Advances in Laser Technologies for Semiconductor Memory Yield and Repair Applications

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Abstract

This paper presents advances in laser technology and future directions for processing laser fuses used in semiconductor memory yield and repair applications. It includes results from recent work with UV diode-pumped solid-state lasers, ultrafast lasers, and master oscillator fiber power amplifier laser systems (Tailored Pulses). In addition, an assessment of the benefits of laser fuses for memory yield and repair applications compared to electronically processed fuses is provided.

I. Introduction

Semiconductor memory companies employ one-time programmable fuses along with redundant memory cells to boost yield. This is an essential step in manufacturing because under typical conditions the number of "good" chips on a wafer is very low, and this can be increased to nearly 100% yield by using a repair scheme. This occurs during the Wafer Sort step and involves processing a series of fuses on the chip either electronically by a tester (e-fuse) or by a laser machine tool (laser fuse). The technology for laser and e-fuse is different, and details of both laser [1,2,3,4] and e-fuse [5,6,7] are presented elsewhere. Both of these technologies can provide unique advantages for manufacturers, and both types of fuses can be used on the same chip. For example, most DRAM [8] and NAND FLASH chips use exclusively either laser or e-fuse, while embedded memory and logic programming chips might employ 90% e-fuse, 10% laser fuse. This demonstrates that there are a variety of considerations that must be made when choosing a redundancy scheme for a device, including cost, throughput, design complexity, materials required, reliability, and physical size. The physical size and area requirements for redundancy schemes is becoming increasing important as design rules for memory products continue to get smaller. Both the size and distance between fuses (the fuse pitch) must shrink. In addition, the required number of fuses per chip will significantly increase in the future which means that throughput and reliability will increase in importance. Both laser and e-fuse technology will potentially face unknown real-world process challenges as the number of required fuses per wafer moves into the multi-millions. This manuscript will discuss laser technology solutions that are being pursued in order to meet these challenges, and also compare and contrast some of the unique features of laser and e-fuse.

A. Overview of Laser and E-Fuse

The literature provides examples of different types of e-fuse technologies, but it is difficult to find significant details about state of the art devices (likely because of proprietary issues). A fairly detailed presentation of one e-fuse can be found here [5]. Briefly, the e-fuse is blown by applying a higher-than-nominal voltage by a wafer tester causing electromigration of a silicide material resulting in substantially increased resistance in the fuse. This process does not involve a physical rupture of the fuse element and can be performed during several different device test steps (high-temperature wafer test, low-temperature wafer test, first-pass package test, and post-stress package test).

Figure 1 shows the laser fuse process. A laser fuse is a conductive metal line or wire suspended in a surrounding dielectric material (usually SiO_2). The fuse is blown by using laser energy to melt and vaporize a portion of the material (along with the overlying dielectric) to form a highly resistive cut. In its early years, laser fuses were constructed from polysilicon lines. Today, they have moved into the metal layers located higher in the semiconductor device stack. Over the past several years, a bifurcation has developed in the industry. One path includes DRAM manufacturers who typically use two to three layers of aluminum as metallization. For these manufacturers, circuit density is critical and fuse pitch is often less than 2.0 μm with typical fuse dimensions are less than 0.5 μm in both width and thickness. Fuse pitches of 1.0 μm are now found in research labs and pilot lines. Along a second path are Embedded Memory manufacturers in logic type applications. In this case, metallization can consist of as many as ten or more layers of copper, and device performance metrics (such as current capacity) often require the upper metal layers to approach or exceed 1.0 μm in thickness. Hence, Embedded Memory fuses can be significantly thicker than DRAM fuses depending on which metal layer they reside. As fuse pitch is required to shrink, the fuse widths must shrink below 1.0 μm resulting in fuses that are thicker than they are wide.

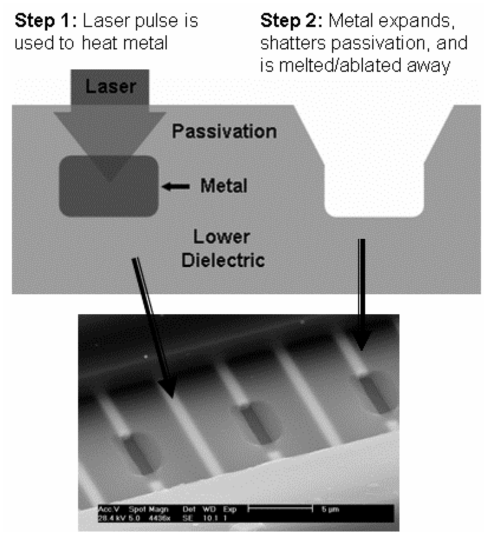

Figure 1. Summary of laser fuse process.

To address these different needs, Electro-Scientific Industries in Portland, OR, USA, which has been involved in laser fusing since the onset of the industry, has focused on different solution paths for different laser fuse applications. Historically, memory repair has relied upon IR diode-pumped solid state lasers in the 1W class with pulse widths of ten or more nanoseconds with practical spot sizes down to ~1.5 μm ($1/e^2$). For DRAM-type applications moving forward, spot sizes of less than 1 μm will be required and the strategy to provide these spot size has been to transition from IR to Green (532 nm) and UV (355 nm) lasers. For embedded memory applications, pulse width considerations and the need for flexible pulse shapes have driven the solution path towards master oscillator-power fiber amplifier (MOPFA) technology to provide temporal "Tailored Pulses". Ultrafast lasers with pulse widths in the picosecond (ps) to femtosecond (fs) range are also being explored for both applications, to determine if ultrafast can offer smaller effective spot sizes and mitigate damage to surrounding and underlying materials compared to nanosecond pulses.

B. Comparison of Laser and E-Fuse

Some comparisons can be made between laser and e-fuse technologies from the laser fuse perspective. This kind of analysis can assist manufactures with deciding which type of fuse is best for each application:

1. Location, physical size and pitch requirements. E-fuses are located in the active region of the device, while laser fuses have the option of being placed in either the active region (polysilicon) or any of the higher metal interconnect regions. Laser fuses are currently limited to pitches based on the smallest spot size the laser tool can accurately provide while e-fuses are reported to be scalable with the technology node. This ability to scale is one of the potential advantages of e-fuse over laser fuse, although it is difficult to quantify the differences based on published literature. Projections of fuse area requirements are possible using the International Technology Roadmap for Semiconductors as a guide, but this type of exercise still requires many assumptions, and is best left to individual designers. From our perspective, we would very much welcome a comparison of the physical dimensions of the e-fuse option to the laser fuse option in leading-edge production devices. To be fair, the comparison should include the total area of the silicide e-fuse region itself, the associated cathode and anode, any extra circuitry required, and finally any additional probe or bond pads that might be required. For the laser fuse case, not only the fuse link, but also contacts at the ends of the link and exclusion zones

at the ends and sides of the links must be included. Looking at the previously mentioned reference [5] by Rizzolo et al, the total area of the e-fuse including the anode and cathode is approximately 4.3 x 1.7 μm or 7.3 μm^2 per fuse, which are dimensions that can also be achieved by laser fuse. While the Rizzolo citation is quite recent, it describes e-fuses used in a computer system (IBM z9) that was introduced in 2005, suggesting that the e-fuse in this particular reference may be from a previous technology node or technology qualification. Technology generations have changed in the past two years, requiring a comparison of current designs at the current technology node.

2. Capital costs. Laser machine tools cost less than tester tools. From a tooling perspective, the laser plus tester solution is lower cost than the tester only (e-fuse) solution. The laser and tester can run in parallel, and as the laser throughput increases by using higher rep rate and multi-beam laser systems the two-tool solution becomes even more effective.

3. Implementation costs to convert. For customers already invested in laser fuses, the costs have already been incurred for the installed base and the learning, process optimization, and die design optimization. Converting to e-fuse brings with it the cost of new learning and process and design optimization. Obviously, manufacturers must evaluate these costs to make an assessment for their own situation. ESI always welcomes participation in this kind of opportunity and offer up to date roadmaps and details about the current state of the art for laser fuse technologies.

4. Intellectual property (IP) considerations. There is considerable recent IP around e-fuse processing, primarily around its use on embedded memory or other logic devices (IBM, TSMC and others have invested heavily in this space). Design and implementation of e-fuse materials will vary in difficulty for different manufacturers depending on the films stack, and/or if integration of new materials is required. In contrast, Laser fuses do not require new IP or new films in the device structure.

5. Failure rates. Laser fuse has proven track record of high yields across many products and designs. E-fuse works well for lower fuse count logic designs, and chip yields for high fuse count designs remain to be demonstrated. As bit density and number of fuses per wafer increases, the statistical failure rate of both laser and e-fuse may become significant. The result is that either or both fusing processes may require multiple fusing cycles to correctly process the fuses. To date, the number of laser fuses per wafer has been small compared to the statistical failure rate and has not been an issue. In the future, this may become significant. From the laser fuse standpoint, ESI is in the process of evaluating statistical failure rates for laser fuses to determine when/if fusing re-attempts might become necessary as fuse count per wafer increases.

6. Throughput. E-fuse is typically used in embedded memory and logic applications where fuse counts per die and per wafer are low. These applications might use 100 fuses per die, 300 die per wafer, or 30,000 fuses per wafer. On the other hand, DRAM applications typically require 10,000 fuses per die, 1000 die per wafer, or 10 million fuses per wafer. Laser fuses can be processed significantly faster than e-fuse. Excluding tool and software overhead, each e-fuse currently requires ~200 μs to process, while each laser fuse requires 10-20 ns. E-fuse developers are aware of this difference and are investigating adding additional circuitry to the e-fuse structure to allow for parallel processing. At the same time, laser machine tools are moving to lasers with higher repetition rates with parallel processing capability using multi-beam architecture. Laser rep-rates of 1.2 kHz were employed in early 1990's, are currently at 100 kHz, and onward to 200 kHz. Lasers are also becoming available with rep rates in the MHz regime. For multi-beam processing, two-beam processing is currently available, this will extend to 4, 6 or 8 beams as increases in laser energy allow. Figure 2 shows how laser rep rate has increased since 2002.

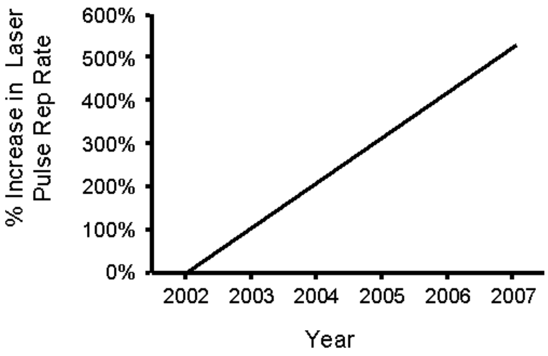

Figure 2. Graph showing percentage laser pulse frequency increases over the period 2002 – 2007.

II. Discussion

A. Small Spot UV processing

One of the primary issues for laser fuse has been to reduce the total space requirement for the fuses with each technology node. The strategy has been to reduce the laser spot size or diameter by moving from classic IR laser wavelengths of primarily 1064 nm and 1340 nm to Green (532 nm) and UV (355 nm) wavelengths. IR wavelengths are commonly used to process devices down to 70 nm technology nodes. Green laser processing technology has been production qualified on 70 nm DRAM but is not yet qualified at 58 nm. Green laser processing becomes limited by depth of focus issues for spot sizes below 1.2 μm. There is hope that this issue may be mitigated by the use of ultrafast laser pulses (as described later in this paper), spatial, or temporal pulse shaping but the resultant technology still does not avoid the fundamental restrictions of depth of focus at small spot sizes. Shorter wavelengths in the UV region provide a larger depth of focus that is essential to overcome typical process variations on semiconductor product wafers. 355 nm UV has been qualified on 58 nm DRAM and has shown spot size capability to address the needs of 32 nm DRAM devices.

Investigations into the use of UV sources for memory repair began in the 1990's [9]. One such laser is shown in Figure 3. In this figure, the pumping diode is fiber-coupled into the 1064 nm vanadate engine that in turn feeds a harmonic module producing 355 nm radiation. The design includes air purge lines to the harmonic module to keep the harmonic crystals contamination free.

To date, customers are processing 1.4 μm fuse pitches using spot sizes down to 0.7 μm on production tools, and are investigating spot sizes down to 0.5 μm diameter on laser equipment in demo labs. In addition to spot size, accuracy to position of the beam is also essential to position ultra small spots on the fuse. Figure 4 shows the results of IR and UV processing for a challenging fuse layout [10]. The aluminum lines being processed are 300 nm wide, 200 nm thick and lie in a 1μm pitch. The lines are encased in a thin layer of dielectric and sit on dielectric over silicon. Processing was conducted using 355 nm UV wavelength. An industry standard 1.34 μm laser was used for the comparison IR processing. The minimum spot size achievable with this laser, 1.6 μm, was used for this study. The photos on the left side of the figure show the IR results. The top left photo shows two lines have been cut, one with pulse energy 0.0200 μJ and one with 0.0218μJ as labeled. A cross-section photo centered on the fuse processed with 0.0218 μJ is shown directly below in the lower left of the figure. In this photo, the leftmost structure is a typical uncut fuse. In the center of this photo lies a processed fuse structure; notice that the aluminum line is absent in this structure. On the right side of the photo is a second unprocessed fuse. Notice the void in the aluminum line of this fuse. Such damage to the neighboring structure is not permitted since it presents a reliability concern. Behavior such as this is common when using IR wavelengths for tight pitch layouts and represents a limit for the technology as demonstrated here. The photos on the right side of Figure 4 show that use of a UV wavelength overcomes this limitation for the fuse pitches of interest. Here, a 355 nm laser is used to provide an 800 nm spot size at the work surface, and two links are processed, one at pulse energy 0.18 μJ and one at 0.22 μJ as labeled. A cross section centered on the fuse processed at 0.22 μJ is shown in the lower right photo of the figure. It is evident that the aluminum line has been severed and that no neighboring structure damage exists (the void to the right of the processed fuse is a void in the Pt decoration film deposited to enhance image contrast). That this is the case for a relatively high pulse energy (compare the UV pulse energies to those for the IR case) and for a UV spot size larger than the minimum that can be achieved with this wavelength provides evidence that this solution path should enable the use of tighter pitch layouts when circuit density is a primary concern.

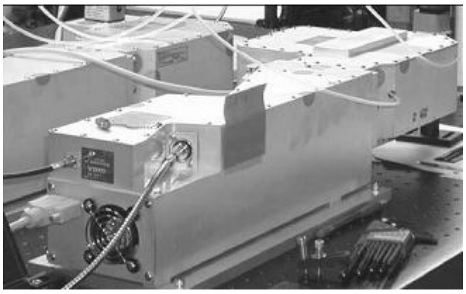

Figure 3. Photograph of UV DPSS laser in the foreground. The pumping diode is fiber coupled into the IR engine that in turn feeds a harmonic module to produce 355 nm radiation.

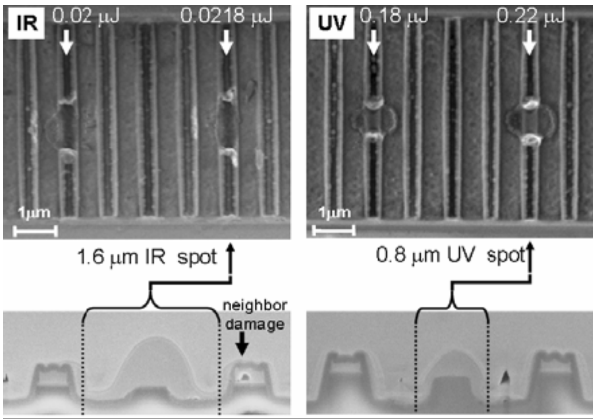

Figure 4. Comparison of IR and UV fuse processing. Details of the photos can be found in the text.

B. Tailored Pulses

Laser fuses in embedded memory applications present a different set of challenges to those encountered in DRAM-type applications. The fuse is often comprised of copper and can exceed 1 μm in thickness. The characteristic issue with processing fuses of this thickness with traditional methods is demonstrated in Figure 5. Here, a copper fuse 1μm wide and greater than 1 μm thick lying under approximately 500 nm of dielectric has been processed using typical IR DPSS laser techniques. Along the length of the fuse cut at what was the copper fuse dielectric interface is residual copper that presents a reliability concern. Oftentimes, simply increasing the pulse energy is not a solution for this issue since this may result in neighbor fuse or underlying silicon damage. Figure 6 shows sketches of typical DPSS laser pulse shapes. For a given energy, the shorter time duration pulse has a faster rise time and higher peak power. These characteristics are attractive since they enable rapid coupling of laser energy into the uppermost portion of the fuse. This produces a temperature rise in that fraction of the fuse which results in pressure being applied to the overlying encapsulating dielectric until such time when this material ruptures releasing pressure in the surrounding materials and removing the molten portion of the fuse material. By releasing pressure in the stack, concerns of cracking, delamination, or other types of damage that can cause long-term reliability issues are reduced. Once the top dielectric has ruptured, the energy in the remaining portion of the laser pulse must be sufficient to remove what is left of the fuse material. In this case, the slow falling tail of the longer pulse width is an attractive characteristic since it allows for the steady removal of material through vaporization and liquid splashing effects. (The details of these phenomena can be found in [11].)

A pulse shape combining the sharp rise time of a short pulse width with the slow falloff of the long pulse width would be of interest for use with thick fuse processing since it combines the most salient features of each type of pulse. In a DPSS laser architecture, however, it is difficult to produce such a pulse shape. Towards that end, investigation into a MOPFA laser architecture was conducted.

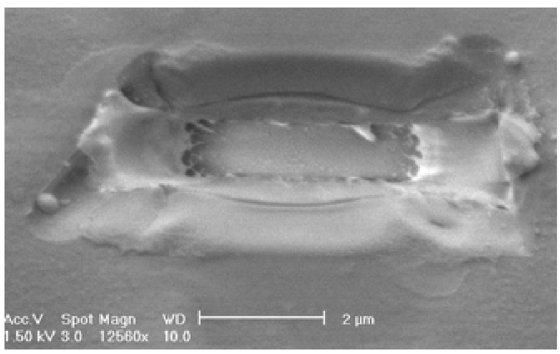

Figure 5. A thick metal fuse with remaining material along the length of the cut presents an unacceptable reliability concern.

Figure 7 shows a sketch of a MOPFA laser. In the master oscillator (MO) portion of the unit, a diode seed laser feeds a series of modulators and gain fibers. Adjustments to the RF signal input to the modulators allows for adjustment of pulse widths and pulse shapes. The output from the MO is then fiber-coupled into a fiber amplifier. The result is a near diffraction limited (M2 < 1.05), 1064 nm wavelength source operating with 1W of power at a 100kHz repetition rate. Figure 8 shows some sample pulse shapes obtainable with this laser captured with an ET-3000 pulse detector manufactured by Electro-Optics Technologies (www.eotech.com). Notice that the longer pulse width, approximately 25 ns full-width half-maximum (FWHM), has a similar rise time of approximately 2 ns compared to the short pulse width case of 4 ns FWHM. Here, rise time is defined as the time it takes to go from 10% to 90% peak power. Thus, the longer pulse width has the desired attributes of a sharp rise time coupled with and followed by an extended "tail" or "shelf" region.

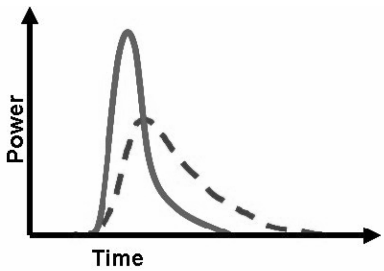

Figure 6. Typical DPSS laser pulse shapes.

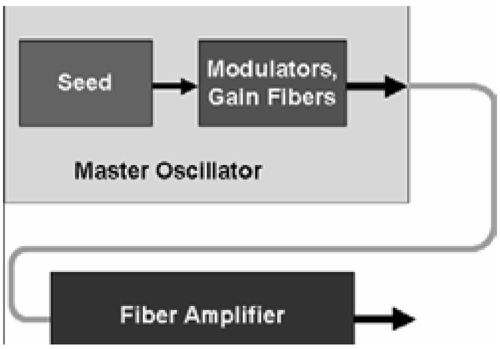

Figure 7. MOPFA layout

Processing results obtained to date with this pulse shape and pulse width have been favorable. Figure 9 provides an example of such work conducted in a laboratory arrangement producing an approximately 3 µm spot size at the work surface. Shown on the left side of the figure are pulses with different pulse widths, 11 ns and 25 ns, but with the same basic pulse shape consisting of a sharp leading edge followed by an extended falloff. To the right of each pulse capture image is a processing result for a 1.3 µm thick, 1µm wide copper link using a 1.6 µJ laser pulse. In these cases, the fuses lie under 70 nm of dielectric. In both cases, the top dielectric is cleanly ruptured and no evidence of underlying stack damage, which could appear as cracking at the top surface, is evident. The link processed with the 11 ns pulse width, however, still contains copper and is therefore conductive. In contrast, the link processed with the 25 ns pulse width is cleanly severed indicating the importance of the appropriate combination of rise time and pulse length extension in achieving the desired results. To close out this discussion, Figure 10 illustrates the result of using the 25 ns pulse width from Figure 9 for processing the structure shown in Figure 5. Notice that the fuse is now cleanly disconnected.

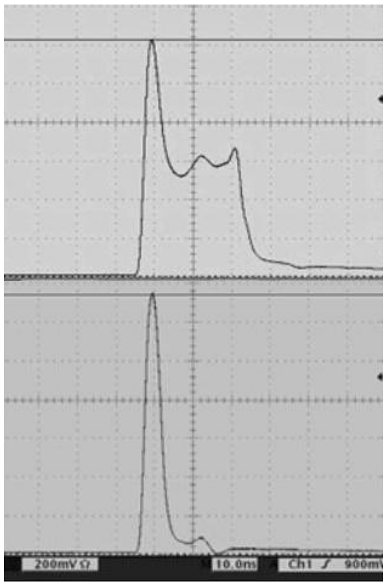

Figure 8. Examples of pulse shapes from a MOPFA laser used for processing thick metal fuses.

Overall, the pulse width and pulse shaping flexibility coupled with the high quality beam propagation characteristics provided by MOPFA technology make this an exciting technology worthy of exploration for processing of challenging fuse geometries. Work is underway to further explore the boundaries of this technology and its processing capabilities.

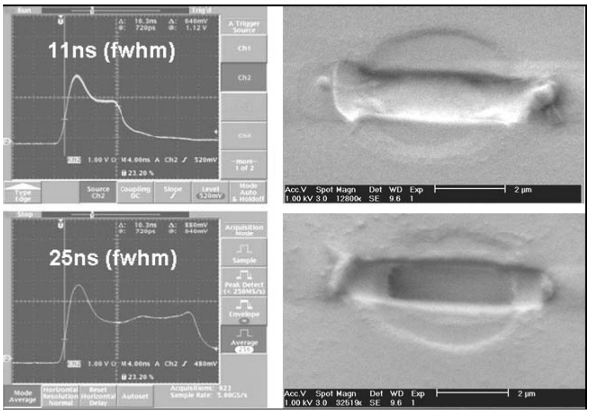

Figure 9 MOPFA pulse shapes and the processing results for a 2.8µJ energy pulse.

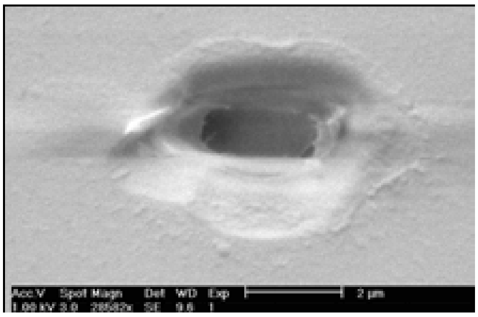

Figure 10 Representative fuse processing results for MOPFA laser using a 25ns pulse width. Pulse energy was 1.75 µJ. The fuse geometry in this case is identical to that in Figure 6.

C. Ultrafast Laser

The interaction of ultrafast lasers with materials is fundamentally different than what occurs with longer pulsewidths [12,13]. The objective for ultrafast processing is to achieve "non-thermal" processing of materials. In general, lasers with pulse widths faster than 10 ps (0.01 ns) are classified as ultrafast. For comparison, the lasers used for currently available laser fuse processing systems employ laser pulsewidths in the range of around 10 ns. The ideal situation for ultrafast processing is for all of the laser energy to directly sever chemical bonds in the fuse material (non-thermally) resulting in extremely localized ablation (sometimes referred to as a "laser drill"). If such a technology exists, it would mean that ultrafast could be used to ablate laser fuses with no risk of damage to underlying features. In addition, since the effects of ultrafast are related to the energy density, the intense center portion of the Gaussian laser spot would remove more material per pulse than the areas in the outer edges of the spot. This would (in theory) suggest that ultrafast can provide significantly smaller relative spot sizes at any wavelength. In reality, while ultrafast lasers can drive non-thermal processing, it is highly likely that some amount of thermal effects will always be present regardless of how fast the pulse is.

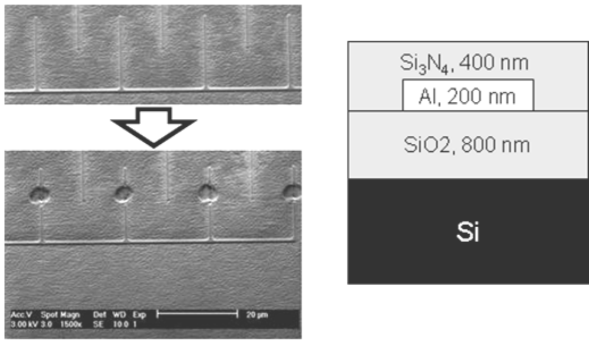

Figure 11. Dimensions and cross section of Al "fuse" demonstration wafer. ~1µm wide Al lines with ~10 µm pitch were processed using a <700 fs IR ultrafast laser.

In an effort to evaluate these claims, Figure 11 shows the structure and dimensions of the Al "fuse demonstration structure" and a SEM image of these structures before and after processing by single fs laser pulses. The laser used had a 1045 nm wavelength linear polarization, a rep rate of 100 kHz, and pulse duration of <700 fs. The spot size was approximately 2 µm. The test wafer was made from Al metal lines on top of SiO_2 and passivated with Si_3N_4 shown in Figure 11. The Al test structure line widths were 1 µm with a 10 µm pitch. Figure 12 shows a close-up view of the results. For a single 0.5 µJ pulse the process looks quite different than using a similar IR pulse with a pulse width of ~10 ns. The fs laser has ablated both the fuse and surrounding nitride material at the same rate to cause a circular depression with a flat bottom. While this result appears to support the laser drill theory, FIB cross-section analysis detected damage to the Si substrate under this feature (to be reported in a future work). Another interesting effect is that the single 0.5 µJ pulse produced a depression feature of ~4 µm, although the $1/e^2$ spot diameter of the beam was closer to 2 μm. This would appear to not support the theory that ultrafast could provide smaller effective spot sizes than classic laser technology. However, Figure 12 also shows the result of processing the fuse with a 0.5 μJ pulse train (10 pulses at 0.05 μJ). In this situation, the resulting depression feature is only ~2 μm. This suggests that pulse trains might hold more promise for realizing smaller effective spot sizes using ultrafast.

This data also provides preliminary concerns that ultrafast might never be highly effective as a laser drill. Although ultrafast pulses drive non-thermal interactions, other interactions including thermal interactions are still present. This would explain the observed Si damage under the fuse processed by a single pulse in Figure 12. At higher pulse energies, our study also observed thermal effects such as melting and splashing, and an example is show in Figure 13. Even if thermal effects can never be completely removed, this technology clearly shows promise and will continued to be investigated.

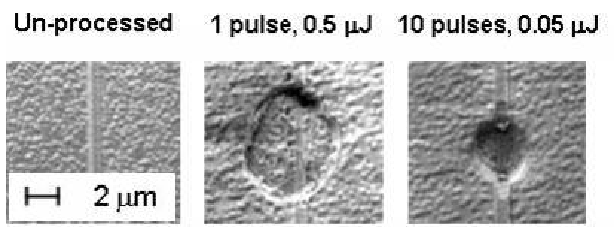

Figure 12. Effect of single vs. pulse trains from <700 fs IR ultrafast laser onto Al fuse demonstration structure. Laser spot size is ~2 μm.

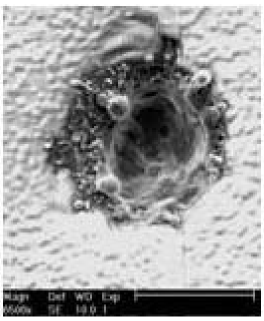

Figure 13. Example of thermal effects such as melting and splashing observed using ultrafast processing.

III. Conclusions

Semiconductor products will continue to face numerous challenges as design rules continue to shrink. Both laser and/or e-fuse technologies will be required for both repair operations and yield enhancement applications. This paper has provided 3 technology strategies that will keep laser fuse technologies viable in the upcoming years. UV technology provides smaller laser spot sizes, allowing for reduction in the total area required for laser fuses. MOPFA lasers can provide Tailored Pulses to overcome processing issues and to maximize process margins. Ultrafast lasers provide an opportunity to also overcome processing issues by taking advantage of non-thermal laser processing.

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