Analysis of Laser Metal Cut Energy Process Window and Improvement of Cu Link Process by Unique Fast Rise Time Laser Pulse

Joohan Lee and Joseph J. Griffiths
GSI Lumonics
Wilmington, Massachusetts, U.S.A.
jlee@gsilumonics.com

Abstract – In this work, we show that the stress-relief effect caused by breakthrough of passivation by upper cracks as well as the mechanism of the laser cutting process by using finite element modeling. With this understanding of stress-relief effect, a unique laser pulse with fast rise and fall time was considered for the Cu link structure in the simulation. Results show that the fast rise time laser heats up the upper part of a link rapidly and promotes fast top-oxide cracking, which relieves stress around the metallization faster and thereby avoids undesirable lower-corner cracking. A useful guideline is obtained for the maximum laser energy process window through finite element modeling.

1. INTRODUCTION

Laser technology has found widespread applications in the repair of integrated circuit chips, which exhibit large-scale redundancy in their designs, for yield enhancement. A laser processing systems have been used to remove the defective elements and replace them with redundant ones [1].

However, material leftover at the bottom of the processed cut-site and the lower-corner cracks have been reported as a major reliability issue [2]. In previous work, we have shown the dynamics and the energy process window of laser metal cut processes as well as the existence of stress relief effect on passivation break through experimental observations and 2-D finite element simulations [3]. In this work, we present results from more advanced finite element modeling that directly shows the stress relief effect without having two separate stages for the laser cut process. Also, a fast rise time laser pulse on Cu link structure was simulated for the first time to see if this unique shaped pulse can help avoid the lower corner cracking by faster stress relief on lower corner.

2. FINITE ELEMENT MODELING –PROCESS WINDOW ANALYSIS

Model and Simulation Curves

To simulate the crack formation process, a custom Finite Element Model (FEM) was created with a commercial MSC *Mentat* software as shown in Fig. 1. Since most of our concerns are at the upper and lower corners of the metal structure, a triangle mesh was used for the simulations. This was done in order to make sure that there were enough elements around the corners of the structure without any discontinuation. Therefore, the elements around the two corners are much denser than other regions in the model. Only half of the structure has been simulated to save computation time.

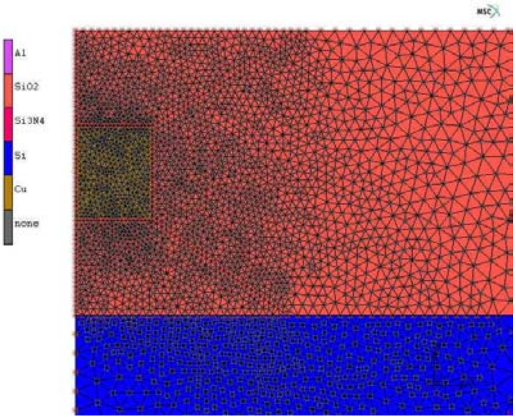


Fig 1. Finite element model for analysis of laser cut process.

Sample simulation curves of the induced stresses, at the upper and lower-corners of metal line under the laser heating, as a function of time are illustrated in Fig 2. The induced stresses are plotted on the vertical axis, in units of GPa and time is plotted on the horizontal axis, in units of ns. The two curves that are plotted are actually the results of two nodes closest to the Al corners in dielectric. Therefore, the stress values measured were somewhat lower than the actual stresses at the right on the upper and lower-corners of metal line. It is considered that there exists a steep gradient of stresses between the Al corners and the closest nodes, and it is around from 300 MPa to 400 MPa depending on the location of node.

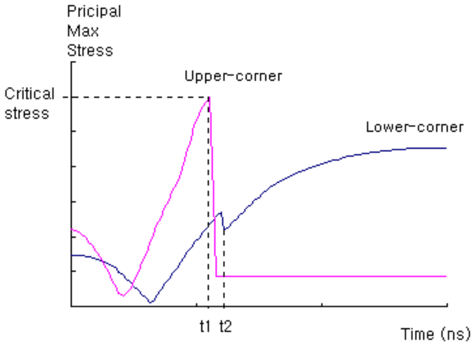


Fig. 2. FEM result : Sample curves from simulation results.

The simulation results in Fig. 2 reveal that both the upper-corner stress (labeled as *Upper-corner*) and the lower-corner stress (labeled as *Lower-corner*) begin to be relieved for the first short time of laser heating to compensate the compressive stress caused by the fabrication of the structure at high temperature. After the relaxation, the stresses start to increase. However, the stress at the upper-corner is greater than that at the lower-corner most of the time. The critical stress (stress necessary for crack initiation) at the upper corner occurs at time t_1 in Fig. 2 where the crack initiates at upper-corner. In the simulations, it was clearly noticed that the stress at the upper-corner was sharply released upon passivation break at t_2 and disappeared.

The release of stress at the lower-corner, as a result of crack development at the upper-corner, can be noticed in Fig. 2. It is a small shoulder on the curve at a time of t_2. When the upper-corner crack completely breaks the overlaying passivation and reaches the free surface, at time t_2, it is thought that the stress relief effect at lower-corner ends. However, the stress relief effects on the lower-corner observed throughout the simulations were much less than actual since it was impossible to model the molten metal flow and rupture caused by laser energy.

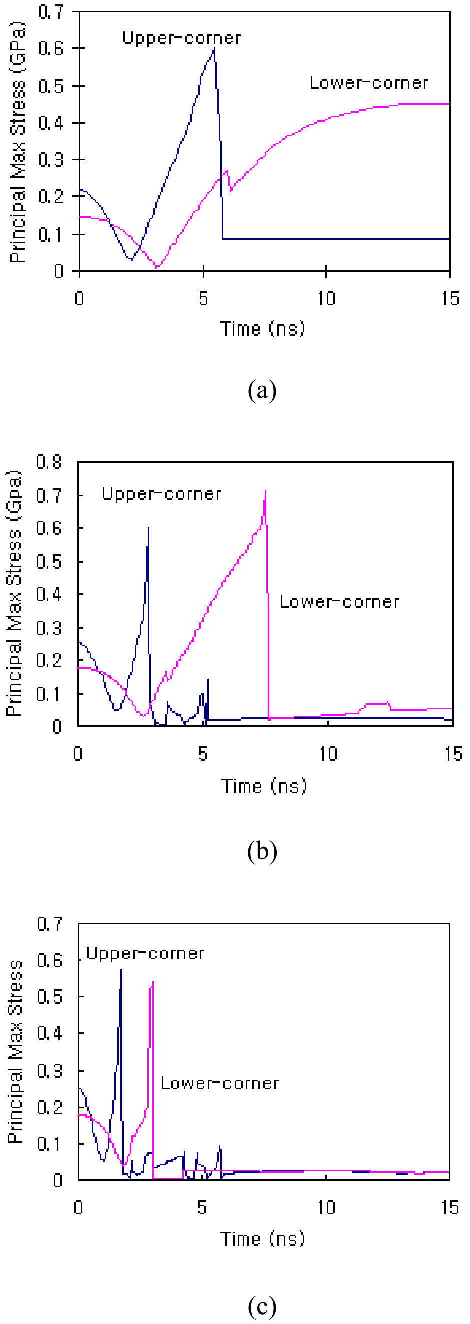
Laser Cut Process Cases

The simulations using different laser energies were performed to illustrate the three main outcomes for a laser cut process. In these simulations, an aluminum line measuring 0.8µm thick and 1.2µm wide, with a 1.0µm thick passivation layer, was used. A 7ns conventional gaussian laser pulse and a round $1/e^2$ spot size of 2.5µm in diameter, was utilized to simulate the cut process. With the spot size of more than 2 times larger than metal line width, uniform laser energy density on the top of link was assumed. Laser energies of 0.3µJ, 0.5µJ, and 1.2µJ, were selected for these simulations. Prior to the impingement of the laser, the structure was assumed to be at room temperature.

In each of the three simulations, the critical stress for dielectric cracking was assumed to be 1 GPa [4]. The crack propagation speed was found to be dependent on the laser energy. That is, a higher laser energy produced a higher propagation velocity. From the simulation, the time for crack propagation was approximately 1 ns and this was from the calculation based on the fact that the crack propagation speed is limited to approximately 1/3 the speed of sound in the brittle, solid materials [5]. Therefore, a time of 1 ns is needed for the crack to propagate through a 1µm thick passivation layer. The explosion and ejection of material were assumed to occur at the same time that the crack penetrated the free surface (i.e. at time t_2), even though the explosion happens after passivation breakthrough.

The results of the simulation of a 0.3µJ laser energy are displayed in Fig. 3 (a). As seen in the graph, an upper-corner crack was initiated at time t_1 = 5.5ns and the stress at the upper-corner was released instantly. The stress relief at the lower-corner can be found from 6.4 ns to 6.7 ns. We have shown through experimental observations that most stress relief occur at a time when the crack reaches the free surface and the ejection of material occurs even though the stress starts to be released from the time of cracking initiation [3].

The time for complete melting of the metal structure was calculated (by the simulation program) to occur at 8.0ns. Therefore, from the simulation for a 0.3µJ laser energy, at time t_2 the heat diffusion from the surface did not melt the entire metal structure. This incomplete melting causes some aluminum to remain at the bottom of the cut-site after the ejection of material.



(a)

(b)

(c)

Fig. 3. Results of finite element simulation with various laser energies, spot size: 2.5µm $1/e^2$ diameter. Laser energies: (a) 0.3µJ, (b) 0.5µJ, and (c) 1.2µJ.

When the laser energy was increased to 0.5µJ, initiation of the upper-corner crack was simulated to begin at time t_1= 2.8ns. The simulation results are displayed in Fig. 3 (b). In this case, the diffusion of heat in the aluminum line caused the aluminum to completely melt at the same time that the crack penetrated to the free surface (t_2 = 3.8ns). Therefore, all the molten aluminum, as well as the passivation layer of the cut-site, was ejected by the cut process. However, the stress curve at the lower-corner kept increasing after the passivation break and crack was initiated at the corner at a time of 7.5ns. This occurred due to the impossibility of simulating molten metal flow. Therefore, the stress development after passivation break (t_2 = 3.8ns) should be ignored.

When a laser energy of 1.2μJ was applied, initiation of the upper-corner crack was simulated to occur at time t_1 = 1.7ns. The simulation results for this case are displayed in Fig. 3(c). For this case, however, the diffusion of heat in the metal structure caused the entire structure to melt (at time t = 2.4ns) before the crack reached the free surface (at time t_2= 2.7ns). Also the lower-corner stress (*Lower-corner*) reached σ_c before t_2. This results in the development of a lower-corner crack. Therefore, cracking initiated at lower-corner at time t = 2.4ns.

From the results of the three cases, it is apparent that the stress difference between the upper and lower-corners (for the same instant of time) increases when the laser energy is increased. However, a higher energy also increases the lower-corner stress curve (*Lower-corner*) faster. Therefore, this steeper slope for *Lower-corner* indicates that the lower-corner stress achieves the critical value faster. And the chance that lower-corner cracks could develop should be increased.

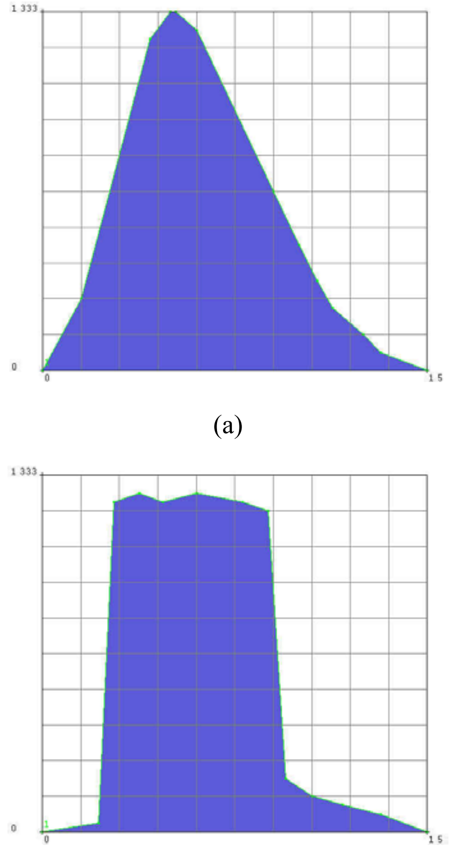
The experimental observation results, which are consistent with the FEM results, are detailed with FIB cross sectional images in [4].

3. MODELING OF COPPER LINK PROCESS BY FAST RISE TIME LASER

We have shown that the high end of a laser cut processing window is determined by the fracture dynamics of the metal-dielectric system rather than substrate damage in narrow aluminum based processing. When it comes to the copper link processing, the substrate damage is less likely to be the limiting factor, than aluminum links, due to the multiple highly reflective silicon nitride layers in spite of higher power required for cutting. Therefore the lower-corner cracking poses more serious reliability concern. With the understanding of this stress relief effect detailed so far, a unique pulse shape with fast rise and fall time has been simulated in order to see if this helps avoid the lower-corner cracking.

Fig. 4(a) shows the power profile of a conventional gaussian laser pulse over time used for first simulation, whereas Fig. 4(b) indicates fast rise/fall time laser pulse over time for second simulation. The pulse width is 7ns in FWHM for both cases and the energies over time for two pulse are same. In the conventional pulse, the peak is on about 1/3 of the whole pulse time. The rise and fall time for fast rise/fall time pulse are 1.5 and 2ns or so, respectively.

Fig. 5(a) and (b) show the stress profile results over pulse duration from the two finite element analyses. Compared to the conventional pulse result, the fast rise time laser pulse had faster heating of upper part of a link within a shorter time. This fast heating develops upper corner stress and cracking faster as can be seen the steeper angle of upper corner stress curve. Due to the faster cracking and subsequent stress release effect, the lower corner cracking has been delayed about 1 ns compared with the conventional pulse. Therefore, the time interval between upper and lower corner crackings for fast rise time laser pulse is longer than that for conventional pulses.



(a)

(b)

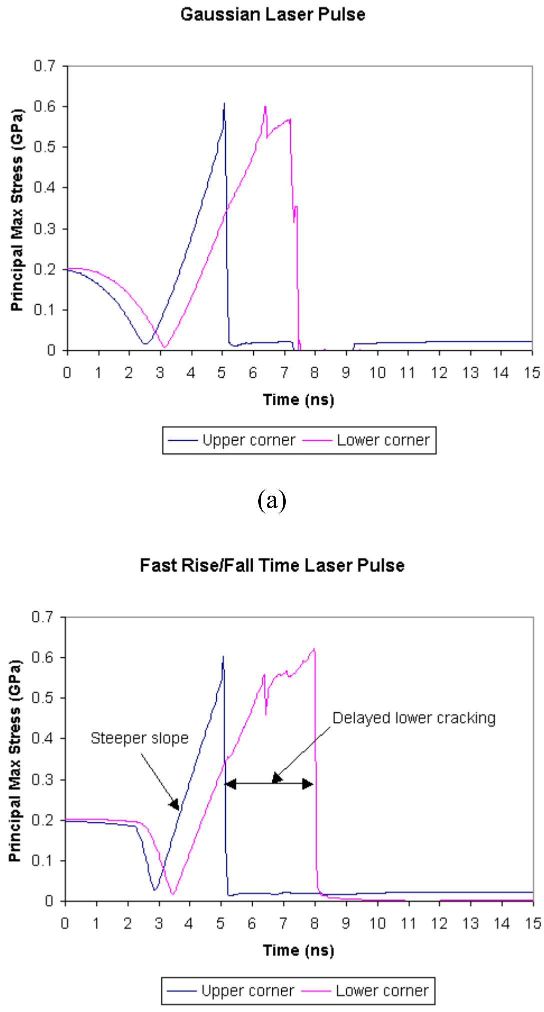
Fig. 4. Two laser pulses over time used for finite modeling, (a) gaussian laser pulse (b) fast rise/fall time laser pulse.

Another benefit of the fast rise time laser pulse is that the reflectivity of metal decreases over laser heating due to fast heating of the line and hence promotes absorption of laser energy efficiently. Therefore, metal links are cut more efficiently at lower nominal energies and less likely to have lower corner cracking beneath the link.

It is noted that the simulation does not include the material removal on passivation explosion and the delay in lower corner cracking should be even larger when we account for the stress relief effect from material removal.

4. DISCUSSION

The continuous shrinking of device dimensions of Si MOS technology has dominated the scaling of repair technologies. Because the density of memory cells has been of primary importance in reducing their cost, the reduction in cell size has been achieved by the use of smaller interconnect line width as well as by the cell structure complexity [1]. However, it has been reported that a narrower metal line increases the probability of generating cracks from the lower corners as well as the upper corners of Al metal line [6]. Therefore, it is more critical to avoid the lower-corner cracking in order to achieve the successful cut process.



(a)

(b)

Fig. 5. Stress profiles under laser heating, (a) gaussian laser pulse and (b) fast rise/fall time laser pulse.

On the other hand, industry is gradually adopting low-k dielectric materials for an insulator due to their device speed advantage. Moreover, combination of the copper process with the introduction of materials with low dielectric constants will reduce RC time delays significantly. However, most of low-k dielectrics are porous and brittle and, thus they exhibit low cracking resistance and yield strength. Therefore, having low k material under the link will increase the chance to have lower corner cracks significantly due to its softness. From this perspective, it is more critical to prevent the lower corner cracking.

Commercial wafers have been processed with both conventional gaussian and fast rise/fall time laser pulses by GSI Lumonics *M430 WaferRepair^{TM} System*, and the results were found to be consistent with the simulation results. That is, the fast rise time pulse (ShapedPulse^{TM}) had less tendency for lower corner cracking than the conventional gaussian pulse. In copper processing, lower corner cracking was found to be critical failure mode for the low-k material underneath, hence the use of fast rise/fall time laser pulse is more important.

5. CONCLUSIONS

Analysis of energy process window in laser metal cut process was performed by FEM and it showed the stress relief effect on lower-corner at the passivation breakthrough of upper-corner cracks. Utilizing the stress relief effect, it is shown that fast rise time laser helps avoid lower-corner cracking in copper cut process as well as aluminum.

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AUTHOR BIOGRAPHY

Joohan Lee received the B.S. degree in chemical engineering from Yonsei University, Seoul, Korea in 1996 and the M.S. and Ph.D. degrees in chemical engineering from University of Maryland, College Park, MD in 1999 and 2001, respectively. He is currently employed at GSI Lumonics, Wilmington, MA 01887. His research interests include the thermal, mechanical, and electrical interactions and failure mechanisms of dielectric and metallic materials used in microelectronics, the reliability issues of inter-level metal laser linking and cutting and their applications, electromigration, interconnect reliability, the various aspects of silicon wafer processing, and wafer-scale integration.