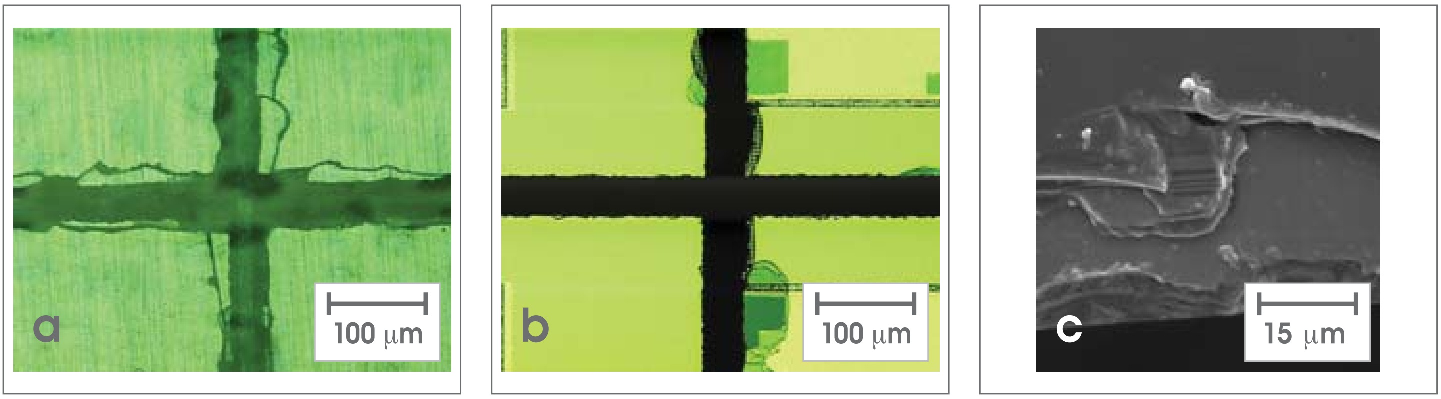

Figure 1: *Typical examples of problematic cut quality: (a) Back-side chipping; (b) Delamination – optical micrograph; (c) Delamination – SEM micrograph.*

However, cut quality is not the only problematic issue in the singulation of wafers containing low-k, copper and TEGs in the streets. The low feed rates at which dicing usually needs to be conducted with these wafer raise concerns regarding throughput, which is usually measured as the number units that can be diced per hour (UPH). Other concerns that will be discussed later in this paper include the significant initial investment in large footprint capital equipment and the necessary consumables (dicing blades, DI water, etc.) that accompany the process and that contribute to the overall cost of ownership (CoO).

Singulation Solutions

The most common method currently used to overcome the singulation problems created by the presence of non-silicon elements in the wafer streets consists of a two-step mechanical dicing process. This is nearly always conducted on a two-spindle dicing saw in which the spindles may either lie in parallel ('dual spindle' configuration) or, more commonly, face each other ('twin-spindle' configuration). In the first step, a partial cut is made into the wafer in order to remove the non-silicon components along with some 30% of the underlying silicon. This step needs to be performed at relatively low feed rates in order to overcome the difficulties presented above. In spite of the low feed rate and the attempts of blade manufacturers to offer specific products for low-k materials, this first cut can often be accompanied by severe chipping, metallic smearing and layer peeling. In a second dicing step, the remaining thickness of the wafer is cut all the way through.

Although it is currently the most common method for singulating low-k and other complex silicon wafers, the two-step process outlined in the previous paragraph has several significant drawbacks. The first is the low feed-rate at which the first cut needs to be made in order to overcome cut quality issues. Since both cuts are performed on the same saw, the low feed rate of the first cut dictates also the feed rate of the second cut, although in principle it could be conducted at a higher feed rate. Transferring the wafer to a second saw after the first cut is usually not practical due to the fragility of the partially cut wafer. An additional drawback of the current two-step dicing process is the increase in internal stresses within the substrate that are induced by the repeated interaction with the blades in the two sequential dicing steps. These stresses increase the risk of back-side chipping in the final cut-through step. In addition to feed rate limitations that reduce the throughput obtainable in the process, two-spindle dicing saws are expensive and bulky pieces of equipment, necessitating a significant capital investment and taking up costly footprint in the production hall. Additional costs include hub blades, which are consumed during the dicing process and a constant supply of compressed air and deionized water that are needed to sustain saw operation. Dicing additives may also be used in order to improve cut quality thus adding to the total cost.

Laser Scribing Solution

This paper focuses on an alternative to the first step in the two-step singulation process, which is currently carried out by means of traditional mechanical dicing. This alternative uses a low-power carbon dioxide laser to selectively ablate all non-silicon components in the wafer streets. The process is termed "laser scribing". Laser scribing leaves an array of pure silicon shallow trenches, which may then be diced in a second step by routine mechanical dicing. The trenches formed are wide enough for the second step to be performed completely within the trajectory of the laser scribe. One of the main advantages of this technology is the tremendous increase in throughput in comparison to the first dicing step in the traditional two-step mechanical dicing process. While the first step in mechanical dicing often needs to be conducted at low feed rates typically on the order of 50 mm/s, carbon dioxide laser scribing may be performed at a feed rate of up to 600 mm/s. Additional throughput gain is achieved due to the laser scribing in both directions, while a dicing blade is idle on the return to its starting point in order to dice the next index. Since the second dicing step (through-cut) may now be conducted independently of the first step, it may also be performed at higher feed rate – typically on the order of 100 mm/s. The carbon dioxide laser used in the process is a well-established piece of equipment and ablates only the non-silicon components in the wafer streets. As Figure 2 shows, the silicon itself is nearly transparent to the specific wavelength used and remains virtually unaffected by the radiation. Not only does the radiation have essentially no direct effect on the silicon, but unlike other laser-based processes that can have a detrimental effect on die strength, also secondary thermal effects in this system are negligible due to the very limited heat-affected zone of the carbon dioxide laser. In addition, carbon dioxide-based systems are significantly less expensive than those based upon Nd-Yag type lasers. Figures 3 (SEM image) and 4 (three-dimensional height scan) demonstrate the ability of a carbon dioxide laser scribing system to selectively remove non-silicon components from the wafer streets.

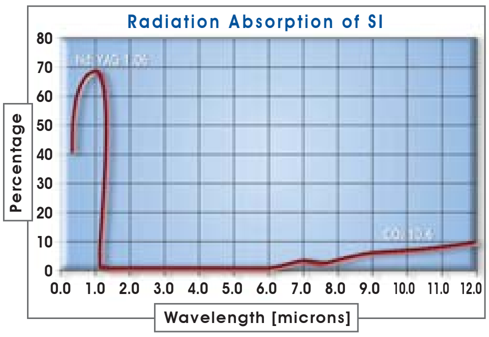

Figure 2: Radiation absorption of undoped silicon at room temperature as a function of wavelength.

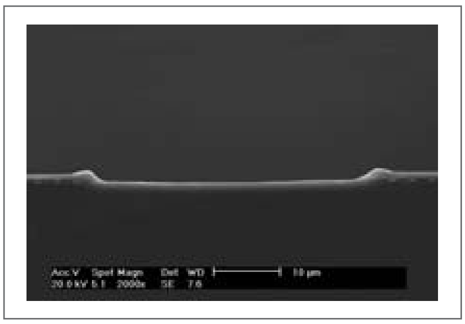

Figure 3: Scanning Electron Microscope (SEM) image of the cross section of an IC wafer after laser scribing with a CO_2 laser. The image shows the clean trench left by the laser.

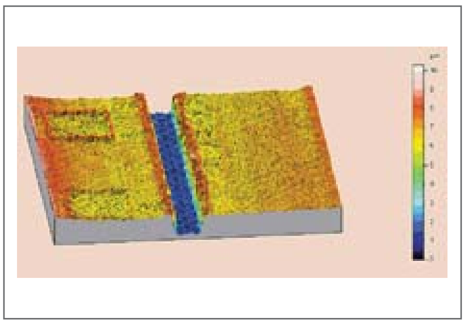

Figure 4: A three-dimensional height scan of a wafer scribed with a carbon dioxide laser showing complete removal of all non-silicon components.

The platform upon which the laser scribing system is mounted has a 1.0 micron indexing accuracy and 4 arc-sec rotary accuracy. It is equipped with a sophisticated vision system used for wafer pattern recognition and automatic alignment. The platform also includes an integral protective coating system that uses a water-based solution to form a thin film, which protects the wafer surface from debris during the laser scribing process. Laser scribing is conducted as a dry process, and the protective coating is subsequently washed away by means of an integrated cleaning station.

This technology is applicable not only to streets incorporating low-k materials and copper but also to other wafers diced in a step-cut, such as those containing test element groups (TEGs), metallic pads and polyimide coating. The application of laser scribing will be demonstrated for both types of wafers in the two case studies presented later in this paper.

Die Strength: Experimental Results and Discussion

To quantify and compare the effect of both the traditional two-step dicing method and the laser-scribing method presented in this paper on final die reliability, we evaluated the back-side mechanical strength of silicon specimens singulated by both methods. Since the strength of brittle materials such as silicon is statistical, we used the well-known two-parameter Weibull statistic approach to verify the statistical strength of both processes. The statistical strength is defined by the failure probability, S: $S=1-\exp[-(\sigma/\sigma_0)^m]$, where σ is the failure strength, σ_0 is the average failure strength, and m is the Weibull modulus. The latter defines the range of failure strength of the specimens. Twenty 43x10 mm^2 specimens were singulated from the wafers, and fracture under 3-point bending in a fully articulated bending bridge. Linear fitting of the ln ln [1/(1-S)] vs. ln σ plot yields the slope, m, of the group of specimens. Two such plots of the above mentioned groups of specimens are shown in Figure 5.

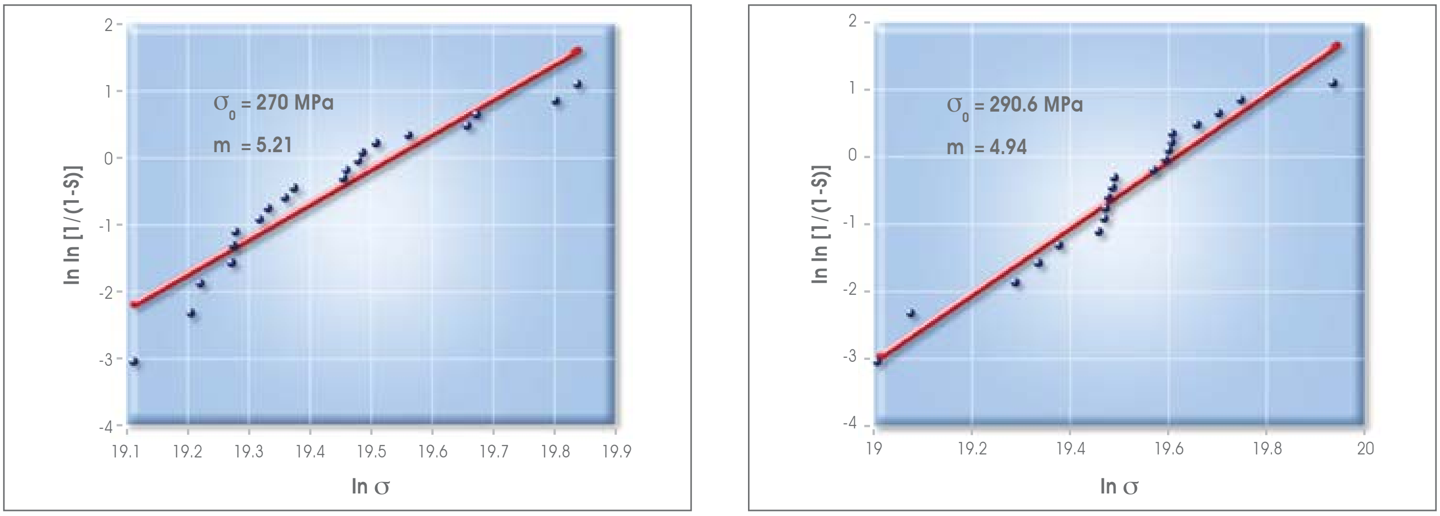

Figure 5: *The ln ln [1/(1-S)] vs. ln s plots of the traditional two-step process (left) and the laser-scribing process (right).*

The Weibull statistical analysis indicates that both processes have similar statistical validity with a slight improvement in average failure strength ("die strength") for the laser-scribing process (290 MPa for laser-scribing process vs. 270 MPa for two-step process).

Case Study I: Low-k Wafer

In this first case study we present an example in which the laser-scribing technology was implemented in the singulation of 290 micron thick low-k wafers from end-user "A" in the US. Figure 6 shows a series of optical micrographs of the street intersection at different stages of the process. Figure 6a shows the as-received wafer. Figure 6b shows the wafer after laser scribing at a feed-rate of 400 mm/s. The scribe line formed is observed to be symmetric with a trench width of 55 – 70 mm in the center of the street. Since typical kerf width of the final cut is on the order of 30-40 microns, the scribe line is wide enough to allow the second step of dicing to be performed completely within its trajectory. As demonstrated in Figure 6b, the scribe process achieves full removal of the low-k material in addition to test element groups and metal pads. Figure 6c shows the wafer after the subsequent dicing step. None of the typical cut quality issues associated with dicing complex wafers are observed, and a maximum back-side chipping of less than 30 microns was obtained, as shown in Figure 6d. This figure shows the worse case observed, whereas average/typical backside chipping was on the order of 5 microns. The effect of laser-scribing low-k wafers on die strength was independently measured by end-user "B" in Europe, who compared the die strength after traditional two-step dicing with that after carbon-dioxide laser-scribing followed by dicing. The conclusions of that study show that difference between the singulation methods had no effect on die strength.

The use of laser-scribing as an alternative to traditional two-step dicing results in a significant increase in throughput. Assuming for a 300 mm diameter wafer with 10 mm indices in both angles, a feed-rate of 50 mm/s in the traditional two-step method and a laser-scribe feed-rate of 400 mm/s followed by a cut through step at 85 mm/s, the throughput of one laser scribing system and two twin-spindle dicing saws can be calculated as equivalent to that of 5-6 twin-spindle dicing saws using the traditional two-step process.

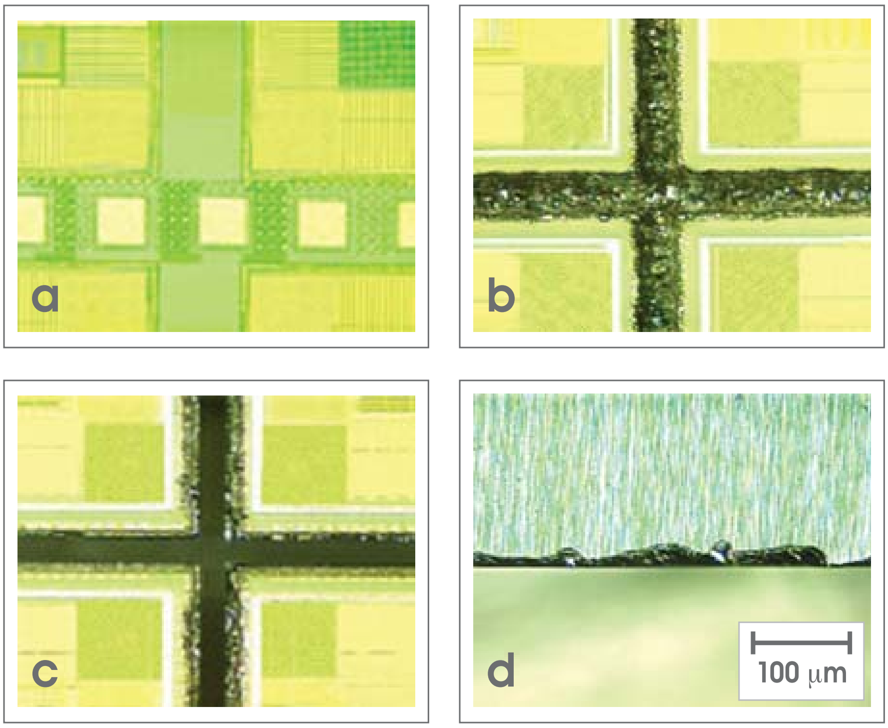

Figure 6: *A series of optical micrographs of the street intersection at different stages of the process on a low-k wafer: (a) The as-received wafer; (b) After laser scribing; (c) After subsequent dicing; (d) Maximum back side chipping observed after dicing.*

Case Study II: Standard Wafer with TEGs in the Streets

The second case study we present demonstrates the applicability of the laser scribing technology to 740 micron thick silicon wafers in which the streets contain test element groups. The wafers were received from end user "C" in the US. Figure 7 shows a series of optical micrographs of the street intersection at different stages of the process. Figure 7a shows the as-received wafer. Figure 7b shows the wafer after laser scribing at a feed-rate of 400 mm/s. As seen in the case of low-k wafers (Case Study I), a symmetric laser scribe is formed in the center of the streets. The figure demonstrates how the carbon dioxide laser remove virtually all of the TEGs and pads in the streets. Figure 7c shows the wafer after the subsequent dicing step. Again, none of the typical cut quality issues are observed. All top-side chipping is confined within the trajectory of the laser scribe and the back-side chipping is reduced by about 50% from an average of 40 microns with the traditional two-step process to an average of 20 microns with the laser scribe process as shown in Figure 7d. A calculation similar to that performed for Case Study I shows that one laser system working at a feed-rate of 400 mm/s combined with two twin-spindle dicing saws cutting at a feed-rate of 40 mm/s has the same throughput as five twin-spindle dicing saws cutting a feed-rate of 40 mm/s. This translates into significant capital equipment and footprint savings.

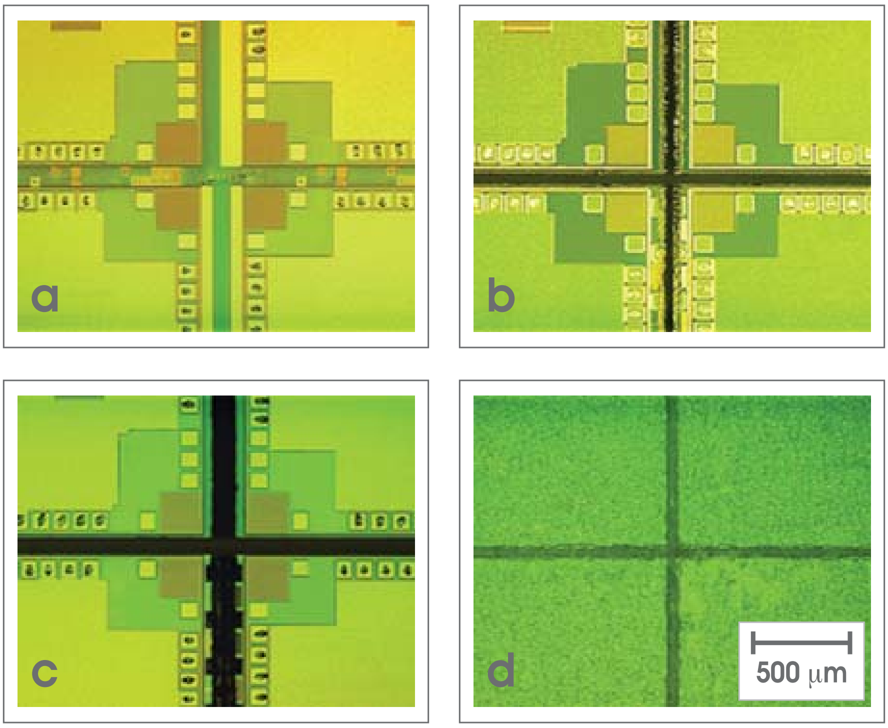

Figure 7: *A series of optical micrographs of the street intersection at different stages of the process on a standard wafer with TEGs: (a) The as-received wafer; (b) After laser scribing; (c) After subsequent dicing; (d) Back side chipping observed after dicing.*

Summary and Conclusions

An innovative process, which combines carbon dioxide laser scribing and mechanical dicing was presented for the singulation of complex wafers containing low-k, copper and TEGs in the streets. Experimental results were presented along with two case studies that demonstrate advantages of this process that include improved cut quality and increased throughput without sacrificing die-strength.

Acknowledgements

The authors would like to extend their gratitude to the Office of the Chief Scientist (OCS) of the Israeli Ministry of Industry and Trade for their financial support in the development of the carbon dioxide laser-scribing system.

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