# LASER PROCESSING OPTIMIZATION FOR SEMICONDUCTOR BASED DEVICES

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This dissertation is dedicated to my wife

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#### ABSTRACT

# LASER PROCESSING OPTIMIZATION FOR SEMICONDUCTOR BASED DEVICES

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Memory devices redundancy repair by link laser processing and laser trimming of components have been two widely used applications of lasers in the electronics industry.

Constantly shrinking memory feature sizes and industry's technology tendency to use metals as link materials rather than polysilicon impose new challenges for link laser processing. Maximizing the volume of the molten link material before the rupture of the overlying passivation has been considered in the past to be a key factor in enhancing the process. Unfortunately, this criterion doesn't work well for processing metal links, due to their small optical absorption depth.

New physical models and analyses of optical interference effects, pre-rupture temperature distribution, mechanical stress within the passivation and post-rupture processes have been developed and are presented in this thesis. The effects of link width and overlying passivation thickness on mechanical stress and link process have been revealed.

A new approach of emphasizing laser absorption contrast between the link material and silicon substrate at longer wavelengths is proposed and analyzed. Higher absorption contrast allows the use of higher laser energy to cleanly cut links without damaging the silicon substrates. While light absorption of most metals remains almost unchanged within wavelength range of 1 to 2  $\mu$ m, it drops dramatically for silicon at longer than 1.2  $\mu$ m. Simulation of laser processing windows at both laser wavelengths of 1 and 1.32  $\mu$ m are in good agreement with experiment results which have proved the expected advantages of using 1.32  $\mu$ m lasers over 1  $\mu$ m lasers for link processing. Severe parameter drift of semiconductor based devices during exposure to laser pulses has been a major problem for functional trimming. Although the excitation of excessive electron-hole carriers within the semiconductor material by the laser beam has been identified as the cause, no real solution had been found. By using laser wavelengths beyond the range within which excessive electron-hole carriers can be excited, such as  $1.32 \mu m$ , laser induced device parameter drift is virtually eliminated. Higher trimming through-put thus becomes achievable.

# CHAPTER 1 INTRODUCTION

#### 1.1 Laser processing of semiconductor based devices

Due to the laser beam's high energies and intensities, good focusability, narrow spectrum band widths, and the availability of continuous wave (CW) or pulsed beams and wavelengths from UV to IR, lasers have found important applications in the electronics industry. Memory chip redundancy link laser processing and laser trimming are two most outstanding examples of laser applications in the industry. However, with wide spread acceptance in the industry, these laser processing techniques are also facing new challenges, which turn out to be the driving force for technological progress.

#### 1.2 Memory chip redundancy laser link processing

The concept of laser implemented redundancy had its genesis in the 1960's in research investigating the electrical connection of different layers in a semiconductor device.<sup>1</sup> This research suggested the laser could be used to connect or disconnect electrical conductors, thereby modifying circuits after completion of most fabrication steps.

In the middle of 1970's, more work was reported on using the laser beam to make connections or disconnections on integrated circuits for modification and personalization of the circuits.<sup>2, 3</sup>

The pioneering research and development effort did not get acceptance in the electronics industry's mass production until the debut of memory chip redundancy processing. In the later 1970's, typical yields for large scale memory arrays such as 64K DRAM's, during their start-up production stage, was less than 10%. Substantial improvement in the yield would have conventionally required major improvement in already low random defect densities. A group at Bell Labs in Allentown, Pennsylvania, undertook the development of an alternative approach using laser "redundant" process to

overcome such low yield.<sup>4-8</sup> Two to four "spare" rows and columns of memory cells were designed into the memory circuit layout. Then wafer level testing was carried out at the earliest possible stage in the memory chip production process. Faulty cells were detected, certain links were then cut by laser pulses to switch out the rows and columns containing the faulty cells. Also other relevant links were cut to activate the spare rows and columns to permanently replace the faulty ones. Thus, the faulty memory device could be repaired. The yield with the help of laser redundancy repairing is increased by a factor of 1.4 to 30 times depending on the pre-laser repair yield and the laser repair yield. A small "penalty" to pay for the dramatic yield improvement was the addition of the spare elements to the device layout, which increased the device sizes by 3% to 5%.

The laser system used at that time was ESI's laser trimming system Model 44 with slight modifications. The laser source used was a CW arc lamp pumped, acousto-optic (A. O.) Q-switched Nd:YAG laser with wavelength at 1.064 micrometers (µm).

An other method, electric current blowing has been tried to cut the links.<sup>7, 9</sup> A 2 µm wide and 5000 Angstrom (Å) thick polysilicon fuse would be burned out with 30 milliamps (mA) of current. However, reliability tests have shown that after a certain time period, an electric current blown fuse opening can become re-connected due to polysilicon migration (growing back), resulting in device failure. Besides, higher real estate costs for the wafer to implement the electrical fuses and the unacceptably high blowing current requirement (greater than 100 mA) for silicide or metal link materials<sup>10</sup> make this approach much less favorable compared to laser link processing.

Laser redundant link process has become a standard process in the industry for mass production of almost all memory devices, as well as a powerful tool in fabrication of other integrated circuits such as programmable logic devices or gate arrays, and application specific integrated circuits (ASIC).

However, laser link processing has its own problems. Severing a few micrometer wide conducting link fabricated on a delicate silicon based device with a laser pulse is a locally violent operation. It had raised many concerns about reliability (both short and long term) of the repaired devices before the process was accepted by the industry.<sup>7,9</sup>

Major reliability concerns for memory redundancy laser repair were and have been as following: (1) reliable opening with a high resistance, no "grow back" of the opening, (2) no risk of shorting the processed link to other nearby circuit features due to slag and debris produced by the laser cutting, nor to the silicon substrate through an excessive large crater within the passivation layers, (3) no damage to the links' surrounding area, nearby circuit features, and the silicon substrate, (4) acceptable cosmetic appearance.

Many variables are involved in memory redundancy link design and laser processing, such as number of the spare rows and columns, location of the links, device circuit design, and the algorithm for the processing (for a particular faulty cell, how many links and which links need to be cut to repaired the device), link materials and dimensions, materials and thickness of the overlying and underlying passivation layers, substrate material and its doping level, and laser parameters used, etc.<sup>11, 12</sup> Not all variables can be freely controlled or changed for the benefit of laser processing. Instead, many of them are almost solely mandated by other considerations, such as the density of the memory device, its operation speed, and other IC fabrication requirements.

One example of the variables affecting the laser processing is the overlying passivation layer. To have the passivation in place before the laser processing is preferred because of device reliability concerns.<sup>7</sup> The passivation layer protects the devices from possible contamination during testing and other later fabrication procedures. For the laser process itself, existence of the passivation reduces the risk of shorting underlying circuit features by laser process induced debris and slag. Early link processing practice proved that the existence of this passivation did not cause problems for the process as long as its thickness is within a reasonable range. As a matter of fact, in most cases it helps the processing.

An another example is the use of metal as the link material. Metal links are more difficult for lasers to process than polysilicon links. For older generation memory devices, redundancy link materials can be chosen to be either polysilicon or metals based on laser processing results. But for newer generation memory devices, despite the difficulty associated with laser processing, metals have become the necessary choice as the link materials. Metal links offer much lower electrical resistance which is demanded by higher speed operation of the devices. This becomes a critical factor when the link dimensions keep shrinking. Also, for newer generation memory devices, there are more layers built on the silicon substrate. Due to the nature of IC fabrication, poly links become deeply buried under those layers. To process the poly links, an additional costly etching process has to be added to reduce the thickness of overlying passivation. In contrast, metal links are usually at the top part of the layer stack structure and therefore they are more readily accessible for laser pulses to process.

Other variables, such as all laser parameters (energy per pulse, pulse width, beam spot size, and wavelength) are more flexible and can be optimized mainly based on the consideration of the laser process itself. However, optimization is impossible without a deep understanding of the process, and the effects of all those variables on the process quality.

So far, the majority of theoretical analyses of memory laser link processing have concentrated on the dependence of process quality on the following factors.<sup>13-16</sup> First, optical interference effects of the multi-layer link structure, such as passivation layers both above and underneath the link, the link itself, and the silicon substrate. Second, laser beam energy absorption behavior of the link material and silicon substrate at laser wavelengths of 1 micron and 0.53 micron. Third, temperature distribution within the structure as result of laser beam energy absorption and thermal conduction (temperature distribution versus laser pulse width and link materials).

A major conclusion drawn by those analyses was that the uniformity of the temperature distribution across the link, or the volume of the molten link material before passivation's rupture plays the most important roll in ensuring link processing's quality. Thus process optimization should aim at maximizing the volume of the molten link material before the rupture, while avoiding damage risks to the devices caused by overheating or excessive thermal conduction. From this stand point, for a given link structure, longer laser pulses should perform better than the shorter ones as long as there is no heat conduction induced damage to the passivation and the silicon substrate.

But experiments have indicated just the opposite: pulse widths as short as 5 to 10 nanoseconds (ns) perform much better in processing most metal links.<sup>17</sup>

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The difficulties metal laser link processing faces and the obvious lack of a satisfactory understanding of the laser link process lead to a suspicion that the laser will no longer be a viable tool for processing next generation of memory devices. Instead, it is thought that ion beams might be the alternative for the purpose.<sup>18</sup>

To explore the full potential of laser link processing, new theoretical analyses and computer simulations of the processing have been researched and developed.<sup>19</sup> Effects on link processing by critical link structure parameters, such as the overlying passivation's thickness and link width, have been investigated by computer simulation of the mechanical stress distribution within the passivation using a finite element method. Based on the knowledge gained from the work, optimization of the thickness of overlying passivation and link width became possible for the first time. The link material's density change upon melting has also been taken into account in the analysis for the first time. Different behavior of polysilicon and metals in this regard has been found to be one of the major contributors as to why metal links are more difficult for the laser to process. Post-rupture analyses, including the silicon substrate's damage risk assessment, has also been developed as a critical part of the whole analysis. To optimize the laser process further, a new concept of maximizing the absorption contrast of laser energy between link materials and the silicon substrate has been proposed, patented, and tested.<sup>20, 21</sup> Instead of searching for ways to maximize the volume of molten link material before the passivation's rupture, emphasis is put on maximizing the absorption contrast by choosing specific laser wavelengths, based upon the fact that while the absorption of most metal materials within a spectral range of 1 to 1.5 µm does not change much, it drops dramatically for silicon at wavelengths longer than 1.2 µm. Link processing using 1.3 µm laser pulses has proved the predicted advantages: much better processing quality and a wider processing window. Some links which were difficult to process with a 1 µm wavelength laser beam have become readily processable using 1.3 µm laser beam.<sup>22-25</sup>

#### 1.3 Functional laser trimming of semiconductor based devices

Resistors made by traditional technology, such as printed thick film resistors or sputtered thin film resistors, are not capable of meeting the high accuracy needed (say, better than 1% to 0.02%, depending on the type of resistors) without additional adjusting or trimming. Sand blasting was used as a way to trim the resistance of thick film resistors into higher values with better accuracy in the early days. But it is a dirty and inaccurate process. Recently, resistor trimming into a lower value with a better accuracy using radio frequency (RF) energy has been reported,<sup>26</sup> but commercial acceptance has been very limited.

The principal of laser trimming is to cut a small portion of the resistor material by vaporizing it with intense pulses of laser energy until the desired resistance value is reached as measured by resistance measurement equipment. Other components such as oscillator crystals, capacitors and printed inductors can be laser trimmed as well.

CW pumped, A. O. Q-switched Nd:YAG laser at 1.064 µm has been the major laser source used in trimming applications due to its almost perfect output parameters for the application and good reliability due to its solid-state nature.

If only the value of the component under trimming is being monitored during the process, the whole device or circuit where the component belongs is not powered up, the trimming process is referred to as "passive trimming". It is easy to perform, but probing pads for each individual component to be trimmed have to be added to the device's layout to allow access for measurement equipment.

In contrast, functional trimming is a process during which the whole device or circuit is powered up to its normal operation condition with proper input signals applied as well.<sup>27-29</sup> The trimming is done on the device's components based upon measurement results of relevant parameters of the whole device, rather than values of those individual components. A chief advantage of functional trimming is that all contributors to the error in the device's parameter are accounted for in the trim process under their normal operating condition, resulting in higher accuracy and throughput. Another advantage is that each individual component which needs to be trimmed does not need independent probing pads, making the device or circuit design more flexible and compact.

For passive trimming, the trimmed component's parameter can drift during or after trimming due to the effect of heat generated by laser energy within the component or its substrate. With great care taken to the proper control of laser parameters used, sound design and fabrication of the components, and the right choice of materials used, this drift can be minimized or eliminated.<sup>29, 30</sup> UV laser trimming (surface ablation) has also been used to reduce heat induced component parameter drift.<sup>31</sup>

On the other hand, for functional trimming of either hybrid integrated circuit (HIC) devices or monolithic thin film devices, the parameters of the whole device can show dramatic drifts during processing.<sup>26, 27</sup> Some devices even "latch up" out of normal function.<sup>32</sup>

The device parameter drift not only prohibits the use of parameter tracking techniques (whereby device parameters are continuously monitored), but also generates severe problems for the traditional "measure and predict" technique, because the system has to wait long enough for device parameter drift to disappear before any meaningful measurement can be taken. For devices suffering from the "latch up" problem during the functional trimming, in some cases, the power supplies to the devices have to be shut off for a certain time period to let the devices return to their normal function. In either case, the throughput is considerably reduced.

It is known that parameter drift is caused by photoelectric reaction of the semiconductor materials and the devices themselves to the laser pulses.<sup>33</sup> But, so far, no real cure has been found.

For HIC devices, trimming targets are usually fabricated on ceramic substrates, with other passive and semiconductor based active components integrated together with it. Spatial separation and shielding of the trimming targets from semiconductor based components were proposed as a method of reducing the effect of scattered laser light on electrical parameters during trimming.<sup>28</sup> For thin films on silicon wafers (monolithic IC), component proximity negates spatial separation. Some researchers investigated the time constant of the laser pulse induced parameter drift and came to a conclusion that the drift can recover quickly compared with the time interval between laser pulses.<sup>33</sup> But their experiments were performed only on a few special components or devices. It is doubtful

that the conclusion will be valid for other real or more complicated devices, due to the independence of the photo-electrical response on the devices circuit structures.

Having noticed that the performance drift is the result of the photo-electric response of the semiconductor material and semiconductor devices to a laser pulse, it is reasonable to predict that the behavior of the performance drift is laser wavelength dependent, as well as semiconductor material dependent. By choosing special laser wavelengths which are beyond the sensitive spectrum of certain semiconductor materials and semiconductor based devices, the laser induced performance drift can be minimized, or totally eliminated.<sup>34</sup>

For silicon based devices,  $1.32 \ \mu m$  is an ideal laser wavelength to serve this purpose, because solid state laser sources at this wavelength are readily available at reasonable cost, and  $1.32 \ \mu m$  is just beyond the spectral sensitivity of silicon which ends at about  $1.1 \ \mu m$ .

Experiments using a 1.32  $\mu$ m wavelength laser beam for functional trimming of silicon based devices have been carried out. Laser induced parameter drift was totally eliminated or greatly reduced. Dramatic improvement of throughput was realized.<sup>32</sup>

Similar principles can be applied to functional trimming of devices based on other semiconductor materials, such as a 2  $\mu$ m laser wavelength for functional trimming of germanium based devices.

#### 1.4 How the thesis is organized

Beyond this brief introduction, the thesis is organized into five chapters.

Chapter 2 (Link processing by laser beams) briefly discusses the history of memory chip laser link processing technology, the requirements of the process, the existing understanding of the process, and problems and new challenges the process is facing.

Chapter 3 (Laser link processing simulation) discusses a new physical model and computer simulation of the process, including simulation of optical interference effects, pre-rupture temperature simulation, analysis of mechanical stress within the passivation, and post-rupture process analysis. Effects of laser pulse width on the link processing are discussed qualitatively. Effects of link structure data and laser parameters on the laser processing window as well as process quality are also discussed.

Chapter 4 (Link processing by longer laser wavelengths) discusses the idea of using laser wavelengths longer than the traditional 1.047 and 1.064  $\mu$ m for maximizing the laser energy absorption contrast between the link materials and the silicon substrate. Advantages of using longer laser wavelengths for memory link processing are analyzed and experimental results are presented.

Chapter 5 (Optimization of functional trimming by laser beams) discusses the performance drift problem of semiconductor material based devices during functional laser trimming. The new idea of using laser wavelengths longer than the traditional 1  $\mu$ m is discussed for solving the problem. Experimental results are presented.

Chapter 6 (summary and future work) briefly summarizes the discussions and explores the possible direction of future work.

# CHAPTER 2 LINK PROCESSING BY LASER BEAMS

#### 2.1 Introduction

Although the importance of memory redundancy link processing by laser beams has been obvious since its first demonstration, it has never drawn wide academic research interest as other laser applications have, such as semiconductor materials laser annealing. Except for a few papers<sup>13-16</sup> published by L. M. Scarfone, J. D. Chilipala and their colleagues, there have been few others available. One reason for this might be that this application, from its very beginning, has been a very device specific process. There are few manufacturers who have been willing to share their information of memory device design or process knowledge, etc. with others. The other reason might be in the strange mix of the "simplicity" and "difficulty" in analyzing the process. On one hand, the process can be considered as quite simple and straight forward. The link material is heated up by a laser pulse, then the overlying passivation ruptures and the process is completed, etc.<sup>13, 16</sup> On the other hand, since many dynamic issues are involved in blowing away link material by a short laser pulse during the process, it is a more difficult problem to fully analyze and simulate than others such as annealing. The process itself has been working so well for polysilicon links, there has been little urgency for more research work until the new challenges of processing metal links emerge.

With the prior understanding of the process,<sup>13-16</sup> optimization of metal laser link processing can go nowhere except to use longer laser pulse widths to the limitation imposed by the laser induced structural damage. But experimental results indicating that laser pulses with much shorter pulse widths than the simulation analysis thought reasonable perform surprisingly better indicate that something is not quite right in the prior analysis. Therefore, in order to meet the challenges of processing newer generation memory devices, a thorough review of the process and the prior understanding becomes necessary.

#### 2.2 Memory redundancy link processing by laser beams

The general concept and method of memory redundancy laser link processing have been explained by several authors.<sup>7, 11, 35</sup> Memory chips are first tested at the wafer level. Which links need to be cut are determined by the test results and the relevant algorithm based on the particular device design. The laser processing system then retrieves the information from the test equipment (or data base from a central computer) for the wafer. The automatic positioning mechanism of the laser system then aligns the laser pulse to the link that needs to be cut. One link is cut by a pulse. A modern processing system is able to cut a few hundred to a few thousand links per second, even without stopping the positioning mechanism (cutting on fly).

Common link dimensions used are between 0.8 to 1.5  $\mu$ m wide, 0.5 to 1  $\mu$ m thick with pitch size of 2.5 to 5  $\mu$ m. The links can be made of a single material, or can consist of two or more "sandwiched" layers made of different materials, including polysilicon, silicides, metals, nitrides, etc. As an example, Figure 2-1 shows the cross section view of a link structure in its width direction. The link is 1  $\mu$ m wide, 0.5  $\mu$ m thick and made of heavily doped polysilicon. On top of the link, there are one or more passivation layers (two layers are shown). Underneath the link, there are also one or more underlying passivation layers (two layers are shown). Silicon oxide or silicon nitride are typical dielectric materials for the passivation. Detailed dimensions of the structure and materials used vary from design to design. The topography of the overlying passivation layer might be different as well. The one shown in Figure 2-1 has a flat top surface.

During the process, a laser beam should be positioned such that its center is aligned at the middle of the link, as shown in Figure 2-2 (A). The laser beam spot size should be large enough to cover the whole link width, but small enough not to risk hitting adjacent links with the normal system positioning error taking into account. For a typical modern laser link processing system, the laser beam spot size on the wafer surface is programmable from 2.5 to 6  $\mu$ m using a zoom lens, with a typical positioning accuracy of 0.35 to 0.5  $\mu$ m. This accuracy can be affected by problems like lower reflection contrast from the special alignment features built on the wafer. Larger positioning error of the laser beam can result in incomplete link cut or higher damage risk to the silicon substrate.

Figure 2-2 (B) shows a laser beam is slightly off a link. The laser energy per pulse is also programmable from a few tenths to a few micro-joules using a "liquid crystal attenuator", or an A.O. attenuator, or other means.









(A) The laser beam is aligned over a link.



Figure 2-2. Positioning of the laser beam over a link.

#### 2.3 Basic requirements of laser link processing

Due to the large number of links that need to be cut for any practical memory chip redundancy repair, laser link processing must meet several stringent requirements before it can qualify as an acceptable mass production tool.

The major issues concerned for the qualification are satisfactory link processing quality, a reasonably large processing window and little damage risk to the device. Other production issues such as throughput, and operation and system cost are also important, but beyond the scope of this discussion.

#### 2.3.1 Processing quality

There are two key quality requirements for laser link processing.

First, the processed link has to be completely open both visually and electrically. Visually, the processed link has to be completely open with no residuals of the link material left in the open area. The opening has to be of adequate length. The two ends of the opening should be regularly shaped. There should be no significant amount of slag or splashes around the cut area. Electrically, the open resistance of the cut has to be higher than a few tens of mega-ohms. "Grow back" of the opening due to migration of the conductive link material for laser processed links is usually not a problem due to the larger size of the cut compared with that of electrically blown fuses.

Second, there should not be any visible damage to the silicon substrate, nor to any circuit features nearby. There should not be any electrically detectable performance deterioration of the device either. Visually, the laser link cut induced crater within passivation should be of a normal size (both in its diameter and depth) and regular shape. The crater has to be quite centered at the position where the link was. No melting or micro-cracks on the silicon substrate, nor sign of damage on any adjacent links or circuit features should occur. Electrically, no significant leakage current increase between the processed link and the silicon substrate, nor between the processed link and its adjacent links should result. No significant performance deterioration of any adjacent passive and active components, such as higher leakage currents of P-N junctions is tolerable.

The visual appearance of the cut is often referred to its "cosmetic appearance". The importance of having a better cosmetic appearance for the cut is not because it looks nicer, but rather cosmetic appearance problems of the cut are very good indicators for quality problems of the process. For instance, visible residual link material around the cut area is often associated with lower open resistance of the cut. An oversized crater indicates excessive heat was conducted into the passivation structure, thus higher risk of device reliability problems. Too deep a crater is often associated with detectable leakage increase between the processed link and the silicon substrate. Off-centered crater indicates laser beam positioning problems, imposing higher damage risk to the silicon substrate or incomplete cut of the link.

#### 2.3.2 Processing window

The laser processing window for a particular link structure is defined as a range of laser energies per pulse within which the links can be safely processed, while other laser parameters such as laser pulse width, laser spot size, and laser wavelength are set up as pre-defined parameters.

The reasons for using laser energy per pulse to define a processing window are obvious. First, for a given link structure, when all laser parameters are set within their reasonable ranges, then percentage wise, laser energy per pulse is the most critical parameter for optimum processing results. Second, for a given laser processing system, laser energy per pulse is also the parameter with the highest fluctuation (instability), as well as the easiest one to purposely adjust.

The low end of laser processing window is determined as a laser energy value  $E_1$  at which the links can just be cut open. Its high end is determined as the laser energy value  $E_h$  at which damage to the silicon substrate or passivation starts to occur. The processing window is then calculated in a percentage term as

#### $\pm [(E_h - E_l) / (2 E_m)] \%,$

where  $E_m$  is the medium laser energy value of the processing window (the middle energy point of the window).  $E_m$  is the laser energy normally chosen for real processing.

No processing window means that for a particular link structure, there is no way to successfully process the link using the laser parameters tested. Damage to the silicon substrate or passivation structure occurs at a lower laser energy than is required for the link to be cleanly cut. A wider processing window, on the other hand, not only means the process is more tolerable to both link structure and laser parameter variations, but more importantly, ensures better processing quality. For a wide processing window,  $E_m$  will have enough margin over the window's low end  $E_1$ , thus the link cut is more complete and clean resulting in higher open resistance of the cut. At the same time,  $E_m$  also has enough margin below the window's high end  $E_h$  (or the damage threshold of the silicon substrate or other device features), so there is little risk of damaging devices.

Thus, in some sense, the analysis of laser link processing actually is to analyze the dependence of the laser processing window on link structure data and laser parameters used. The optimization of laser link processing is to maximize the processing window, either by reducing its low end or increasing its high end, or both.

A "laser energy run" is usually designed and run to verify the processing window for a particular link structure. During the run, the laser energy per pulse starts at a low value, and is increased by a certain amount for each consecutive link cut while scanning cross a bank of links, until a pre-set large energy value is reached. Then processed links are tested to determine the low and high ends of the window. Figure 2-3 shows the result of a laser energy run for a polysilicon link structure. The run starts from laser pulse energy of 0.27  $\mu$ J, stops at laser pulse energy of 0.98  $\mu$ J. The laser spot size is 3.8  $\mu$ m in diameter, the laser pulse width is 4 ns. From this test run, it is determined that for this particular link structure, the lower end of the processing window is 0.52  $\mu$ J. The high end of the window is 0.79  $\mu$ J. The processing window is  $\pm 16\%$ , according to its definition.

Positioning error is another variable having significant effect on laser link processing. If a laser beam is perfectly aligned with a link, the link will receive the precise amount of laser energy thus ensure the cut quality. Also, the link blocks the most intense power, located in the center part of the beam, from hitting the silicon substrate beneath the link, until the entire link is gone. If all the parameters are right, then when the link is disintegrated, the laser energy left should impose no damage risk to the silicon substrate.



Figure 2-3. Result of a "laser energy run".

If the laser beam center is off the link center due to positioning inaccuracy, either incomplete link cut and/or damage to the silicon substrate can occur. A special "vernier test run" is designed and performed to check the sensitivity of the process to positioning error of the laser beam over the link. As shown in Figure 2-4, a link bank with 21 links and pitch size of 5  $\mu$ m is used for the test. The link is 1  $\mu$ m wide. The laser energy used is the medium value of the processing window: 0.62  $\mu$ J. The laser beam is perfectly

aligned over the center link, then adding  $0.25 \ \mu m$  offset for each consecutive link in both directions. The laser beam will hit at the middle of two links at both ends. The result shows that with a 1.25  $\mu m$  offset between the laser beam center and link center, damage to the silicon substrate becomes clearly visible.



(1) Concept drawing for the "vernier test run".



(2) Result of a "vernier test run" with visible damage occurring in both ends.

Figure 2-4. The vernier test run.

#### 2.3.3 Long term reliability of laser processed devices

Laser link processing is a locally violent operation to the delicate memory devices. While a link is processed by a laser pulse, along with the eruption of the overlying passivation and removal of the link material, heat, stress, and a shock wave are generated within the structure. Visible damage, or micro-cracks, within the passivation structure or the silicon substrate can occur. The characteristics of other active circuit features nearby can be permanently deteriorated due to exposure to excessive heat or stress. While all the short term process quality issues discussed above can be tested both visually and electrically just after the process, long term reliability remains a major concern and difficult to assess with a quick verification. Considering that the devices requiring laser repair were originally faulty ones, all the additional negative impacts of laser processing would quite naturally cause more questions concerning the long term reliability of the "repaired" devices. Rugged "burn- in" processes have been used to reveal any long term reliability risks and their relationship with structure and laser parameters, especially during the research and development stages of the memory redundancy laser link processing<sup>7, 16</sup> or qualification of the process on new device structures. It has been proven and widely accepted that with proper laser parameters such as the energy per pulse, pulse width and spot size, if the repaired devices show good test results right after the process, there is little additional long term reliability problem caused by the laser processing.

#### 2.4 Existing understanding and techniques of laser link processing

Existing understanding of laser link processing is best represented by several papers written by the pioneer group in developing the technique.<sup>13-16</sup> According to these papers, the process itself is a thermal-mechanical one in its nature. The link material is a laser energy absorbing medium. When a laser pulse hits the link, part of its energy is absorbed by the link. The rest is either reflected by the structure or transmitted into the silicon substrate. The percentage of laser energy absorbed by the link is determined by the optical interference effects of the multi-layer structure both above and below the link and the absorption coefficient of the link, raising its temperature. At the same time, the heat is conducted into the surrounding structure, including the overlying and underlying passivation layers and the silicon substrate.

After a part of link material gets molten, pressure builds-up under the overlying passivation. This pressure is determined by a so called hard sphere model of liquid metal<sup>13</sup> which treats the liquid metal's atoms as hard spheres and relates the pressure of the liquid metal to its temperature.<sup>36, 37</sup> The temperature used is the one derived from a one dimensional thermal simulation, that is the temperature at the top center point of the link.

Then, without any explanation, an additional arbitrarily chosen 680 °C was added onto the "derived" temperature as the temperature at which the overlying passivation's rupture occurs.<sup>13</sup> It was assumed that when the pressure reaches the adhesive strength of the passivation material, the passivation ruptures. With the rupture of the passivation, all already molten link material under high pressure explodes away, resulting in a link cut of high quality. Contributions to the overlying passivation's rupture by other factors, such as a temperature gradient within the structure, and different thermal expansion coefficients of the materials involved, were considered not critical in comparison to the pressure by molten link material.<sup>16, 38</sup>

It was explained that for a polysilicon link, due to its large optical absorption depth, the laser energy can penetrate deep through the link, resulting in more uniform heating within the whole depth of the link until its top part gets molten. Due to a much higher absorption coefficient of liquid poly than that of solid poly,<sup>13</sup> laser energy absorption within the molten link material increases dramatically, resulting in significantly faster temperature increase or thermal "run away" within the top part of the link, until the overlying passivation layer ruptures. For a polysilicon link structure and temporal laser pulse shapes shown in Figure 2-5(A) and 2-6, the temperature evolution curve with time up to the passivation's rupture point is presented in Figure 2-7(A).<sup>13</sup> The short laser pulse is 35 ns full width at half maximum (FWHM) and 220 ns full duration while the long one is 190 ns FWHM, 740 ns full duration, while both have the same laser energy per pulse.

In contrast, for a metal link, the laser energy absorption is restricted within a very shallow, top part of the link from the very beginning of the process due to metal's much shorter optical absorption depth. The laser beam can penetrate into only a thin top layer of the link. Most lower part of the link material does not receive the laser energy directly, except the heat conducted from the "hot" top part of the link, thus remains at relatively lower temperature. Figure 2-5(B) and 2-7(B), (C) show a metal link structure and the temperature distribution within the link structure for different laser pulse widths.<sup>13</sup>





(A) A polysilicon link structure.

Figure 2-5. Link structures for temperature analysis. (After Scarfone et al., ref. 13.)





<sup>(</sup>B) A metal link structure.



(A) Temperature distribution at different times for a poly link with a short laser pulse.



- (B) Temperature distribution at different times for a metal link with a short laser pulse.
- (C) Temperature distribution at different times for a metal link with a long laser pulse.

Figure 2-7. Temperature distribution at different times for different link materials and laser pulse widths. (After Scarfone et al., ref. 13.)

It was explained that the shape of this temperature distribution within the link was a key criterion for a better processing result: a more uniform temperature distribution meant that by the rupture point of the passivation, more link material volume would have become molten, resulting in a higher probability of a clean cut. That was why the polysilicon link was easier to process than metal links, according to these analyses. Therefore, the goal of link processing optimization was to maximize the uniformity of temperature distribution within the link, or maximize the molten link material's volume before the rupture point of the passivation. What happened after the rupture was considered less important, thus the analysis stopped at the rupture point of the passivation.<sup>13, 16</sup>

Apparently, there are several critical questions the prior analysis did not answer. First, optical interference simulation alone delivers multiple optimized thickness values for the overlying passivation. Which one should be recommended for the best result of laser link processing? Second, the rupture of the overlying passivation layer was independent of the link structure. Neither the link width, nor the thickness of the passivation have any effects on the rupture behavior of the passivation, according to the analysis. Don't these link structure parameters make any difference in laser link processing? Third, for given metal links, there is no way to maximize the molten volume of the link material before the rupture point, except using longer laser pulse widths. If the longer laser pulse widths impose unacceptable damage risk to the devices, can anything else be done to optimize the process?

Nevertheless, laser processing has been working well in mass production environments for polysilicon links. Although the laser processing systems have gone through a dramatic evolution since the first link cutting experiment using ESI's Model 44 laser trimming system,<sup>13</sup> there have been no significant changes in the analysis and understanding of the process itself.

#### 2.5 New challenges to the laser link processing

For newer generation memory devices, the situation has changed. The number of components per die for the integrated circuits has been increasing at a rate of  $2 \times$  per year for the last 30 years.<sup>39</sup> The contribution to this growth from the decreasing line widths

has stayed exactly on the same trend during the period. This trend is expected to continue well into the first decade of the next century despite much higher costs for the same progression rate.<sup>39</sup>

Link processing started on 64 kB devices in 1978. Now testing is being done on 256 MB, and even 1 GB devices. As memory device density increases, their layer stack structures are also increasingly more complex. More layers with different materials are built up on the silicon wafer. Due to the nature of silicon device fabrication, links and features made by polysilicon and similar materials are the ones closer to the wafer, thus becoming deeply buried under many layers. For successful processing of the poly links, as shown in Figure 2-8, additional etching steps have to be added into the fabrication process to etch out a window on top of the links such that the remaining thickness of the overlying passivation layer is within a preferred range. To have a better control over the thickness of these etched windows, an additional metal etch-stop has to be added in the structure. The thickness of the passivation between the link and the etch-stop has to be the thickness preferred for laser link processing. The etching of the overlying passivation layer will stop at the metal etch-stop. Then an additional etching will be required to etch the metal etch-stop, thus make the devices ready for laser processing. There is no doubt that these additional requirements are very costly, and thus unwelcome.

Another disadvantage of using polysilicon and similar link materials is that their electrical resistance becomes unacceptably high with smaller link dimensions, resulting in an unacceptable signal delay and restricting operating speed of the devices. In contrast, metals have much higher electrical conductivity and are typically deposited as links close to the top of the multi-layer structure of the memory devices. Thus metal or metal alloy materials, such as aluminum, tungsten, metal nitride, or their combinations are becoming preferred or mandated as the link materials over the polysilicon for newer generation high density, high speed memory devices. As mentioned previously, the short optical absorption depth of metal link material makes laser processing more difficult. Basic physics not only relates higher electrical conductivity as well.<sup>40, 41</sup> Thus higher laser energy per pulse becomes necessary to compensate for the higher reflectivity to ensure that enough
Passivation and metal layers Etch stop Passivation layer Link		
Underlying Passivation layers		
Si substrate		
(1) D e Passivation and metal layers	eep buried poly link with an tch stop added.	(2) Link pattern coating and developing.
Etch stop Passivation layer Link		
Underlying passivation layers		
Si substrate		

- (3) A few steps of dry etch, down to the etch-stop.(4) Etch the stop away, ready for laser processing.
- Figure 2-8. Additional structure and process steps needed for processing deeply buried polysilicon links.

laser energy is coupled into the link. Or in other words, the low end of laser link processing window becomes much higher for metal links. At the same time, the high end of the processing window remains unimproved (governed by damage to the silicon substrate). The result is, inevitably, a much narrower laser processing window or even no window at all for some link structures.

Typical quality problems associated with narrower processing windows for metal links include: the residual resistance of the link cut is too low to qualify, too much slag and splashes surrounding the cut, damage to the substrate or passivation structure resulting in a high leakage between the link and the substrate, etc.

To solve the first two quality problems, the laser energy used for the process needs to be increased. But the laser energy has to be reduced to avoid the third quality problem (the damage problem). If the conflict can not be resolved, then it simply means that the process can not be qualified for mass production. As an example, Figure 2-9 shows the result of a "laser energy run" for a metal link structure. The laser energies used were from 0.6 to 2.0  $\mu$ J, the laser spot size used was 5.5  $\mu$ m. The result shows that for this metal link structure, the low end of the processing window is 0.9  $\mu$ J while the high end is 1.4  $\mu$ J, thus the whole processing window is  $\pm$  22%, according to its definition. Compared to typical process windows of  $\pm$ 50% for polysilicon links, the window for this metal link is considered as narrow for ensuring yield and quality in mass production.



Figure 2-9. Result of a "laser energy run" for metal links.

Many efforts have been devoted to improve metal laser link processing. One is modifying the laser energy's spatial distribution from a Gaussian shaped one to a "top hat" one.<sup>42-43</sup> Another is modifying the laser beam spot shape from a round one to a nearly squared one.<sup>43-44</sup> The point here is that a "top hat" energy distribution or squared beam spot shape would provide more uniform heating over the link's width direction and cover a sufficiently large length of the link without risking hitting adjacent links. But inevitably, any non-Gaussian distributed beams or not round shaped beams are more sensitive to defocusing. The smaller the laser beam spot size, the more difficult to keep the beam square shaped or "top hat" energy distributed. They can keep their nearly squared shapes or "top hat" energy distributions only within a vary narrow ranges around the designed focusing position (that is they have much smaller focusing depths). They quickly become round shaped and nearly Gaussian intensity distributed when they are off that focusing position, causing more severe intensity variation than an ordinary Gaussian shaped beam would, and thus severe variations of the process quality.<sup>45, 46</sup> Still another effort which has been tried is the double pass processing.<sup>47</sup> Two consecutive laser pulses are used to process a link with a pre-set displacement between them along the length direction of the link. By making a longer opening in the link, the hope is to increase the probability of a higher open resistance without increasing the damage risk to the devices. It does work for some link structures, but slows the process throughput by 50%. And it doesn't work for all link structures

What else could be done to improve metal laser link processing, or to widen the metal link process window? Or has laser processing really reached its limitation so that inevitably it will be replaced by ion beams for metal link processing? The correct conclusion can not be attained until a better understanding of the process is reached.

### 2.6 Summary

Memory redundancy laser link processing has dramatically improved the yield of memory device production with no deterioration of its reliability. The process works well on polysilicon links. One beauty of this process is that it can work with the overlying passivation covering the links thus reducing contamination risks to the devices. In fact, it works even better with the passivation than without it. During the last 25 years, laser link processing has become a mature technology and standard process for memory device mass fabrication.

Testing procedures for laser link processing have been well developed: "energy run" to find the laser process window for the structure and laser parameter used, and "vernier run" to test the sensitivity of laser beam positioning accuracy on link processing quality. These tests, together with electrical performance tests (to measure leakage current, open resistance, etc.) and visual tests have become standard testing methods to qualify the process on any new link structures, as well as a new process on a particular link structure.

Prior research work has delivered some basic understandings of the process. But due to a few false or over-simplified assumptions, it failed to answer several critical questions about the process.

The technical trend of the memory industry is to use metals as the link material. Due to the higher reflectivity, shallow optical absorption depth of metals, and other reasons, metal links are more difficult for a laser to process without damaging the silicon substrate. Developing a new physical model and simulation to gain deeper and sounder understanding of the process has become a critical task for the future success of the process.

## CHAPTER 3

# LASER LINK PROCESSING SIMULATION

## 3.1 Introduction

In searching for a better understanding of laser link processing, a few critical questions must be answered. First, do the multiple optimized thickness values of passivation derived from optical interference effect analysis perform the same for the process? Second, what is the effect of the link width on laser link processing? Third, why is it that shorter laser pulse widths perform better in processing most metal links while the prior understanding implies that longer ones should do better? Fourth, the temperature uniformity within the metal links is not achievable, then is there any other way to optimize the metal link processing?

Several dubious assumptions adopted by prior analyses have to be revisited and corrected for any new simulation, such as: (1) the overlying passivation ruptures when the pressure on it by the molten link material reaches the adhesive strength of the passivation material, (2) the temperature-pressure relationship of the molten link is determined using a "hard sphere" model. But after the rupture temperature was derived based on the rupture pressure requirement and the "hard sphere" model, an additional 680 °C was arbitrarily added onto it as the rupture temperature used for further analysis without any explanation, (3) the link process was considered as basically completed at the rupture point of the passivation.<sup>13, 16</sup>

In fact, because it is made of fragile material, the passivation will rupture when the maximum principal mechanical stress within it reaches its adhesive strength,<sup>48</sup> not when the pressure on its surface reaches its adhesive strength. By assuming the latter, the rupture behavior of the passivation becomes independent to important structure data such as the thickness of passivation and link width. This is obviously wrong. A detailed analysis of the mechanical stress distribution within the passivation must be carried out to reveal the relationship of the rupture versus the pressure and other structure parameters.

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Thermally induced stress is a result of differential thermal expansion within the structure. Different materials have different thermal expansion coefficients at the same temperature, or a single material has different expansion rates at different temperatures and in different directions. One area tends to expand its volume more for some reason, but if it is restricted by its surrounding area, stress occurs. For the pressure generated by molten link material, the basic physics involved is the same. That is, if the molten material tends to expand, but is restricted by its surrounding structure from doing so freely, pressure and stress will be built up. The most drastic volume change of all common link materials occurs upon their melting. While all metals expand considerably upon melting, semiconductor materials such as silicon and germanium contract drastically. For instance, aluminum expands 6% of its volume on melting, but silicon contracts almost 10% of its volume on melting.<sup>49</sup> Compared to this large percentage volume change during the solidliquid phase change, the thermal expansion of a material remaining in its solid state becomes a much less drastic effect. Using the hard sphere model of liquid metal, a formula of P =998.7 $\times$ T was derived by the prior analysis to calculate the pressure P of the molten link material at temperature T. For simplicity, the units included in the constant term (that is, 998.7) do not appear in the formula, but the P is in pound per square inches (psi), when T is in °K.<sup>13, 16</sup> Thus for the molten polysilicon link right above its melting point of 1410 °C, based on the formula, the pressure by the molten polysilicon was as high as  $1.68 \times 10^6$  psi, or  $1.15 \times 10^5$  atmospheric pressures (atm.). This is definitely in contradiction with the reality considering the contraction of the polysilicon on melting. Therefore, in the prior analysis, for the critical rupture behavior of the passivation, both the basic relationships between the load (pressure) on the passivation and the rupture of the passivation, and the load (pressure) and the temperature of the molten link materials used for the analysis were not correct.

The link process is far from its completion at the rupture point of the passivation. Especially for metal links, most link material still remains at low temperature when the passivation ruptures. The process analysis can not be considered completed until the end of the laser pulse and total removal of the link. Therefore, a post-rupture process analysis is of significant importance to the complete understanding of the process. This chapter will report the results of searching for a new physical model and simulation for better understanding of laser link processing, and thus better process optimization.

The new analysis consists of four parts. The first part is devoted to the consideration of optical interference effects. This includes optimizing the thickness of all passivation layers and the link itself to maximize the percentage of laser energy absorbed by the link and minimize the laser energy which penetrates into the silicon substrate. In particular, optical interference effects from underlying layers when the remaining metal link becomes thin compared to its optical absorption depth will be carefully examined. Analysis results prove that this is one of the essential issues for cleanly processing the bottom part of link material without using excessive laser energy. The second part is a prerupture temperature analysis. This includes consideration of temperature distribution within the link structure under exposure to a laser pulse before the overlying passivation ruptures. The results of this analysis will be used to determine the rupture point of the passivation and the volume of molten link material by the rupture point. It will also supply the starting temperature condition for post-rupture analysis. This temperature simulation should be at least two dimensional in order to supply the necessary structural and load information for the mechanical stress analysis. The third part is a mechanical stress simulation. This simulation will resolve the mechanical stress distribution within the passivation caused by the pressure of the molten link material. As a result of the simulation, the rupture point of the passivation is determined. The volume change of the link material upon melting will be taken into account in calculating the pressure. The fourth part of the new analysis is post-rupture process analysis. This includes a link process analysis after the rupture of the overlying passivation, temperature within the link versus time, removal of the rest of link material, and silicon substrate damage risk assessment, etc.

A full link process simulation has been developed based on these four analyses. Effects of different link structure and laser parameters on link processing can be assessed using the simulation. The effect of laser pulse width on the temperature distribution within the link structure will be quantitatively discussed, while other effects of the pulse width on link processing will be briefly and qualitatively discussed. All discussions will be based on a traditional "static" model which means that all dynamic issues relating to removal of material will not be addressed quantitatively in this work. As it will be seen, even without going into the dynamics issues, a much better understanding of the process can be gained, so the process can be better optimized.

Figure 3-1 shows the link structure example which will be used for most of the simulations presented in this thesis.



Figure 3-1. Link structure example used for simulations.

### 3.2 Optical interference effects

Optical interference effects of multi-layer structures on laser processing, such as thin film resistor trimming and memory link cutting, have been well recognized and documented.<sup>13, 50-53</sup>

Most modern memory link structures consist of multiple layers made of different materials. A simplified example is shown in Figure 3-1. The example contains only one overlying passivation layer and one underlying passivation layer besides the link and silicon substrate. Figure 3-2 is a revision of the link structure shown in Figure 3-1 to aid the interference analysis. For simplicity, only one reflection from each interface is shown, while in the reality there are multiple reflections bouncing back and forth between interfaces. All the beams will optically interfere with each other. Based on their phase

relationships, either destructive or constructive interference will result. Their phase relationship is determined by the thickness and refractive index of each layer, and the laser wavelength used. The laser beam is approximated as a planar wave for optical interference analysis.



Figure 3-2. A simplified link structure for optical interference analysis.

The goal of the simulation is to develop a software tool capable of calculating the optical interference effects based on link structure information and laser wavelength used. The effects include the percentage of laser energy absorbed by the link, reflected by the structure, and penetrated into the silicon substrate, respectively. Optimization would then consist of choosing a optimized structure (mainly, optimized thickness of the passivation layers) to maximize the percentage of laser energy absorbed by the link, or maximize the ratio of laser energy absorbed by the link to laser energy penetrated into the silicon substrate, so the laser energy needed for the process can be minimized. This in turn can widen the processing window and reduce the damage risk to the substrate.

Optical interference effects change during the process whenever there is a structure change or phase change of materials involved. An example of a phase change is partial melting of the link, which results in an additional molten layer with a dramatically different refractive index. An example of structure change is the rupture of the passivation and partial removal of the link. Another example of structure change is the case when the process is close to its completion and only a thin layer of link material is still left. For most metal link structures, the original thickness of the link is large compared with its optical absorption depth so that virtually no laser energy can penetrate through the link to reach the underlying passivation. Therefore, there is little contribution to optical interference effects from the structure underneath the link. As soon as the remaining link becomes thin compared to its optical absorption depth, laser energy can penetrate through the remaining link material. Then optical interference effects caused by the underlying layers start to show and play a significant role in whether the remaining bottom portion of the link can be effectively processed.

A full optical interference simulation and layer structure optimization thus has to include all the situations mentioned previously: optimizing the overlying passivation structure when the whole link is in its solid-state phase, optimizing the overlying passivation structure when part of the link becomes molten, and optimizing the underlying layer structure when the remaining link is thin compared to the optical absorption depth of the link material at the laser wavelength used. All simulation results shown here are at the laser wavelength of  $1.047 \,\mu$ m.

Figure 3-3 shows a link structure example used for optical interference simulation when the top part of the link becomes molten. Figure 3-4 shows a link structure example for optical interference simulation when the link becomes thin.







Figure 3-4. A Structure example for optical interference simulation with a thin link layer remaining.

### 3.2.1 Basic formulas

References on optical interference effects for multi-layer structures can be found in many sources.<sup>54, 55</sup> Figure 3-5 shows a demonstration sample of multi-layer structure for interference simulation.

Air	Ī				Si wafer
$n_0=1$	nı	n2	NN-1	ΠN	nsi= 3.54 (at 1.047 μm)
Ao	Aı	A2		An	Asi
Bo	Bı	B2		BN	Bsi
X0	Xı	X2		XN	X

Figure 3-5. Multi-layer structure for optical interference simulation.

The relationship between the incident light wave (right-traveling) and reflected (left-traveling) light wave can be expressed using a  $2 \times 2$  matrix <sup>55</sup>

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A_{si} \\ B_{si} \end{pmatrix},$$
 (3-1)

with the matrix given by

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} \left[ \prod_{i=1}^N D_i P_i D_i^{-1} \right] D_{si} , \qquad (3-2)$$

where N is the number of layers ( air and the silicon substrate are not included),  $n_i$  is the refractive index of the i-th layer,  $X_i$  is the position of the interface between the i-th layer and the (i +1)th layer,  $A_0$ ,  $B_0$  are the amplitudes for the right-traveling and left-traveling plane waves in the medium 0 (air) at  $X = X_0$ , respectively, Ai, Bi are the amplitudes for the right-traveling and left-traveling plane waves in the i-th layer medium at  $X=X_i$ , respectively, Asi, Bsi are the amplitudes for the right-traveling and left-traveling plane

waves in the medium of silicon wafer at  $X = X_N$ , respectively,  $D_i$  is the dynamical matrix for the i-th interface,  $P_i$  is the propagation matrix for the bulk of the i-th layer. For the case of normal incidence of the light wave through the multi-layer structure,

$$D_i = \begin{pmatrix} 1 & 1 \\ n_i & -n_i \end{pmatrix}, \tag{3-3}$$

$$P_i = \begin{pmatrix} e^{i\phi_i} & 0\\ 0 & e^{-i\phi_i} \end{pmatrix}, \tag{3-4}$$

where  $\phi_i = n_i d_i \frac{\omega}{c}$ , c is the phase velocity of the light wave in the vacuum,  $\omega$  is the angular frequency of the light wave,  $d_i$  is the thickness of the i-th layer.

The field reflection and transmission coefficients, r and t, are defined as

$$r = \left(\frac{B_0}{A_0}\right)_{B_{si=0}},\tag{3-5}$$

and

$$t = \left(\frac{A_{si}}{A_0}\right)_{Bsi=0}$$
(3-6)

Thus, reflectance R of the whole multi-layer structure is given by

$$R = \left| r \right|^2 = \left| \frac{M_{21}}{M_{11}} \right|^2 \,. \tag{3-7}$$

Assume that the silicon substrate is a non-absorbing medium for interference simulation due to the small imaginary part of its refractive index. The laser beam is perpendicular to all those interfaces, and thus the transmission coefficient T is given by

$$T = \frac{n_{si}}{n_0} \left| \frac{1}{M_{11}} \right|^2 , \qquad (3-8)$$

where  $n_{si}$  is the refractive index of the silicon substrate, and  $n_0$  is the refractive index of the air, which is equal to 1.

#### 3.2.2 Modeling

For a real multi-layer link structure, if adjacent layers are made of the same material, or different materials but with the same refractive index, they can be considered as a single layer for the simulation.

For a link structure, the air above the structure is considered as the medium 0 with refractive index of 1. The silicon substrate is considered as the last medium with infinite thickness, or there is no reflection from its back surface. In the reality, the back side of the silicon substrate is roughly polished, so this assumption holds well. The imaginary part of silicon's refractive index is neglected due to its small effect on the optical interference simulation.

### 3.2.3 Simulation

The software was developed on a PC using the Turbo Pascal language (Borland International, Inc. 1800 Green Hills Rd. P. O. Box 660001, Scotts Valley, CA 95067). It is capable of checking the interference effects of a structure with up to 10 layers. It can run simulations of the optical interference effects versus thickness of one layer (two dimensional result display) or two layers at a time (three dimensional result display).

The software asks for all structural and physical information as the input before it runs the calculation. These inputs include the number of layers in the structure, which layer is the absorbing layer (that is the links for memory redundancy application, the resistor films for trimming application), which layer (or which two layers) is (are) going to be optimized (the thickness of the layers will be indexed automatically within a certain percentage range, or within a range of the thickness of a quarter wavelength in the material to cover the periodic behavior of the optical interference), the thickness and refractive index of each layer within the structure.

The output data is formatted such that it can be used by several common graphical display software programs directly for two dimensional or three dimensional displays.

### 3.2.4 Simulation result

The refractive indexes (at 1.047  $\mu$ m) used for the optical interference simulation are shown in the Table 3-1.<sup>13, 56</sup> Due to the difficulty in getting the refractive index values of liquid metals, as an approximation, the refractive index of solid state Al will be used for liquid Al in optical interference simulation.

Table 3-1. Refractive index (at 1.047 µm) used for optical interference simulation.

	SiO <sub>2</sub>	Polysilico	Aluminum	
		Solid state	Liquid state	(Solid state)
Refractive index	1.43	3.4 - i × 0.017	4.9 - i × 5.93	1.75 - i × 8.50

Figure 3-6 shows the optical interference effects from the overlying passivation with an aluminum link in its solid state phase, for a link structure as shown in Figure 3-2. Figure 3-7 (A), (B) show the optical interference effects from the overlying and underlying passivation for a poly link in its solid-state phase, for a link structure as shown in Figure 3-2. Figure 3-7(A) is a three dimensional display of the results, while figure 3-7(B) is a contour display of the same results. As examples, Figure 3-8 shows optical interference effects from the overlying passivation when the whole link is in its solid state phase, and when part of the polysilicon link becomes molten, respectively. The thickness of the molten polysilicon link is arbitrarily chosen as of 2000 Å. Figure 3-9 shows the optical interference effects from the underlying layer with only a thin layer of aluminum link material remaining. As an example, the thickness of the remaining aluminum used in this simulation is 100 Å.



Figure 3-6. Optical interference effects from the overlying passivation with an aluminum link.



Fraction of the laser energy absorbed by the link

(A). Three dimensional display of the result.

Figure 3-7. Optical interference effects from the overlying and underlying passivation for the poly link.



Fraction of the laser energy absorbed by the link

- (B). Contour display of the result.
- Figure 3-7. Optical interference effects from the overlying and underlying passivation for the poly link.



Thickness of the overlying passivation (Å)

Upper curve: when part of the link (2000 Å) is molten. Lower curve: when the whole link is in its solid phase.

Figure 3-8. Optical interference effects from the overlying passivation for the poly link.

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Thickness of the underlying passivation (Å)

Figure 3-9. Optical interference effects from the underlying passivation with only a thin layer (100 Å) of aluminum link remaining.

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From Figures 3-6 to 3-9, several important points become clear. First, optimizing optical interference effects is important for widening the laser processing window. For instance, as seen from Figure 3-6, for an aluminum link structure as shown in Figure 3-2, the percentage of laser energy absorbed by the link is 17% for an optimized thickness of the overlying passivation of 5300 Å, and 9% for the worst case of the thickness of 3500 Å. The difference between these two cases is almost a factor of 2. Improving the coupling efficiency of laser energy into the link will proportionally reduce the laser energy needed for processing the link, or reduce the lower end of the processing window. Second, for a polysilicon link, when part of the link becomes molten, there is a significant change in interference effects with the change of the refractive index, as shown in Figure 3-8. Before partial melting of the link, the percentage of laser energy absorbed by the link varies from 6% to 11% for thickness of the overlying passivation from 4000 Å to 5800 Å. After partial melting of the link, the percentage of laser energy absorbed by the link varies from 25% to 44% for thickness of the overlying passivation from 3450 Å to 5300 Å. It can be observed that while the percentage of laser energy absorbed changes dramatically (molten poly is more absorbing than solid poly), the optimum thickness of the overlying passivation shifts approximately 500 Å. Any number between 5300 Å and 5800 Å would be a good choice as the "designed" thickness of the passivation. Third, the interference effects from the underlying passivation with a thin layer of metal link material remaining is also quite dramatic, as shown in Figure 3-9. The laser energy absorbed by the 100 Å thick aluminum link layer is 29% for an optimized case (10,000 Å of underlying passivation), but only 12% for the worst case (7500 Å of underlying passivation). Note that the bottom part of the link is the most difficult part to remove during the process, thus optimization of the underlying layer is of critical importance.

For real devices, there are often several passivation layers made of different materials both above and underneath the link. As a result, optical interference effects are frequently even more dramatic. However, in some cases, manufacturers either have to use non-optimum thickness due to other constraints of the fabrication, or it is difficult to have tight control on the thickness. In these cases, the simulation can make evaluations about the possible consequence on the processing by having the non-optimum thickness as the "designed" thickness or by having inadequate accuracy of the thickness control.

It is also clear from these Figures that periodic behavior of optical interference effects delivers multiple optimized thickness values. The optimized result repeats itself with every increase of thickness equivalent to that of a half-waveplate. For instance, for the case shown in Figure 3-6, the optimized result repeats itself by every 3661Å of the overlying passivation. Considering that SiO<sub>2</sub> has a refractive index of 1.43, this periodic interval is exactly the thickness of a half-waveplate of SiO<sub>2</sub> at the laser wavelength used (1.047  $\mu$ m). This periodic behavior offers multiple choices for structure optimization. The actual thickness used for fabrication would mainly be determined by other IC process considerations. From the view point of thickness control accuracy, thinner layers would be recommended (for the same percentage accuracy of thickness control, thinner passivation will result in smaller deviation from the optimum interference effects peak). On the other hand, for the overlying passivation, the choice of its thickness has also to be governed by the consideration of its rupture behavior, as will be discussed in the mechanical stress simulation.

### 3.3 Pre-rupture temperature distribution simulation

Link cutting using laser pulses is a thermal-mechanical process. Excited electronic states of the absorbing medium, induced by the laser energy, will decay into phonons or vibrations of the ground electronic states. This electron-phonon conversion rate is extremely rapid, occurring within a few picoseconds for many room temperature solids.<sup>55</sup> Thus, the laser pulse width used (from a few tens of nanoseconds to a few nanoseconds) for link processing is long enough for macroscopic theory of material heating by laser pulses to be valid.

Material heating under exposure to a laser pulse with a few nanoseconds width is nothing new. Well written references can be easily found in many sources.<sup>58-60</sup> With an overlying passivation covering the link, the link material has nowhere to go before the passivation is ruptured. Dramatic structure transformation with the rupture of the passivation can be taken care of in the temperature simulation. The simulation can be divided

into two separate parts: one for the process before the rupture (pre-rupture analysis), one for the process after the rupture (post-rupture analysis).

The pre-rupture temperature simulation results will serve the following purposes: determining the temperature distribution within the structure versus time and its relationship with link structure data and laser parameters, supplying input data needed for the mechanical stress analysis such as the pressure on the passivation, determining how much link material has become molten by the passivation rupture point (thus will be blown away along with the rupture of the passivation), and supplying the starting temperature and structure condition for post-rupture analysis.

## 3.3.1 Basic formula and the finite element method

In this section, the basic formulas used in the temperature simulation, including the differential equations for the thermal conduction and formulas for determining the laser energy absorption within the link volume will be presented. The finite element method for deriving the numerical solutions of these differential thermal equations will be explained.

## 3.3.1.1 Differential thermal conduction equations

The basic thermal equation can be written as 61, 62

$$\rho C_p \frac{\partial T}{\partial t} = K \nabla^2 T + P(x, y, z, t), \qquad (3-9)$$

where  $\rho$  is the density of the material under consideration,  $C_p$  is the specific heat of the material, T is the temperature field (a function of position and time), K if the thermal conductivity of the material, P is the volume heat generation rate.

The physical meaning of Equation 3-9 is that the volume heat increase rate (left side of the Equation) is equal to the heat flow rate (first term of the Equation's right side) plus an additional volume heat generation rate (second term of the Equation's right side).

#### 3.1.1.2 Numerical solution of the thermal problem

Due to difficulties associated with analytically solving the differential Equation 3-9 for most real cases, numerical methods are often used instead. Both the continuous time

and coordinate space domains are divided into a series of small steps of time intervals and space nodes, respectively. Then the differential Equation 3-9 can be approximated by a finite-difference Equation 3-10 for a three dimensional heating problem. The Equation for the i-th node lying in the bulk of the sample is given by

$$\frac{C_i \left( T_i^{n+1} - T_i^n \right)}{\Delta t} = P_i^n + \sum_{m=1}^6 {}_i K_m^n \left( T_m^n - T_i^n \right), \tag{3-10}$$

where  $T_m^n$  is the temperature of the m-th node adjacent to i-th node at time t<sup>n</sup>,  ${}_iK_m^n$  is the thermal conductance between m-th node and i-th node,  $P_i^n$  is the heat generation rate at i-th node, at time t<sup>n</sup>,  $C_i$  is the heat capacitance of the material within the i-th node, and  $\Delta t$  is the time interval used. For a three dimensional problem, one C, one P and six Ks may be associated with each internal node at a particular time.

The Equation indicates that the temperature at the i-th node at a future time moment  $(t^{n+1})$  can be expressed as a function of temperatures of the node itself and its nearest neighbor nodes (six nodes for a three dimensional problem, four nodes for a two dimensional problem) at the current time moment  $(t^n)$ . This is usually referred to as an explicit method, or forward differences method.<sup>62</sup> Figure 3-10 shows nodes and heat flows for a two dimensional case.



Figure 3-10. Two dimensional nodes and heat flows.

The explicit method is straightforward, easy to solve, but with the disadvantage that for a defined node dimension, there is a restriction of how large the time interval may be while assuring convergence of the numerical result. "Converge" means that if there is any error in the approximation, it will not grow with time and cause instability of the simulation. The stability criterion governing the selection of the time interval  $\Delta t$  is given by <sup>61, 63</sup>

$$\Delta t < 0.5 \times \Delta x \times \Delta y \left( \frac{C_p \times \rho}{K} \right), \tag{3-11}$$

where  $\Delta x$  and  $\Delta y$  are sizes of the smallest two dimensional finite elements used, K is its thermal conductivity,  $\rho$  is the density of the material involved, and C<sub>p</sub> is the specific heat of the material involved. For instance, for aluminum link material, when  $\Delta x$  and  $\Delta y$  are selected to be 0.025 µm, then the time interval should be no longer than 0.002 ns.

The reason behind the temporal restriction is that during the time interval selected, the heat flow calculation is done under the assumption that the temperature of the involved nodes remain constant. But the physical reality is that the temperature of a node from which heat is flowing will cool down, while the temperature of the neighboring node into which the heat is flowing will increase. By assuming fixed temperatures for both nodes, with a larger time interval, unrealistically high heat flow can be derived. Thus errors will occur.

Note the thermal diffusion length is defined as<sup>64</sup>

$$L = 2 \times \sqrt{D_{th} \times t} \quad , \tag{3-12}$$

where  $D_{th}$  is the thermal diffusibility which equals  $K/(\rho \times C_p)$ , in cm<sup>2</sup> / sec., and t is the elapsed time. For example, the thermal diffusion length for a time period of 10 ns for SiO<sub>2</sub> is 1600 Å. Equation 3-12 can be re-written as  $t = 0.5 \times L^2 \times (\rho \times C_p/K)$  which is very similar to the Equation 3-11. Thus, one physical meaning of the restriction on the time interval is that the interval should be kept small enough so that the thermal diffusion length for the time interval remains smaller than the node's dimension.

There are many techniques<sup>65,66</sup> available to accelerate the simulation without causing instabilities. One is the implicit method. It expresses a future nodal temperature in terms of its current value and the future values of its neighbors' temperature. It is a less

direct method than the explicit method, more equations need to be solved to get the result. But there is no serious restriction on the magnitude of the time interval for the implicit method. Another is a modified explicit method or "Levy method".<sup>67</sup> It allows stable calculations with a much larger time interval than allowed for the classical explicit method.

Due to available computer power, it was decided to use the explicit method in the thermal simulation and software development.

### 3.3.1.3 Laser parameters

The spatial distribution of the laser energy is assumed to be Gaussian shaped. Figure 3-11 shows the spatial distribution along the positive x axis assuming that the beam center is at the x=0 point, the Gaussian beam waist (radius) is 5  $\mu$ m. The assumed temporal distributions of the laser intensity  $E^0(t)$  for laser pulses with the same energy but different pulse width are shown in Figure 3-12. The laser energy density E at position x, y and time moment t can be described as

$$E(x, y, t) = E^{0}(t) \times \exp\left[-\frac{2(x^{2} + y^{2})}{\omega_{0}^{2}}\right] , \qquad (3-13)$$

where  $\omega_0$  is laser beam waist (radius) to  $1/e^2$  of its peak intensity points.



Distance from the beam center-in µm

Figure 3-11. The spatial laser energy distribution.

Other laser parameters such as energy per pulse and pulse width are variables. They can either be pre-set or optimized during the simulation.



Figure 3-12. The temporal distributions of the laser intensity.

### 3.3.1.4 Laser energy absorption

The laser energy penetrating through a link's top surface is the total incident laser energy minus the reflected energy, calculated based on the optical interference simulation. Laser intensity variation within the link volume due to the optical interference effects is neglected for simplicity of the temperature simulation.

Assuming the laser intensity entering into the link material surface is  $I_{0}$ , then the laser intensity at the depth z underneath the surface is expressed by

$$I = I_0 \exp(-\alpha z), \qquad (3-14)$$

where  $\alpha$  is the optical attenuation coefficient of the link material. From Equation 3-14, when  $z = 1/\alpha$ , then  $I = I_0/e$ .  $1/\alpha$  is called the "optical absorption depth" which is a useful parameter for estimating how deep the laser beam can penetrate into the absorbing medium. For instance, an absorption depth of 5 µm for polysilicon at the laser wavelength of 1  $\mu$ m means that for a 1  $\mu$ m thick poly link, the laser beam can go through the link with only a small amount of attenuation (18%), so the whole link will be evenly heated by the laser beam. However, notice that 82% of the laser energy penetrates through the link without being absorbed. This large amount of laser energy imposes a larger damage risk to the silicon substrate. In contrast, an absorption depth of a couple of hundred Angstroms or so for most conductive metals indicates that the laser beam will only be able to penetrate and heat the top surface region of the metal links.

Based on Equations 3-13 and 3-14, the laser energy absorbed ( $\Delta E$ ) by the i-th node located at (x, y, z) with dimensions  $\Delta x$ ,  $\Delta y$ , and  $\Delta z$ , at time t, and for time interval  $\Delta t$ , can be expressed as

$$\Delta E(x, y, z, t) = E^{\circ}(t) \times \exp\left[-\frac{2(x^2 + y^2)}{\omega_0^2}\right] [1 - \exp(-\alpha \Delta z)] \exp(-\alpha z) \Delta x \Delta y \Delta t$$
(3-15)

### 3.3.1.5 Physical data versus temperature

Physical data required for the temperature simulation are the absorption coefficient or the complex refractive index, the thermal conductivity and capacity, the latent heat, and the melting and evaporation temperatures of all materials involved in the link structure.

Since the process covers a wide temperature range and since material phase transitions are involved, all the optical and thermal parameters should be expressed as functions of the temperature and phase of the materials. Figures 3-13 shows the absorption versus temperature for silicon and heavily doped silicon,<sup>13</sup> which will be further discussed in the Chapter 4. Figures 3-14 to 3-15 show the thermal conductivity, density and specific heat capacity versus temperature and phase for silicon, heavily doped silicon, silica glass (SiO<sub>2</sub>).<sup>13</sup> Figures 3-16 shows the (1-R), thermal conductivity and specific heat capacity versus temperature for aluminum.<sup>41, 68</sup> R is the reflectivity of the material. Note that they are all functions of the temperature and material's phase condition.



Figure 3-13. Absorption vs. temperature for silicon and heavily doped silicon. (After Scarfone et al., ref. 13.)



Figure 3-14. Thermal conductivity vs. temperature for silicon, heavily doped silicon and SiO<sub>2</sub>. (After Scarfone et al., ref. 13.).



Figure 3-15. Specific heat capacity vs. temperature for silicon and silica glass, density vs. temperature for silicon. (After Scarfone et al, ref. 13.)



Figure 3-16. (1-R), thermal conductivity and specific heat vs. temperature for aluminum. (After von Allmen, ref. 41, 68.)

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### 3.3.2 Link structure modeling

The modeling of a link structure for pre-rupture temperature distribution simulation is based on the following considerations and assumptions.

First, adjacent layers made of thermally similar materials can be treated as a single layer. Also, due to the short laser pulse width and corresponding small thermal diffusion length involved, the passivation structures can be considered as infinite in their lateral directions (x and y). The same can be done for the silicon substrate in the z direction. But for simplicity of the simulation and reduction of the total number of finite nodes, the finite thermal boundaries are set up in each direction a few thermal diffusion lengths away from the top center of the link. Temperatures at these boundaries are considered to be fixed at the constant starting values.

Second, the laser beam is assumed to be accurately aligned at the link, that is the beam spot is centered on the link. Considering the facts that the laser beam intensity is symmetric in both lateral directions and the coverage by the laser beam spot along the length of the link is greater than the width of the link, the heat flow in the link's length direction is neglected, or there is no temperature gradient in the length direction of the link. Thus, link heating can be simplified to a two dimensional problem.

Third, due to the symmetry of the laser energy spatial distribution and the link structure, only a half cross section of the link structure on one side of its symmetry axis (z) needs to be analyzed, as shown in Figure 3-17. Due to the nature of the IC fabrication processes, the passivation next to the link is part of the overlying passivation. (Similarly, for a three dimensional simulation, the structure can also be simplified by solely considering the structure within the quadrant of +x, +y, +z. But for the previously mentioned reason, no three dimensional simulation results will be given in this writing).

Forth, the size of the finite nodes is chosen based on simulation accuracy requirements. However, the interface lines or surfaces between different materials within the structure are pre-set as part of the dividing lines between nodes, no matter what the nodal sizes are. Consequently, there will be no a single node consisting of more than one material.

### 3.3.3 Simulation software

Many computer software programs are available for solving thermal problems, such as "Heating 5".<sup>69</sup> But for our purposes, it was decided to develop our own code, so that numerous features convenient for our applications can be built into the program. The program is developed based on the explicit numerical method using the Turbo Pascal programming language (by Borland International, Inc.) on a PC. It is capable of calculating either one, two, or three-dimensional temperature distributions within the link structure versus time under exposure to a laser pulse. The program code is attached as the Appendix to the thesis.



Figure 3-17. Link Structure modeling and division into finite elements for temperature simulation.

Several practical issues for the simulation and program are listed below.

First, it is assumed that the heat loss due to surface radiation and convection is negligible. This will impose virtually no error in the pre-rupture temperature simulation since for the laser pulse widths used, the top surface of the passivation remains cool up to the rupture point of the passivation. For post-rupture process, considering the removal rate of the link material and the short time scale involved, this assumption still holds.

Second, considering the critical effect (to be shown below) of the corner radius of the passivation structure on the stress concentration and the possible melting in the link edge area which will affect the effective corner radius for the stress simulation, selection of nodal dimensions smaller than the corner radius is preferred. But if the selected nodal dimensions are too small, then the simulation would take too long to run. So a compromise in selecting nodal dimensions of  $0.025 \ \mu m$  by  $0.025 \ \mu m$  was made for the simulation based on the results of a few testing runs. With these nodal dimensions, for aluminum link material, the time interval in the simulation should be no longer than 0.002 ns, based on Equation 3-11.

Third, most physical data used for the temperature simulation, such as the refraction index, thermal conductivity and capacity of the materials involved are functions of temperature and phase of the materials. Thus, materials physical data are dealt with by special functions written in the program to supply the correct data for each node based on its temperature and phase conditions during the simulation.

Fourth, the program monitors the temperature at each node to determine whether the node is ready to undergo a phase change. If it is, the node will be maintained at its constant phase transition temperature until the transition is completed. The ratio of the heat received by a node for phase transition to the total latent heat required is defined in the program as a phase transition ratio. This ratio is a measure of the fraction of the node material which has completed the phase transition. For a solid-to-liquid phase transition, the ratio represents a liquid-solid mixture within a node. For a liquid-to-vapor phase transition, it indicates the percentage of material in the node which has already evaporated. Physical and structural data used for simulation are adjusted based on this ratio during the phase transition. It is possible that during one time interval, a node receives more heat than needed to make up the required latent heat. For the solid-to-liquid phase transition, if a phase transition ratio larger than 1 is detected, the software will convert the excess heat into a temperature increase in its liquid phase.

Fifth, since the thermal conductivity used for the simulation is a function of temperature, material and phase condition, different results for the same heat flow between two adjacent nodes could be derived based on which direction the flow is calculated (or which node's physical data are used). This will result in severe errors at the interface between different materials, or different phases of a material, where the physical data for the adjacent nodes are significantly different. To overcome this, the heat flow between any two adjacent nodes is calculated using averaged thermal conductivity of the two nodes.

### 3.3.4 Pre-rupture temperature simulation results

For the sake of comparison, the link structure geometry used in the simulation is the same for both polysilicon and aluminum links, as shown in Figure 3-1. The laser energy per pulse is 0.75  $\mu$ J. The laser beam spot size (diameter) is 5  $\mu$ m, and the laser wavelength is 1.047  $\mu$ m.

Ideally, the pre-rupture temperature simulation should stop at the moment when the overlying passivation ruptures. But the rupture point is unknown until the mechanical stress simulation results become available. Thus, pre-rupture simulation of the temperature distribution versus time will run up to the point when the highest temperature within the link reaches its evaporation point. One assumption adopted here is that the rupture will occur no later than the link material starts to evaporate, due to dramatic volume expansion (thus pressure increase) associated with the evaporation.

Due to reasons which will be explained later, for mechanical stress simulation, as well as damage analysis for the silicon substrate, the temperature simulation has to be at least two dimensional. So, results from one dimensional temperature simulation will merely be presented for its usefulness in explaining a few particular issues. The majority of the discussions will be based on results derived from the two dimensional simulations.

Figures 3-18 to 3-21 all show one dimensional temperature distributions along the z axis for the polysilicon and aluminum links under exposure to laser pulses of 5 ns and 50 ns (FWHM), respectively. Note that for a short laser pulse, the molten volume of the poly link is significantly larger than that of the aluminum link when the highest temperature in the poly link is close 3200 °C, in the aluminum link is close to 1400 °C. The different temperatures chosen for different link materials are based on our analysis of the passivation's rupture, which will be discussed in the mechanical stress simulation. But for a longer laser pulse, the situation becomes more complicated. The molten link material volume at a certain time of the laser pulse is not only affected by its optical absorption depth, but also the thermal conductivity, the melting point, and the latent heat of melting of the link material. For instance, due to aluminum excellent thermal conductivity and lower melting point, despite its smaller optical absorption depth, for a laser pulse 50 ns long, and a link 5000 Å thick, most of the aluminum link material can reach temperatures close or above its melting point, when the highest temperature in the link is over 1400 °C. If the prior understanding of the process was right, the aluminum link should be easy to process. But there was no experimental result to support this. One reason for this is that the size of thermally affected area increases with the laser pulse duration time. A part of the bottom area of the overlaying passivation becomes molten due to heat conducted from the link. For the 50 ns laser pulse width simulated, the thermal effected area is much larger than that for the 5 ns laser pulse width, implying higher damage risk to the passivation structure. More importantly, according to the discussions to be presented later, laser pulses with shorter pulse width or higher intensity cut the links much cleaner without imposing higher risk of forming slag and debris in the cut area. Thus, only the case of 5 ns laser pulse width will be further simulated for our discussion.

As seen from Figures 3-18 and 3-20, for laser pulse width of 5 ns, there is virtually no heat conducted into the top 4000 Å area of the overlying passivation for either link structure. So for two dimensional thermal simulations, in order to reduce the number of infinite elements, thus the simulation run time, the overlying passivation is reduced to 2500 Å thick in the model, unless otherwise specified. With this modification of the model, the area of 2500 to 7500 Å in depths, 0 to 0.5  $\mu$ m in widths is where the link located.


Figure 3-18. Temperature distribution along the z axis at different times for the poly link exposed to a 5 ns laser pulse.



Figure 3-19. Temperature distribution along the z axis at different times for the poly link exposed to a 50 ns laser pulse.



Figure 3-20. Temperature distribution along the z axis at different times for the aluminum link exposed to a 5 ns laser pulse.



Figure 3-21. Temperature distribution along the z axis at different times for the aluminum link exposed to a 50 ns laser pulse.

Figures 3-22 to 3-25 show three dimensional or contour displays of the two dimensional temperature distributions, for the poly and aluminum links. The highest temperature in the poly link is 2500 °C, in the aluminum link it is 1000 °C. The laser parameters used are: 5 ns for the pulse width and 5  $\mu$ m for the beam spot size.



Figure 3-22. Two dimensional temperature distribution at 4.52 ns for the poly link (three dimensional display).



Figure 3-23. Two dimensional temperature distribution at 4.52 ns for the poly link (contour display).



Temperature (°C)

Temperature (°C)

Figure 3-24. Two dimensional temperature distribution at 3.91 ns for the aluminum link (three dimensional display).

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Temperature (°C)

Figure 3-25. Two dimensional temperature distribution at 3.91 ns for the aluminum link (contour display).

The simulation results are judged based on the temperature in the link. The characteristic temperatures of interest, such as the link material's melting point, evaporation point and the passivation's rupture point are different for different links. So the time chosen for the temperature curve in these Figures are different for different links. Note that for the 5 ns wide laser pulse, the heating by the laser pulse to the poly link is more uniform than that to the aluminum link along the Z axis (the depth direction) of the link. But in the lateral direction at the top of the link, it appears that the temperature distribution for the aluminum link is more uniform than that for the poly link. This lateral temperature distribution profile is a critical factor in the link processing simulation. In fact, it is the lateral temperature distribution at the top surface of the link which will determine the pressure on the overlying passivation, thus the stress in the passivation structure. Figures 3-26 and 3-27 show the lateral temperature profile at the top of the link at different times for both poly and aluminum links. Note that the lateral temperature distribution on the top of the links is indeed more uniform for the aluminum links than for the poly. This can be understood considering the small absorption coefficient of the poly when it is in its solid state, and then the more than two orders of magnitude increase in the absorption due to the solid-liquid phase transition (more severe thermal run-away with the phase transition), while for aluminum, the absorption changes by a factor of less than three due to the phase transition. The higher thermal conductivity and lower melting point of aluminum than that of poly also have their contribution to this lateral temperature profile difference. As will be discussed later, the different lateral temperature distribution profiles for links made up of different materials will have significant effects on the pressure pattern of the molten link materials, and thus the rupture behavior of the overlying passivation. From Figures 3-26 and 3-27, another important piece of information for mechanical stress analysis is that when the temperatures at the top center points for the poly link and aluminum link reaches 3200 and 1400 °C respectively, the temperatures at the corner areas of the links are still below the melting point of the overlying passivation (1400 °C for SiO<sub>2</sub>), which means that the corner radius has not been affected by the laser heating up to these points, yet.



Figure 3-26. Temperature distribution at the top of the poly link at different times.



Figure 3-27. Temperature distribution at the top of the aluminum link at different times.

#### 3.4 Mechanical stress simulation

Due to the fact that it is made of a fragile material such as SiO<sub>2</sub>, the passivation will rupture when the maximum principal mechanical stress within the material reaches its adhesive strength, not when the pressure on the material reaches its adhesive strength as suggested by prior analyses.<sup>13-15</sup> Several factors make contributions to the mechanical stress within the passivation, such as the pressure by the molten link material, the temperature gradient within the structure, different thermal expansion coefficients of the materials involved, the shock wave caused by violent interaction of the laser pulse with the link structure, and residual stress within the passivation. When compound materials are used to make the links, volume expansion due to decomposition of the compound link materials can make a contribution to the mechanical stress, as well.

Rough estimation shows that before link material melts, the mechanical stress caused by temperature gradient alone within the structure is small and not adequate to cause the rupture of the passivation.<sup>13</sup> This expectation has its experimental support from successful laser annealing of silicon without damaging the overlying oxide layer.<sup>38</sup> Since thermal expansion coefficients of most common link materials are larger than that of the two most common passivation materials: SiO<sub>2</sub> and SiN, higher temperature within a link will generate a stress pattern similar to that caused by the pressure of the molten link material. Thus, to some degree, this temperature gradient induced stress will help the rupture of the overlying passivation caused by the molten link's pressure.

The effects of the shock wave on the passivation's rupture is beyond the scope of this work and will not be discussed. It is expected that the shock wave might in general help the rupture of the passivation, as well as the removal of the link material. At the same time, it can be a risk factor for device reliability, too.

The residual stress within the  $SiO_2$  passivation is a compressive one due to the difference between the thermal coefficients of expansion of the silicon substrate and  $SiO_2$  passivation.<sup>70</sup> Its magnitude is relatively small (~3×10<sup>4</sup> newton/cm<sup>2</sup>), thus will be neglected in the analysis.

In short, only the stress caused by the pressure of molten link material will be considered in our simulation. In prior analyses, the pressure by the molten link material was calculated using a hard sphere model of liquid metal. The way the model is used resulted in a high pressure value for polysilicon material right above its melting point. Considering the fact that polysilicon contracts significantly upon melting in a "free" space (in the air), with the restriction of its volume by the passivation structure, the pressure within the liquid polysilicon should be less than one atmospheric pressure. This means that there should be a negative (contraction) pressure on the overlying passivation rather than a high positive (expansion) pressure. Based on the problems involved in the link processing, in order to determine the relationship between the pressure of the molten link material and its temperature, a few directly measured thermodynamic coefficients, such as the thermal pressure coefficient, coefficient of thermal expansion, and isothermal compressibility coefficient are used.<sup>37</sup> Having the volume change of the link material upon melting taken into account, as will be seen later, there will be a significant difference in the rupture behaviors of polysilicon and metal links. This is believed to be one of the important reasons why metal links are more difficult for a laser to process than poly links.

## 3.4.1 Mechanical stress analysis using finite element method

For a given structure and a known set of loads on a structure, in an elastic case, mechanical stress within the structure can be determined by the following formulas <sup>71, 72</sup>

$$\varepsilon_{x} = \frac{1}{E} \Big[ \sigma_{x} - \mu \big( \sigma_{y} + \sigma_{z} \big) \Big],$$
  

$$\varepsilon_{y} = \frac{1}{E} \Big[ \sigma_{y} - \mu \big( \sigma_{x} + \sigma_{z} \big) \Big],$$
  

$$\varepsilon_{z} = \frac{1}{E} \Big[ \sigma_{z} - \mu \big( \sigma_{x} + \sigma_{y} \big) \Big],$$
  

$$\gamma_{xy} = \frac{1}{G} \tau_{xy},$$
  

$$\gamma_{yz} = \frac{1}{G} \tau_{yz},$$
  

$$\gamma_{zx} = \frac{1}{G} \tau_{zx},$$
  
(3-16)

where  $\sigma_{X, y, z}$  are the stress components in X, Y, Z directions,  $\varepsilon_{X, y, z}$  are the strain components in X, Y, Z directions,  $\gamma_{XY, yZ}$ , zx are the shearing stress components in XY,

YZ, ZX planes,  $\tau$  xy, yz, zx are the shearing strain in XY, YZ, ZX directions respectively, E is the Young's modulus or elastic modulus of the structure material, G is the modulus of rigidity or sheering modulus of elasticity, and  $\mu$  is the Poisson ratio.

For link processing, the laser beam spot covers a larger dimension in the length direction of the link than the width of the link itself. Thus it can be approximately assumed that there is no temperature gradient, nor distortion in the length direction of the link. In other words, there is no strain in the length direction of the link. This means that the stress analysis can be simplified to a two dimensional "plane strain" analysis. Assuming the length direction of the link is in the Y axis, then  $\varepsilon_y$  and  $\tau_{xy}$ , yz equal zero for the plane strain problem, the above Equations 3-16 can be simplified to the following

$$\varepsilon_{y} = 0,$$

$$\varepsilon_{x} = \frac{1 - \mu^{2}}{E} \left( \sigma_{x} - \frac{\mu}{1 - \mu} \sigma_{z} \right),$$

$$\varepsilon_{z} = \frac{1 - \mu^{2}}{E} \left( \sigma_{z} - \frac{\mu}{1 - \mu} \sigma_{x} \right),$$

$$\gamma_{zx} = \frac{1}{G} \tau_{zx},$$
(3-17)

Analytically solving these equations for most real problems is impossible. Finite element analysis thus is often used to get numerical solutions.<sup>73-76</sup> A general finite element computer program block diagram for solving the structure stress problem is shown in Figure 3-28, where [K] is the structure stiffness matrix, {D} is the structure node displacement vector, and {F} is the structure external force vector.<sup>76</sup>



Figure 3-28. Finite element stress analysis computer program block diagram.

### 3.4.2 Modeling of the link structure for finite element analysis

Based on the symmetry of the link structure and the laser beam itself, the model of link structure for the mechanical stress analysis can be simplified to half of its cross-section shown in Figure 3-29, which is similar to what is used for the temperature simulation. This simplification will save the computing time and memory size needed for the simulation. The Z axis here is the symmetry axis of the link structure and the laser beam axis. Lines of BC, CD and DE outline half of the link cross-section in its width direction. AH represents the top surface of the overlying passivation. FG is the interface between the passivation layer and the silicon substrate. GH is an assumed boundary of the passivation with an adequate distance from the link. For the sake of simplification, both the overlying and underlying passivation layers are assumed to be made of the same material, so mechanically they are considered to be a single layer. In other words, there is no interface between the overlying passivation and the underlying passivation. Note that only the passivation structure is the object of the stress analysis. The link is considered as a load source onto the passivation.



Figure 3-29. A typical link cross-section structure model used for stress simulation (plane strain).

For the mechanical stress analysis, one critical issue is to correctly determine the boundary condition for the problem concerned. This includes the determination of boundary geometry, the mechanical freedoms of the boundaries, and the loads on the boundaries.

For the boundary geometry, the corner radius at the corner C, the position of the interface BC, and the position of GH are of great concern. As will be seen later, the corner radius at C significantly affects the stress concentration in the area. From the temperature simulation presented above, part of the bottom area of the overlying passivation becomes molten before the rupture of the passivation, so the interface BC should be actually considered as the interface between the solid passivation and the liquid materials (including liquid passivation and link materials), rather than the original interface between the passivation and the link. But as can be seen from Figures 3-18 and 3-20, for laser pulse width of 5 ns, the modification of this boundary BC is very minimal. Stress simulation test runs have also shown that the effect of this small boundary modification on the stress results is negligible. The position of GH should be set as close to the Z axis as possible to reduce the size of the structural model, but far enough to keep the simulated stress result in the GH's neighboring area negligible which means no significant error will be introduced to the stress simulation result in the link area by the position selection of the boundary GH.

As for the freedom of the boundaries, it is obvious that there is no movement allowed for any boundary in the Y direction due to the nature of the plane strain. AH is the top surface of the overlying passivation, thus is free to move in both X and Z directions. AB and EF are part of the symmetry axis Z of the link structure, so only free to move along the Z axis, otherwise the structure would no longer be continuous. FG is the interface between the underlying passivation and the silicon substrate, and is considered as to be fixed in both Z and X directions due to the strong support of the substrate. BC, CD and ED are free to move in both X and Z directions. If GH is set far from the Z axis, then it can either be considered to be free or not free to move in both X and Z directions, since the stress result in its neighborhood caused by the loads on boundaries BC and CD is negligible, anyway. For the loads on the boundaries, only the pressures on boundary BC, CD and ED by the molten link material are considered as the effective loads for the stress analysis. According to the hard sphere model of the liquid metal,<sup>36, 37</sup> ions within the liquid metal are considered as hard-spheres, with packing factor (or the fraction of the total volume occupied by these hard spheres) of  $\eta$ . Then the relationship between the pressure, volume and temperature of the liquid metal can be expressed by

$$PV = \frac{\left[\left(1 + \eta + \eta^2 - \eta^3\right)nkT\right]}{\left(1 - \eta^3\right)} \quad , \tag{3-18}$$

where P is the pressure of the liquid metal, V is the volume in which the liquid metal is confined, n is the mole number per volume of the liquid, and T is the temperature of the liquid metal. In fact, this formula is similar to the ones for gas, but with some modifications based on experimental results. Using  $\eta$ =0.45 for metals at the melting point, Equation 3-19 can be rewritten for liquid silicon<sup>13</sup> as

$$P = 998.7 \times T,$$
 (3-19)

where T is the temperature in °K, and P is the pressure in pounds per square inch. Similarly, for aluminum link,

$$P = 968.2 \times T.$$
 (3-20)

As mentioned previously, all metals expand a great deal upon melting, while semiconductor materials typically contract dramatically. Some semi-metals contract only slightly upon melting. The effect on the pressure of the molten link material due to the material's volume change upon its melting is not counted in these formulas. Significant errors in calculating the pressure of molten materials will occur for materials which contract upon their melting. For instance, from Equation 3-19, at temperature right above the melting point of 1410 °C for polysilicon, there would be an enormous  $1.15 \times 10^5$  atm. expansion pressure (compare to the stress of  $1.9 \times 10^5$  atm. needed to break the SiO<sub>2</sub> passivation). In reality, assuming poly-silicon performs the same as silicon does upon melting (contracts 10% of its volume), contraction pressure beneath the passivation will result, instead. In fact, it has been pointed out that there are limitations to the formulas derived based on the hard sphere model. In some cases, the formulas fit better for alkali metals, but in some other cases, the formulas fit other metals better.<sup>37</sup> It is suspected that for different kinds of materials, different values of  $\eta$  might be needed in order to better match the calculated results with the experiment results.

Since formula 3-18 was actually constructed to match the experimentally measured data, but in its present form it can not represent the behavior of materials which contract upon melting, other experimentally measured thermodynamic properties are used in our simulation to relate the pressures of the liquid metals to its temperatures.

Three thermodynamic properties will be used for the purpose. They are the coefficient of thermal expansion  $\alpha_p$ , the isothermal compressibility  $\chi_T$ , and the thermal pressure coefficient  $\gamma_{\nu}$ .<sup>37</sup> They are defined as

$$\alpha_{P} = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_{P}, \qquad (3-21)$$

$$\chi_T = -\frac{1}{V} \left( \frac{\partial V}{\partial P} \right)_T \quad , \tag{3-22}$$

$$\gamma_{\nu} = \left(\frac{\partial P}{\partial T}\right)_{\nu} = \frac{\alpha_{P}}{\chi_{T}} , \qquad (3-23)$$

where V is the volume, P is the pressure, and T is the temperature of the liquid material. Table 3-2 shows the volume changes upon melting, measured values of the thermodynamic coefficients just above the melting points for several materials.<sup>37, 49</sup> As an approximation, the coefficients measured at the temperature just above their melting points will be used for calculations over a whole temperature range from their melting points up to evaporation points. The effects of pressure on these coefficients and the melting point <sup>77</sup> will also be neglected in the simulation. The values within the parenthesis are assumed values based on the similarity of the materials. They will be used until measured ones become available.

Using the thermodynamic coefficients, the relationships of the pressure (in units of atm.) versus temperature for aluminum and silicon can be derived. For silicon, due to its contraction upon melting, the pressure is less than one atm. just above its melting point. In contrast, for aluminum, the restriction by the passivation on its volume expansion generates a high pressure after it becomes molten. The results are shown in Figure 3-30.

The effects of pressure change on the behavior of melting are neglected for both materials. The pressure load by the molten polysilicon or aluminum link material on the passivation then can be calculated based on both Figure 3-30 and the temperature profile derived from the thermal simulation (shown in Figures 3-26 and 3-27).

	Volume change upon melting (%)	$\gamma_v \times 10^{-12}$ (newton cm <sup>-2</sup> deg <sup>-1</sup> )	$\chi_{\rm T} \times 10^{17}$ (newton <sup>-1</sup> cm <sup>2</sup> )	$\alpha_p \times 10^5$ (deg <sup>-1</sup> )
Al	6.0	4.79	2.42	11.59
Cu	4.4	7.85	1.49	11.70
Si	- 9.6	(3.50)	(3.00)	(10.50)
Bi	-3.4	2.92	4.21	12.29

Table 3-2. Volume changes upon melting, measured values of thermodynamic coefficients just above the melting points for several materials.

Both temperature and pressure of the molten link material are functions of time and position. In other words, within the volume of molten link material, pressure varies with position at a given moment. This indicates that the molten material is not in an equilibrium state due to the short time scale involved. In fact, this pressure difference within the liquid link material is just one of the driving forces that generates a shock wave during the process. The behavior of the shock wave, including its magnitude, propagation pattern, and its effect on link processing is considered to be the dynamic issue of the process, and will not be discussed by this work. However, it can be reasonably expected that for the molten polysilicon, since there is an expansion region and a contraction region within it at the same time depending on the temperature distribution, the shock wave is more pronounced than in the case of metal links. In general, the shock wave will help break the overlying passivation, as well as the removal of the molten link material along with the rupture of the passivation with little risk of forming slag and debris.



Figure 3-30. Pressure vs. temperature for aluminum and polysilicon links.

## 3.4.3 Mechanical stress simulation and the results

The finite element simulation of the mechanical stress is done using a commercially available software program package called I-DEAS, by SDRC, Inc. (Structural Dynamic Research Corp. 2000 Eastman Dr. Milford, Ohio 45150).

The physical data of the  $SiO_2$  passivation material used in the simulation are as follows: the Young's modulus is  $7.3 \times 10^7$  millinewton/mm<sup>2</sup>, the Poissons ratio is 0.17, and the Sheer modulus is  $3.6 \times 10^7$  millinewton/mm<sup>2</sup>.<sup>78</sup>

After specifying how to divide the finite elements (nodes), such as triangle nodes or rectangle nodes, and the dimensions of the nodes, the division of the nodes will be implemented automatically by the program itself. The finite nodes are denser in the corner area which the program knows would be an area with concentrated stress. Figure 3-31 the sharp corner C modified to a round one with a defined radius. The smaller the nodal dimensions, the more accurate are the stress simulation, however, the more computing time will be needed for a run.

For the plane strain problem, the program considers a piece of structure with an unit thickness. Any point force lying in the plane, applied at an edge of the structure, is in the unit of force/length, while for an edge force, as well as the stress itself are in force/length<sup>2</sup>. In fact, the scalability nature of the mechanical stress problem allows a convenient transfer between different unit systems. For the link structure concerned, it is easier to run the simulation using a nanonewton/nm (nN/nm) unit system. As a reminder, 1 nanonewton/nm<sup>2</sup> (nN/nm<sup>2</sup>) equals  $1 \times 10^4$  atm., and the adhesive strength of SiO<sub>2</sub> is  $19 \times 10^4$  atm. All the stress results presented hereafter will be in unit of nN/nm<sup>2</sup> (that is, in  $10^4$  atm.), unless otherwise specified.

To examine the characteristic features of the stress distribution within the passivation, a point force of 450 nN/nm and an edge force of 1 nN/ nm<sup>2</sup>, both in the -Z direction were used as the load, respectively. The point force is applied at the center point B. The edge force is applied over the length of 450 nm on the interface edge starting from the center point B to the corner C. The radius at corner C is assumed to be 50 nm, the half width of the link is 500 nm (0.5  $\mu$ m), and the overlying passivation thickness is 400 nm. The mechanical stress distribution results are shown in Figures 3-32 and 3-33. Also shown in the figures are displacements (mechanical distortion) of the structure (exaggerated for better visibility). It is interesting to note that although the two stress patterns in the area close to point B where the point force is applied are different, the amplitudes of the two maximum principal stresses in the corner area are very similar:  $5.76{\times}10^4$  atm. for the point force of 450 nN/nm applied at the center point B, and  $5.15 \times 10^4$  atm. for the edge force of 1 nN/nm over the edge of 450 nm long. This implies that for this "enclosed" structure (a link enclosed within the passivation), the maximum principal stress in the corner C area is not sensitive to where a force is applied on the interface BC. In contrast, as we know it, for an "open" structure such as a beam supported only at its one or both ends, the stress in its supported end area is very sensitive to the location where the force is applied.



Figure 3-31. Finite element (node) division of a half of the link cross section plane for the stress simulation.



Figure 3-32. Mechanical stress distribution for the link structure under the point force applied at its center point B.

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Figure 3-33. Mechanical stress distribution for the link structure under the edge force.

To reveal the characteristics of the stress within the passivation structure further, Figure 3-34 shows the maximum principal stress versus the location where a point force of 100 nN/nm is applied. The relatively flat curve confirms the insensitivity of the maximum stress in the corner area to the location where the force is applied. Figure 3-35 shows the maximum principal stress versus the corner radius of the overlying passivation under a point force of 100 nN/nm. It proves that there is stress concentration as the corner gets sharper. Figures 3-36 and 3-37 show the maximum principal stresses versus link width and overlying passivation thickness under the point force of 100 nN/nm at the center point B. As a reminder, for the results shown in Figures 3-35 to 3-37, unless it becomes a variable itself, the corner radius at C is assumed to be 50 nm, the link half width is 500 nm, and the thickness of the overlying passivation is 400 nm.



Figure 3-34. Maximum principal stress vs. location where the point force (100 nN/nm) is applied.







Figure 3-36. Maximum principal stress vs. different link half width under the point force (100 nN/nm) at point B.

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Figure 3-37. Maximum principal stress vs. thickness of the overlying passivation with the point force (100 nN/nm) at point B.

Based on Figures 3-34 to 3-37, and the linear scalability of the mechanical stress, it is possible to make a rough estimation of the maximum stress under different loads for the link structure without going through detailed stress simulation again. This is particularly convenient for people who are interested in making such an estimation but with no access to a stress analysis software program. For instance, for every 0.05 micron in the width direction of the link, a point force representing the pressure by the molten link material over the area can be determined using Figure 3-30 and the temperature profile at the top of the link (which is derived from the thermal simulation). Assuming the corner radius is 0.05  $\mu$ m, link half width is 0.5  $\mu$ m, and the overlying passivation thickness is 6000 Å, then the maximum stress in the corner area caused by each individual point force can be determined based on Figure 3-34. The total maximum stress by all these forces is the sum of all these stresses. Then, based on figures 3-35, 3-36 and 3-37, maximum stress for a

different corner radius, link width, or overlying passivation thickness can be determined. Using this estimation method for the aluminum link structure and previously described laser parameters, it is determined that when the temperature at link's top center point is 1200 °C (see Figure 3-27), the maximum stress in the corner C area is about 20 (×10<sup>4</sup> atm.). As will be shown below, the computer simulated result of the maximum stress is 20.8 (×10<sup>4</sup> atm.) for the same case. The small difference between these two results proves that the estimation method is a meaningful tool for the purpose.

Figures 3-38 and 3-39 show the stress distribution pattern for the polysilicon link and aluminum link based on the non-uniform pressure load derived from the pre-rupture simulation (Figures 3-26, 3-27 and 3-30). The maximum value marked on the colored bar for each stress distribution pattern represents the maximum principal stress for each case. Figure 3-38 shows that when the highest temperature in the poly link reaches 3200 °C, the maximum stress in the passivation's corner area is  $12.0 (\times 10^4 \text{ atm.})$ , which is not adequate to rupture the SiO<sub>2</sub> yet. For the aluminum link, as shown in Figure 3-39, when the highest temperature in the link reaches only 1200 °C, the maximum stress reaches 20.8 (×104 atm.), which is greater than the adhesive strength of the  $SiO_2(19 \times 10^4 \text{ atm.})$ . An important conclusion can be drawn here is that, due to the contraction of polysilicon upon its melting, rupture of the overlying passivation will not occur until the temperature at the top center of the poly link reaches its evaporation point. This allows more poly link material to become molten before the rupture. In contrast, for the aluminum link, passivation rupture occurs when the temperature at the top center of the link reaches 1200 °C. This temperature is well below the aluminum evaporation point, so the molten aluminum link volume is significantly less compared to that for poly link.

Note that the displacements displayed in these stress distribution figures are exaggerated for better visibility. It is important to check the displacement for debugging purposes. Because with a given load on a known structure, the structure deformation can be judged using common knowledge. For instance, for the link structure discussed, with the pressure upward on the interface BC, the center part of the passivation will be forced upwards. If the displayed distortion of the structure is in contradiction with what is expected, then something might be wrong in the simulation.





Figure 3-39. Stress distribution under pressure by the molten aluminum link when the temperature at the link's top center is 1200 °C.

### 3.4.4 Rupture of the overlying passivation

Common dielectric passivation materials used for memory chips, such as silicon oxide (SiO<sub>2</sub>) and silicon nitride (SiN) are fragile materials. For a fragile material, when the tensile principal stress within it reaches its adhesive strength, rupture will occur. In fact, the rupture of the passivation starts from a small crack at the corner area where the stress is highly concentrated. The propagation or growth of the crack finally results in a complete rupture. During the growth of the crack, an additional space will be generated either as a result of the crack growth itself or partial lifting-up of the passivation layer. Thus the pressure by the molten link material can be released. However, whenever the crack gets started, it generates a very sharp notch or tip at the end of the crack, resulting in even more severe stress concentration. This concentrated stress at the crack tip area can be easily 100 times higher than the pressure load itself, causing an instant failure of the structure.<sup>48, 79</sup> Occasionally, in the case that there is a second passivation layer on top of the first overlying passivation, especially when that second layer is made of a stronger material than the first layer, then the growth of the crack might stop at the interface of these two layers, or the crack will grow along the interface between these two layers rather than upwards to open the whole passivation. This can result in failure of opening the passivation or an irregular opening in the passivation.

Of course, before the stress reaches the adhesive strength of the material (that is, before the crack starts to occur), distortion of the overlying passivation itself can yield an additional space for the molten link material, as well. For most real link structures, this distortion or displacement is very small in its magnitude, so its effect on both the pressure and the stress results can be neglected. For instance, for the aluminum link structure discussed, the maximum displacement at the rupture point is only  $2 \times 10^{-3}$  Å. If the link itself is very thin, melting of the tiny volume of the link material available might merely cause partial distortion of the overlying passivation which is adequate to release the pressure by the molten material, so no rupture will occur. The case of laser trimming of thin films with overlying passivation is a such example: the trimming can be performed without breaking the overlying passivation. In some cases, if the overlying passivation has poor adhesion to its underlying structure, the whole passivation layer might be pushed

upwards and apart from its underlying structure. The molten link material can expand into the gap between the overlying passivation and its underlying structure, so the pressure gets released. As a result, the overlying passivation has failed to be ruptured and so has the laser link processing.

## 3. 5 Effects of the rupture of the overlying passivation on link processing

In general, link material can be cut by a laser pulse through either being "blown away" in its liquid state or "evaporating away" in its vapor state, or both. Blowing away of link material in its liquid state eliminates the need of the huge amount of latent heat of evaporation, but imposes higher risks of forming slag and debris in the surrounding area. In fact, it is the existence of slag and debris after laser processing which serves as the evidence that "blowing away" of liquid material is one of the important mechanisms of material removal by the laser beams.<sup>80</sup>

The existence of the overlying passivation allows pressure to build within the molten link material until the passivation ruptures. All molten link material will be "violently" blown away by the high pressure along the rupture of the passivation, thus there is little risk of forming debris and slag in the cut area. Quantitative analysis of the effects of the overlying passivation on link processing will be discussed in this section.

# 3.5.1 Estimation of the heat and laser energy needed for cutting a link

Rough estimation of how much heat would be needed to remove a certain amount of link material, either by blowing it away in its liquid state or evaporating it away in its vapor state, will be helpful in understanding the physics behind the process. For this purpose, thermal properties of several materials are shown in Table 3-3,<sup>68</sup> where  $T_{melt}$  is the melting point,  $T_{vapor}$  is the evaporation point,  $\Delta H_s$  is the heat needed to heat the material per volume from 27 °C to its melting point,  $\Delta H_{sl}$  is the latent heat of fusion per volume,  $\Delta H_l$  is the heat needed to heat the material per volume from its melting point to its evaporation point,  $\Delta H_{lv}$  is the latent heat of evaporation per volume, and  $H_{total}$  is the total heat needed to heat the material per volume from 27 °C to its vapor phase.

	T <sub>melt</sub> (K)	T <sub>vapor</sub> (K)	_ΔH <sub>s</sub> (μJ /μm <sup>3</sup> )	$\Delta H_{sl}$ (µJ /µm <sup>3</sup> )	$\Delta H_{l}$ ( $\mu J / \mu m^{3}$ )	$\Delta H_{lv}$ ( $\mu J / \mu m^3$ )	H <sub>total</sub> (µJ /µm <sup>3</sup> )	$\Delta H_{lv}/H_{total}$ (%)
Al	933	2793	0.0015	0.00094	0.0046	0.025	0.032	77.96
Ti	1943	3562	0.0048	0.0017	0.0047	0.038	0.049	77.00
W	3680	5828	0.0099	0.0034	0.0075	0.075	0.096	78.27
Si	1685	3514	0.0033	0.0046	0.012	0.035	0.055	63.43

Table 3-3. Thermal properties of several materials.

It can be noticed from Table 3-3 that except tungsten, values of  $H_{total}$  for these materials are not that different from that of silicon. For all materials listed,  $\Delta H_{lv}/H_{total}$  varies from 63% for silicon to 78% for tungsten (which is also a widely used link material), indicating that the latent heat of evaporation is the largest part of the total heat needed to remove the material through evaporation. In other words, any removal of material without going through evaporation process can save a great amount of heat.

To translate the heat needed for the material removal into the laser energy needed, laser energy-heat conversion efficiency should be included. Define  $\eta_s$ ,  $\eta_l$  as the average laser energy coupling efficiency into solid and liquid link materials, respectively. These coupling efficiencies include factors such as the optical interference effects, laser beam overlap factor over the link, absorption coefficient of the material at the laser wavelength used. The total laser energy E needed to cut the link of volume  $\Delta V$  is determined by

$$E = (\Delta H_{s} + \Delta H_{sl}) \Delta V/\eta_{s} + \Delta H_{l} \Delta V/\eta_{l} + \Delta H_{lv} \Delta V_{v}/\eta_{l}, \qquad (3-24)$$

where  $\Delta V_v$  is the link volume removed through evaporation. For most materials,  $\eta_l$  is significantly larger than  $\eta_s$  due to the dramatic increase in the absorption coefficient after the material becomes liquid, so the "weight" of the latent heat of evaporation in determining the total amount of laser energy needed is reduced somewhat, based on the Equation 3-24.

Assuming the laser spot size is 5  $\mu$ m, the link is 1  $\mu$ m wide and 0.5  $\mu$ m thick, the cut opening is 2  $\mu$ m long, then the removed link material volume is 1  $\mu$ m<sup>3</sup>. According to

Equation 3-24, the total laser energy needed to cut an aluminum link is estimated to be 0.5  $\mu$ J, assuming  $\Delta V_v / \Delta V = 0.5$ . From the estimation, it is easy to realize that for processing a given link made of a given material, improving the laser energy coupling efficiency (by either optimizing the optical interference effects or maximizing the overlapping factor of the laser beam spot over the link) and maximizing the link material volume removed in its liquid phase (or in other words, minimizing  $\Delta V_v$ ) are of critical importance in reducing the total laser energy needed for the process (reducing the lower end of the processing window).

### 3.5.2 Effects of the rupture of the overlying passivation on link processing

It is assumed that the rupture of the overlying passivation takes almost no time. As soon as the maximum tensile principal stress within the passivation reaches the adhesive strength of the material, the passivation ruptures instantly. It is also assumed that along with the rupture of the overlying passivation, all molten link material will be blown away. Before the rupture, there is an enormously high non-equilibrium pressure within the molten link volume (the pressure is a function of the molten link material's temperature, thus a function of position within the link). With the rupture of passivation, a sudden release of the pressure causes explosive removal of the molten material at high speed, and in the form of tiny particles. This reduces the risk of forming debris or slag in the cut area. Since the blowing away of the molten link material eliminates the need of the latent heat of evaporation, the total laser energy needed for the link process, in the presence of an overlying passivation, is reduced. However, the amount of laser energy required for the link to reach a certain temperature before the rupture is increased due to the existence of the overlying passivation which is acting as a heat sink to the link. All these effects can be accurately simulated using the simulation program developed.

Based on pre-rupture temperature simulation and the rupture point derived from the stress analysis, remaining link structure after the rupture for the polysilicon link or the aluminum link can be determined, as shown in Figures 3-40 and 3-41. For the poly link, 48% of the link volume is gone upon rupture, compared with only 14% for the aluminum link.

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Temperature (°C)

Figure 3-40. Remaining polysilicon link structure just after rupture of the passivation.



Temperature (°C)

Figure 3-41. Remaining aluminum link structure just after rupture of the passivation.

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Figures 3-42 and 3-43 show the simulation results (including the post-rupture process simulation which will be discussed in Paragraph 3.6) of the total laser energy needed to fully cut the poly and aluminum links under different assumed rupture temperatures of the overlying passivation. The rupture temperature is defined as the temperature at the top center point of the link when the passivation ruptures. As has been discussed, the rupture temperature depends on the thickness of the overlying passivation and the passivation material for a given link.

For the sake of comparison, also shown in those two figures are the laser energies needed to fully cut the links if there was no overlying passivation. In the simulation, this is dealt with as if the passivation was ruptured at the temperature of 0 °C, which is below the simulation starting temperature of 20 °C so to the simulation it is equivalent to that there is no passivation. The results are the data points marked with the character "A".

Data points marked with the character "B" represent the laser energies needed to fully cut the links if there was overlying passivation, but the passivation acted only as the heat sink over the links, its rupture did not result in blowing off molten link materials. For the poly link, data point B is simulated for the rupture temperature of 3200 °C, while for the aluminum link it is simulated for the rupture temperature of 2100 °C. This simulation helps to determine the laser energy loss due to the heat loss to the passivation before its rupture: the heat loss to the passivation is equal to the laser energy difference between the data points "B" and "A". For instance, for the poly link, assuming the rupture point is 3200 °C, the laser energy loss due to the heat loss to the passivation is 0.02 µJ.

Note that the results shown in Figures 3-42 and 3-43 are the total laser energies needed to fully cut the links, including the laser energies needed for the post-rupture process, which will be discussed later. So these results represent the full effects of the overlying passivation on the link processing. The optical interference effects from the passivation are not included in these results to avoid mixing up of these different effects in the analysis. The laser energy coupling efficiencies were assumed as the same (determined by the refractive indexes of the link materials), no matter if there is passivation or not.

The results prove that the rupture of the overlying passivation helps save a significant amount of laser energy needed to process the links, especially for the poly links.

Assuming the rupture temperature of 3200 °C for the poly link, the laser energy saving is  $0.08 \ \mu$ J, or 15%. This energy saving is non-trivial, but not as big as expected before the detailed simulation was done. There are three reasons for that. First, the existence of the overlying passivation as a heat sink causes heat loss into the passivation. Second, the laser energy's coupling efficiency is getting much higher after the link material becomes molten, so the weight of the latent heat of evaporation in governing the total laser energy needed is reduced somewhat. Third, removal of highly absorbing liquid link material has an adverse effect on the laser energy coupling into the remaining link material.

Note that the energy savings directly depend on the rupture point of the passivation. For the aluminum link, when the rupture temperature is 1200 °C, the laser energy saving is negligible. As will be seen later, 1200 °C is the real rupture point for the process of the aluminum link structure, thus partially explaining why the aluminum link is more difficult for the laser pulse to process.



Figure 3-42. Laser energy needed to fully cut the polysilicon link vs. different rupture temperatures. (A: No overlying passivation. B: If the passivation rupture did not result in blowing the link material.)


Figure 3-43. Laser energy needed to fully cut an aluminum link vs. different rupture temperatures. (A: No overlying passivation. B: If the passivation rupture did not result in blowing the link material.)

In the two dimensional simulation discussed above, the most difficult part of the link to cut is the farthest right part next to the side passivation. This part of the link sees less laser energy than the center part does and suffers from higher heat loss to the passivation. For poly links, less heat will be conducted from its hot center area to the right edge due to poly's poor thermal conduction. In the finite element simulation, only one or two nodes in the farthest right node column would have reached the melting point before the rupture of the passivation. After the molten link material in the central part is gone along with the rupture of the passivation, this edge of the link receives even less heat conducted from its hot central neighbors. Those two factors make the right edge of the link the least removed by the rupture of the passivation. However, it is reasonable to expect that in the real world, due to the associated shock wave, the violent removal of the central part of the link, the contraction of polysilicon link material upon melting, and the surface tension effect of the molten material, this furthest right part of the link material will be knocked or pulled into the central opening area after it becomes molten, so the whole process should become more efficient. Thus the simulation results shown in Figures 3-42 and 3-43 should be considered as conservative estimations. To further demonstrate this perception, Figure 3-44 shows an one dimensional simulation result for the polysilicon link. Since only the structure on the Z axis (see Figure 3-17) is considered, the incident laser intensity is the one at the center of the beam spot, and it is assumed that there is not any lateral heat conduction, the needed laser energy derived from the one dimensional simulation would be noticeably less than the real laser energy needed to process the link. It is expected that the more realistic number should be somewhere between these two results.



Figure 3-44. Laser energy needed to cut a polysilicon link vs. different rupture temperatures, based on the one dimensional simulation. ("A": No overlying passivation. "B": The passivation rupture did not result in blowing the link material.)

## 3.6 Post rupture process analysis

Upon the rupture of the overlying passivation, the link removal process is far from being completed. The simulation has to go on with the remaining laser pulse and link material until the whole laser pulse is completed. The starting temperature condition for this post-rupture analysis is the temperature distribution at the rupture point derived by the pre-rupture temperature simulation. The remaining structure is the original link structure minus the overlying passivation and the molten link material at the rupture point which are presumably gone along with the rupture, as shown in Figures 3-40 and 3-41.

The post-rupture analysis of the removal of the remaining link material consists of analysis of the optical interference effects from the remaining link and underlying passivation layer(s), and removal of the link material by laser heating-evaporation without the overlying passivation.

Based on the simulations which have been discussed previously plus the postrupture process simulation, both the laser energy threshold of the process (or the lower end of the processing window), and the laser damage threshold of the process (or the high end of the processing window) can be determined. If the simulation result shows that there is residual link material left on the completion of the laser pulse, then the laser energy per pulse used in the simulation is not adequate. A higher pulse laser energy should be tried for another simulation run, until the minimum laser energy needed to fully cut the link is found. This laser energy is the energy threshold of the process, or the lower end of the processing window. If the silicon substrate gets damaged by the end of the laser pulse, then the laser energy per pulse used is not acceptable for the process. A lower laser energy per pulse needs to be tried again for another simulation run until the maximum laser energy at which the damage will not occur is found. This laser energy is the laser damage threshold of the process, or the high end of the processing window.

In this section, only the removal of the link material will be discussed. The damage issue of the silicon substrate will be discussed in Chapter 4.

As has been mentioned before, the removal of the link material can be either in its liquid form or vapor form, or both. It is reasonable to expect that higher laser intensity will result in earlier evaporation and higher evaporation rate of the link material, thus higher evaporation recoil force. This in turn reduces the accumulated amount of the liquid link material available for splashing, which is helpful in reducing the risk of forming slag and debris in the link cut area.

Detailed discussion of the dynamic behaviors of link material's removal under exposure to a laser pulse, such as the percentages of link material evaporated and splashed, the evaporation recoil force exerted on the remaining link material, the splashing pattern of the liquid link material by the recoil force, the dropping back of these blown away liquid link materials, and the formation of the slag and debris is beyond the scope of this work. Other mechanisms of material removal by a laser pulse, such as boiling and surface tension are not considered to be important factors in the link processing. Boiling of material due to laser heating will result in violent blowing away of the material. It requires a certain period of time to allow the formation of the nucleation for the boiling to occur.<sup>68</sup> Thus for laser pulse width of only a few or a few tens of nanoseconds for link processing, boiling is not likely a vital mechanism of material removal. The mechanism that the molten links are being pulled apart by the surface tension of the molten material is not the likely contributor for the link cut either, because from experience, hardly any resolidated balls at the opened link ends can be observed.

## 3.6.1 Effect of laser pulse width on link processing

For post-rupture process, the removal of the link material in its liquid state will be mainly governed by factors such as the evaporation recoil force or recoil pressure, the surface tension and viscosity of the molten link material, the dimensions of the molten link material and opening of the overlying passivation, etc.<sup>68, 80, 81</sup> For a given link structure, the most important variable is believed to be the evaporation recoil pressure, which is closely related to the evaporation rate of the material, or the laser pulse intensity used. For too low a laser pulse intensity, or too long a laser pulse width with a given pulse energy, the evaporation rate of the link material will be too low to generate an adequate recoil pressure for an effective "splashing" of the liquid material. With a reduced laser pulse width, thus higher intensity, the link material evaporation rate increases, as does the evaporation recoil pressure on the molten link material. When the evaporation recoil

pressure has just reached the threshold of splashing the liquid material, the splashing will not be a violent one. At the same time, the accumulated volume of the molten material is relatively large, due to the fact that the thermal conduction time available is relatively long, the evaporation rate of the material is relatively slow and there was no previous liquid splashing. Most molten material is at temperatures well below its evaporation point. All these factors contribute to a higher probability of splashing molten link material in form of large droplets at lower temperatures and speeds, thus higher risks of forming slag and debris in the cut area. The percentage of material removed in its liquid state (splashed) can be as high as 90%, due to the large accumulation of the molten material before the splashing.<sup>68</sup> For a shorter laser pulse, the evaporation rate becomes higher. The depth of the molten link material volume will not be much larger than the material's optical absorption depth since the molten material will not be able to accumulate. For most metals, the optical absorption depths are in the range of a few tens of nano-meters. Thus, it is likely that the molten link material will be blown away in the form of small particles, at higher temperatures and speeds, lessening the risk of forming debris and slag in the area. It is also likely that a higher percentage of link material will be removed through evaporation, a lower percentage of material will be splashed in its liquid state.

From this qualitative reasoning, it is expected that a shorter laser pulse cuts the link cleaner than a longer pulse does. Also, a laser pulse with an amount of energy which has enough margin over the processing threshold cuts the link better, because the process will be completed before the laser pulse intensity falls to too low a value.

#### 3.6.2 Post-rupture process simulation

For the post-rupture simulation, it is assumed that for the short laser pulse width used, 50% of the remaining link material will be removed by direct evaporation, while another 50% will be removed by "splashing" in its liquid state at the temperature just below its evaporation point. This assumption can be easily implemented in the simulation using a latent heat of evaporation equal to 50% of its real value. The results are shown in Figures 3-45, 3-46. Since the post rupture simulation is done based on other simulations previously discussed, factors such as the optical interference effects, the rupture of the

overlying passivation, the link structure change upon the rupture of the passivation, etc. have all been included in the results. The laser pulse used for the post rupture simulation is the continuation of the pulse used for the pre-rupture analysis. Figure 3-45 indicates that the laser energy of 0.5  $\mu$ J is not enough to fully cut the aluminum link, since there is residual link material remaining in the right low corner upon the completion of the laser pulse. Figure 3-46 indicates that the laser energy per pulse of 0.75  $\mu$ J is just adequate to fully cut the aluminum link. There is no residual link material left upon the completion of the laser pulse.



Figure 3-45. The aluminum link processed by a laser pulse with energy of 0.5  $\mu$ J, showing an incomplete cut.



Temperature (°C)

Figure 3-46. The aluminum link processed by a laser pulse with energy of 0.75  $\mu$ J, showing a complete cut.

Table 3-4 shows the simulation results of the laser energy needed to process the polysilicon and aluminum links under different circumstances. For the sake of comparison, the laser energy per pulse used in the simulation is 0.75  $\mu$ J for the poly link, and 1.0  $\mu$ J for the aluminum link in the simulation, so the timings of the passivation rupture and link cut completion are similar for both links. Other laser parameters used are unchanged: laser pulse width of 5 ns, laser spot size of 5  $\mu$ m. The overlying passivation rupture temperature is 3200 °C for polysilicon link, 1200 °C for aluminum link based on the simulation results.

	The polysilicon link	The aluminum link
No passivation, no liquid splashing.	0.593	0.778
No passivation, 50% liquid splashing.	0.392	0.493
With passivation (excluding the interference effects), (1) No liquid splashing. (2) 50% liquid splashing.	0.518 0.354	0.799 0.491

Table 3-4. Laser energy needed to fully cut the links (in  $\mu$ J).

#### 3.7 Summary

Improved physical modeling and computer simulation, aiming at meeting the new challenges of processing metal links by lasers have been developed. The simulation consists of simulating five major factors important to the process, the optical interference effects, the pre-rupture temperature distribution within the link structure, the mechanical stress distribution within the passivation, the effects of the passivation's rupture on the process, and the post-rupture process.

Close dependence of each critical physical step of the laser link processing on important link structural data and laser parameters used have been revealed by these simulations. These steps include the heating of the link structure by the laser pulse and the resulting temperature distribution within the link structure, the stress build up within the passivation caused by the molten link material, the rupture behavior of the passivation, the link material removal with the rupture of the passivation and after the rupture of the passivation, etc. Both link structure and laser parameters can be optimized based on the knowledge gained.

The important rolls of the overlying passivation on link processing are better understood. The passivation can be either an AR coating or HR coating or somewhere between the two over the link to strongly affect the laser energy coupling into the link during different stages of the process. Its existence allows a pressure to build by the molten link material, so when the passivation ruptures, all the molten link material can be cleanly blown away without going through the evaporation process, reducing the amount of laser energy needed for the processing. Optimization of the overlying passivation based on the above understanding can help reducing the lower end of the processing window without adversely affecting the high end of the window.

The mechanical stress analysis reveals the dependence of the rupture of the overlying passivation on critical link structural data, such as the link width and thickness of the passivation. Considering that for newer generation memory devices, the link widths are getting narrower, the link structure multi-layer stacks are becoming more complex with wider thickness variations of the passivation layers, this knowledge becomes critical for ensuring the success of the process.

Besides the large optical absorption depth of the polysilicon link material, the significant effects of its contraction upon melting on the link processing also has been included in the simulation. It is believed that these two factors are responsible for the "easiness" of its processing by a laser pulse, compared to metal links.

Post-rupture process analysis is also a critical part in understanding the laser link processing. In order to remove as much link material as possible in its liquid state to reduce the laser energy needed for the process without increasing the risk of forming debris and slag, a shorter laser pulse width or higher laser intensity is preferred.

# CHAPTER 4

# LINK PROCESSING BY LONGER LASER WAVELENGTHS

## 4.1 Introduction

The optical interference effects from a multi-layer link structure, the temperature distribution within the link structure versus laser energy and pulse width, the effects of the overlying passivation's rupture on link processing, and the post-rupture process have all been discussed in detail. Optimizations of these effects are all effective in reducing the laser energies needed to process the links, that is, in reducing the lower end of laser processing window. Unfortunately, for many metal link structures, efforts at optimization fail to deliver a satisfactory overall range of the window, since the high end of the window is too close to the lower end of the window. Thus, finding ways to increase the high end of the processing window (the damage threshold of the silicon substrate) becomes a critical challenge for further improving the laser link processing.

In fact, there are several common damage phenomena in laser link processing, such as damage to the passivation, damage to adjacent links, and damage to the silicon substrate. Usually, the damage to the silicon substrate and adjacent links are the most intolerable ones. If there is any visible sign of melting, a crater, a micro-crack or cavity within the silicon substrate after the process, damage to the silicon substrate is considered to have occurred.<sup>82</sup>

The effects of laser pulse width on the damage risk have been discussed by the prior analyses along with some experimental results. A shorter green laser wavelength of 0.532  $\mu$ m has also been tried for the link processing.<sup>14</sup> Despite the better optical coupling efficiency into the metal links of the green laser energy, the overall processing results by the 0.532  $\mu$ m laser beam is not any better than that by 1  $\mu$ m for both poly and metal links. Smaller absorption depths of link materials at the 0.532  $\mu$ m were blamed for the poor results based on the criterion of temperature distribution uniformity within the link.

As far as the high end of the processing window is concerned, the temperature uniformity within the link does not have a noticeable effect on it. Rather, the damage threshold of the silicon substrate is mainly determined by its absorption behavior with the laser parameters used. By having a careful look at the light absorption curve of silicon versus wavelength, one may notice the dramatic reduction near the wavelength of  $1.2 \,\mu\text{m}$ . Silicon becomes dramatically less absorbent at wavelengths longer than  $1.2 \,\mu\text{m}$ . In contrast, the absorptive behaviors of most metals do not change much within the wavelength range from 1 to  $2 \,\mu\text{m}$ . The combination of these two facts strongly suggests that by using laser wavelengths longer than  $1.2 \,\mu\text{m}$ , the behavior of the metal link cut itself will not change much (the lower end of the processing window will not change much), but the damage threshold of the silicon substrate will be much higher than that at  $1 \,\mu\text{m}$ , or the high end of the processing window will be increased considerably.

Considering the availability of diode pumped solid-state laser sources, Nd:YAG and Nd:YLF lasers with their output wavelengths around  $1.32 \ \mu m^{83}$  are good choices for the purpose. Although the lasing gain of those materials at  $1.32 \ \mu m$  are lower than that at  $1.064 \ \mu m$  or  $1.047 \ \mu m$ , the laser pulse widths available at  $1.32 \ \mu m$  are longer than that at  $1.064 \ \mu m$  or  $1.047 \ \mu m$ , with the advance of the technology using higher pumping intensity and new lasing materials such as Nd:YVO<sub>4</sub>, 8 to 10 ns pulse widths at  $1.32 \ \mu m$  will be soon available.<sup>84, 85</sup>

The link processing experiments using  $1.32 \ \mu m$  laser have proved the expected advantages of using longer laser wavelengths for the purpose. Much wider processing windows have been realized for many kinds of metal link structures. With higher laser pulse energies at  $1.32 \ \mu m$  becoming acceptable to the process, higher open resistance of the link cuts has also been demonstrated.<sup>19</sup>

In this chapter, the damage issues relating to the silicon substrate and the advantages of using longer laser wavelengths for link processing will be analyzed, and experimental results will be presented.

#### 4.2 Light absorption by silicon

Under exposure of a laser beam, surface melting of the silicon substrate usually occurs before visible formation of crater or cavity, since the latter involves material removal or small scale explosion which require higher laser energies.

Melting of silicon wafer's surface, either with or without the overlying passivation, under exposure to a laser pulse of nanoseconds pulse width at several different laser wavelengths, such as  $0.532 \mu m$ ,  $0.6943 \mu m$ ,  $1.064 \mu m$  and  $10.6 \mu m$  has been thoroughly investigated as a key issue for semiconductor materials laser annealing.<sup>58-61, 86, 87</sup> For determining the damage threshold of the silicon substrate in our simulation, the damage is defined as that at least one finite node within the silicon substrate has completed its phase transition from solid to liquid. Melting of merely one node might not be visible in the real process. But as will be discussed later, silicon melting significantly increases its optical absorption, thus the difference between the threshold of the visible damage and the threshold of one node's melting is very minimal.

#### 4.2.1 Light absorption of silicon versus wavelengths and doping levels

The light absorption behavior of semiconductor materials is very closely related to their energy band structures. In fact, it have been widely investigated and documented as important ways of studying the energy band structures of semiconductor materials.<sup>88-94</sup>

Electromagnetic radiation with wavelengths ranging from UV to IR interacts exclusively with electrons, since nuclei are too heavy to respond significantly to the light wave frequencies of the electromagnetic field. Moreover, the photon energies of interest are too small to affect core electrons. Therefore, the optical properties of matter are largely determined by the energy states of its valence electrons (bound or free). Unless the photon energy is greater than the bounding energy of the valence electrons, they respond only weakly to the electromagnetic wave and mainly affect its phase velocity. Free electrons are able to be accelerated, that is to extract energy from the field. When they undergo frequent collisions with atoms, the energy is transmitted to the lattice and the external field is weakened. The behavior of valence electrons in semiconductor materials is described by their characteristic energy band structure. For the energy band structure, one critical parameter is its energy gap between the conductive band and valence band.

For light wavelengths with photon energies greater than the energy band gap of the semiconductor material, light absorption by the semiconductor is strong and dominated by the direct excitation of electron-hole carriers. For longer light wave-lengths corresponding to photon energies smaller than the energy band gap, the absorption behavior is significantly affected by the absorption by free carriers and the band gap narrowing when the temperature of the material increases.<sup>56</sup> Figure 4-1 shows the optical absorption coefficient versus photon energy for Si, Ge and GaAs.<sup>88</sup>



Figure 4-1. Absorption coefficient vs. photon energy for Si, Ge and GaAs. (After Dash et al., ref. 88.)

For silicon, the absorption coefficient decreases dramatically around a photon energy range of 1.17 eV. which is its indirect energy band gap. For link processing, the strong absorption of light with photon energies greater than 1.17 eV. by silicon, such as in the visible or UV spectrum, means the damage threshold of the silicon substrate is low, thus it is not practical to use the laser wavelengths in the visible and UV spectrum for the application.

For light wavelengths with photon energies between the direct energy band gap and the smallest indirect energy band gap of the silicon, Macfarlane et al. found that the light absorption was due primarily to phonon-assisted indirect transitions from the  $\Gamma^{v}_{25}$ , point in the valence band to a point along the  $\Delta$  branch in the conduction band.<sup>94</sup> Several phonons have been found to participate in this absorption process, but those primarily involved are the transverse and longitudinal acoustical phonons with k vectors in the <100> direction. The expression for the absorption coefficient is

$$\alpha(h\nu, T) = \sum_{i=1}^{2} \sum_{l=1}^{2} (-1)^{l} \times \frac{\alpha_{i} [h\nu - E_{g}(T) + (-1)^{l} k\theta_{i}]}{(\exp[(-1)^{l} \theta_{i} / T] - 1)} , \qquad (4-1)$$

where the contribution arising from the interaction with the transverse acoustical phonon (i=1) is given by

$$\alpha_1(E) = 0.504\sqrt{E} + 392(E - 0.0055)^2,$$
  

$$\theta_1 = 212K,$$
(4-2)

and the contribution arising from the interaction with the longitudinal acoustical phonon (i=2) is given by

$$\alpha_2(E) = 18.08\sqrt{E} + 5760(E - 0.0055)^2,$$
  

$$\theta_2 = 670K,$$
(4-3)

where  $\theta_1, \theta_2$  are the respective phonon energies in degrees Kelvin,  $E_g(T)$  is the energy band gap.

For light wavelengths with photon energies smaller than the indirect band gap, direct excitation of electron-hole carriers becomes impossible, except for multi-photon process which is a high order process with very low probability of occurrence. Thus the major contribution to light absorption is free carrier absorption. Free carrier absorption is directly proportional to the concentration of free carriers and the free carrier absorption cross section, thus it can be written as

$$\alpha_{FC} = \sigma \times n_i , \qquad (4-4)$$

where  $n_i$  is the free carrier concentration and  $\sigma$  is the free carrier absorption cross-section. The concentration of free carriers  $n_i$  is mainly determined by the doping level and the temperature of semiconductor material. In general, the free carrier absorption cross-section  $\sigma$  increases with longer wavelengths<sup>95</sup>

$$\sigma \propto \lambda^n$$
, (4-5)

where n is usually a value between 2 to 3.5, depending on the doping level and wavelength. The value of  $\sigma$  at 1.064 µm has been measured by Svantesson et al.,<sup>96</sup> thus the value of  $\sigma$  at 1.32 µm can be calculated based on the Equation 4-5. Assuming n=2, for silicon with a doping level of 10<sup>17</sup> cm<sup>-3</sup>, at room temperature and 1.32 µm, the free carrier absorption is 0.69 cm<sup>-1</sup> from this calculation.

## 4.2.2 Regenerative behavior of absorption in silicon

Absorption in silicon increases dramatically with the increase of its temperature, resulting in a more dramatic temperature increase. This is often referred to as "thermal run-away" or regenerative behavior of absorption. Two major factors are responsible for the increase of the absorption with temperature. First, the energy band gap of silicon shrinks when the temperature increases. The temperature dependence of the energy band gap is given by <sup>97</sup>

$$E_g(T) = E_g^{0} - AT^2 / (\beta + T), \qquad (4-6)$$

where T is the temperature in K,  $E_g^{0}$  is the energy band gap at temperature of 0 °K, which is 1.17 eV., or 1.155 eV after subtracting out the exciton energy of 15 meV,  $E_g$  is the energy band gap at temperature T, A= 4.73 x 10<sup>-4</sup> eV/K, and  $\beta$ = 635 K. It can be seen from this formula that when the temperature of the silicon reaches 579 °C, its energy band gap becomes comparable to the photon energy at 1.32 µm (0.94 eV.). Second, the free carrier concentration will increase with the temperature increase due to the fact that the intrinsic carrier concentration increases with the temperature as<sup>98</sup>

$$n_i \propto \exp(-E_g / 2kT), \tag{4-7}$$

where  $E_g$  is the energy band gap, T is the temperature. For instance, for silicon, at a temperature of 500 °C, the intrinsic carrier concentration increases to about  $1 \times 10^{17}$  cm<sup>-3</sup>. This means for a silicon wafer with doping level of  $1 \times 10^{17}$  cm<sup>-3</sup>, the total free carrier's concentration doubles at a temperature of 500 °C.

At its melting point, silicon is very much the same as most metals from the point of view of its conductivity as well as optical absorption. For our purpose, it is assumed that the absorption coefficient of silicon will converge to the same value for both 1.047 and  $1.32 \mu m$  when the temperature reaches its melting point.

Thus, the absorption of silicon at 1.32  $\mu$ m, at room temperature, starts at a much smaller value, then increases at a faster pace with the temperature of silicon than that at 1  $\mu$ m. This implies that the regenerative behavior of absorption in silicon at 1.32  $\mu$ m is much larger than that at 1  $\mu$ m.

There are not much experimental data available about the light absorption of silicon with different doping levels and at different elevated temperatures within the wavelength range from 1.2 to 1.5  $\mu$ m or so, except Jellison's measurement of the optical absorption coefficient of pure silicon at 1.152  $\mu$ m for the temperatures up to 1000 °C,<sup>99</sup> and T. Sato's work on the refractive index of Silicon at 1.56  $\mu$ m.<sup>100</sup> Based on the discussions we have had so far, for silicon with a doping level of 1×10<sup>17</sup> cm<sup>-3</sup>, its absorption coefficient versus temperature at 1.32  $\mu$ m is estimated and presented by the dotted line in Figure 4-2. This curve will be used in the simulation to determine the damage threshold of silicon at 1.32  $\mu$ m. Also shown in the Figure 4-2 are the absorption curves of silicon (both pure and doped to 2×10<sup>20</sup> cm<sup>-1</sup>) versus temperature at 1.047  $\mu$ m for comparison.



Temperature ( °C)

——— Silicon absorption coefficient at 1.047 μm.
 Silicon absorption coefficient at 1.32 μm.

Figure 4-2. Light absorption coefficient of silicon at different wavelengths and temperatures.

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## 4.3 Light absorption by metals

Conductive metals are characterized by their small absorption lengths (in the order of 10 nm) over the whole optical spectrum due to the larger density of free electrons available. There is a critical wavelength  $\lambda_{cr} = c/v_p$  for each metal, around which the light absorption behavior changes significantly, where c is the velocity of light,  $v_p$  is the plasma frequency of the free-electron plasma, determined by <sup>54</sup>

$$\nu_{p} = \left(\frac{1}{2\pi}\right) \sqrt{\frac{Ne^{2}}{m_{e}\varepsilon_{0}}} \quad , \tag{4-8}$$

where N and  $m_e$  are the effective density and mass of the free electrons respectively, and

$$\varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m.}$$
 (4-9)

For example,  $\lambda_{cr}$  for aluminum is below 100 nm. For light wavelengths below this critical  $\lambda_{cr}$ , metal's reflectivity drops sharply. For light wavelengths longer than  $\lambda_{cr}$ , the reflectivity of metals tends to remain as a constant.

If the period of the light wave is long compared to the average time between two collisions of an electron with the lattice (practically, for light wavelengths longer than 10  $\mu$ m), the reflectivity R of the metal can be expressed by the classical Hagen-Rubens formula <sup>54</sup>

$$R = 1 - 2\sqrt{\frac{\nu}{\sigma}} \quad , \tag{4-10}$$

where  $\sigma$  is the conductivity of the metal and v is the frequency of the light wave. The appearance of the conductivity in the expression for an optical constant reflects the fact that the absorption of light in a metal is caused by the same collisions that produce the electrical resistance of the metal. Although formula 4-10 is generally good for wavelengths longer than 10 µm, the conclusion that the optical absorption of metals are related to their conductivity is valid for the wavelengths longer than  $\lambda_{cr}$ , such as 1 µm. Since the conductivity of a metal is a function of temperature, its optical absorption is also a function of temperature. The higher the temperature, the smaller the conductivity, thus the higher the optical absorption. Figure 4-3 shows the absorption versus wavelengths for several different metals.<sup>101</sup> As can been seen from the figure, the absorption of metals do not change much within the wavelength range from 1 to  $1.5 \mu m$ .



Wavelength (µm)

Figure 4-3. Absorption versus wavelength for several different metals. (After M. J. Weber, ref. 101.)

# 4.4 The high end of laser link processing window

The high end of the laser processing window is determined by damage to the devices during the processing. The most frequent occurrences are damage to the silicon substrate and damage to the adjacent links and other circuit features. This section will discuss the factors which affect the high end of the laser link processing window.

# 4.4.1 Damage to the silicon substrate during laser link processing

For the laser link processing, the surface melting of the silicon substrate under exposure to a laser pulse is similar to the cases studied for laser annealing, except that for link processing, there are laser energy absorbing links which are shielding the silicon substrate from being directly exposed to the most intense center part of the laser beam until the links are removed. Only the edge part of the laser beam can directly hit the silicon substrate without being blocked by the links. Thus, the damage threshold of the silicon substrate depends not only on the silicon substrate's doping level, but also the link structure parameters such as the link material, its dimensions, and the optical interference effects. The software program developed for the pre-rupture and post-rupture temperature simulation has been modified to extend its capability to cover the simulation of the silicon substrate's damage threshold during the laser process. The software code is attached with this thesis as the Appendix.

For determining the damage threshold of the silicon substrate, the information of the doping level within the substrate in the area just underneath the link bank has to be known. For most memory devices, there is a thin layer of epitaxialy grown, heavily doped silicon layer (epi layer) on top of the lightly doped substrate. <sup>97</sup> This epi layer imposes the highest damage risk under exposure to a laser pulse. Or in other words, it has the lowest damage threshold. Information about the epi layer's thickness, the kind of dopant and the doping level is considered as proprietary by memory device manufacturers. So far, this information has not been available for our analysis. This is one of the major reasons why only the assumed absorption curve of silicon with doping level of  $1 \times 10^{17}$  at 1.32 µm, as shown in Figure 4-1, is used in the analysis.

Figures 4-4 and 4-5 show the temperature distribution within the polysilicon link structure at the point when damage to silicon substrate occurs, using a laser pulse of 1.047 and 1.32  $\mu$ m, respectively. Figure 4-6 shows the temperature distribution within the aluminum link structure when damage to silicon substrate occurs, using a laser pulse of 1.047  $\mu$ m. Temperature distribution within the aluminum link structure using a laser pulse of 1.047  $\mu$ m. Temperature distribution within the aluminum link structure using a laser pulse of 1.32  $\mu$ m is not shown due to the similarity to that using 1.047  $\mu$ m. Laser parameters used for the simulation are as follows: the laser pulse width is 5 ns, the laser pulse energy

at 1.047  $\mu$ m is 1  $\mu$ J, the laser pulse energy at 1.32  $\mu$ m is 2  $\mu$ J, and the laser beam spot diameter is 5  $\mu$ m. In these Figures, the links were in the area of depth from 2500 Å to 7500 Å, half width from 0 to 0.5  $\mu$ m. Temperature of 0 °C in the link area means the link material has been removed. Below a depth of 17500 Å is the silicon substrate.



Figure 4-4. Temperature distribution within the polysilicon link structure when damage to the silicon substrate occurs, using a 1.047 µm wavelength laser pulse.



Figure 4-5. Temperature distribution within the polysilicon link structure when damage to the silicon substrate occurs, using a  $1.32 \mu m$  wavelength laser pulse.



Figure 4-6. Temperature distribution within the aluminum link structure when damage to the silicon substrate occurs, using a 1.047  $\mu$ m wavelength laser pulse.

As has been mentioned, the damage to the substrate is judged by the condition that at least one node of the substrate has completed the phase transition from solid to liquid. Note that for both polysilicon and metal links, the damage in the silicon substrate first occurs in the edge area, where the laser beam can hit directly. The temperature peak in the passivation area just next to where the link was is the result of the heat conduction from the heated link to the passivation before the link is removed.

Table 4-1 summarizes the simulation results of the damage thresholds of the silicon substrate for different links and at different laser wavelengths.

Table 4-1. Damage thresholds of the silicon substrate for different links and at different laser wavelengths.

	Damage threshold of the silicon substrate ( $\mu$ J)				
Laser wavelength	Poly link	Aluminum link	No link		
1.047 µm	0.622	0.643	0.468		
1.32 μm	1.301	1.330	0.961		

With the 1.32  $\mu$ m laser beam, the damage threshold of the silicon substrate doubles over that with 1.047  $\mu$ m. Note also that the damage threshold without link is significantly lower than that with link.

The effect of laser beam alignment accuracy over the link on the damage to the silicon substrate can also be simulated using the same software program developed. In fact, this would be the simulation of the vernier test run for the link structure. The results for the polysilicon links are shown in Table 4-2. The simulation is done under the assumption that the link width is 1  $\mu$ m, the laser wavelength used is 1.047  $\mu$ m, the laser beam spot diameter is 5  $\mu$ m, and the laser pulse width is 5 ns. It can be seen that when the laser beam is accurately aligned over the link, the damage threshold is the highest (the same value as shown in Table 4-1 for the case with the link). When the beam alignment offset increases, the damage threshold decreases. The worst case is when the laser beam

is totally off the link, the damage threshold of the substrate drops to the value shown in the Table 4-1 for the case when there is no link at all. The simulation results for the 1.32  $\mu$ m laser processing is not shown here, but as long as the 1.32  $\mu$ m laser pulse energy used is less than the damage threshold of the case when there is no link (0.961  $\mu$ J, as shown in Table 4-1), a vernier test run will show no damage to the substrate, no matter what the laser beam offset over the link is.

	Offset (µm)							
	0	0.1	0.2	0.3	0.4	0.5	0.6	No link
Damage	0.622	0 591	0.565	0.544	0.526	0.511	0.499	0.468
threshold	0.022	0.571	0.505	0.544	0.520	0.511	0.477	0.400

Table 4-2. Damage thresholds ( $\mu$ J) of the silicon substrate at 1.047  $\mu$ m with different offset of the laser beam center over the link.

Note that while the absorption coefficient of the silicon substrate at room temperature used in the simulation for 1.32  $\mu$ m is about 2 to 3 orders of magnitude smaller than that for 1.047  $\mu$ m, the laser energy damage threshold of the silicon substrate at 1.32  $\mu$ m is only two times higher than that at 1.047  $\mu$ m. This is the result of the more severe "thermal run-away" behavior of the silicon at 1.32  $\mu$ m. In other words, when the temperature of the silicon substrate increases, the advantage of using the longer laser wavelengths in realizing the higher damage threshold is reduced. Thus, to fully utilize the advantage of the 1.32  $\mu$ m laser processing, anything which can adversely affect the temperature of the silicon substrate should be carefully avoided, except the inevitable direct laser heating. For instance, the original temperature of the wafer should be kept as low as possible and the thickness of the underlying passivation should not be too thin (otherwise, there will be a noticeable heat conduction between the heated link and substrate during the processing, thus the temperature of the substrate will increase).

#### 4.4.2 Damage to other device features

Damages to other device features can include damage to adjacent links and damage to the passivation structure. As link pitch sizes become smaller, there is higher risk of damaging the adjacent links by the laser beam during the process. The often seen damage to adjacent links includes burn mark on the adjacent links, electrical shortage between the processed link and its adjacent links, or mechanical damage to the adjacent links due to oversized crater in the passivation.

The burn mark on the adjacent links can be a result of either oversized laser beam spot size, misalignment of the laser beam over the link, or reflected laser energy from the link under process. In some cases, the last one might be the only reasonable explanation of the damage to the adjacent links. This implies that during the link processing, the molten link material pulls into a curved shape in its width direction due to the surface tension of the liquid material, so part of the laser energy is reflected by the curved surface at such angles that it can hit the adjacent links.

Electrical shortage between the processed link and its adjacent links, or mechanical damage to the adjacent links are related to the damages in the passivation. Damages in the passivation are generally in the form of oversized, or irregular craters. It can be the result of excessive heat conducted into the passivation (for instance, if the laser pulse width is too long or the laser energy used is to high), or of the residual stress within the passivation, or simply because the overlying passivation is too thick. If the crater goes deep into the underlying passivation, it might cause unacceptable electrical leakage between the processed link and the silicon substrate. Some new passivation materials<sup>82</sup> used are mechanically weak, or have a low melting temperature, or even light absorption by themselves. Then oversized craters both in the diameter and depth can occur.

If there are active components too close to the links, permanent performance deterioration of these components might occur after the laser processing, such as higher leakage of P-N junctions, etc. It is recommended that active components of the device should not be built in the area too close to the links (depending on the detailed link structure and the temperature profile after the processing, as shown in Figures 4-4 to 4-6).

#### 4.5 Link processing results using 1.32 µm wavelength laser

Several 1.32  $\mu$ m wavelength laser link processing systems have already been built by Electro Scientific Industries, Inc. Portland, Oregon for test processing a variety of memory link structures. Table 4-3 shows experimental results of the processing windows using 1.047 and 1.32  $\mu$ m lasers for links made of WSi, WTi and aluminum.

	Laser Energy Processing Window					
	1.047 μm		1.32 μm			
	μJ	± %	μJ	± %		
Silicide (WSi)	0.43 - 1.1	44	0.57 - 2.67	65		
Metal (WTi)	0.34 - 0.75	38	0.57 - 2.91	67		
Metal (Al)	0.63 - 0.86	15	0.75 - 2.08	47		

Table 4-3. Results of processing windows using 1.047 and 1.32 µm lasers.

For these different link structures, the high ends of the processing windows improve by factor of 2 to 3 at 1.32  $\mu$ m over 1.047  $\mu$ m, while the lower ends of the windows become slightly higher. The small change in the low end of the window is due to both slightly lower absorption of the link materials at 1.32  $\mu$ m than that at 1.047  $\mu$ m, and the slightly longer laser pulse at 1.32  $\mu$ m than that at 1.047  $\mu$ m (15 ns versus 4 to 9 ns). For the aluminum link, the processing window using the 1.047  $\mu$ m laser is as narrow as ±15%. It increases to a large range of ±47% when the 1.32  $\mu$ m laser beam is used. That is an improvement by a factor of three. These results agrees with the simulation results presented.

Results of the laser energy runs using 1.047 and 1.32  $\mu$ m are shown in Figure 4-7. The range of the laser energies used is from 0.6 to 2.0  $\mu$ J and the laser beam spot size is 5.5  $\mu$ m. Damage to the silicon substrate starts at 1.3  $\mu$ J at 1.047  $\mu$ m, but does not occur up to 2.0  $\mu$ J at 1.32  $\mu$ m, which is the highest energy by the laser source used for this test.



(a). Laser energy run using a 1.047 μm laser.



(b). Laser energy run using a 1.32 µm laser.

Figure 4-7. Results of the laser energy run using a 1.047  $\mu$ m laser and a 1.32  $\mu$ m laser.

Figure 4-8 shows the results of a laser energy run for another link structure, using a 1.32  $\mu$ m laser (compare to the result of energy run using 1.047  $\mu$ m for the same link structure shown in Figure 2-3). The 1.32  $\mu$ m laser energy range used is 1.22 to 1.85  $\mu$ J, the pulse width is 16 ns, the beam spot size is 3.8  $\mu$ m. The high end of the laser energy of 1.85  $\mu$ J is limited by the laser source. No sign of any damage to the silicon substrate at this energy level is observed. The result of a laser energy run using a 1.047  $\mu$ m laser for the same link structure has been shown in Figure 2-3. The laser energy range used is 0.27 to 0.98  $\mu$ J, the laser pulse width is 4 ns, the laser spot size is 3.8  $\mu$ m. Damage to the silicon substrate starts to occur at laser energy of 0.79  $\mu$ J.



Figure 4-8. Results of a laser energy run using a 1.32µm laser beam.

Figure 4-9 shows a vernier testing run result for a metal link structure using 1.047 and 1.32  $\mu$ m. The results prove that the process is more tolerant to the positioning error of the laser beam with 1.32  $\mu$ m. The link width is 1  $\mu$ m. The laser parameters used are as follows: the laser pulse energy is 0.62  $\mu$ J, the laser pulse width is 4 ns, the laser beam spot diameter is 3.8  $\mu$ m for the 1.047  $\mu$ m laser. For the 1.32  $\mu$ m laser, the laser pulse energy is 1.3  $\mu$ J, the laser pulse width is 16 ns, the laser beam spot size is the same 3.8  $\mu$ m. The Figure shows that when the 1.047  $\mu$ m laser beam center gets off the link by about a half of

the link width, damage to the substrate occurs. In contrast, for  $1.32 \ \mu m$  laser processing, there is no damage to the silicon substrate even when the laser beam is totally off the links at the energy level of  $1.3 \ \mu J$  used.



(a). Vernier test run using a 1.047 μm laser.



(b). Vernier test run using a 1.32 µm laser.

Figure 4-9. Results of a vernier test run using a 1.047 µm laser and a 1.32 µm laser.

Figure 4-10 shows a highly magnified view of metal links processed by 1.047 and 1.32  $\mu$ m lasers. For the links processed by 1.047  $\mu$ m with laser pulse energy of 0.62  $\mu$ J, laser pulse width of 4 ns and beam spot diameter of 3.8  $\mu$ m, there is splashed link material around the cut, resulting in either lower opening resistance or long term reliability problems. The links cut by the 1.32  $\mu$ m laser with laser pulse energy of 1.3  $\mu$ J, pulse width of 15 ns and beam spot diameter of 3.8  $\mu$ m are clean, with no sign of damage to the silicon substrate.



(a). Metal links processed by a 1.047  $\mu m$  laser.



- (b). Metal links processed by a 1.32  $\mu m$  laser.
- Figure 4-10. Highly magnified view of metal links processed by a 1.047 µm laser and a 1.32 µm laser.

Figure 4-11 shows measured results of the open resistance of links cut by 1.047 and 1.32  $\mu$ m lasers. It is impressive to see 3 orders of magnitude higher open resistance of the two different metal link structures processed by the 1.32  $\mu$ m laser than that by the 1.047  $\mu$ m one.

## 4.6 Other issues of laser link processing using the longer laser wavelength

A few practical issues of using the longer laser wavelengths instead of 1  $\mu$ m to process the links need to be discussed.

The first is the laser sources. Considering the availability of the laser source and the fact that the shorter the laser wavelength is, the smaller the focused beam spot sizes can be, 1.32 µm laser would be an ideal choice for the purpose. Nd:YAG and Nd:YLF are the most common solid-state lasing mediums for laser radiation generation of 1.32 µm. To be exact, 1.3188 µm for Nd:YAG and 1.321 or 1.313 µm for Nd:YLF.<sup>83</sup> Since the lasing gain of Nd: YAG is the highest at 1.064 µm and 10 times lower at 1.32 µm, special measures, such as special resonator mirror coatings, should be used to obtain the lasing action at 1.32 µm while suppressing the lasing action at 1.064 µm. Also due to the lower lasing gain at 1.32  $\mu$ m, the laser pulse width available at 1.32  $\mu$ m is noticeably longer than that at 1.064 µm of Nd:YAG or 1.047 µm of Nd:YLF. For instance, laser pulse widths around 5 ns at 1.047 µm are common for commercially available diode pumped, A.O.Qswitched Nd:YLF lasers. So far, the shortest laser pulse width at 1.32 µm wavelength from commercially available diode pumped, A.O.Q-switched Nd:YLF lasers are 15 to 16 ns. Using stronger pumping, shorter laser pulse width such as 8 to 10 ns at 1.32 µm with a new lasing material Nd: YVO<sub>4</sub> should be feasible. This will further improve the 1.32  $\mu$ m laser processing results for most metal link structures. If for similar link processing applications, the laser beam spot size is not a key issue but even higher damage threshold to the silicon substrate is required, then even longer laser wavelengths such as 1.5 or 2 µm should be investigated. Good laser sources in this spectrum range are erbium doped glass lasers at wavelength of 1.54 µm, and holmium, erbium and chromium co-doped YAG lasers at wavelength of 2.1 µm.<sup>103</sup>

1.047 µm, 4 ns 1.32 µm, 15 ns 1,00E+14 1,00E+13 A LEAST AND A REAL PROPERTY AND A REAL PROPERT 1,00E+12 .... ·法巴律司的法认可能在有关于共同的律师 1,00E+11 **进行和小儿目常表现了影响**和"你们的"的目标自己的"你们"。在这些你们的"你们"的"你们",你们们们们们们们们们们 的。但在16月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的18月1日的 "你的是我们的事实"的。我们们的时候是已经不是我们就是我们能能。 1,00E+10 1,00E+09 Open resistance (Ohm) 新教授**于**教育的教育和教育部長的主要。如果我们的关系。 (1)内午在一家运行正的 影响相比的石炭 1,00E+08 STRATIGE STRATES CONTRACTOR 1,00E+07 中國首都特定局 制造和运行的家族的方 · 和144 全国人民的中国的东西的东西的东西的东西和美国大学的大学校和美国大学校中国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校和美国大学校 他的鲜棉带 Salar States 1,00E+06 2. Lot & Margin grade is the Market of 1. 1913年1月1月日日前日本 1,00E+05 (注意)是 法告诉我,我, **深叶花均均均常**。清秋之 (1) (1) (1) 1,00E+04 的和意志是的是的医+Set~ 这些 新新社会的 1,00E+03 计计算法 医子宫间的 的洞境的现在分词 1,00E+02 Fusebank 1 ALL STREET, DESCRIPTION OF STREET, STRE Fusebank 2 1-218 - 2841 1,00E+01 1,00E+00 10 20 30 40 50 60 70 80 90 100 0 Die

Figure 4-11. Resulting open resistance of metal links processed by 1.047 and 1.32 µm wavelength lasers.

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The second practical issue is the laser beam spot size. The theoretical limitation of the smallest focused Gaussian laser beam spot size is linearly proportional to the laser wavelength, which means that the smallest beam spot size achievable at 1.3  $\mu$ m is 1.3 times larger than that at 1  $\mu$ m. According to experience, the smallest beam spot size practically achievable is about two times of the wavelength used, considering issues such as focusing depth, and working distance, etc. So far, the smallest laser beam spot sizes that have been used for link processing are around 2.5  $\mu$ m for 1.047  $\mu$ m laser sources. Thus it is considered to be practical for the 1.3  $\mu$ m laser to deliver similar spot sizes with some extra efforts on the beam delivery optics. Other issues such as optics, coatings, and detectors for the new wavelengths are considered to be fairly easy to solve. For instance, instead of silicon detectors for 1.047  $\mu$ m, germanium or InGaAs detectors can be used to detect 1.3  $\mu$ m laser pulses for the purpose of system control with satisfactory sensitivity.

## 4.7 Summary

A much wider laser processing window has been realized using a 1.32  $\mu$ m laser wavelength instead of 1  $\mu$ m for both heavily doped polysilicon and metal links. This is mainly due to the fact that while the absorption of link materials at those two wavelengths remains almost constant, the absorption of silicon substrate at 1.32  $\mu$ m is considerably less than that at 1  $\mu$ m, resulting in a much higher damage threshold for the substrate. In other words, the high end of the laser link processing window is increased significantly using a 1.32  $\mu$ m laser, while the lower end of the window is almost unchanged, resulting in an overall much wider processing window.

The processing results of several different link structures, including polysilicon and metal links with different dimensions and layer structures using both 1.047 and 1.32  $\mu$ m laser wavelengths have proved the advantages of using 1.32  $\mu$ m for the application.

For most link materials and structures tested, the processing window ranges improve by a factor of about two, mainly due to the significant improvement in the high end of the window when using  $1.32 \,\mu\text{m}$ . Since higher laser energy at  $1.32 \,\mu\text{m}$  wavelength can be used for the processing, the cuts are cleaner with less debris and slag than the ones

processed by 1.047  $\mu$ m. The open resistance of the link cuts processed by the 1.32  $\mu$ m laser is substantially higher than that by the 1  $\mu$ m laser. For two metal link structures tested, the open resistance of links processed by the 1.32  $\mu$ m laser is three orders of magnitude higher than that processed by the 1  $\mu$ m laser. Due to the wider laser processing window available at the 1.32  $\mu$ m wavelength, the 1.32  $\mu$ m laser pulse energy used for the processing can be chosen at the level with enough margin over the lower end of the window. This is believed to be responsible for the advantages of cleaner cuts and higher open resistance using 1.32  $\mu$ m.

Both analysis and experimental results support that maximizing the absorption contrast of laser energy between the link materials and silicon substrate is a key criterion for laser link processing enhancement. For metal link processing, this is even more critical due to the higher laser pulse energies usually needed for processing metal links.

The improvement of the link process using 1.32  $\mu$ m is dependent on the doping level of the silicon substrate (or the doping level within the epi layer on top of the silicon substrate) and other link structure parameters. So far, the tests of 1.32  $\mu$ m processing were done on the same link structures without any layer structure modification. For better processing results, optimization of the passivation layer structure at the new laser wavelength from the point view of the optical interference effects is needed. The longer pulse width of the 1.32  $\mu$ m lasers available for the tests has been another restricting factor. Further improvement is possible when shorter 1.32  $\mu$ m laser pulse widths become available.

All the analyses and experimental results have suggested that the  $1.32 \mu m$  wavelength laser processing will be able to meet the tough redundant link processing requirements of new generation memories for years to come.

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# CHAPTER 5

# OPTIMIZATION OF FUNCTIONAL TRIMMING BY LASER BEAMS

#### 5.1 Introduction

As has been briefly mentioned, functional trimming is a process during which the devices are powered-up to their normal operating conditions with proper input signals applied. The monitored parameter or parameters during the process are not the values of the individual components trimmed, but the relevant parameters of the devices. This technology has been widely used for trimming thin films on the semiconductor wafer level (monolithic ICs), as well as thick or thin films on the hybrid integrated circuit devices (HICs). For monolithic ICs, trimming targets are fabricated on the same silicon wafer together with other active and passive components or features of the devices. For HICs, trimming targets are built on the ceramic substrates. Then they are integrated with other passive and semiconductor based active components to form the completed devices.

Besides the desired parameter tunings of the components trimmed by the laser beams, there are undesirable performance drifts of the devices during the trimming. <sup>29, 103</sup> The performance drifts are the results of the interactions of the laser beams with the device structures at large, especially semiconductor material based components and the semiconductor material. Figure 5-1 shows the schematic of Model INA2128 Dual, Low Power Instrumentation Amplifier made by Burr-Brown. The four 25 k $\Omega$  resistors in it need to be laser trimmed so the amplifier can meet a stringent gain specification. Figure 5-2 shows the dramatic output voltage drift of the device during laser trimming when a 1.047 µm laser beam is used.

These undesirable performance drifts can be divided into two different categories, the unrecoverable drift and recoverable drift. The unrecoverable drift is regarded as a permanent damage to the device by laser beams, such as damage to any active components


Figure 5-1. Schematic of the INA2128 Dual Amplifier.



(Vertical scale: 5 V/Division; Horizontal scale: 0.1 ms/Division)



or the silicon substrate, and unacceptable deterioration of critical performances of circuit features within the device. Following certain design guidelines and careful control of the laser parameters used, the unrecoverable performance drift or permanent damages to the devices by the laser beams can be avoided or minimized. On the other hand, although the recoverable performance drift during functional trimming imposes no damage threat to the devices, it has long been a big problem for the process. The drift occurs whenever the devices are exposed to the laser pulses, then slowly decays within a certain time period after the laser pulses end. The existence of this drift not only prohibits the use of device performance tracking techniques (whereby device performance is continuously monitored for process control purposes, thus realizing higher processing speed), but also dramatically reduces the process speed when the "measure and predict" technique is used. For the "measure and predict" technique, after a laser pulse or a series of laser pulses is fired, the device performance is measured for predicting how many more laser pulses might be needed to bring the device performance into the desired accuracy range. This sequence will be repeated until the device performance meets the desired accuracy. Due to the laser induced performance drift, any measurement of the performance has to be put on hold until the drift disappears. Some devices can even be "latched-up" under exposure to laser pulses. In this case, power supplies to the devices have to be shut off for a certain time period for the devices to recover.

Two effects are responsible for the recoverable performance drift of the devices during trimming: thermal heating and photon induced photoelectric effects.<sup>29</sup>

The laser trimming process by its nature is a thermal process. Part of the component's material is removed by a laser energy induced heating-evaporation process. Trimming by UV laser ablation might be an exception to this thermal model. The thermal behavior of the thin films and dielectric substrates under exposure to the laser pulses has been discussed in detail.<sup>105, 106</sup> For a thin film on a silicon wafer, laser energy absorbed by the wafer is another contributor to the thermal effects. The thermal properties of the film and substrate materials involved, the mechanical structure data of the components trimmed, and the laser parameters used (energy per pulse, laser beam overlapping ratio and laser pulse width) are critical in determining the thermal effects of the process. When

the trimming is done on films purposely made of materials with a high thermal coefficient (high TC), thermal induced parameter drift of these film components can result in server performance drift of the whole device. The thermal effect is relatively localized and slow changing with the time. The dimensions of thermally affected zone during the process can be estimated by the thermal diffusion length. For instance, functional trimming is commonly done with a laser pulse of about 40 ns total duration time for modern monolithic ICs. According to Equation 3-12, the dimension of thermally affected area within a silicon wafer is  $1.9 \,\mu\text{m}$ .

The photoelectric effect differentiates itself from the thermal effect in several noticeable ways. First, it is not a localized effect. The photoelectric effect not only can be caused by an exposure to the main laser beam, but also an exposure to the scattered laser photons. The distribution of the scattered laser photoelectric effects are faster than the measure or simulate. Second, in most cases, photoelectric effects are faster than the thermal effects in time response. But this does not necessarily mean the performance drift of the device due to the photoelectric effects is also a fast one. The circuit structure of the device is a more critical factor in determining the overall time constant of the drift. Third, photoelectric effects are very much wavelength dependent, while the thermal effect is less wavelength sensitive.

In early studies of the laser induced performance drift, it was proposed to use some special separation and shielding methods for HIC devices in order to protect any semiconductor based components from being affected by the scattered laser photons, so the drift can be reduced or eliminated. It also has been found that the trimming process has to be performed without any illumination light to avoid any effects of this light on the performance of the devices.<sup>107</sup>

More detailed investigation of the performance drift during trimming has been reported.<sup>33</sup> After testing the drift for several different kinds of silicon based components specially designed and fabricated for the study, such as resistors, p-n junctions, transistors, etc., the conclusion drawn was that "the delay times required to eliminate photo-excitation effects will be a small part of the interval between laser pulses". This might be true for all those components tested, but is not necessarily valid for others, since the overall response

time constant of a device to laser photons can be depending more on the detailed circuit structure, rather than the nature of the individual components. For instance, a resistor R alone is a component with fast response time constant, while a resistor R plus a capacitor C become a device with a slow time constant of RC. Figure 5-2 shows an example of the performance drift's slow time constant. The drift lasts almost 0.1 millisecond after the exposure to a laser pulse with 20 ns width (FWHM).

So far, the most common lasers used for both passive and functional trimming are CW arc lamp or diode pumped, A. O. Q-switched Nd:YAG lasers with wavelength of 1.064  $\mu$ m, or Nd:YLF lasers at 1.053 or 1.047  $\mu$ m. These lasers look almost ideal for the application. All laser output parameters (the output power level, the laser pulse repetition rate and the laser pulse width) are just right for the application. They are mature, reliable, readily available and cost effective solid-state lasers. Normally, shorter laser wavelengths might be attractive for the applications based an the fact that it can deliver smaller laser beam spot sizes and better coupling of the laser energies into the metal film targets. But trimming experiment using shorter laser wavelengths such as 0.532  $\mu$ m did not help solve the performance drift problem.

Note that all silicon based light-sensing devices, such as photo-diodes, CCD, etc. are unable to sense lights with wavelengths longer than 1.1  $\mu$ m. They become virtually blind at wavelengths longer than 1.1  $\mu$ m. It is reasonable to expect that other silicon based devices should perform no better in sensing lights than these specially designed light sensing devices. Thus it is reasonable to expect that if a silicon based device is functionally trimmed using laser wavelengths longer than 1.1  $\mu$ m, say 1.32  $\mu$ m, the photon induced performance drift can possibly be minimized or totally eliminated.<sup>34</sup> This expectation has been successfully proven by experiments.<sup>108</sup>

#### 5.2 Parameter drift of silicon based devices during functional trimming using

#### 1 µm laser wavelength

As mentioned, only the recoverable performance drift of the devices due to photoelectric effects during the functional trimming will be discussed in this work. The emphasis will be on searching for a cure to the drift problem, rather than trying to merely simulate the drift behavior itself.

The basic physics involved in the parameter drift during trimming consists of two parts, the photo-electric interaction of the laser beam with the semiconductor material and the effects of this interaction on the performance of the components and devices.

The interaction of light with semiconductors has been widely studied and documented. The mechanisms of the interaction vary with the energy band structure of the semiconductor, the dopant and its concentration, the temperature of the semiconductor, and the light wavelengths. As far as the performance drift of the devices is concerned, the responsible mechanism is the laser photon induced hole-electron carrier population. In order to cause the excitation, the photon energy has to be greater than the energy band gap of the material. In the case that the material has an indirect energy band gap structure, with the help of phonons, excitement of the carriers will be possible when the photon energy is greater than the indirect band gap, but smaller than the direct energy gap.

Free carriers can also be excited from intermediate energy levels of dopants within the energy band gap of the semiconductor material. But since these energy levels are either close to the top or bottom of the band gap, photon energies required for the excitation are very close to the energy band gap itself.

While the indirect energy band gap for silicon is about 1.17 eV at 27 °C, photon energies for the traditional laser wavelengths of 1.064 or 1.047  $\mu$ m used for the functional trimming are 1.16 eV and 1.18 eV, respectively. Thus those laser photons are just energetic enough to excite hole-electron carrier pairs within the silicon with the help of phonons.

Higher temperature will cause the energy band gap to shrink, as discussed in Chapter 4, resulting in more effective carrier excitation by these laser photons. Excess carriers can also be generated at higher temperature due to thermal excitation.

From the point view of the photoelectric effects of the semiconductor materials, the two most important effects on the performance drift of devices are the photoconductive effect and photovoltaic effect.<sup>109, 110</sup>

The photoconductive effect is the change in the electrical conductivity of the object caused by photon induced carriers. The conductivity drift is governed by the

following two Equations

$$\frac{d(\Delta N)}{dt} = A_d \eta E_{q,s} - (\frac{\Delta N}{\tau_c}) , \qquad (5-1)$$
$$\Delta N = N(t) - N , \qquad (5-2)$$

where N is the total number of free carriers in the exposed material when there are no incident photons,  $\Delta N$  is the increase in total number of free carriers caused by the incident photons,  $\eta$  is the efficiency in converting incident photons into free charge carriers (the quantum efficiency),  $\tau_c$  is the average free charge carrier lifetime, A<sub>d</sub> is the area of the material exposed to the photons, and E<sub>q,s</sub> is the incident photon flux density in unit of photons cm<sup>-2</sup> s<sup>-1</sup>.

The photovoltaic effect is the effect that photon induced electron-hole pairs at, or near a P-N junction region affect the Femi level in both P and N regions, and the shift of the Femi level is sensed as a voltage signal at the P-N junction terminals. The voltagecurrent curve of the P-N junction will shift as the result of this effect, as shown in Figure 5-3. Curve (A) is without photon illumination, and curve (B) is with photon illumination. Curve (B) is characterized by the open-circuit voltage V<sub>0</sub> and short-circuit current I<sub>sc</sub>. The short-circuit current I<sub>sc</sub> is given by

$$I_{sc} = e \eta E_{a,b} A_d \quad , \tag{5-3}$$

where e is the electronic charge,  $\eta$  is the quantum efficiency,  $A_d$  is the sensitive area of the responsive element, and  $E_{a,b}$  is the photon flux density of the illumination.

As can been seen, both the amplitude and time constant of these two photo-electric effects are not only depending on the density of laser photons, but also on the characteristics of the devices themselves. Of critical importance here is the quantum efficiency  $\eta$ , which is a function of the incident light wavelength, among other things. Figure 5-4 shows the spectral response curves of several different types of silicon photodetectors.<sup>111</sup> It does show that at the traditional laser wavelengths of 1.064 and 1.047  $\mu$ m used for functional trimming, silicon based devices have significant response, resulting in severe performance drift during the trimming. But the spectral response curves of silicon based photodetectors cut off at the wavelength of about 1.1  $\mu$ m.



(a). Unilluminated condition. (b). Illuminated condition.

Figure 5-3. V-I curve of a P-N junction with and without illumination. (After Crowe et al., ref. 110.)



Figure 5-4. Spectral response curves for several different types of silicon photodetectors. (After Pressley at al. ref. 111.)

#### 5.3 Functional trimming using longer laser wavelengths

The spectral response curves of silicon based photodetectors cut off at wavelength of about 1.1  $\mu$ m, as shown in Figure 5-4. For wavelengths longer than 1.1  $\mu$ m, silicon photodetectors become virtually blind, although doping in silicon will create energy levels within the energy gap which will extend the spectral response curves into a slightly longer wavelength range. So far there are no silicon based photodetectors that can be practically used to sense wavelengths longer than 1.1  $\mu$ m.

Other silicon based devices will respond to photons no better than these special photon sensing devices do. Using longer laser wavelengths beyond the spectral ranges within which silicon based photodetectors can respond, performance drift of all kinds of silicon based devices during the trimming can either be totally eliminated or drastically reduced.

Based on the availability of the laser sources and the consideration that shorter wavelengths will deliver smaller spot sizes desirable for the application,  $1.3 \mu m$  laser is an ideal choice for the purpose.

The same principal applies to devices based on other semiconductor materials. For instance, the spectral response for germanium based devices cuts off at a wavelength of approximately  $1.8 \mu m$ . For functional trimming of germanium based devices, thus laser wavelengths longer than  $1.8 \mu m$  can be used to eliminate the performance drift.

## 5.4 Experiment results of functional trimming of silicon devices with 1.32 $\mu$ m laser wavelength

A functional trimming test on a variety of silicon based devices using the diode pumped, A.O. Q-switched 1.32  $\mu$ m laser has been done on an Electro Scientific Industries, Inc.'s 8000 system at Burn-Brown. One of the devices trimmed is the amplifier shown in Figure 5-1. Figure 5-5 shows the drastically reduced performance drift when the device is trimmed by a 1.32  $\mu$ m laser beam. Note that the horizontal time scale is the same as that in Figure 5-2, but the vertical scale is 0.2 volts per division in Figure 5-5, instead of 5 volts per division in Figure 5-2.





### Figure 5-5. Performance drift of the amplifier using a 1.32 µm laser for functional trimming.

Careful experiments were carried out to make sure that the long term stability of the resistors trimmed were unchanged with the new laser wavelength processing. Figure 5-6 shows the stability comparison of resistors trimmed by both 1.047 and 1.32 µm lasers. The comparison is done using these two laser wavelengths to trim resistors located side by side, so any effects of device variation from location to location are ruled out. Then the devices were baked at 500 °C for one hour and re-tested. This aging process is believed to be equivalent to 1000-hour normal operation of the devices.<sup>32</sup> Two curves representing the resistance values after the aging of the resistors trimmed by two different laser wavelengths trace very closely to each other, indicating that there is no detectable stability difference of the resistors trimmed using the two different laser wavelengths.



Figure 5-6. Stability comparison of resistors trimmed by 1.047 and 1.32 µm wavelength lasers.

A voltage regulator is another device functionally trimmed using both 1.047 and 1.32  $\mu$ m laser beams, in order to bring its regulated output voltage to a predetermined accuracy level. Figures 5-7 and 5-8 show the output voltage waveforms of this voltage regulator under the functional trimming. The performance drift is severe when the 1.047  $\mu$ m laser is used, but is totally eliminated when the 1.32  $\mu$ m laser beam is used for the trimming.



Figure 5-7. Output voltage of a voltage regulator trimmed with a 1.047  $\mu m$  laser.



Figure 5-8. Output voltage of a voltage regulator trimmed with a 1.32 µm laser.

#### 5.5 Summary

Laser functional trimming of semiconductor based devices, such as HICs and monolithic ICs, is a widely used production process. It has long been troubled with performance drift of the devices under exposure to the laser beam during the process. The cause of this drift has been known as the excitation of excess electron-hole carriers within the semiconductor material or device structures by the laser photons.

Any device made of a particular semiconductor material only responds to a defined lightwave spectrum based on the energy band structure of the semiconductor. Noticeable amounts of electron-hole carriers can only be excited by photons with energies greater than the energy band gap (direct or indirect energy band gap) of the semiconductor material. Thus, in order to eliminate the performance drift of semiconductor based devices during the functional trimming, a new approach of using laser wavelengths with photon energies smaller than the energy band gap of the semiconductor material is proposed.

For silicon based devices, a wavelength of  $1.32 \ \mu m$  is a good choice for the purpose.  $1.32 \ \mu m$  laser functional trimming experiments have been carried out on two different kinds of devices. Total elimination or drastic reduction of the performance drift has been demonstrated. No other adverse effects on the devices trimmed using  $1.32 \ \mu m$  have been observed.

It is expected that for germanium based devices, laser wavelengths of longer than  $1.8 \ \mu m$  can be used for the same purpose.

It can be foreseen that this new technique will have an important impact on the functional trimming technology, as well as the design and fabrication of semiconductor based devices subject to functional trimming.

### CHAPTER 6 SUMMARY AND FUTURE WORK

#### 6.1 Summary

Memory device repair by redundancy laser link processing has been a standard process of mass production in the industry for more than two decades. Constantly shrinking memory feature sizes and the industry's technology trend of using metals as link materials rather than polysilicon impose new challenges to the process technology. To meet the new challenge, prior understandings of the process have been critically reviewed. New physical models and simulations have been developed. They include full analyses of several critical stages of laser link processing: the optical interference effects, the thermal simulation before the passivation's rupture, effects of the passivation's rupture on the link processing, the post-rupture process analysis, and assessment of the damage risks to the silicon substrate.

Effects of the overlying passivation and its rupture on link processing have been studied in detail. The relationship of the passivation's rupture with critical link structural data such as link width and thickness of the overlying passivation has been revealed through the mechanical stress simulation.

The post-rupture process analysis and qualitative discussion of the effect of laser pulse width on the link processing prove that shorter laser pulses are preferred for better process results. Higher laser intensity or shorter laser pulse width at the same laser wavelength helps in blowing link material in its liquid state with less risks of forming debris and slag in the cut area.

To further widen the laser processing window, a new approach of maximizing the laser energy absorption contrast between the link materials and the silicon substrate has been proposed and analyzed. Larger absorption contrast will allow the use of higher laser pulse energies and intensities to process the links without damaging the silicon substrate. Based upon the fact that light absorption by silicon drops dramatically at wavelengths

longer than 1.1  $\mu$ m, while for most metal materials absorption in the 1 to 1.5  $\mu$ m range only changes slightly, a much larger absorption contrast between the link materials and the silicon substrate is realized using a longer laser wavelength such as 1.32  $\mu$ m.

Extensive testing has proved the predicted advantages of laser link processing using 1.32  $\mu$ m laser over the 1  $\mu$ m laser. In most cases, the laser processing window improves at least by a factor of two. The results are in excellent agreement with the simulation results. Due to the fact that higher laser energies at the new wavelength can be safely used to process the links, better link processing qualities are demonstrated. The cuts are cleaner, and the opening resistance is approximately two orders of magnitude higher than that processed by the traditional 1  $\mu$ m lasers.

It is expected that the knowledge gained from this work and the new  $1.32 \mu m$  laser processing technique will help in optimizing the designs of link structures and the laser processing systems, and the process itself to meet the tough production requirements of new generation memory devices for the foreseeable future.

Traditional laser functional trimming of semiconductor based devices using 1 µm laser has long been troubled by laser induced performance drift of the devices. The process speed has to be significantly reduced, so that enough time is available for the devices to recover from the drift before any accurate measurement can be carried out for process control. Although it is known that this performance drift is the result of excessive electron-hole carrier excitation within the semiconductor materials and devices induced by the laser photons, no cure had been demonstrated prior to this work.

Using new laser wavelengths which are beyond the spectral range within which the electron-hole carrier excitation can occur for a particular semiconductor material, performance drift of the semiconductor material based devices during the functional trimming can be dramatically reduced, or totally eliminated. For silicon based devices, a  $1.32 \mu m$  wavelength laser is an ideal choice for the purpose.

Experiments of functionally trimming several silicon based devices using 1.32  $\mu$ m lasers have demonstrated the virtual elimination of the device performance drift. Thus much higher throughput and accuracy can be realized. The technique can be applied to

functional trimming of other semiconductor material based devices as well, such as 2  $\mu$ m laser wavelength for germanium based devices, etc.

It is expected that the elimination of the performance drift of semiconductor material based devices during functional trimming using the optimized laser wavelengths opens a door for better device designs and new trimming process techniques to emerge in the near future.

#### 6.2 Future work

The knowledge gained from this thesis work might be helpful in developing other new processes or new processing techniques. The following are a few possible examples.

The first example is a proposal of new link structure design which was inspired by the thesis work.<sup>112</sup> For all the memory laser link processing discussed so far, only the link material itself is the desired laser energy absorbing medium. Laser energy absorption by the silicon substrate and the heat conduction into the passivation are not desired for the process. However, after all possible optimizations discussed in this thesis, for some real link structures, satisfactory laser processing is still difficult to realize. For instance, some links made of material with high melting point such as tungsten, and with abnormally large thickness (thicker than 2 µm in some cases) are difficult to process even with the 1.32 µm wavelength laser. One major problem is that the open resistance is too low to qualify. The reason might be that there is a small amount of residual conductive link material remaining in the cut open's bottom area or on its side wall after the laser processing. The proposal is to purposely use some laser absorbing dielectric materials to fabricate the passivation layer just underneath the link. The laser energy absorbed by this passivation layer would supply an additional driving force in cleaning the residual conductive link material to realize the desired open resistance. By controlling the absorption coefficient of the dielectric material used and the thickness of the layer made of the dielectric material, the laser induced crater size in the dielectric layer can be controlled for the best result of the processing.

The second example is to use even shorter laser pulses or partially mode locked laser pulses for link processing. For A. O. Q-switched 1.32  $\mu$ m laser sources, so far the shortest laser pulse width is 15 ns or so, compared to 4 ns at 1.047  $\mu$ m. It is expected that

1.32  $\mu$ m wavelength laser pulses with pulse width shorter than 10 ns might be able to deliver further improved results. The experiment of using the shorter pulse 1.32  $\mu$ m laser for link processing will be carried out as soon as the laser source becomes available. A partially mode-locked 1.32  $\mu$ m laser (Q-switched plus some degree of mode-locking) might be a good alternative if it is difficult to get shorter pulse widths from standard A. O. Q-switched 1.32  $\mu$ m lasers.

The third example is the link making processing. The capability of link making in addition to link cutting will dramatically increase the flexibility in design and fabrication of a variety of IC chips. A research group at Massachusetts Institute of Technology has been working on the conductive link making process using laser beams.<sup>113-115</sup> The idea is that a laser pulse can generate a crack in the passivation between conductive lines or pads within a multi-layer structure. Then the conductive material molten by the same laser pulse will expand and fill into the crack, forming an electrical connection between the conductive lines or pads. The process developed so far is still a long way from being qualified for mass production use. However, most technical issues involved in the laser link making process are quite similar to what has been investigated in this thesis work. But for link making, the laser induced crack has to be generated in a more stringently controllable manner to perform the "constructive" task, rather than the more tolerant "destructive" task in link cutting. A smaller processing window, thus tighter control of all parameters than that for link cutting are inevitable. The knowledge gained from this thesis work will be a good start for further investigating the technique of the link making.

On the other hand, several issues important to the laser link processing have been purposely neglected in the simulations discussed by this thesis. They need to be studied and investigated in the future. First, the dynamics of the link material's removal need to be investigated, such as how the link material is blown away, the speed distribution (both its amplitude and direction) of the blown away material, information on the recoil force by the evaporated material, the response of the molten link material to the recoil force, the shock wave induced by the laser pulse and its effect on the processing, and the plasma formation and its effect on laser energy absorption. Although a few of them have been briefly studied and reported, such as the recoil force intensity, plasma formation during laser drilling and cutting, significant modification might be needed to adopt them for laser link processing. These dynamic issues might be difficult to solve, but quantitative analysis of effects on laser processing results by important variables such as the laser pulse width will not be possible without the understanding of these dynamic issues. Second, how the slag and debris are formed, the dependence of their formation to the link structural data, laser parameters, and environment need to be studied and understood. Third, crack growth dynamics within the overlying passivation and its effect on link processing need to be further studied. Forth, it is expected that for some compound link materials, such as TiN and WSi, there might be decomposition during the laser processing. This decomposition could be partially a thermally induced process and partially a photo-chemical process. It can be an important factor affecting the results of laser processing and thus needs to be investigated.

For the functional laser trimming, one topic of interest is to see if the performance tracking technique can be used after the elimination of performance drift with the 1.32  $\mu$ m lasers. The time needed for high accuracy measurement of the devices performance is one of the major factors restricting the trimming throughput. For the passive trimming, continuous parameter comparison or the performance "tracking technique" is a key in getting around this bottle-neck to enhance the process speed. As has been discussed, performance drift due to the photo-electric effects prohibits its use in functional trimming. The new technique of using 1.32  $\mu$ m lasers for functional trimming with the 1.32  $\mu$ m laser processing, it will have an important impact on the trimming technology for years to come.

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# Appendix. The computer simulation program of the temperature within the link structure, and the damage threshold of the silicon substrate

#### PROGRAM SimuMain;

{Laser processing simulation. Yunlong Sun, ESI. Jan. 96 for 2D sim. of a aluminum link structure.}

#### CONST

{The following laser and link parameter	ers need to be changed if the physical model or-}
{materials involved are different for the	e simulation needs to be run. }
Trupt= 4000;	{Rupture temperature.}
Trans1= 0.08;	{Percentage of laser energy gets into solid link, }
	{or total minus reflected.}
Trans2 = 0.30;	{Percentage of laser energy gets into liquid link,}
Epulse=1;	{Laser pulse energy-in µj.}
Pulsewidth=5;	{Laser pulse width-in ns.}
Wo= 2.5;	{Gaussian laser beam waist radius-in µm.}
DeltaX = 0.025;	
DeltaZ = 0.025;	{Node size in Z direction, in nm.}
Tstart= 20;	{Starting temperature.}
Pai= 3.14159;	
{The folowings are constants for alumi	num link material.}
{They are in traditional units. The unit	ts will be converted in the program.}
{The C at the beginning means that it i	s a constant input.}
CKmax= 2.5; {Max.K esti	mated within the whole operation range for aluminum. }
{for the por	pose of calc StabDT. in W/cm-deg.}
{Data for the Link material:}	(Specific heat of link material in cal/a dea.)
CC = 0.215;	(Specific heat of link material in g/cm <sup>3</sup> )
CRno= 2.70;	{Density of fink material-in g/cm.}
1 melt= 660;	{Meeting point of link material-in deg.}
CCliq= 0.28 /;	{Specific neat of molten link material-in cal/g-deg.}
CRholiq = 2.37;	{Density of molten link material.}
CAlphaS=100/000;	{Attenuation coef. of solid link material-in 1/cm.}
CAlphaL=1100000;	{Atte. coef. of liquid link material-in 1/cm.}
CLHsI= 94.7;	{Latent heat of fusion of link-in cal/g.}
CLHvapo= 2515;	{Latent heat of evaporation of link-in cal/g.}
Tvapo= 2520;	{Link evaporation temperature.}
{Data for the passivation material:}	
CCp= 0.22;	{Specific heat of $SiO_2$ -in cal/g-deg.}
CRhop= 2.33;	{Density of $SiO_2 - in g/cm^2$ .}
CCliqp=0.2;	{Specific heat of molten $SiO_2$ -in cal/g-deg.}
CRholiqp= 2.48;	{Density of molten SiO <sub>2</sub> material.}
CLHslp= 200;	{Latent heat of fusion of $SiO_2$ .}
CLHvapop= 3872;	{Latent heat of evaporation of $SiO_2 - in cal/g.$ }
Tvapop= 2520;	{Passivation evaporation temperature.}

{Passivation evaporation temperature.} {Melting temperature of SiO<sub>2</sub> passivation.}

{Array's geometry:}

Tmeltp= 1660;

Mmax= 30; dmax = 40;

Mlin=20; dface1 = 9;dface2 = 29;

#### TYPE

TwoDArray= ARRAY[0..Mmax, 0..dmax] OF double; TwoDArraylink= ARRAY[0..Mlin, dface1+1..dface2] OF double; {TwoDArrays= ARRAY[0..Mmax, dface1+1..dmax] OF double;}

#### VAR DA

V I LAC	
Told: TwoDArray;	{At moment of t-old, the temperature for each node,}
	{two space dimensions-X, Z, in deg.}
Tnew: TwoDArray;	{At moment of t-new, the temperature for each node,}
	{two space dimensions-X, Z, in deg.}
P: TwoDArraylink;	{Heating source volume density at time moment of t,}
	{for different X, Z. in- $\mu j/ns-\mu m^3$ .}
Thick: double;	{layer thickness - in $\mu$ m.}
AlphaS, AlphaSC: double;	{Attenuation coeff. of solid link: AlphaS is a function of T.}
	{AlphaSC is the value at 20 °C.}
AlphaL, AlphaLC: double;	
AlphaSL: double;	{Atten. coeff. of solid-liquid mix.}
Mix: double;	{The mix % on melting: liqid/total.}
K: TwoDArray;	

{For the followings, the one with "p" as the last character means a date of  $SiO_2$  passivation,} {otherwise a date of the link material.}

Kmax: double;	{Thermal conductivity, solid state-in µj/ns-µm-deg.}
C, Cp: double;	{Specific heat, solid state-common in µj/µg-deg.}
Cliq, Cliqp: double;	{Specific heat, liquid-in µj/µg-deg.}
Rho, Rhop: double;	{Density, solid state-common in $\mu g/\mu m^3$ .}
Rholiq, Rholiqp: double;	{Density, liquid-in $\mu g/\mu m^3$ .}
LHsl: double;	{Latent heat of fusion-in $\mu j/\mu m^3$ .}
LHslp: double;	{Latent heat of fusion for SiO <sub>2</sub> -in $\mu$ j/ $\mu$ m <sup>3</sup> .}
LHmelt, LHmeltp: Double;	{Total heat needed to melt a node-in µj.}
LHvapo, LHvapop: Double;	{Total heat needed to vapo. a node-in µj.}
Qsl: TwoDArray;	{Heat accumulated during solid to liq transition -in µj.}
Qlv:TwoDArray;	{Heat accumulated during liq to vapor transition -in µj.}
Pflux: double;	{Laser power flux-in $\mu j/(ns^*\mu m^2)$ .}
Pomax: double;	{Laser peak power area density at its max.}
	$\{at X=Z=0,-in \mu j/(ns^*\mu m^2).\}$
Po: double;	{Laser peak power area density, with Time,}
	{At X=Z=0,-in Pomax.}
Ptotal, Pused: double;	{Total waveform area and the area where the link's gone.}
Pmid: double;	{Mid value, the same unit as Pomax.}
Hlost, Hlosl: double;	{Heat lost to top and underlying passivation.}
Eab: double;	{Total laser energy absorbed by the link.}
Judge, Judge2: Integer;	{For case judgement.}
m, d: integer;	{Node loop account in X, Z axises.}
Xm, Zd: double;	{Node coordinate position- in µm.}
Xend, Zend: double;	{Boundary for three axises- in $\mu$ m.}

{For 1 D simulation, set Mmax=0.} {Max. node index-node No in X direction is Mmax+1,} {in Z direction is dmax+1.}

{Bottom of the overlying passivation, not link yet.} {Node No. Bottom of the link.}

{Boundary temperature- in °C.} Txend, Tzend: double: TCounter: Longint; {Time evolusion counter. } {Up limit of time counter. } TCmax: Longint; Time: double; {Time -t- in ns.} {Time step interval - in ns. } DeltaTime, TCmax1, JJ: double; {Largest t interval allowed for stable calc.} StabDT: double; {Mid Value for conducted heat.} Cond1, Cond2, Cond3: double; {Heat=Cond\*DeltaTime\*Node Volume.} MidV1, MidV2, Midv3, MidV4: double; {Middle value for thermal conduction calc.} {Heat=MidV\*DeltaTime\*Node volume.} MidQ1, MidQ2, MidQ3: double; {Middle value.} J1, J1max, J2, J3, J4: Longint; MYFILE: TEXT; PROCEDURE ConvUnit(VAR Kmax, C, Rho, Cliq, Rholiq, AlphaSC, AlphaLC, LHsl, LHslp: double); {Convert all constants into: µm, µj, ns units.} BEGIN {From W/cm-deg to µj/ns-µm-deg.} Kmax:= CKmax \* 0.0000001; {From cal/g-deg to µj/µg-deg.} C:= CC \* 4.184; {From  $g/cm^3$  to  $\mu g/\mu m^3$ .} Rho := CRho \* 0.000001;Cliq:= CCliq \* 4.184; Rholig:= CRholig \* 0.000001; {From 1/cm to  $1/\mu m$ .} AlphaSC:= CAlphaS \* 0.0001; AlphaLC:= CAlphaL \* 0.0001; {From cal/g to µj/µg.} LHsl:= CLHsl \* 4.184 ; LHslp:= CLHslp \* 4.184 ; END: PROCEDURE ConvUnitp(VAR Cp,Rhop,Cliqp,Rholiqp: double); {Convert all constants into: µm, µj, ns units } BEGIN {From cal/g-deg to µj/µg-deg.} Cp:= CCp\*4.184; {From g/cm<sup>3</sup> to  $\mu$ g/ $\mu$ m<sup>3</sup>.} Rhop:= CRhop\*0.000001; Cliqp:= CCliqp\*4.184;Rholiqp:= CRholiqp\*0.000001; END; PROCEDURE SetValue(VAR Told, Tnew: TwoDArray; VAR Qsl, Qlv: TwoDArray); VAR ml, dl: integer; BEGIN FOR ml:= 0 TO Mmax DO FOR dl:= 0 TO dmax DO BEGIN Told[ml,dl]:= Tstart; {Set up the starting value.} Qsl[ml,dl]:=0;Qlv[ml,dl]:=0; END: Tnew:= Told; {Set up the starting value.}

END;

PROCEDURE EstMaxStabDT (VAR StabDT: double); {Estimate the largest time interval according to the smallest node size,} {Kmax, and the stability requirement.} BEGIN StabDT:=0.5\*DeltaX\*DeltaZ\*C\*Rho/Kmax; {in ns.} writeln('Max. Stable time interval is: ', StabDT:8:6, ' ns.'); END; PROCEDURE CalcsLHmelt(VAR LHmelt, LHmeltp: Double); {Amount of latent heat to melt each node.} BEGIN LHmelt:= DeltaX \* DeltaZ \* 1 \* Rho \* LHsl; LHmeltp:= DeltaX \* DeltaZ \* 1 \* Rho \* LHslp; {In  $\mu j$ . Dimension unit of the node is um. LHsl is in  $\mu j/\mu g$ .} {The node is 1 µm thick-in Y direction.} END; PROCEDURE CalcsLHvapo(VAR LHvapo, LHvapop: Double); {Amount of latent heat to vapo a node.} BEGIN LHvapo:=0.5\*DeltaX\*DeltaZ\*1\*Rho\*CLHvapo\*4.184; LHvapop:=0.5\*DeltaX\*DeltaZ\*1\*Rhop\*CLHvapop\*4.184; {In µj. Dimension unit of the node is µm.CLHvapo is in cal/g.} {The node is 1 µm thick-in Y direction.} {0.5: liquid splashing factor; 4.184: unit conversion.} END; PROCEDURE CalcsPo(VAR Po: double); {According to pulsewidth, waveform, calcs peak power density vs. time.} {Po is a relative value with Pomax, it has no any unit, } {i.e. in the waveform expression, Pomax is normarized to be as 1.} VAR J: double; {Actualy is an integer, but has to be assigned as double-} {to avoid type incompatibility.} BEGIN J:=(1/16)\* TCmax; {TCmax/16 has been rounded, so J is an integer.} {Now assign the waveform data, at 17 moments.} {Pulsewidth-FWHM-is 6 times of the intervals, not 8.} IF TCounter= 0 THEN Po:= 0:IF TCounter= J THEN Po:= 0.03;IF TCounter= 2\*J THEN Po:= 0.07;IF TCounter= 3\*J THEN Po:= 0.18;IF TCounter= 4\*J THEN Po:=0.3: IF TCounter= 5\*J THEN Po:=0.5; IF TCounter= 6\*J THEN

Po:=0.78: IF TCounter= 7\*J THEN Po:= 0.95: IF TCounter= 8\*J THEN Po:= 1:IF TCounter= 9\*J THEN Po:= 0.95; IF TCounter= 10\*J THEN Po:= 0.78;IF TCounter= 11\*J THEN Po:= 0.5: IF TCounter= 12\*J THEN Po:= 0.3;IF TCounter= 13\*J THEN Po:= 0.18;IF TCounter= 14\*J THEN Po:= 0.07;IF TCounter= 15\*J THEN Po:= 0.03:IF TCounter= TCmax THEN Po:=0;

{Linear interpolation, to get all Po value:} IF (TCounter> 0) AND (TCounter< J) THEN Po:= 0.03 \* TCounter /J;IF (TCounter> J) AND (TCounter< 2\* J) THEN Po:= 0.03 + (0.07 - 0.03)\* (TCounter - J)/J;IF (TCounter> 2\* J) AND (TCounter< 3\* J) THEN Po:= 0.07 + (0.18 - 0.07)\* (TCounter - 2\* J)/J;IF (TCounter> 3\* J) AND (TCounter< 4\* J) THEN Po:= 0.18 + (0.3 - 0.18)\* (TCounter - 3\* J)/J;IF (TCounter> 4\* J) AND (TCounter< 5\* J) THEN Po:= 0.3 + (0.5 - 0.3)\* (TCounter - 4\* J)/J;IF (TCounter> 5\* J) AND (TCounter< 6 \* J) THEN  $Po:= 0.5 + (0.78 - 0.5)^* (TCounter - 5^* J)/J;$ IF (TCounter> 6\* J) AND (TCounter< 7\* J) THEN Po:= 0.78 + (0.95 - 0.78)\* (TCounter - 6\* J)/J;IF (TCounter> 7\* J) AND (TCounter< 8\* J) THEN Po:= 0.95+ (1-0.95)\* (TCounter-7\* J)/J;IF (TCounter> 8\* J) AND (TCounter< 9\* J) THEN Po:= 1+ (0.95-1)\* (TCounter- 8\* J)/J;IF (TCounter > 9\* J) AND (TCounter < 10\* J) THEN Po := 0.95 + (0.78 - 0.95)\* (TCounter - 9\* J)/J;IF (TCounter> 10\* J) AND (TCounter< 11\* J) THEN Po:= 0.78 + (0.5 - 0.78)\* (TCounter - 10\* J)/J;IF (TCounter> 11\* J) AND (TCounter< 12\* J) THEN Po:= 0.5+ (0.3-0.5)\* (TCounter-11\* J)/J;IF (TCounter> 12\* J) AND (TCounter< 13\* J) THEN  $Po:= 0.3 + (0.18 - 0.3)^* (TCounter - 12^* J)/J;$ IF (TCounter> 13\* J) AND (TCounter< 14\* J) THEN Po:= 0.18 + (0.07 - 0.18)\* (TCounter - 13\* J)/J;IF (TCounter > 14 \* J) AND (TCounter < 15\* J) THEN Po:= 0.07 + (0.03 - 0.07)\* (TCounter - 14\* J)/J;IF (TCounter> 15\* J) AND (TCounter< TCmax) THEN

```
Po:= 0.03+ (0- 0.03)* (TCounter- 15* J)/J;
END;
```

```
PROCEDURE CalcsPomax(VAR Pomax: double);
{According to input laser energy, beam spot size, pulsewidth,}
{calcs max. peak power density. See equation 4.}
VAR
TCL: integer;
                                         {Local time counter.}
MidV: double;
BEGIN
                                         {Reset MidV.}
MidV := 0;
FOR TCL:= 1 TO 16 DO
BEGIN
TCounter:=round(TCL*(1/16)*TCmax-TCmax/32);
                                                    {CalcsPo needs TCounter.}
CalcsPo(Po);
                                         {For each time moment, calc Po.}
MidV:= (Po*DeltaTime*Tcmax/16)+MidV;
{Waveform intergration with time, in ns*(how many Pomax).}
END:
writeln('MidV:',MidV:9:6,' TCmax:',TCmax:10,' DeltaTime:', DeltaTime:7:5);
Pomax:= ((2*Epulse)/(Pai*Wo*Wo))/MidV;
writeln('Pomax: ',Pomax:9:7);
                                         \{in \ \mu j/(\mu m^* \mu m^* ns).\}
END;
PROCEDURE GetAlphaS(VAR AlphaS: double);
{According to temperature, get different AlphaS value for solid link.}
VAR
dl: integer;
                                         {Local loop counter.}
BEGIN
for dl := 0 to dmax do
BEGIN
if (dl > dface1) and (dl <= dface2) then
AlphaS:= AlphaSC;
                                         {For aluminum, its variation vs. tepmerature is neglected.}
END:
END;
PROCEDURE GetAlphaL(VAR AlphaL: double);
{Get Alpha value for the liquid state.}
VAR
DL: INTEGER:
BEGIN
for dl := 0 to dmax do
BEGIN
if (dl> dface1) and (dl<= dface2) then
AlphaL:= AlphaLC;
END;
END;
PROCEDURE CalcsP(VAR P: TwoDArraylink);
{Calcs the laser heating density for each link node at specific time moment,}
{according to the temperature and state for each node, calc the P for each node- 2 D array with m, d.}
VAR
ml, dl: integer;
                                          {Local counter for m, d.}
```

BEGIN FOR ml:= 0 TO Mlin DO FOR dl:= (dface1+1) TO dface2 DO {Set zero first.} P[ml,dl]:=0;FOR ml:= 0 TO Mlin DO begin {Evenly divided node.} Xm:= DeltaX\*ml; IF (Told[ml,dface1+1]<Tmelt)and(Told[ml,dface1+1]>=20) then Pmid:= Po\*Pomax\*Trans1\*exp((-2\*Xm\*Xm)/(Wo\*Wo)) {Effecitve laser power area density at Time moment of t.} ELSE  $T \ge T$  and  $T \ge 0.$ Pmid:= Po\*Pomax\*Trans2\*exp((-2\*Xm\*Xm)/(Wo\*Wo)); FOR dl:= (dface1+1) TO dface2 DO begin AlphaS:= AlphaSC; AlphaL:= AlphaLC; {Node has been gone.} IF Told[ml,dl]=0 then Begin P[ml,dl]:=0; Pmid:=Pmid; end: IF (Told[ml,dl]=Tmelt) and (Qsl[ml,dl]<LHmelt) then {Node's in solid to liquid transition.} BEGIN AlphaSL:=AlphaS\*(1-Qsl[ml,dl]/LHmelt)+AlphaL\*Qsl[ml,dl]/LHmelt; P[ml,dl]:=Pmid\* (1- exp(-AlphaSL\* DeltaZ))/DeltaZ: Pmid:=Pmid\* exp(-AlphaSL\* DeltaZ); END: IF(Told[ml,dl]<=Tvapo)AND(Told[ml,dl]>=Tmelt)AND(Qsl[ml,dl]>=LHmelt) THEN {Node's in liquid state.} BEGIN P[ml,dl]:=Pmid\*(1-exp(-AlphaL\*DeltaZ))/DeltaZ; Pmid:=Pmid\*exp(-AlphaL\*DeltaZ); END: IF (Told[ml,dl]>=Tstart) AND (Told[ml,dl]<Tmelt) THEN {Node's in solid state.} BEGIN P[ml,dl]:=Pmid\*(1-exp(-AlphaS\*DeltaZ))/DeltaZ; Pmid:=Pmid\*exp(-AlphaS\*DeltaZ); END: END: {of "For dl:= dface1+1 to dface2 do".} END: of "For ml := 0 to Mlin do".{of the procedure, output P[ml,dl].} END: PROCEDURE GetHDSiK (VAR K: TwoDArray); {Define K for passivation- High Doped Si-FOX with Temperature and states.} VAR ml, dl: integer; BEGIN For ml:= 0 to Mmax do For dl := 0 to dmax do {Assign the K value of High Doped Si at a few temperature points.} Begin

IF (dl>dface1)and(dl<=dface2)and(ml<=Mlin) then {The Aluminum link.} BEGIN IF Told[ml,dl]=0 THEN {Node has been gone.} K[ml,dl]:=0; IF Told[ml,dl]=20 THEN {When it's at the start temperature.} {in W/cm-deg.} K[ml,dl]:=2.3; IF Told[ml,dl]=200 THEN {in W/cm-deg.} K[ml,dl]:=2.4; IF Told[ml,dl]=660 THEN {in W/cm-deg.} K[ml,dl]:=2.1; {Interpolation to get the K value } IF (Told[ml,dl]>20) AND (Told[ml,dl]<200) THEN K[ml,dl]:=2.3+(Told[ml,dl]-20)\*((2.4-2.3)/(200-20));IF (Told[ml,dl]>200) AND (Told[ml,dl]<660) THEN K[ml,dl]:=2.4+(Told[ml,dl]-200)\*((2.1-2.4)/(660-200));{In phase transition.} IF (Told[ml,dl]=Tmelt) THEN K[ml,dl]:=1.6; IF (Told[ml,dl]>Tmelt) THEN {In liquid state.} K[ml,dl]:=1.1; END {For the passivation and FOX layers.} Else BEGIN If Told[ml,dl]=0 then K[ml,dl]:=0; {When is at the start temperature.} IF Told[ml, dl]= 20 THEN {in W/cm-deg.} K[ml,dl]:=0.013; IF Told[ml,dl]=1000 THEN {in W/cm-deg.} K[ml,dl]:=0.025; IF Told[ml,dl]=1500 THEN K[ml,dl]:=0.055; {in W/cm-deg.} IF Told[ml,dl]>1500 THEN K[ml,dl]:=0.055; {in W/cm-deg.} {Interpolation to get the K value.} IF (Told[ml,dl]> 20) AND (Told[ml,dl]<1000) THEN K[ml,dl]:=0.013+ (Told[ml,dl]-20)\*((0.025-0.013)/(1000-20)); IF (Told[ml,dl]> 1000) AND (Told[ml,dl]<1500) THEN K[ml,dl]:=0.025+(Told[ml,dl]-1000)\*((0.055-0.025)/(1500-1000));END: {Convert the unit to  $\mu j/ns-\mu m$ -deg.} K[ml,dl]:=0.0000001\* K[ml,dl];END: END: PROCEDURE Display(var Tnew:TwoDarray); VAR J2, J3, J4: integer; Begin writeln; writeln(MYFILE);

writeln('Time moment:', TCounter\*DeltaTime: 9:3, ' ns.'); writeln(MYFILE, 'Time moment:', TCounter\*DeltaTime: 9:3, ' ns.'); write( MYFILE,' '): write( ' X: '); for J2:= 0 to Mmax do BEGIN write(DeltaX\*J2:6:3); write(MYFILE, DeltaX\*J2:6:3); end: writeln: writeln(MYFILE); FOR J3:= 0 TO dmax DO {Loop Z axis} BEGIN write(10000\*DeltaZ\*J3:7:0, ''); write(MYFILE, 10000\*DeltaZ\*J3:7:0, ''); FOR J4:= 0 TO Mmax do Begin write(Tnew[J4,J3]:6:0); write(MYFILE, Tnew[J4, J3]:6:0); end: writeln; writeln(myfile); END: END: {The main program.} BEGIN writeln('2-D LASER PROCESSING SIMULATION, Yunlong Sun. ESI.'); writeln; assign(MYFILE,'SIMdata.txt'); rewrite(MYFILE); ConvUnit(Kmax, C, Rho, Cliq, Rholiq, AlphaSC, AlphaLC, LHsl, LHslp); ConvUnitp(Cp, Rhop, Cliqp, Rholiqp); Zend:= DeltaZ \* (dmax+1); {Set original value for these 2-D Array.} SetValue(Told, Tnew, Qsl, Qlv); {Estimate the max. stable time interval StabDT.} EstMaxStabDT(StabDT); write('Input the time interval (\*no big than StabDT\*)-in ns: '): readln(DeltaTime); {Get input of the DeltaTime.} {Time interval remains constant during the simu.} {Calc latent heat needed to melt a node.} CalcsLHmelt(LHmelt,LHmeltp); {Calc latent heat needed to vapor a node.} CalcsLHvapo(LHvapo,LHvapop); TCmax:=16\* round(((8/3)\*Pulsewidth/DeltaTime)/16); writeln('TCmax: ', TCmax:10,' Deltatime: ',DeltaTime:7:5); {Based on the waveform and time interval, calc time steps needed.} {The whole pulse length is (8/3 \* pulsewidth), then rounded to an integer.} {Because the waveform data assingment divides the pulse into 16 divisions, TCmax/16 is rounded.} J1max:= round(TCmax/1000); {Each 1000 time interval display the T once.} Judge:= 0;Judge2:=0; Ptotal:=0; Pused:=0; Hlost:=0;

Hlosl:=0; Eab:=0; {Set to zero first.} CalcsPomax(Pomax); {from E, Pulsewidth, Wo, Waveform, Calc Pomax for Gaussian beam.} FOR TCounter:= 0 TO TCmax DO {Time revolution.} Begin Time:= TCounter\*DeltaTime; CalcsPo(Po): {Laser pulse waveform factor-with time.} Ptotal:=Ptotal+Po\*Deltatime; End; FOR TCounter:= 0 TO TCmax DO {Time revolution.} Begin For m := 0 to mmax do for d := 0 to dface1 do Told[m,d]:=0; write('\*'); Time:= TCounter\* DeltaTime; {Laser pulse waveform factor-with time.} CalcsPo(Po); If Told[mlin, dface2]>=Tstart then Begin Pused:=Pused+Po\*DeltaTime; {2D Array, laser heating volume density for link m,d } CalcsP(P); GetHDSiK(K); {The following deals with the thermal conduction at defferent position- bondary or inner.} {For different state, the equation is the same, but different K will be used-determined by GetK.} FOR m:= 0 TO Mmax DO {Scan along the X axis.} {Scan along the Z axis.} FOR d := 0 TO dmax DO BEGIN {Xm=0, Z axis, due to symitry, T[m-1,d]=T[m+1,d].} IF m= 0 THEN BEGIN IF d= 0 THEN {Top boundary, no heat into the air, m=d=0.} BEGIN If Told[m,d]=0 then MidV1:=0 else Midv1:= 0.5\*(K[m,d]+K[m+1,d])\*(Told[m+1,d]-Told[m,d])/sqr(DeltaX);If Told[m,d]=0 then MidV3:=0 else MidV3 := 0.5\*(K[m,d]+K[m,d+1])\*(Told[m,d+1]-Told[m,d])/sqr(DeltaZ);Cond1 := 2\* MidV1 + MidV3;END:  $\{m, d=0.\}$ IF (d>0) AND (d<dmax) THEN {d is not 0, not dmax, m is still 0.} BEGIN If Told[m,d]=0 then Cond1:=0 else Begin Midv1:= 0.5\*(K[m,d]+K[m+1,d])\*(Told[m+1,d]-Told[m,d])/sqr(DeltaX);MidV3 := 0.5\*(K[m,d]+K[m,d+1])\*(Told[m,d+1]-Told[m,d])/sqr(DeltaZ);If Told[m,d-1]=0 then MidV4:=0 else
```
MidV4 := 0.5*(K[m,d-1]+K[m,d])*(Told[m,d-1]-Told[m,d])/sqr(DeltaZ);
Cond1:= 2*MidV1+ MidV3+ MidV4;
end;
End:
IF d= dmax THEN
                                       {Bottom left coner, MidV3=0.5*MidV4.}
BEGIN
Midv1:= 0.5*(K[m,d]+K[m+1,d])*(Told[m+1,d]-Told[m,d])/sqr(DeltaX);
MidV4:= 0.25*(K[m,d-1]+K[m,d])*(Told[m,d-1]-Told[m,d])/sqr(DeltaZ);
Cond1:= 2*MidV1+MidV4:
END:
END:
                                       {of "if m=0".}
IF (m>0) AND (m<Mmax) THEN
                                       {m is>0, but not Mmax.}
BEGIN
IF d=0 THEN
                                       {The top boundrary layer.}
{For m>0, d=0, no heat into the air, MidV4=0.}
BEGIN
If Told[m,d]=0 then
Cond1:=0
Else
Begin
If Told[m-1,d]=0 then
MidV2:=0
else
MidV2 := 0.5*(K[m-1,d]+K[m,d])*(Told[m-1,d]-Told[m,d])/sqr(DeltaX);
Midv1:= 0.5*(K[m,d]+K[m+1,d])*(Told[m+1,d]-Told[m,d])/sqr(DeltaX);
MidV3 := 0.5*(K[m,d]+K[m,d+1])*(Told[m,d+1]-Told[m,d])/sqr(DeltaZ);
Cond1:= MidV1+MidV2+MidV3
END:
End; {d=0}
IF (d>0) AND (d<dmax) THEN
                                       {Neither m, nor d is at the boundary.}
BEGIN
If Told[m,d]=0 then
Cond1:=0
Else
Begin
If Told[m-1,d]=0 then
MidV2:=0
else
MidV2:= 0.5*(K[m-1,d]+K[m,d])*(Told[m-1,d]-Told[m,d])/sqr(DeltaX);
If Told[m,d-1]=0 then
MidV4:=0
else
MidV4:=0.5*(K[m,d-1]+K[m,d])*(Told[m,d-1]-Told[m,d])/sqr(DeltaZ);
Midv1:=0.5*(K[m,d]+K[m+1,d])*(Told[m+1,d]-Told[m,d])/sqr(DeltaX);
MidV3:=0.5*(K[m,d]+K[m,d+1])*(Told[m,d+1]-Told[m,d])/sqr(DeltaZ);
Cond1 := MidV1 + MidV2 + MidV3 + MidV4:
END;
End:
IF d=dmax THEN
                               {Floated bottom, MidV3=0.5*MidV4.}
BEGIN
```

```
Midv1:=0.5*(K[m,d]+K[m+1,d])*(Told[m+1,d]-Told[m,d])/sqr(DeltaX);
MidV2:=0.5*(K[m-1,d]+K[m,d])*(Told[m-1,d]-Told[m,d])/sqr(DeltaX);
MidV4:=0.25*(K[m,d-1]+K[m,d])*(Told[m,d-1]-Told[m,d])/sqr(DeltaZ);
Cond1:=MidV1+MidV2+MidV4
END:
                               {of "m is >0, but not Mmax".}
END:
IF m=Mmax THEN
                               {2-D sim. Right side edge.}
BEGIN
                               {For the top right node, MidV4=0.}
IF d=0 THEN
BEGIN
If Told[m,d]=0 then
Cond1:=0
Else
Begin
If Told[m-1,d]=0 then
MidV2:=0
else
MidV2:= 0.25*(K[m-1,d]+K[m,d])*(Told[m-1,d]-Told[m,d])/sqr(DeltaX);
{Reduce MidV2 by an half-assuming MidV1 is half of MidV2: right boundary is-}
{not thermaly insulated, nor at a fixed temperature for less simulation error.}
MidV3 := 0.5*(K[m,d]+K[m,d+1])*(Told[m,d+1]-Told[m,d])/sqr(DeltaZ);
Cond1:= MidV2+MidV3
END:
End: {d=0}
IF (d>0) AND (d<dmax) THEN
Begin
If Told[m,d]=0 then
Cond1:=0
Else
Begin
If Told[m-1,d]=0 then
MidV2:=0
else
MidV2:= 0.25*(K[m-1,d]+K[m,d])*(Told[m-1,d]-Told[m,d])/sqr(DeltaX);
If Told[m,d-1]=0 then
MidV4:=0
else
MidV4:=0.5*(K[m,d-1]+K[m,d])*(Told[m,d-1]-Told[m,d])/sqr(DeltaZ);
MidV3:=0.5*(K[m,d]+K[m,d+1])*(Told[m,d+1]-Told[m,d])/sqr(DeltaZ);
Cond1:=MidV2 + MidV3+ MidV4
END:
End;
IF d=dmax THEN
                                {Right bottom node, MidV3=0.5*MidV4.}
BEGIN
MidV2:= 0.25*(K[m-1,d]+K[m,d])*(Told[m-1,d]-Told[m,d])/sqr(DeltaX);
MidV4 := 0.25*(K[m,d-1]+K[m,d])*(Told[m,d-1]-Told[m,d])/sqr(DeltaZ);
Cond1:= MidV2+ MidV4
END;
                                {of "
END;
                                        is Mmax."}
                                {End of the thermal conduction calculation.}
```

{The following determines the temperature change and phase transition.} {Temperature check starts from high towards low to avoid wrong repeating.} IF (d<=dface1) or (d>dface2) or (M>Mlin) THEN {The passivation.} Begin If Told[m,d]=0 then Tnew[m,d]:=0; If Told[m,d]>=Tvapop then Begin Qlv[m,d]:=Qlv[m,d]+Cond1\*DeltaX\*DeltaZ\*DeltaTime; IF Qlv[m,d]<0 then BEGIN Tnew[m,d]:=Told[m,d]+Qlv[m,d]/(Rholigp\*Cligp\*DeltaX\*DeltaZ); Qlv[m,d]:=0;END; IF Qlv[m,d]>=LHvapop THEN {Phase transition from liquid to vapor completed.} Tnew[m,d]:=0;{Phase transition from solid to liquid not completed yet.} If Qlv[m,d]<LHvapop then BEGIN {T fixed until the phase transition completed.} Tnew[m,d]:=Tvapop; END; END: {of "if T=Tvapop".} If (Told[m,d]>Tmeltp) AND (Told[m,d]<Tvapop) then BEGIN Tnew[m,d]:=Told[m,d]+DeltaTime\*(Cond1)/(Rholigp\*Cligp); Qlv[m,d]:=0;IF Tnew[m,d]>= Tvapop THEN {For node first reaches Tvapop, return possible overshot T to Tvapop, } {use the extra heat as part of the latent heat of fusion, fix T=Tmelt.} BEGIN Qlv[m,d]:= (Tnew[m,d]-Tvapop)\*DeltaX\*DeltaZ\*Rholiqp\*Cliqp; IF Qlv[m,d]< LHvapop THEN Tnew[m,d]:= Tvapop ELSE {Within one time interval, phase transition completed.} Tnew[m,d] := 0;End: END; IF Told[m,d]=Tmeltp THEN {Passivation layer, different melting temperature, c, Rho.} BEGIN Qsl[m,d]:=Qsl[m,d]+(Cond1)\*DeltaX\*DeltaZ\*DeltaTime; IF (Qsl[m,d]>=LHmeltp) THEN {Phase transition from solid to liquid completed, } {exceesive heat is used to raise liquid node's temperature.} BEGIN {writeln('At:',Time: 4:2,'ns, Node[',m:2,',',d:2,'] melt completed.');} Tnew[m,d]:=Told[m,d]+(Qsl[m,d]-LHmeltp)/(Rholigp\*Cligp\*DeltaX\*DeltaZ); Qsl[m,d]:=LHmeltp; END ELSE {Phase transition from solid to liquid not completed yet.} BEGIN Tnew[m,d]:=Told[m,d]; {T fixed until the phase transition completed.} {writeln('melt at node m:', m,' d: ', d,' MeltRatio: ',Qsl[m,d]/LHmeltp:5:4);} END;

{ of "if T=Tmeltp".}

END;

```
IF Told[m,d]<Tmeltp THEN
BEGIN
Tnew[m,d]:=Told[m,d]+DeltaTime*(Cond1)/(Rhop*Cp);
Qsl[m,d]:=0;
IF Tnew[m,d]> Tmeltp THEN
{For node first reaches Tmelt, return possible overshot T to Tmelt,}
{use the extra heat as part of the latent heat of fusion, fix T=Tmelt.}
BEGIN
Qsl[m,d]:= (Tnew[m,d]-Tmeltp)*DeltaX*DeltaZ*Rhop*Cp;
IF Qsl[m,d]<= LHmeltp THEN
Tnew[m,d]:= Tmeltp
                                {Within one time interval, phase transition completed.}
ELSE
Begin
Tnew[m,d]:= Tmeltp+(Qsl[m,d]-LHmeltp)/(DeltaX*DeltaZ*Rholiqp*Cliqp);
Qsl[m,d]:= LHmeltp;
End:
END;
                                {of "IF Told[m,d]<Tmeltp THEN". }
END:
                                {Passivation.}
end:
IF(d>dface1)and(d<=dface2)and(m<=Mlin)THEN {Link.}
Begin
If Told[m,d]=0 then
Tnew[m,d]:=0;
If Told[m,d]>=Tvapo then
Begin
Qlv[m,d]:=Qlv[m,d]+(P[m,d]+Cond1)*DeltaX*DeltaZ*DeltaTime;
IF Qlv[m,d]<0 then
BEGIN
Tnew[m,d]:=Told[m,d]+Qlv[m,d]/(Rholiq*Cliq*DeltaX*DeltaZ);
Olv[m,d]:=0;
END;
                                {Phase transition from liquid to vapor completed.}
IF Qlv[m,d]>=LHvapo THEN
Tnew[m,d]:=0;
If Qlv[m,d]<LHvapo then {Phase transition from solid to liquid not completed yet.}
BEGIN
                                {T fixed until the phase transition completed.}
Tnew[m,d]:=Tvapo;
END;
                                {of "if T=Tvapo".}
END;
If (Told[m,d]>Tmelt) AND (Told[m,d]<Tvapo) then
BEGIN
Tnew[m,d]:=Told[m,d]+DeltaTime*(P[m,d]+Cond1)/(Rholiq*Cliq);
Qlv[m,d]:=0;
IF Tnew[m,d]>= Tvapo THEN
{For node first reaches Tvapo, return possible overshot T to Tvapo,}
{use the extra heat as part of the latent heat of fusion, fix T=Tmelt.}
BEGIN
Qlv[m,d]:= (Tnew[m,d]-Tvapo)*DeltaX*DeltaZ*Rholiq*Cliq;
IF Qlv[m,d]<= LHvapo THEN
Tnew[m,d]:= Tvapo
```

ELSE {Within one time interval, phase transition completed.} Tnew[m,d] := 0;End; END: IF Told[m,d]=Tmelt THEN BEGIN Qsl[m,d]:=Qsl[m,d]+(P[m,d]+Cond1)\*DeltaX\*DeltaZ\*DeltaTime;IF (Qsl[m,d]>=LHmelt) THEN {The transition from solid to liquid completed, it's in liquid state,} {the extra overshot heat will be used to raise temperature of the node.} BEGIN {writeln('At:',Time: 4:2,'ns, Node[',m:2,',',d:2,'] melt completed.');} Tnew[m,d]:=Told[m,d]+(Qsl[m,d]-LHmelt)/(Rholiq\*Cliq\*DeltaX\*DeltaZ); Qsl[m,d]:=LHmelt; END ELSE {Phase transition from solid to liquid not completed.} BEGIN Tnew[m,d]:=Told[m,d]; {T fixed until the phase transition completed.} { writeln('melt at node d: ', d,'MeltRatio: ',Qsl[m,d]/LHmelt:5:4); } END; END; {of "if T=Tmelt".} IF Told[m,d]<Tmelt THEN BEGIN Tnew[m, d]:= Told[m,d]+DeltaTime\*(P[m,d]+Cond1)/(Rho\*C); Qsl[m,d] := 0;IF Tnew[m, d]> Tmelt THEN {For node first reaches Tmelt, return possible overshot T to Tmelt, } {the extra heat is used to melt some part of the node, fix T=Tmelt.} BEGIN Qsl[m,d]:= (Tnew[m,d]-Tmelt)\*DeltaX\*DeltaZ\*Rho\*C; IF Qsl[m,d]<= LHmelt THEN Tnew[m,d]:= Tmelt ELSE {Within one time interval, phase transition completed.} Begin Tnew[m,d]:= Tmelt+(Qsl[m,d]-LHmelt)/(DeltaX\*DeltaZ\*Rholiq\*Cliq); Qsl[m,d]:= LHmelt; End; END: {of "IF Told[m,d]<Tmelt THEN".} END; End: {link.} END; {of m, d loop.} {Display the temperature distribution} FOR J1:= 1 TO J1max DO BEGIN JJ:=1/DeltaTime; IF TCounter = JJ \* J1 THEN {Every 1 ns, displays temperature.} BEGIN {Display temperature.} Display(Tnew); writeln('Pomax: ',Pomax:9:7,' Po: ',Po:9:7); writeln('Time moment:', TCounter \* DeltaTime : 9:3,' ns.');

Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end; {of "FOR J1:= 1 TO J1max DO".} end; IF (Tnew[0,dface1+1]>= Tmelt)and(Tnew[0,dface1+1]<900)and(Judge=0)then BEGIN judge:=1; {Only write once when T>Tmelt} Display(Tnew); Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end: IF (Tnew[0,dface1+1]>=1000)and(Tnew[0,dface1+1]<1100)and(Judge=1) then BEGIN {Write once when 1200>T>1000.} judge:=0; Display(Tnew); Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end: IF (Tnew[0,dface1+1]>=1200) and (Tnew[0,dface1+1]<1300)and (Judge=0) then BEGIN {Write once when 1600>T>1500.} judge:=1; Display(Tnew); Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end: IF (Tnew[0,dface1+1]>=1400)and(Tnew[0,dface1+1]<1500)and(Judge=1) then BEGIN {Write once when 1200>T>1000.} judge:=0; Display(Tnew); Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end; IF (Tnew[0,dface1+1]>=1600) and (Tnew[0,dface1+1]<1700)and (Judge=0) then BEGIN {Write once when 1600>T>1500.} judge:=1; Display(Tnew); Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end; IF (Tnew[0,dface1+1]>=1800)and(Tnew[0,dface1+1]<1900)and(Judge=1) then BEGIN {Write once when 1200>T>1000.} judge:=0; Display(Tnew): Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); end: If Tnew[0,dface1+1]>=Trupt then {Rupture!!!!} Begin For m := 0 to Mmax do For d := 0 to Dmax do Begin If  $d \le dface1$  then Tnew[m,d]:=0 else if (Tnew[m,d]>=700) and (M<=Mlin) then Tnew[m,d]:=0 {All nodes over 700 degree are gone with rupture.}

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else Tnew[m,d]:=Tnew[m,d]; end; Display(Tnew); Writeln(Myfile,'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); End; IF (Tnew[Mlin,dface2]=0) and (Judge2=0) then {The end of simulation.} Begin Judge2:=1; Display(Tnew); Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); {Display only once} End; Told:=Tnew; For m:= mlin-3 to mlin do For d:=dface1+1 to dface2 do If (Told[m-1,d]=0) and (Told[m-1,d+1]=0) and (Told[m,d]>1000) then Told[m,d]:=0;{of "If Tnew[mlin, dface2]>=Tstart then".} end; END: {of "FOR TCounter:= 0 TO TCmax DO", the time loop } Writeln(Myfile, 'Used laser energy:', Epulse\*Pused/Ptotal: 7:4,' µj'); writeln('\*\*\*\*\*\*\*\* DONE \*\*\*\*\*\*\*\*'); CLOSE(myfile); END. {of the main program.}

# VITA

Yunlong Sun was born on the 26th of Dec. 1943 in Shanghai, China. He graduated from Solid-State Physics & Semiconductor Specialty, Electronic Engineering Department, Qin-Hua University, Beijing, China in 1966 (It required six years study. At that time, there were not any degree titles in China for the higher education system).

### 1967-1979

Technician, then an Engineer, North China Research Institute of Electro-Optics (NCRIEO), Beijing, China, solid-state lasers and their relevant electronics, application systems.

### 1979-1980

Visiting Scholar in the Optical Science Center, University of Arizona, Tucson, Arizona.

# 1980-1982

Visiting Scholar at Ginzton Lab, Stanford University, single frequency solid-state laser. Developed the world's first single frequency Nd:YAG laser with bandwidth of less than 200 KHz.

#### 1982-1989

Senior Engineer, Director of the Laser Division, Deputy Chief Engineer of NCRIEO, Beijing, China, working on or in charge of several national key projects such as the "Satellite Laser Ranging System", "Laser Trimming System", "500 W Pulsed Nd:YAG Laser Industry Laser Processing System". Developed a single frequency Nd:YLF oscillator for China's national laser fusion project. Different national awards were bestowed due to the satisfactory completion of all of those projects.

### 1989-1990

Visiting Scholar at Ginzton Lab, Stanford University.

# 1990- Present

Senior Scientist, Electro Scientific Industries, Inc. Portland, Oregon, frequency conversion of YAG laser and their applications, diode pumped solid state laser, interaction of the laser beam and matters.

During last twenty years, he published over twenty papers and authored five US patents. Another two patents are pending.

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