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Characterization of Laser Micromachining Process for Low-k / Ultra Low-k Semiconductor Device

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ABSTRACT

This paper presents the development works of using a 355nm ultraviolet (UV) laser diode ablation process for low-k/ULK semiconductor device. The effects of laser micromachining parameters, i.e. laser power, laser frequency, feed speed, and defocus amount were investigated. The laser processed die samples were thoroughly inspected and characterized, included the die edge/side grooving quality, the grooving shape/profile, and the grooving depth. High power optical microscopy, scanning electron microscopy (SEM), and focused ion beam (FIB) are the inspection tools/methods used in this study. Package reliability and stressing were carried out to confirm the robustness of the laser grooving process parameter and condition in mass production environment. The dicing defects caused by the laser were validated by using failure analysis. The advantages and limitations of laser grooving process were also discussed. It is shown that, laser grooving is possibly one of the best solutions to choose for dicing quality and throughput improvements for low-k/ULK wafer dicing. Laser process is feasible, much faster, and simple process compared to the conventional blade dicing process.

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INTRODUCTION

Mechanical blade dicing has been widely employed in the semiconductor industry and it is the most conventional process in semiconductor manufacturing to produce singulated integrated circuit (IC) chips. With the rapid down scaling of wafer fabrication technology, from node size 90nm to 45nm and 40nm where low k/ULK dielectric is applied to improve RC delay. The innovation of ultra low k (ULK) dielectric materials in wafer fabrication such as SiCOH and SiLKTM have much weaker interlayer adhesion compared to the predecessor material SiO2 (Z.J. Wang, 2005). This is because to achieve lower dielectric constant; the material needs to be very porous and as close to the air, for example, where the dielectric constant value of air is equal to 1, the lowest (T.B. Lau, 2008). Therefore, mechanical blade dicing of low k/ULK devices poses a big challenge to achieve good dicing qualification. Among the challenges that were widely recognized are defects like passivation and metal layers peeling, chipping, cracks, and inter-layer dielectic (ILD) delamination. These defects are the result of grinding and shearing mechanism involved when saw blade is cutting through the wafer in a direct contact manner. Higher porosity dielectric materials are harder and brittle in nature, causing weaker interlayer adhesion characteristic, and such grinding and shearing effects will generate enough force to delaminate the metal layers, and hence producing the defects as stated. Micro crack is likely to occur during blade sawing, and it will propagate into the active die area during reliability stress and hence causes latent electrical failure. Therefore, blade dicing may cause worse reliability concern due to the mechanical damages and defects found after blade dicing process (U. Efrat, 1993; T.A. Cheung, 2005; W.S. Koh, 2009).

The severity of the ILD peeling and delamination of blade dicing on low-k/ULK wafer was related to the porous dielectric materials used, the metalized ILD stack and the scribe features placed on the saw street, and such dicing defects cannot be eliminated by using the conventional blade dicing alone (H. Zhao, 2003; T.A. Tran, 2012). Getting rid of the unfriendly scribe features away from the saw street is a very costly operation and is not possible due to the complexities involved in the wafer design and fabrication. To achieve a defect free

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dicing process, specifically for low k/ULK wafers, laser dicing technology has been brought out due to its promising dicing responses over the conventional blade dicing technique. The principle of laser dicing is using the focused laser light onto the Silicon (Si) wafer by using a condenser lens to cause ablation. When the laser light is irradiated on a Si wafer, and the intensity of the laser light is over the threshold, the light is converted into electrical, thermal, photochemical, and mechanical energy. It follows that a neutral atom, molecule, positive and negative ion, radical, cluster, electron and light are released explosively and the surface of the Si wafer is etched (M. Kumagai, 2007; B.S. Yibas, 2008; A.K. Dubey, 2007).

The laser grooving process is performed first on the active side of the wafer. In this process, dielectric films and scribe features are ablated from the dicing street between adjacent die. Full singulation of the die is accomplished by cutting through the remaining silicon in the dicing street with a diamond saw process. Unlike traditional blade sawing, laser grooving is a thermal energy based process; with no direct tool-to-work piece contact. When a focused laser beam with high energy density hit on the Si wafer, thermal energy is transferred and absorbed by Si; heats will spread/transform to the low-k/ULK ILD metal layers and melted into molten and vaporized solids, which can be disposed of and removed by the flow of air pressure (K.S. Lee, 2006; K.Y. Yow, 2010; H.H. Tan, 2011).

Chaware et. al. have studied a model of laser grooving for 90nm low k bumped wafer. It is using a combined laser and blade sawing process, good and promising dicing responses were reported (R. Chaware, 2006). ILD peeling, chipping, delamination and crack from the mechanical blade dicing can be arrested and compensated by the laser grooving process. The adhesion strength between the metal layers in the die is sustained and the strain produced by blade sawing has been minimized. Based on the works and result findings that have been documented to-date, here is our motivation and opportunity to discover and explore more on the process feasibility and robustness of laser grooving in low-k wafer processing.

Research Methodology and Experimentation:

I. Experimental Study

The experimentation is conducted by utilizing one of the established laser grooving machines in the market. It is a Q-switched Nd:YAG laser diode with a wavelength 355nm. The laser process outcomes and responses are governed by the changes of the process input parameters such as laser power, laser frequency, feed speed, and defocus amount. The significant laser process parameters and its respective operating ranges were studied in this experiment are:

- Laser power: 0.5W to 4.5W
- Laser frequency: 40kHz to 200kHz
- Feed speed: 50mm/s to 400mm/s
- Defocus amount: 0mm to 0.2mm

The next process after laser grooving is blade sawing. Saw process parameters for this study are based on the current established saw recipe used in assembly, see below:

- Blade rotation: 25kRPM to 55kRPM
- Table speed: 10mm/s to 40mm/s
- Cut depth intoSi: 57% of the wafer thickness
- Cut depth into tape: 18% of the tape thickness
- Blade thickness: 25um to 30um

The nominal blade dicing recipe is robust to apply as the weaker Cu/low-k materials have been all ablated and melted after laser grooving. The mechanical damages and stresses on the post laser grooved wafer are expected to be lesser compared to the wafer that underwent the only blade dicing process.

II. Laser Grooving Process Parameter Optimization:

As the Nd:YAG laser used in this development work is the Diode Pumped Solid State (DPSS) type and transmits in pulse form, one of the important process parameters that affect the kerf quality is the pulse repetition rate/laser frequency. It is found that high frequency laser pulse always yields better kerf quality.

However, by the physic of laser operation, the higher the laser frequency is, the lower the laser output power can be achieved. Laser power is essential to reach the sufficient grooving depth that remove all the sensitive low k/ULK metallization, which is typically 8um to 10um thick.

Other equally important parameters are the laser feed speed and defocus amount. Feed speed needs to be carefully optimized, because higher feed speed can help to reduce the amount of adherence debris/molten particles along the grooving edge, however, an overly fast feed speed can cause discontinuities in laser grooving, see Fig. 1.

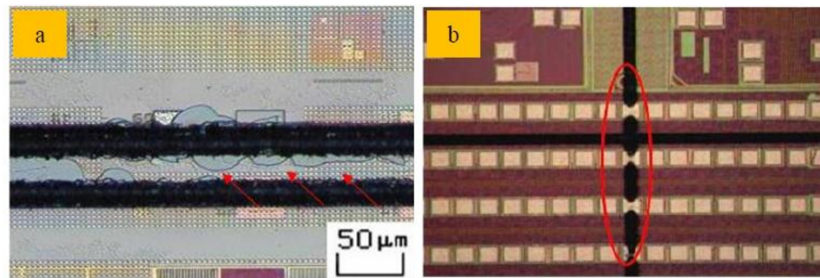

Fig. 1: Laser grooving defects (a) ILD peeling , (b) incomplete cut / discontinuities.

As a general guideline, for most wafers with the commonly used scribe features, the overlapping percentage is usually controlled between 60-90%. The calculation for overlapping percentage of the laser pulse is presented as in the equation below (J.C. Ion, 2005):

$$Overlap\ \% = \left[1 - \frac{s}{df}\right] \times 100\%$$

s : feed speed
d : laser beam diameter
f : repetition frequency

On the other hand, the defocus amount parameter will influence the laser beam size that pass along the wafer surface, which will result in laser kerf width changes. Process optimisation of the combination of above mentioned parameters is required to reach the required kerf width, grooving depth and edge quality. In the process of laser grooving, the target grooving depth is typically only 10um to 15um, which is already sufficient to remove all the low k/ULK metallization with a good margin. The remaining of silicon is then separated through the following process of mechanical saw.

In order to accommodate both laser groove and blade dicing on a 120um scribe width, the maximum laser grooving kerf width allowable is between 70-76um. A dicing blade with the blade thickness in between 25um-30um is selected for singulation the entire wafer with a step cut method. The best compromise between process cycle time and the grooving kerf quality, a designed 70-75um laser kerf width is established by using a 5-pass laser grooving process for a 300mm diameter wafer, and the wafer thickness is 280um.

In the 5-pass laser grooving process, the two outermost grooving lines are optimized for the best quality. Therefore, these lines are usually grooved with lowest laser power, but at a higher laser frequency and zero defocus. On the other hand, for the remaining inner lines, the parameters are tuned to give wider and deeper kerf depth, which can only be achieved by taking the lower repetition frequency that gives high laser power. The defocus setting of the center line is also the largest to achieve the widest kerf width possible. Some guidelines for parameter setting such as using the energy density method (Joules/cm2) is found to be useful as a baseline for optimization. The energy density equation is given as below (J.C. Ion, 2005):

$$Energy\ density = \frac{4P}{f\pi d^2}$$

P : average power
d : laser beam diameter
f : repetition frequency

RESULTS AND DISCUSSION

I. Topside Grooving Quality Inspection:

The optimized 5-pass laser grooving process produces very good topside grooving quality with zero dicing defect. The upper layer of the heavy metallization was effectively removed by the 5-pass laser ablation process, and produced a wide laser groove path to accommodate the mechanical blade to be placed at the center of the laser groove kerf with sufficient space for the normal kerf drifts. High metal density scribe structures are unfriendly to be diced through using conventional blade dicing, resulted in high occurrences of passivation peeling and delamination. However, laser grooving has proven its capability to resolve the critical dicing defects. This result reflects that the goal to achieve a dicing defect free process is possible by using laser. Topside cutting quality comparison between the conventional blade dicing and laser grooving is shown in Fig. 2.

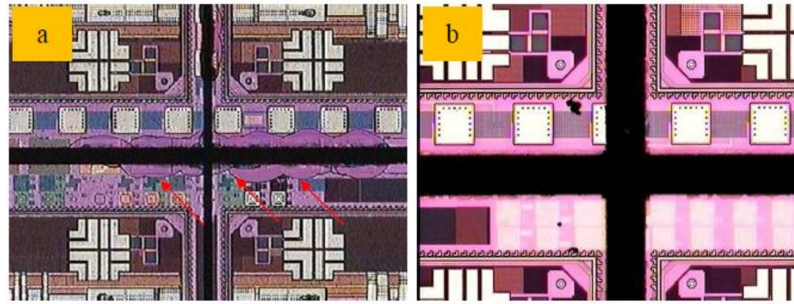

Fig. 2: Topside cutting quality comparison (a) blade dicing, (b) laser grooving.

II. Laser Groove Shape/Profile:

The results of using different laser process parameters can result in different grooving profiles and geometry. Fig. 3 presents the relationship between the power density (kW/mm-2) and the street index (um) using Parameter A and Parameter B. The graphical graph shows the outermost laser pass of the grooving (for 1st and 2nd laser pass) pose the highest power density; it's intended to provide sufficient thermal energy to evaporate-off all the weaker and brittle ILD metal layers before proceeding to blade sawing. The lowest power density observed always at the center of the groove for the two laser parameter. The generated grooving geometry for Parameter A look like a typical V-shape groove. In fact, the grooving geometry for Parameter B looks like a U-shape groove, a typical bathtub shape when examined under SEM.

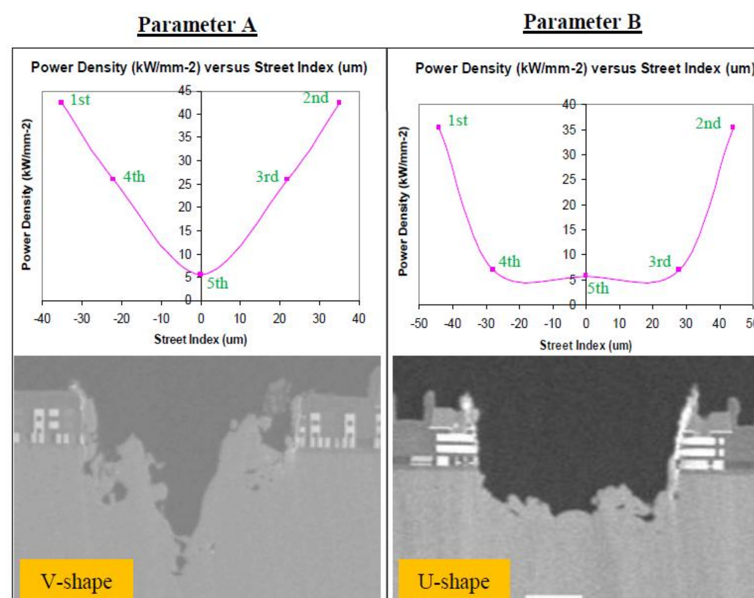

Fig. 3: Relationship between the power density (kW/mm-2) versus street index (um), using Parameter A and Parameter B.

III. Laser Groove Depth Inspection:

Laser groove depth is another important physical characteristic to inspect, which reflects the quality of the grooving surface. Inspection is performed on the groove depth and the die side wall of the groove. The minimum requirement to meet for the grooving depth is at least 10um in this study, insufficient grooving depth is not acceptable due to the higher risk will find metal layers peeling and delamination after blade sawing. The presence of a thin metal remnant at the center of the groove will cause the blade to drift resulting in off-center dicing issue. Fig. 4 shows the low k ILD metal layers had been fully grooved-off at the outermost of the grooving lane; all recipes achieve a minimum 10um grooving depth. In this study, higher power density and lower effective feed speed were found to be favourable for deeper grooving depth. Parameter A and Parameter B have exceeded the 10um grooving depth requirement. However, for Parameter A, there was a rougher grooving edge observed specifically on the die sidewall region. Clearly, Parameter B looks better than Parameter A, where the grooving die edge quality is smoother, clean, and the U-shape groove is preferred, see Fig. 5.

Australian Journal of Basic and Applied Sciences, 8(22) Special 2014, Pages: 24-30

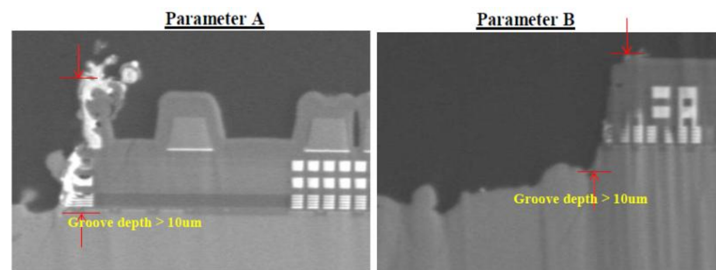

Fig. 4: Cross-sectional view of the produced laser groove depth for Parameter A and Parameter B.

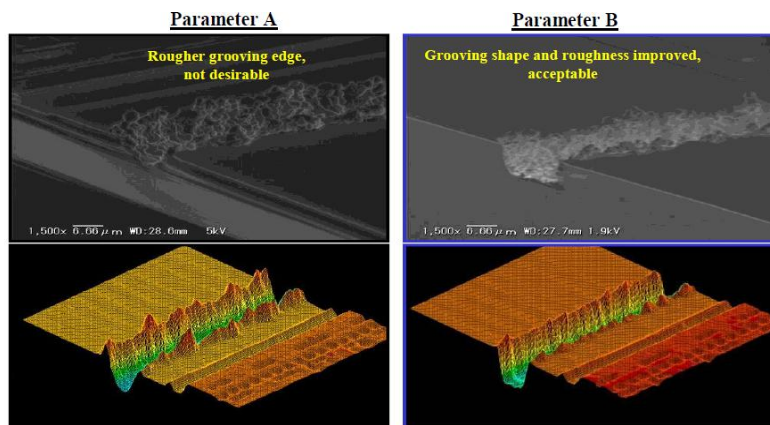

Fig. 5: Laser grooving edge quality and roughness inspection for Parameter A and Parameter B.

IV. Laser Grooving Defects and Challenges:

One of the most serious defects that was encountered during the laser process development is a hairline crack. It happens randomly along the laser kerf edge with no correlation to the scribe structures. The hairline cracks observed were in the range of 5-15um as illustrated in Fig. 6. Hairline crack does not look serious from the top view under low power optical scope. However, cross section into the defect by using FIB method revealed that the crack has indeed propagated and affected the low k/ULK metallization and circuitry. Under package stress test, this crack has a high possibility extending inward to the die and cause catastrophic failure. To resolve the hairline crack produced by the laser, process parameters fine tuning is needed by assessing all possible combination of critical process parameters (laser power, laser frequency, feed speed, and defocus amount) in order to obtain the optimum amount of energy density for 5-pass grooving.

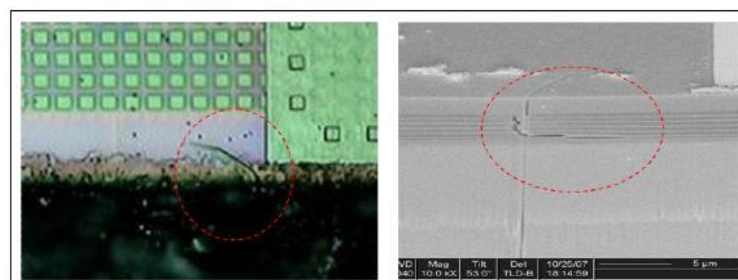

Fig. 6: Laser grooving defect, hairline crack.

Heat affected zone (HAZ) induced by laser during its high temperature ablation process is also another area of concerns. As laser grooving kerf is very close to die specifically for narrow scribe width design, the generated heat from the laser is easily spread near to the active die circuitry/metallization of the die and cause adverse effects on the die. HAZ is harder and brittle in nature, the HAZ is not desirable and it cannot be totally eliminated but has to keep as low as possible. One of the effective way to minimize HAZ is by selecting laser type with nanoseconds pulse range instead of microseconds. The shorter the pulse duration, the lesser time is allowed for heat from a laser to travel far reaching the adjacent die. There are some other important measures needed our attention other than HAZ, like the mechanical property of laser machined, i.e. die surface roughness, the recast layer thickness, the dross adherence, the mirco-hardness and the residual stress. Fig. 7 shows the SEM and optical photos of the HAZ and dross adherence inside the groove.

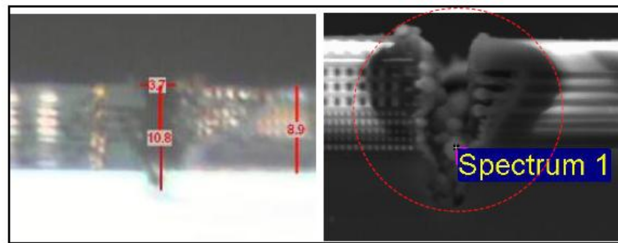

Fig. 7: SEM and optical photo of HAZ and dross adherence inside the groove.

Laser and blade saw kerf placement accuracy is crucial when comes to narrow saw scribe width wafer design. It's important to avoid the mechanical blade from breaching into the side wall edges of the laser groove. Else, severe die topside ILD peeling and chipping can happen. A robust and effective in-line process control is necessary to reduce the chances of having off-center cutting for the mechanical blade dicing saw. Short kerf check (SKC) is an in-line process control tool used to trigger off-center dicing, and machine will stop for the user to make adjustment and correction. The problem can be resolved at an early stage before it was too late. Fig. 8 shows the blade saw kerf is off-center and result in peeling breach over to the die edge seal ring.

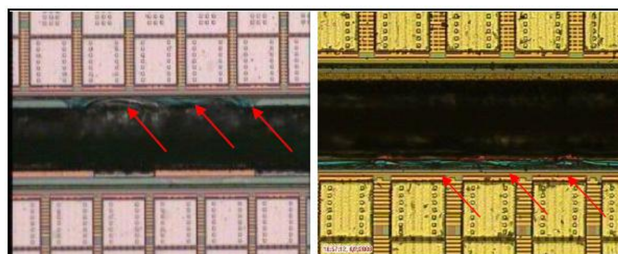

Fig. 8: Blade saw kerf damage the die side wall of the laser groove due to off-center cutting.

Other small cosmetic defects such as passivation peeling (Fig. 1a) and metal bulging (Fig. 9) due to laser process heat spread across the metal scribe structures are very common to see in laser grooving.

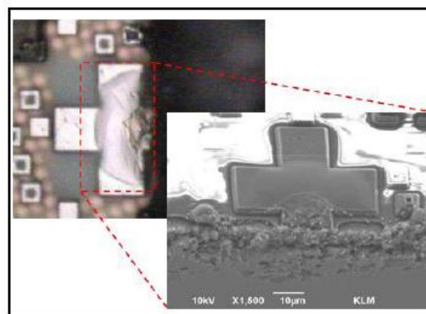

Fig. 9: Metal bulging due to laser grooving process heat transfer on the scribe structure.

Package reliability assessments were performed on the assembled dies which were processed with the optimized 5-pass laser parameters and diced with the step cut approach. No dicing related failures were found at time zero, after 4000 cycles of air-to-air temperature cycling (-65ºC /150ºC), and 192 hour HAST. Therefore, laser grooving and blade dicing was one of the potential solutions that significantly improved the dicing yield and reduced dicing defects for low k/ULK wafers.

Conclusions:

Based on the results of the study, the laser grooving process parameters played an important role in improving the die topside grooving quality; this included the laser power, laser frequency, feed speed and defocus amount. The combination of all these parameters has a significant effect in achieving optimum laser grooving shape/profile, laser groove depth and laser kerf width. Significant improvements were observed in reducing the die topside peeling/delamination and chipping through laser grooving process parameters optimization. Lower effective feed speed and higher energy density produced deeper laser groove depth. The low-k/ULK metallization has been grooved-off, which exceeded the requirement of at least 10um groove depth. Reliability stressing was conducted under MSL 3 at 260 degree C condition, at time zero, after 4000 cycles of air-to-air temperature cycling (-65ºC /150ºC) and 192 hour HAST, confirmed no failure due to laser process.

Therefore, laser grooving is possibly one of the best solutions for low-k/ULK wafer dicing, to improve the dicing quality and yield.

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