Improvement of Laser Fuse Processing of Fine Pitch Link Structures for Advanced Memory Designs

Joohan Lee, Joseph J. Griffiths, and James Cordingley
GSI Group Inc.
60 Fordham Rd.
Wilmington, MA 01887
jlee@gsig.com

Abstract

Metal fuses for laser redundant links have been widely used for years in laser repair application to enhance yield. Shrinking design rules in IC fabrication have necessitated decreased fuse pitches in the redundancy circuitry. Current infrared (IR) lasers are facing the 2um pitch barrier due to the diffraction limited spot size and depth of focus (DOF) capabilities. In this work, we present experimental results showing how we have achieved successful laser cut processes of future metal fuse structures down to 1.0um pitch using a combination of the small spot of short wavelength laser and the polarization effect to tightly pitched neighbor structures. Inline polarization with link length minimizes the adjacent link damages and thus improves the energy process window for robust cutting. Electrical measurement data of metal link structures with various pitches, metal width and top passivation thicknesses shows the importance of controlling of top oxide thickness on the fine pitch structure. This enabling technology provides a viable production solution for laser fuse processing down to 45nm node technology and below.

I. Introduction

One of the more established final steps in fabricating ICs with circuit redundancy, such as memory, involves laser processing of fuses (or links) to disable defective circuit elements and replace them with good redundant ones [1]. Polysilicon has been widely used for link material due to its superior cut quality from unique material properties.

However, due to the high resistance and complex fabrication process limitations of deeply buried polysilicon fuses, industry has driven the migration of fuse material to aluminum. Copper has been also used as link material for high performance logic devices and high speed SRAM due to its enormous benefits when compared to aluminum, such as its low resistance, power dissipation, manufacturing cost and superior resistance to electromigration. Recently, those benefits have made even DRAM makers investigate Copper to replace Al for materialization in their chips.

In the laser processes of the polysilicon, Al or Cu links, IR laser wavelengths, such as 1.064μm Nd:YAG, 1.047μm Nd:YLF and 1.342μm $Nd:YVO_4$ lasers have been widely used due to their relatively stable processes, favorable absorption characteristics of Si and acceptable process windows.

In previous works, we explored the failure mechanism and status of current laser cut processes of those two major materials (Aluminum and Copper) [1]-[4]. In the works, lower corner cracking as well as substrate and neighbor damages were discussed in-depth and we defined the laser energy process window based on the finite element simulation results and various experimental observations.

The design rules of the IC fabrication process have decreased over the past 20 years. The continuous shrinking of transistor device dimensions of Si CMOS technology has been the main driver for the scaling of laser fuse repair technology. 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 [5]. With this trend, decreased fuse pitches have been required in the redundancy circuitry and the demand for even smaller fuse pitch has been accelerated for advanced generations of state-of-the art memory designs

The resulting decreased fuse pitch and size have necessitated a laser process with smaller minimum spot size and better focus margin in order to avoid damage to adjacent fuse structures. Furthermore, processing of reduced fuse metal line widths using laser beam increases the chance for lower-corner cracking and neighbor link damage due to metallization with high aspect ratios and tightly pitched metal lines. Therefore, clean cutting with low laser energies combined with excellent beam positioning accuracy has also become more desirable for shrinking fuse pitch structures that tend to be more susceptible to laser damage than Si substrate.

However, conventional 1.0~1.3μm wavelength lasers have demonstrated limited capability as an acceptable and reliable production process below approximately 2.0μm pitch structures due to their diffraction limited spot size and depth of focus (DOF) capabilities. As fuse pitches continue to decrease, the limitation from neighbor fuse damage, as a major failure mode, for fine pitch fuse structures has eliminated the advantage of less damage to Si substrate from a 1.3μm laser. As a result, new production-proven laser processing solutions needed to be established to support advanced generations of devices.

Extensive manufacturing and qualification studies have been conducted in order to achieve robust laser fuse processing with small spot sizes, large focus margins and excellent beam positioning accuracy, thereby yielding a practical and viable laser fusing system for both current & future fine pitch processes.

This paper reports experimental results that were obtained with laser fuse processing of state-of-the-art memory devices with a short wavelength laser (532nm) that allows a much smaller spot and a larger depth of focus window than conventional laser wavelengths. Specially, polarization effects of the irradiating laser beam with regard to the coupling into the targeted link as well as neighbor link structures are reported on and discussed. Also, an analysis of various fuse structures, with variations of fuse pitch, width and top passivation, provides an understanding of laser fuse processing of ultra-fine pitch structures down to 0.8um pitch.

II. Experimental setup

The test wafer, with aluminum lines, was fabricated using a standard two-level metal CMOS process for this particular short wavelength laser experiment. The upper metallization, used for this study, was sputtered Al (1% Si, 0.5% Cu) and etched to form variously wide fuses and 0.4μm thick lines. The Al lines were undercoated with 0.02μm and 0.01μm thick TiN/Ti layers, respectively. In addition, these lines are overcoated with 0.1μm/0.01μm thick TiN/Ti layers. This produces a thickness of whole metal line stack of 0.54μm. A passivation layer, consisting of various thicknesses of SiO_2, covered the metallization for the purpose of reliability during the laser process.

There are 6 pitches ranging from 0.8μm~1.8μm with a 0.2μm step. Also, each pitch has 5 different fuse widths (0.2μm~0.6μm with a 0.1μm step). The Passivation layer of SiO_2 was etched to form 3 different thicknesses for these experiments and the thicknesses are 3100Å, 3400Å and 4900Å, on average, across each wafer (3 wafers in total).

Therefore, there are a total of 90 different linear aluminum fuse structures. Each structure is designed to have two different formats; one is to check the cut quality (parallel structures to blow all links as shown in Fig. 1 and 2) and the other is to check for damage to adjacent structures in order to ensure the acceptability of cut processing (serial structures to blow every other link as shown in Fig 3). Electrical measurements were conducted after microscopic observations of the processed "cut" fuse structures.

The laser system used to perform these experiments was a GSI Group M555 laser fuse processing system. The system employs a diode-pumped, Q-switched, frequency doubled Nd:YVO_4 laser (532nm) operated in the saturated single-pulse mode. Pulses, with lengths of approximately 13ns in FWHM scale, were directed through focusing optics to produce a beam of $1/e^e$ diameter of 0.7~1.8μm spot at focus. The positioning accuracy of the laser system was less than 0.15μm.

III. Process Studies of Different Polarization Effects

In order to control and minimize the hole size at cut sites after laser irradiation, the effect of polarization was investigated experimentally. Laser pulses with three different polarizations, along the link (inline), circular, and across the link (cross), were applied on the same structures and the three process windows of interest (energy, alignment, and focus) were examined. It was found that a great improvement in all process windows could be attained by choosing the correct polarization.

Fig. 1 shows failed cuts due to the large holes at the cut sites processed with cross polarization. Those large holes are thought to be caused by propagating lower-corner cracks and thus causing neighbor link damages.

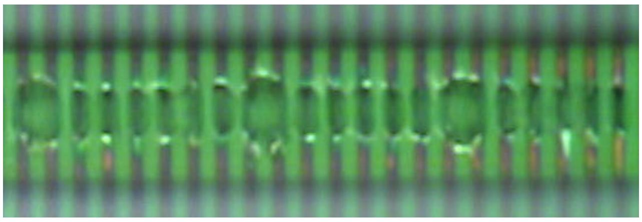

Fig. 1. Top view image of failed cuts due to the large holes that cause neighbor link damage. Pitch: 1.0μm, link width: 0.4μm. Processed with cross polarization, 0.9μm spot and a laser energy of 0.10μJ. Parallel structures to check cut quality of targeted structures.

On the other hand, Fig. 2 displays successfully cut structures by utilizing inline polarization. Same laser parameters and link structures as the previous experiment were used except for the different polarization. No large holes were noticed and materials at the cut sites (links) were clearly removed. Based on the experimental observations, it is considered that cross polarization has higher chance for large holes at cut sites which causes neighbor structure damage. The detailed discussion of this mechanism will be followed in a later section with simulation results.

All of the energy, alignment and focus studies were conducted using 3 different polarizations for all different structures with various pitches, metal line widths and passivation thicknesses. Each process windows were decided by microscopic observations. Fig. 4 shows results of relative energy process windows of links processed with 3 different polarizations.

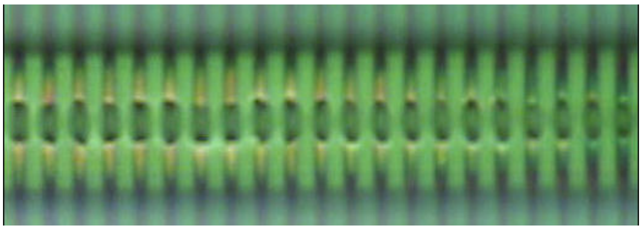

Fig. 2. Top view image of successful cuts from using inline polarization. Pitch: 1.0μm, link width: 0.4μm. Processed with 0.9μm spot and a laser energy of 0.10μJ. The links are parallel structures to check cut quality of targeted structures.

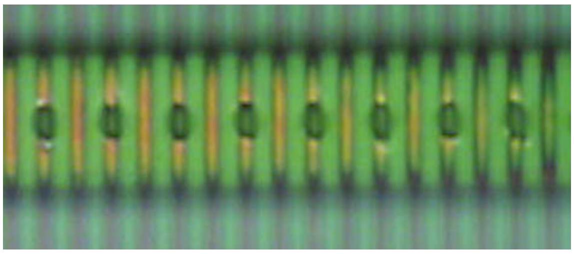

Fig. 3. Top view image of successful cuts from using inline polarization. Pitch: 1.4μm, link width: 0.5μm. Processed with 0.9μm spot and a laser energy of 0.10μJ. The links are serial structures for checking neighbor structure damage and supposed to irradiate laser beams every other links.

The relative energy process window is defined by half the ratio of the difference between high and low end energies of the process window (E_h-E_l) to the average energy (E_a = $(E_h+E_l) / 2$).

$$\text{Relative Process Window} = \frac{1}{2} \times \frac{E_h - E_l}{E_a}$$

This normalized, non-dimensional term considers the performance of the laser systems clearly and eliminates the dependence of absolute energy to determine the performance the characteristics of different laser systems [4].

As can be clearly seen in Fig. 4~6, inline polarization improved all of three process windows especially for structures with pitches of less than 1.6μm. These results indicate that inline polarization is more reliable for tight fuse pitch structures. Also, based on the observations that all process windows were limited by neighbor link damage, inline polarization is thought to have less energy absorption into neighbor links.

Each data point in figure 4~6 indicates an average value for all various widths and top passivation structures for a specified pitched structure. It is also noted that 0.8μm was not considered due to the poor electrical results; this tight fuse pitch structure will be discussed in the following section.

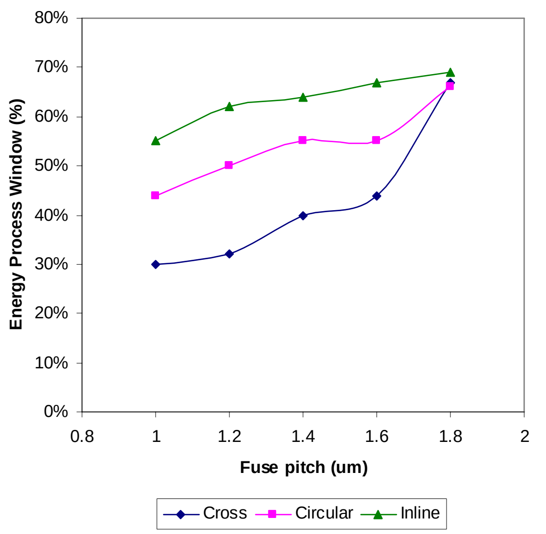

Fig. 4. Results of energy process windows with a variation of polarization. Spot size: 0.9μm.

It is interesting to note that the differences of the relative energy process window become significant for different polarization with a decrease in fuse pitch. When the pitch is large enough, the relative energy process windows for all types of polarization converge and it is thought that the process performance results for cross polarization will exceed the other two types of polarizations for greater than 1.8μm pitch.

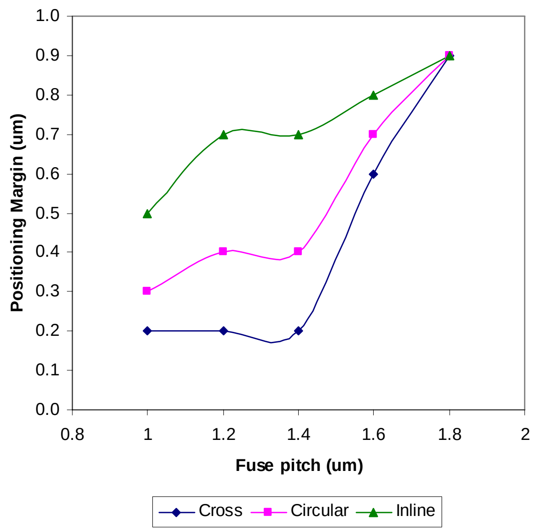

Fig. 5. Results of alignment margin with a variation of polarization. Spot size: 0.9μm, laser energy: 0.10μJ.

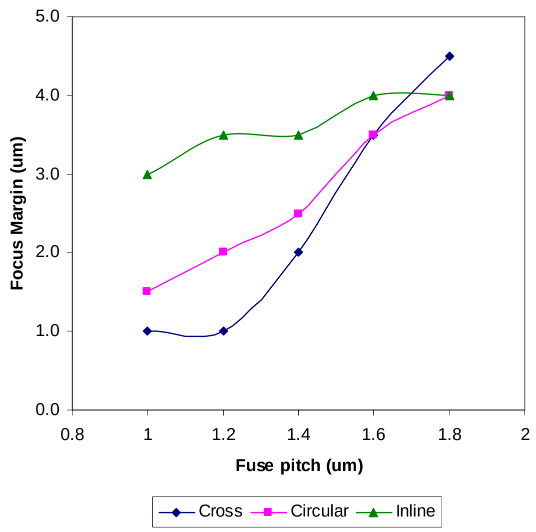

Fig. 6. Results of focus margin with a variation of polarization. Spot size: 0.9μm, laser energy: 0.10μJ.

Not only the energy, but alignment positioning and focus windows also converge when the link pitch gets large enough to change the major failure mode from adjacent link damage to other failure mechanisms, such as Si substrate damage or link material leftover. In the case of focus margin, cross polarization provides the benefit of clean material removal and allows larger focus margin than the other two polarizations.

Figures 5 and 6 show results from alignment positioning and focus studies for 3 polarizations respectively. It shows results that are consistent with the energy studies that inline polarization works best for ultra-fine pitch structures. Microscopic inspection revealed that all the windows were limited by the adjacent fuse damage for the cases of ultra-fine fuse pitch structures (< 1.6um). Therefore, we concludes that inline polarization is less process susceptible to adjacent fuse damage limitations at these aggressive pitches.

In order to understand these phenomena, simulations were performed to measure the absorption into the targeted link in conjunction with varying the polarization. For these simulations, a commercial ZEMAX model was used.

Fig. 7 shows that intensity absorption changes with a variation of polarization from simulations and the schematic of a cross-sectional view of the metal link structure. The metal line that formed from plasma etching process has a trapezoidal shape in cross section as shown in the drawing. Therefore, it has an angle of less than 90° with the incident laser beam. This angle is specified as θ in the drawing.

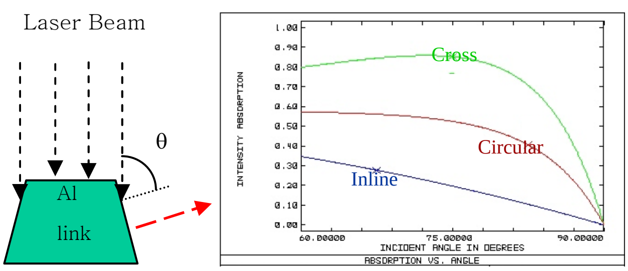

Fig. 7. Simulation results showing that absorption of laser changes with a variation of incident angle on the side wall of link. (x axis: incident angle (θ), y axis: relative intensity absorption (%)).

The graph shows that inline polarization has the smallest coupling into the sidewall of link structure with a change of incident angle of laser beam. This explains two things. First, less absorption into the sidewalls of link structure will help the targeted link avoid creating lower-corner cracking. This is because most of laser beam will heat the top part of the link and generate upper-corner faster cracking than circular or cross polarization modes. As mentioned previously, a large hole created by lower-corner cracking will cause neighbor structure damage.

On the other hand, cross polarization (as shown in Figure 7) will have more absorption into the lower-corner of metal line as well as sidewall, thereby presenting a higher likelihood for lower-corner cracking. The propagating cracks from lower-corner will generate a large hole and damage the adjacent link structures especially when the pitch is tight.

However, Fig. 7 indicates a more efficient absorption into the targeted link with cross-polarization compared to the other two types of polarizations. Therefore, it is considered that cross polarization can remove the material more efficiently. This suggests that relatively large pitched structures will gain a benefit from cross polarization.

Second, the absorption changes with polarization type can also be used for the explanation of absorption into the neighbor link. If we assume that there is a slight absorption into the sidewall of neighbor link from the laser beam irradiation (Gaussian spatial shaped beam), inline polarization will have the smallest coupling into the neighbor link structure due to the absorption phenomena in Fig. 6. Cross polarization will tend to have more absorption into the sidewall of neighbor link and therefore damage the structure sooner than inline polarization.

IV. Fuse Structure Optimization

Various fuse metal structure designs and laser parameters were tried and the results were measured electrically to ensure the practical implementation of the 532nm wavelength laser on future metal structures as well as current and ultra-fine pitch metal structures in production today.

Fuse structures were processed with the 532nm wavelength laser with 0.9μm spot and inline polarization. This parameter setting (spot size and polarization) was determined based on experimental data with various spots and polarizations. Specifically, the effect of oxide thickness of top passivation and the link width on yield after repair were considered. Three different passivation thicknesses (3100Å, 3400Å, and 4900Å) and five different fuse widths (0.2μm, 0.3μm, 0.4μm, 0.5μm and 0.6μm) were taken into consideration.

Fig. 8 displays electrical test results with a variation of fuse pitch for three different passivation thicknesses. Structures with relatively thin passivation on top (3100 and 3400Å) show stable electrical results down to 1.0μm pitch. The acceptable FTA is defined to be higher than 99.0%. However, the thick passivation structure (4900Å) resulted in instable FTA when it is pitched below 1.6μm. This indicates that the importance of controlling of passivation thickness as well as limitation of possibly shrinkable fuse pitch based on the current structure. Previous simulation results showed that higher chance for large hole at the cut site for deeply buried structures with thicker oxide on the top. This is due to the more focused tensile stress at the lower-corners having thick passivation. Visual inspection of the various blown links under microscope also confirms this and adjacent structure damage was more noticed in the structures with 4900Å thick passivation.

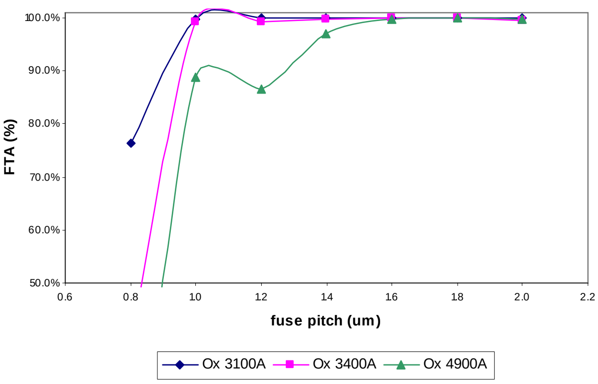

Fig. 8. Yield after repair with a variation of link pitch for 3 different top oxide thickness structures. 100% yield indicates electrical test of all adjacent link structures passed the test and not damaged.

When the fuse pitch reaches 0.8μm, yield after repair of all the structures starts to fall and none of the structures showed acceptable yield. However, it is clear that thicker passivation shows significantly poor yield as fuse pitch shrinks.

As a result, we conclude that the optimum passivation thickness is under 3100Å.

Fig. 9 presents the electrical test results of fuse structures with a variation of fuse link width. Specially, thicker passivation of top of link structure deteriorates the yield result significantly, which is the same as aforementioned case. It has been reported that narrower metal link increases the probability of generating cracks from the lower-corners as well as upper-corners of metal line [6]. In Fig. 9, yield decreases with a narrower metal link for all passivation thicknesses and visual inspection revealed that the hole size at cut sites got significantly large for narrower structures, thereby generating adjacent link damage. Furthermore, it is thought that thick passivation with narrower link width shows the most significant fall in yield. It is due to the fact that a narrower link with thicker passivation decreases the stress difference between the upper and lower-corners or even more stress focused on lower-corners, thereby creating large holes at a cut site by propagation of lower-corner crack.

On the other hand, the results in Fig. 9 describe that a controlled thin passivation can help yield a more stable process for narrow link structures to some extent.

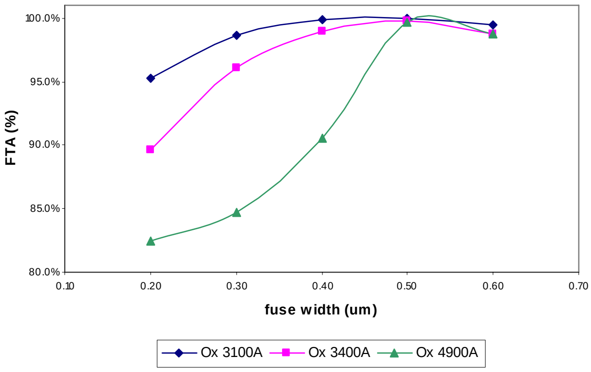

Fig. 9. Yield after repair with a variation of link width for 3 different top oxide thickness structures. A 100% FTA indicates electrical test of all adjacent link structures passed the test.

V. Conclusions

We have shown successful laser fuse cutting of ultra−fine pitch structures down to 1.0μm using a small spot 532nm wavelength laser through visual observations and electrical tests.

It was found, through experimental observations, that significant process improvement in energy, alignment position and focus windows can be attained during laser processing of ultra−fine pitch metal line structures by choosing the correct polarization. In the processing of fine pitch structures, all process windows are limited by neighbor link damage from the direct laser coupling into the adjacent structures. Inline polarization can help mitigate this effect and improve the overall process window.

Neighbor link damage from lower−corner cracking of a targeted link is also one of the critical failure modes as the pitch and width of the fuse decrease with shrinking design rules in CMOS chip fabrication. Thick passivation and high aspect ratio metal lines will shrink the process margins for reliable laser fuse cutting and controlled process optimization is needed for robust laser processing.

References

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