Challenges and Future Directions of Laser Fuse Processing in Memory Repair

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Abstract

This paper reviews the current status of laser fuse processing and discusses the challenges ahead. Various processing parameters are discussed including laser wavelengths, laser pulse duration and shaping, laser beam polarization, laser beam positioning accuracy, and thermal effect, and their impacts on fuse size limitation. We also examine the interrelationships among these parameters. Experiments and evaluations have been conducted, including the use of new laser sources and processing techniques, improved optical system, and beam positioning system. The results, together with several potential solutions for the next generation of laser memory repair system, are presented.

Introduction

Laser fuse processing has been widely used in semiconductor memory repair. DRAMs, and memories in general, are quite susceptible to process defects. Redundant elements are switched in to replace the defected elements by means of laser blown fuses, thus, enhancing the effective yield.

Memory technology has progressed at a rapid pace since the invention of the one-transistor/one-capacitor DRAM cell in the late 1960s. In recent years, there has been a shift from a technology generation strategy (4 Mb/0.7 μm, 16 Mb/0.5 μm, etc.) to a shrink strategy (64 Mb/0.35 μm/0.25 μm/0.2 μm, etc.) with shorter development cycles. The fuse pitch for 0.14-μm node technology is 2.8 μm or less depending on the materials used. As the industry moves to 0.09-μm node technology and beyond, smaller fuse dimensions are expected. The fuse pitch will be less than what the current laser systems are capable of, which is 2 microns or less. This puts significant challenges to the equipment manufacturers. The capability of laser processing of finer pitch fuses has become the bottleneck to further miniaturization of redundant fuses and one of the major considerations in memory fuse design.

We will first review the current status of laser processing of memory links. Solutions for effective processing of aluminum and copper links are developed and presented here. Finally, future direction for fine pitch memory link processing is discussed

Current Technology for Laser Link Removal

To improve the yield of IC memory devices, laser technology has been used as a redundancy repair tool and is now widely accepted as an industry standard process.[1]

Poly-silicon has been widely used for the link material in the past due to its superior cut quality. Material properties, such as the deep absorption in the 1μm wavelength range, provide relatively uniform temperature distribution. This promotes clean removal of link material by laser irradiation. However, its high resistance and complex processing limits its use in deep sub-micron application. As the designs include multiple wire layers, the tolerances of the wiring and the dielectric layers make it very difficult in reducing precisely the thin layer thickness over poly-silicon links.

Recently, metal links have become the trend. Aluminum fuses begin to replace poly-silicon and have been studied recently for their manufacturability and reliability.

Aluminum has a relatively low melting point and high surface tension so the molten and vaporizing link has a tendency to splatter. To prevent retention of traces of metal and link splattering the metal has a layer of oxide over in order for the molten metal to build up pressure before explosively vaporizing through the oxide layer. The thin oxide layer is part of the process and separates the metal link layer from the upper layer of metal, which contains the pads that connect to the outside world. The oxide layer may be made up of several layers, which can have variability due to process variability of at least 10% per oxide layer. This oxide layer impacts the percentage of laser energy that couples into the link due to variations caused by interference effects of the oxide layer. For aluminum under the oxide layer this variation in energy coupled into the link can range from 8% to 17% dependent on the layer thickness.

In order to achieve successful laser cutting of an aluminum line, material leftover at the bottom of the cut site and lower corner cracks are major reliability issues. These two failure modes have been defined as low and high bound of the laser process window. [2] Fig.1 shows a long, undesirable lower-left corner crack, which poses a reliability concern since it may form a short circuit or damage to surrounding structures. The asymmetric cracking is caused by the laser-spot positioning error. Damages to the neighbor fuse structures or substrate due to excessive spot and energy is also another failure mode at high laser energy.

For high performance logic devices and high speed SRAM, copper has been investigated as link material due to its enormous benefits when compared to aluminum, such as its low resistance, power dissipation, manufacturing cost and superior resistance to electro-migration. However, there have been found some difficulties in the laser

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processing of copper fuses because of the different material properties and fabrication of copper metallization, such as lower coefficient of thermal expansion and higher melting point as well as its thick structure.

To improve the laser process of the metal links, various technologies have been studied and some implemented. Attempt has been made to modify the laser beam spatial distribution from “Gaussian” to “ top hat”, as well as to change the beam spot shape from round to rectangle or square.[3] Another attempt is to use longer (1.3 microns) wavelength.[4] Though the absorption of the silicon wafer at the longer wavelength is much less, the long wavelength puts a limit on the smallest spot size the optics can produce.

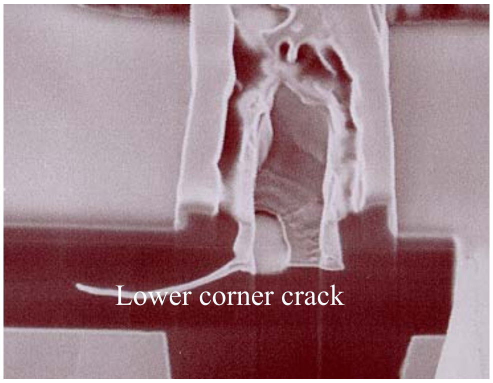


Fig. 1. An FIB cross-sectional image of a failed laser metal cut site due to undesirable lower corner cracking.

Laser Pulse Shaping

To minimize heating and absorption of the substrate, the laser pulse width is kept as short as possible and the pulse is shaped with a fast rise and fall times.

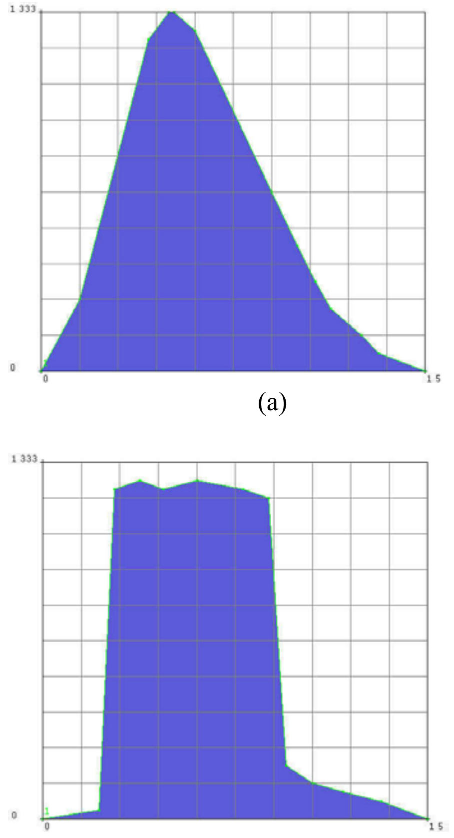
Theoretical modeling has been developed to illustrate the advantages of such a short pulse-shaped laser over the conventional Q-switch lasers.

Material leftover at the bottom of the processed cut-site and the lower-corner cracks has been shown to be a major reliability issue. It also limits the high end of the laser processing window (energy) rather than the 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.[5]

Fig. 2(a) shows the power profile of a conventional Gaussian laser pulse over time used for first simulation, whereas Fig. 2(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. 3(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 cracking for fast rise time laser pulse is longer than that for conventional pulses.



(a)

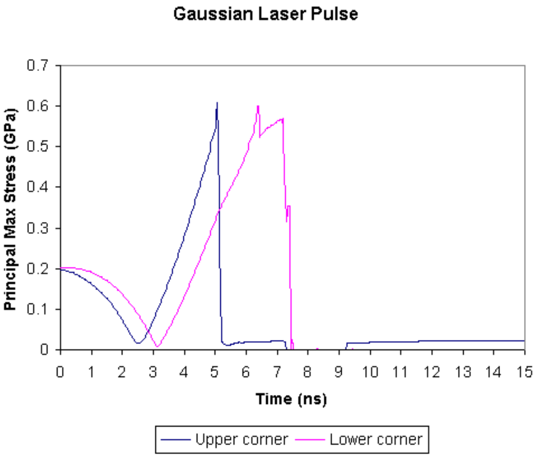
(b)

Fig. 2. Two laser pulses over time used for finite modeling, (a) Gaussian laser pulse (b) fast rise/fall time laser pulse.

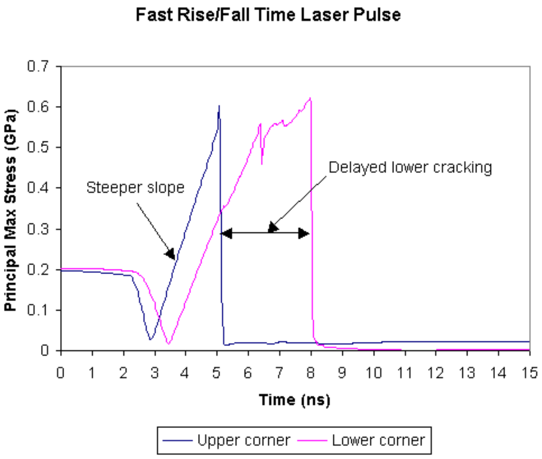
Another benefit of the fast rise time laser pulse is that the reflectivity of metal decreases over laser heating due to fast heating of the line and hence promotes absorption of laser energy efficiently. Therefore, metal links are cut more efficiently at lower nominal energies and less likely to have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

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

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 even more important and beneficial.



(a)



(b)

Fig. 3. Stress profiles under laser heating, (a) Gaussian laser pulse and (b) fast rise/fall time laser pulse.

Effects of Laser Beam Polarization

As copper is highly reflective in 1 micron wavelength range, copper processing requires high laser energy in order to perform a reliable cut. In addition, copper has a low coefficient of thermal expansion and requires a higher temperature to initiate cracking at upper corner as compared to aluminum. Bigger hole sizes after processing are typical for cut site.

When the tensile stress reaches the critical stress of dielectric, cracks initiate and propagate within dielectric perpendicularly to the local maximum principle tensile stress. However, the dielectric layer has a weak point around the fuse corners due to the chemical mechanical polishing (CMP) process as well as the interface between Si_3N_4 and SiO_2. So the critical stress for cracking is considered to be lower than for other types of metal fuses. For this reason, the cracks tend to take a different path, which follows the weak interface of Si_3N_4 and SiO_2, and upper cracks propagate laterally as shown in Fig. 4. These laterally propagating upper cracks contribute to the large cut site. On the other hand, thermal diffusion from the link into dielectric layers on the top of link by relatively high laser energy irradiation could be attributed to severe delamination of Si_3N_4 and SiO_2 layers and this also may contribute to large cut site.

Therefore, the hole size is also another limiting factor for the high end of energy process window together with a lower corner cracking. For this reason, the copper fuse requires bigger fuse pitch than that of aluminum fuse. A big hole at the cut site, after a laser irradiation, is shown in Fig. 5. The width of copper fuse is 0.7μm and the spot size used was 3μm in this case.

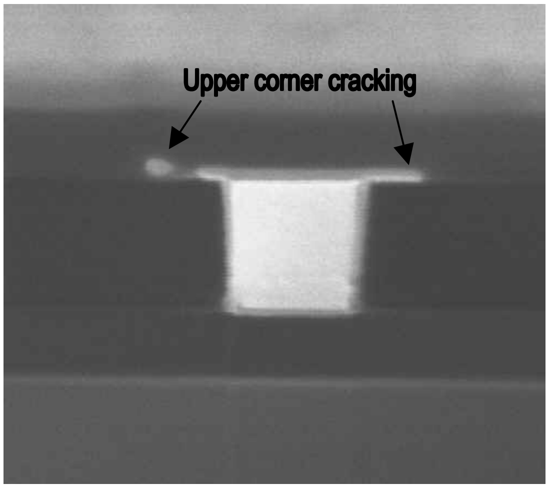


Fig. 4. An FIB cross-sectional image of Cu cut site processed with a low laser energy showing the initiation stage of upper corner cracking.

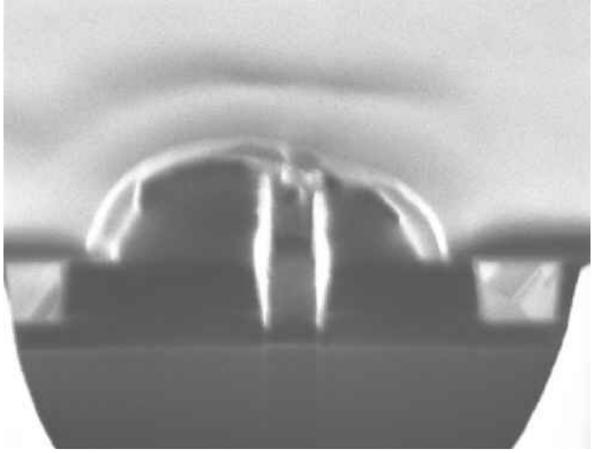


Fig. 5. An FIB image of processed cut site of Cu fuse showing a big size of hole.

In order to control and minimize the hole size after laser irradiation, the effect of polarization was investigated experimentally. It was found that a great improvement in processing window could be attained by choosing the correct polarization as can be seen in Fig. 6. Laser pulses with three different polarizations, along the link, circular, across the link, were applied on the same structures and the process windows were examined. Three blue vertical lines indicate the absolute laser energy ranges where the links were processed successfully. The energy range was determined by optical microscopic observations. Material remaining was the lower limit and neighbor damage caused by big-hole size, which was defined by larger diameter than the fuse pitch, was the upper limit in determining the process window.

The red dotted line indicates the change of relative process window depending on polarization mode. The relative process window is redefined by the ratio of difference between high and low end of process window (E_h-E_l) to the average energy ($E_a = (E_h+E_l) / 2$).

$$\text{Relative Process Window} = \frac{E_h - E_l}{E_a}$$

This normalized, non-dimensional term considers the performance of the laser systems clearly and eliminates the dependence of the absolute energy window on the characteristics of different laser systems.

Fig. 6 demonstrates that the energy process window is strongly dependent on polarization. Specifically it indicates that cross-link polarization is optimum for this particular structure. The relative process window with a variation of polarization changes significantly depending on the polarization mode. It is believed that changing polarization results in a unique heat distribution in the link.

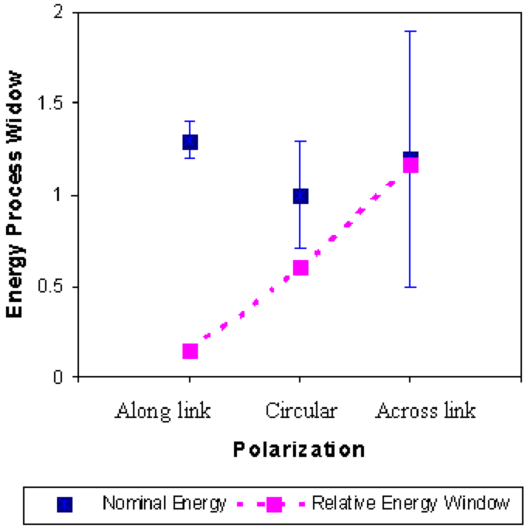


Fig. 6 Effects of polarization on energy process window

Fig. 7 displays two trends of the relative process windows with a variation of spot size and the impact of changing spot size with polarization. The two curves show the same polarization trend ,while the minimum process window of a 2.3µm 1/e^2 diameter spot is smaller than that of 2.8µm spot. However, with a polarization across the link, the process window is almost the same. This indicates that polarization is critical on laser energy window of copper processing especially when a smaller spot size is required.

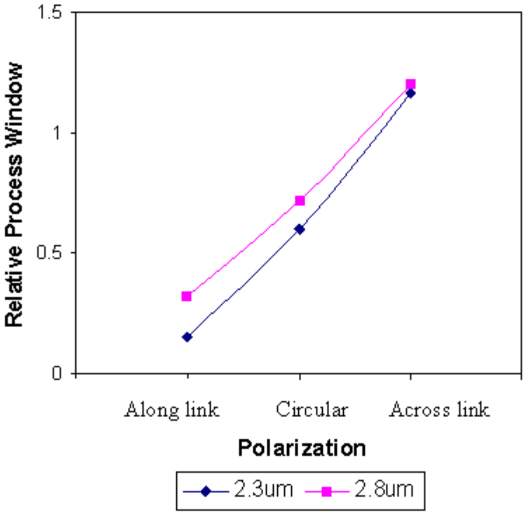


Fig. 7. Comparison of the changes of relative energy process window processed with two different spots size and variation of polarization

Laser Beam Positioning

Laser beam has to be focused and positioned on the link precisely in order to have a successful removal process. As the widths and pitches of fuse links decrease due to high density requirement, it requires excellent laser beam positioning accuracy, as well as smaller beam size and reasonable focal depth.

Current laser repair system has the positioning accuracy around 0.2 microns. It can handle the current generation links that have link pitches around 2 to 3 microns.

Special calibration and measurement tools together with the patented stage technology have been developed to assure the beam position accuracy.

Challenges

The memory manufacturers are developing smaller link structures. They are also finding ways to improve insulator thickness variations and to shield substrate from damage.

The biggest challenge for laser systems is the reduction in links' width and pitch. The laser system has to go beyond the current capabilities to meet these challenges. New technology will be required as dimensions shrink and parts increase in size. While each individual enhancement is important and beneficial to the whole process, the laser memory repair process should be taken as a total process, as various process parameters are correlated.

In order to process the link with a finer pitch, the laser beam spot size has to be reduced while maintaining reasonable depth of focus. The beam positioning accuracy has to be improved while maintaining high throughput and production worthy energy process window. More importantly, the thermal effect caused by the laser beam has be to minimized or eliminated so that the advantages of the above mentioned improvements on beam size and accuracy can be fully realized.

Future Directions

One of the directions is to reduce the spot size. New lens design has pushed the limit of optics. For example, the smallest beam spot size practically achievable for production at 1.3 microns is about 1.7 microns while spot size of less than 1.3 microns can be achieved with 1-micron wavelength. Since the theoretical limitation of the smallest focused Gaussian laser beam spot size in linearly proportional to the wavelength used, shorter wavelengths can be used to get even smaller spot sizes. However, the concern with the silicon substrate at shorter wavelengths has to be addressed.

Another direction is to use shorter pulse width lasers. The thermal effect at shorter pulse duration can be reduced or eliminated, therefore, damage on the neighboring links can be minimized or avoided. Moreover, the process is much more controllable and the damage to the substrate can be minimized.

Figure 8 shows the test result of an aluminum link severed with an ultra short pulse laser. With ultra short laser pulses, the thermal effect is reduced or eliminated. With the combination of smaller spot size, better beam positioning accuracy and low or no thermal effect, the laser processing of ultra fine pitch links becomes feasible.

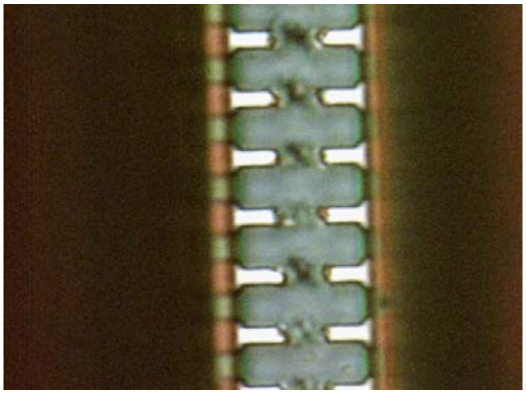


Fig. 8 Aluminum link severed with an ultra short pulsed laser.

Conclusions

Laser processing of IC memory links has become an standard industrial process. Over the years, various laser process technologies have been developed. Technical improvements like laser pulse shaping, laser polarization selection, development of better beam positioning stages, and better beam delivery and monitoring system, have pushed the capabilities of the current laser memory repair system to another level. And they are servicing the industry well at the moment.

As the industry road map calls for finer pitch for the memory fuse links, it presents a challenge to laser system manufacturers. New technologies have to be developed in order to meet this challenge. Initial test results on different laser sources suggest a very promising future for laser link processing.

Acknowledgments

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