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Laser Drilling of Vertical Vias in Silicon

W. Doyle Miller, Richard A. Gassman, David M. Keicher

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W. Doyle Miller
Advanced Packaging Department 1333

Richard A. Gassman
Multichip and Custom Products Department 2277

David M. Keicher
Physical and Joining Metallurgy Department 1831
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

Any advance beyond the density of standard 2D Multichip Modules (MCM) will require a vertical interconnect technology that can produce reliable area array interconnection with small feature sizes. Laser drilled vertical vias have been controllably produced in standard silicon (Si) wafers down to 0.035mm (0.0014 inches) in diameter. Several laser systems and their system parameters have been explored to determine the optimum parametric set for repeatable vias in Si. The vias produced have exhibited clean smooth interior surfaces with an aspect ratio of up to 20:1 with little or no taper. All laser systems used, their system parameters, design modifications, theory of operation, and drilling results shall be discussed.

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LASER DRILLING OF VERTICAL VIAS IN SILICON

ABSTRACT:

Any advance beyond the density of standard 2D Multichip Modules (MCM) will require a vertical interconnect technology that can produce reliable area array interconnection with small feature sizes. Laser drilled vertical vias have been controllably produced in standard Si wafers down to 0.035 mm (0.0014 inches) in diameter. Several laser systems and their system parameters have been explored to determine the optimum parametric set for repeatable vias in Si. The vias produced have exhibited clean smooth interior surfaces with an aspect ratio of up to 20:1 with little or no taper. All laser systems used, their system parameters, design modifications, theory of operation, and drilling results shall be discussed.

INTRODUCTION:

The Vertical Via Technology Development program was initiated to establish an enabling process technology for a known limitation of 2D MCM packaging technology; specifically, vertical interconnection. The program was established and funded under an internal development program called the 3D Packaging Program. This program was to demonstrate 3D packaging by stacking 2D MCM's with area array vertical interconnects (vias) for dense high speed advanced electronics. The design that was implemented was a real time image analysis system which needed a large I/O, memory, processing throughput, and high frequency operation. This required the use of a 3D packaging structure to satisfy proximity interconnection and give the necessary speed. The vias for this development project were vertical holes of controlled dimensions, electrically isolated from each other and the substrate, and filled with an electrically conducting material. After much study, laser drilling was chosen as the most viable process for forming vertical holes. This paper will confine its discussion to the drilling process.

Laser drilling offered the greatest control of precise parameters and had a quick turnaround time. The desired results for the laser drilled vias were: accurately controlled via diameters, excellent interior wall geometries, minimal thermal/mechanical impact to the substrate, and compatability with downstream processing. The complete via technology process is very complex and utilizes several diverse technologies which may conflict, therefore care must be taken to insure a compatable process. Process compatability is an example of some of the other types of requirements that make determining "optimum" process parameters for the laser system and vias so complex. The laser system parameters that were studied were: laser type, wavelength (as it applies to the absorption of photons in Si), power densities, optical system design, atmosphere, process time, and long-term stability of drilling process.

Before we discuss the actual experiments and their results, the relationship between photon wavelength and absorbtion of that photon's energy should be understood. The primary laser system used on this project was the Nd:YAG which radiates at its fundamental wavelength of 1.064 microns. At this wavelength, each photon has an energy of 1.16 eV. The wafers we use are high purity single crystal Si with a resistivity of 20 ohm-cm at room temperature (25° C). The Si has an optical absorption coefficient at 1.064 microns (1064 nm) of aproximately 200 (cm^{-1}), which means it is almost transparent to this wavelength. The optical absorption coefficient at 532 nm is approximately 8000 (cm^{-1}) and at 266 nm the absorption exceeds $1x10^6$ (cm^{-1}). Using Lambert's Law, we see that the penetration depth of the light into the sample decreases proportionally to the increase in the absorption coefficient, which is exponentially dependent on wavelength of the light. This is clearly seen in the absorption coefficient numbers given and is experimentally verified in the measured values given in Table 5, showing sample thickness, wavelength and absorption for Si. This means that at shorter wavelengths (as we go from IR to visible to UV), the absorption depth decreases, the percentage of beam energy absorbed increases, and the energy per photon doubles (with each wavelength harmonic, E_{ph} = 1.16eV, at 1064nm; E_{ph} = 2.32eV, at 532nm; and E_{ph} = 4.65 eV, at 266nm.). This combined effect of smaller penetration depth, increased photon energy and increased percentage of beam absorption results in orders of magnitude increase in volumetric energy density deposition upon the Si from the illumination of the laser beam. This produces different physical effects in Si such as going from melting/vaporization at 1.064 to vaporization/ablation at 0.532 to complete ablation at 0.266. These changes in effect permit additional process control for smaller scale features. Our goal was to obtain as much feature control as was possible with current hardware.

This investigation started with the use of a Nd:YAG laser at its fundamental wavelength of 1064 nm. As we studied the results from our initial experiments, we came to a limitation of this laser. It would not allow enough control to produce satisfactory holes. There seemed to be too much remelt and microcracking in the holes which made post processing that much more difficult. From this we continued to investigate potential solutions with the fundamental but also investigated doubling the frequency to improve the results. We did develop a process which greatly improved the results with the fundamental frequency but saw more control and smaller ultimate vias with the doubling effort. The doubling effort led us to trepanning, shield gases, and design changes in the laser cavity which have brought us to the tight control of the output. In addition, we did some preliminary investigation of UV lasers such as the KrF excimer (248 nm). We sent some samples to Resonetics (a laser manufacturer) and were impressed with the results. We also had an opportunity to actually work with the University of South Florida and their excimer laser. We were able to collaborate on some common experiments using the laser. We are also planning to investigate the use of a quadrupled Nd:YAG that would radiate at 266 nm, also in the UV. The details of these experiments and their results are discussed in this report.

EXPERIMENT:

1.064μm Wavelength

The first vertical vias were laser drilled using a standard Nd:YAG Q-Switched laser at the fundamental wavelength (1064 nm). See Table 1.

Table 1. U.S. Laser characteristics and parameters used for drilling silicon.

U.S. Laser System - C.W. pumped Q-switched Nd:YAG Laser

Wavelengths - 1064 and 532 nm

Pulse Lengths -	130 - 190 ns
Laser Mode -	Multi- Mode
Pulse Energies -	3.3-5mJ (1064 nm) and 0.4-0.7mJ (532 nm)
Pulse Frequency -	3 kHz
Exposure Time -	50ms

The absorption of laser energy in semiconductor materials can create different physical mechanisms such as melting, vaporization, or ablation depending on the energy and wavelength of the laser.[1] The original experimental test matrix was developed specifically to determine if via formation was possible in Si substrates at the fundamental wavelength. Initial parameters were set at a Q-Switch repetition rate of 3 kHz, an exposure time of 40-50 ms, a 0.7 GW/cm^2 irradiance, and a F.L. lens of 90 mm. Although the laser system produces high energy with these short pulses, a single pulse does not produce great enough energy to penetrate through the Si substrate thickness. The number of pulses is determined by the Q-switch rep. rate and exposure time. Therefore a series of pulses were required. The initial experiment was successful in producing holes in Si. The original holes showed taper, inconsistant geometries, and significant silicon reflow on the interior walls as seen in Figure 1. Guided by these initial results, it was determined that multiple exposures of the laser pulse (50 ms exposure time) might remove some of the reflow. An experimental test matrix was established to verify this. Repetitions, from 2-10 attempts on the same location, were processed. Analyzing the cross-section micrographs of these holes showed that there was no discernable difference in hole geometries. The repetitions had very little impact on removing all reflow due to a very small percentage of absorbed power. However, in next assembly when 25-37 micron diameter Au wire was easier to thread through each via for interconnection. The operation proved easier and less rework was required. A repetition rate of 3 appears to optimize the process. Repetition rates greater than 3 only added valuable time to the process.

Helium was the next experimental variable for two reasons. First, its thermal conductance properties would create an excellent atmosphere to reduce thermal impact to the substrate and reduce damage in and around the hole. Second, the flow down through the via would help expel Si material during processing. The expected results should show smoother interior geometries of the hole with reduced substrate damage. A test matrix was set-up to determine this effect. See Table 2.

Figure 1A & 1B. Cross-section micrographs of original vias drilled with the initial experimental laser parameters.

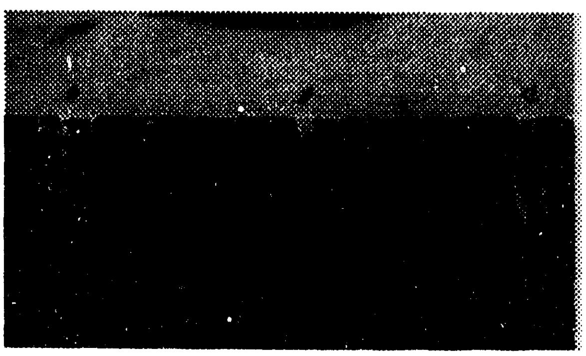


Figure 1A. Cross-section micrograph of two vias drilled with the original experimental parameters at the fundamental wavelength.

Figure 1B. Micrograph showing extreme material melt at the fundamental wavelength.

Table 2. Helium Test Matrix

Helium Pressure (P.S.I.)	Helium Flow Rate (C.F.H.)	Lamp Current	Pulse Repetition Rate
3	20	13	1
3	40	13	2
3	60	13	3
3	20	15	1
3	40	15	2
3	60	15	3
3	20	17	1
3	40	17	2
3	60	17	3

After analyzing SEM micrographs of holes drilled in a helium atmosphere versus non-helium atmosphere it was determined that there was no significant evidence that helium was beneficial to the process. As seen in Figures 2A and 2B interior walls did not appear smoother, there was no reduction in Si melt on the wall surfaces and substrate damage around the via did not show improvement.

The next experimental change made to the system was in the optical rail. The equation for theoretical spot size is $s = (4\lambda/\pi)(f/d)M^2$ where λ= wavelength, f = lens focal length, d = beam diameter entering the lens and M^2 is a beam quality factor. When the beam quality factor approaches the theoretical limit of 1.0 (at TEM_{00}) the theoretical spot size equation is reduced/which is aberation free to $s = 1.27\lambda(f/d)$. From the equation, it is obvious that a smaller focal length lens will produce a smaller spot size and consequently the higher power densities. In general, a large absorbed power density is the key to induce vaporization which will reduce melt flow. Absorbed power density (measured as power per volume) depends on three factors, two of which will be discussed later. The primary factor for absorbed power density is the diameter of the focused spotsize. A minimum spotsize is achieved with a large beam diameter and a short focal-length lens.[2] The holes drilled with the 40 mm focal length lens (Figures 3A and 3B) were more consistant and had more uniform diameters than those using 90 mm and 212 mm lenses (Figures 2A and 2B). The interior walls of the holes (in Figure 3A) also exhibited much less thermal melt and eccentricity than the holes seen in Figure 2A and 2B. The melt flow indicates the beam is heating a liquid region which melts its way through the Si in an uncontrolled way. In Figure 3B. the frozen drip pattern illustrates how molten Si material is being forced up against the beam path indicating the melted material is obviously being pushed upward in the hole as a result of the internal dynamics of the melt which has no exit. Melting also maximizes the residual stress field around the hole after drilling and could cause fracturing of the substrate in via arrays.[3] The top of each via showed less material melt, but still exhibits microcracking around the via from the porosity left by the melt flow. In order to better control the diameter during drilling, it is essential to vaporize or ablate the material rather than melting it.

Figure 2A & 2B. Helium shielded via vs. Non-helium shielded via.

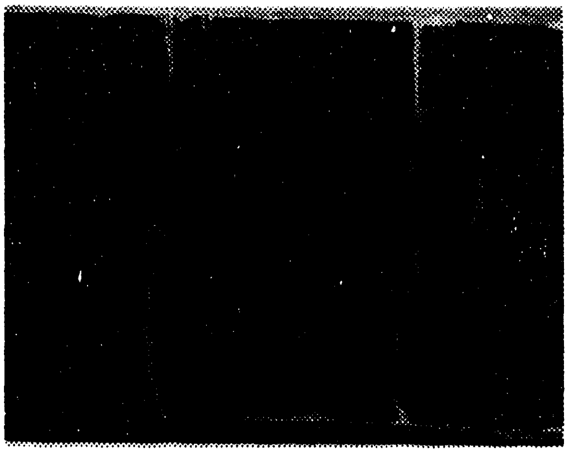


Fig 2A. Via drilled in a helium atmosphere. Flow rate 40 CFH. Pressure 2 PSI. Standard laser parameters. Via exhibits Si melt resolidified on interior side walls.

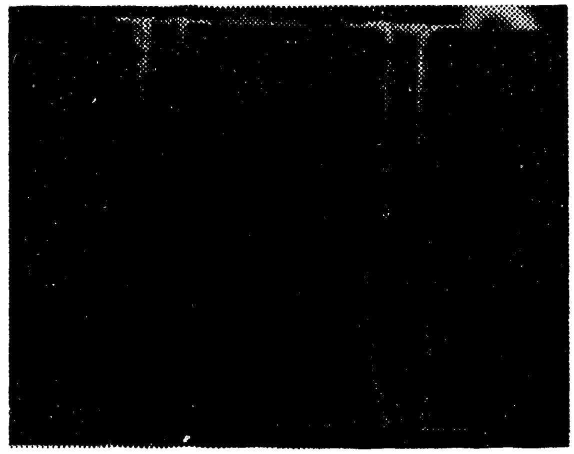


Fig 2B. Via drilled in ambient atmosphere. Standard laser parameters. The wall geometries are comparable to the vias drilled in a helium atmosphere.

Figure 3A & 3B. Micrograph of cross-section via drilled with 40mm FL lens.

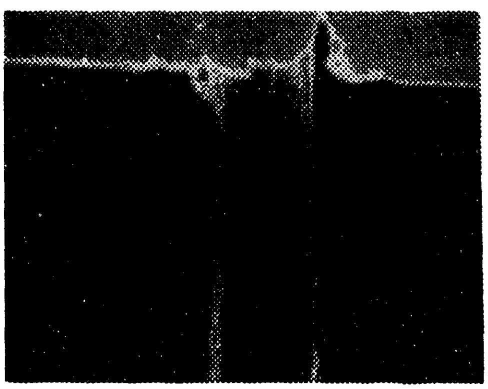


Fig 3A. Micrograph of via drilled with a 40 mm F.L. lens. The interior walls exhibit less material reflow and surrounding sub-the strate damage.

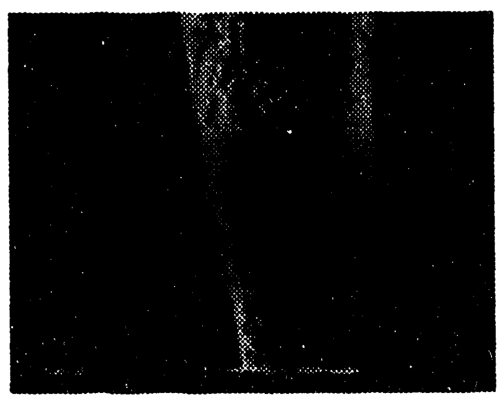


Fig 3B. Micrograph of the same via showing excessive Si material redeposited at the bottom of via against the beam path. The via diameter is ≅ 100 microns.

1 From the comparison of Figure 3A to all previous holes, the hole diameter was reduced from approx. 0.080 mm (0.003") to 0.040 mm (0.0015"). The new holes also exhibit much less melt flow, porosity, and substrate cracking due to the higher energy densities provided by the smaller spotsize. This proves that a small focal length lens, possessing a smaller focused spot size, does have a positive impact on hole diameter control. The clearer holes indicate that a further increase of the energy density could improve the quality of hole walls even more and reduce the thermally induced mechanical stress field caused by melting during the drilling process. From the beginning, we also knew that with a multimode beam (our original setup did not produce a TEM_{00} beam at all power settings and was not utilizing diffraction limited optics), the beam quality factor was not minimized, the spotsize was not minimized, and subsequently the power densities decreased. A perfect beam (TEM_{00}) has a beam quality factor, M, of 1.0 and any deviation from perfection will only increase it. Since the beam quality factor, M^2, is squared in the equation, a small deviation from perfection will greatly increase the spotsize diameter. To optimize the laser for drilling, a TEM_{00} beam with diffraction limited optics is necessary.

As we varied system parameters in an attempt to optimize hole formation, we discovered that lamp current has a significant impact on hole diameter but not on hole morphology. During the original experiment the current was varied from 11-17 amps to determine the impact on wall cleanliness. There were inconsistant results from this experiment which made it difficult to draw any conclusions about how lamp current affects interior walls. However, what was realized is that when the current to the krypton arc lamp is increased the spot size of the beam will increase proportionately. This increase comes from the beam quality factor term in the spotsize equation. With increased power, the diameter of the beam increases due to a thermal lensing effect of the Nd:YAG rod. As you pump harder (with more lamp current) laser emission occurs at other frequencies when the gain exceeds the internal losses for these frequencies. These other frequencies are detemined by the energy band structure of the laser medium. The internal losses are a function of the quality of the laser medium (i.e. the YAG crystal). As you pump the laser harder you produce a higher "mode" or additional frequencies in addition to the fundamental frequency of the laser. These higher transverse modes lead to a deviation from the ideal Gausian profile which affects the beam quality factor. Therefore, at the fundamental wavelength, hole diameters were related to the drive current for the arc lamps in our multimode system as shown in Table 3.

Table 3. Via Diameter vs. Lamp Current

Lamp Current	Via Diameter
11 amps	≅ 37.5 microns
13 amps	≅ 50.8 microns
15 amps	≅ 76.2 microns
17 amps	≅ 101.6 microns

All information was obtained using the U.S. Laser, Nd:YAG Laser System

Once we realized that we needed to obtain a higher quality beam for stable operation, we measured the temporal profile of the beam from the U.S. Laser System using a high speed silicon detector and Nicolet Model# 320 oscilloscope. These measurements were performed to determine pulse repeatabilty and pulse duration at specific current values. This equipment also allowed determination of the mode structure of the beam which allowed us to improve the cavity configuration, pulse duration, and peak powers. This was done to prove the laser's long term stability for the type of application envisioned for this work. Once modified, the pulse repeatability was very good which produced more consistant results in our drilling. No deviation was observed in peak power and pulse duration. Pulse durations were measured at the full wave half maximum (FWHM) value of the peak power for lamp current ranging from 11-17 amps. The pulse durations did vary from 130-190 nano-seconds, but they were very consistant at a given lamp current. These modifications proved that the laser system was consistant over the necessary parameters.

The final development while working with the fundamental wavelength produced the best results for hole geometries to date. We modified our drilling process by drilling each via twice (A process that has been done before). This time the lamp current was varied for each exposure duration. Essentially, we drilled a bore hole at 10 amps producing a hole of $\cong$ 25 microns diameter. With the bore hole in place, a second via at the exact same location was drilled with 14-16 amps to create a final via of $\cong$ 75 microns in diameter. The purpose of this experiment was to determine if a small bore hole would allow Si material to be expelled during the final drilling process to obtain the desired via diameter and less redeposition. The resultant holes exhibited good geometries from entrance to exit and showed minimal material reflow. In addition, the process proved to be repeatable. See Figure 4. After analyzing the SEM micrographs it was obvious that the small bore hole did allow a significant amount of Si material to be expeled from the hole without resolidifying on the interior walls. Also the bore hole at this current was small enough to allow minimal reflection of the laser beam in the hole and adequate absorption of the energy into the Si to create a good hole.

The Nd:YAG laser system operating at the fundamental wavelength proved that hole formation in Si substrates with a laser is feasible. With careful consideration of laser parameters the process for drilling holes in Si produced adequate interior wall geometries and good repeatability. However, at the fundamental wavelength we were limited by the low absorption of the Si and the relatively large beam diameters, limitations due to multimode operation. First, at 1.064 microns, absorption was not great enough to produce vaporization and avoid melting. Second, even though this system gave us the required diameters for the next sub-process, we were limited to a range of 25-100 micron diameter holes. With the system operating at this wavelength, careful analysis of the beam must be performed when process parameters are changed to insure TEM_{00} mode operation.

Table 5. Measured Optical Properties in Si

Thickness (mm)	Wavelength (nm)	Absorption (%)	Transmission (%)	Reflection (%)
0.051	532	63	0.0	37
0.051	1064	20	69	11
0.102	532	63	0.0	37
0.102	1064	27	45	28
0.635	1064	67	8	25

Figure 4. Cross-section micrograph of optimum via developed at the fundamental wavlength.

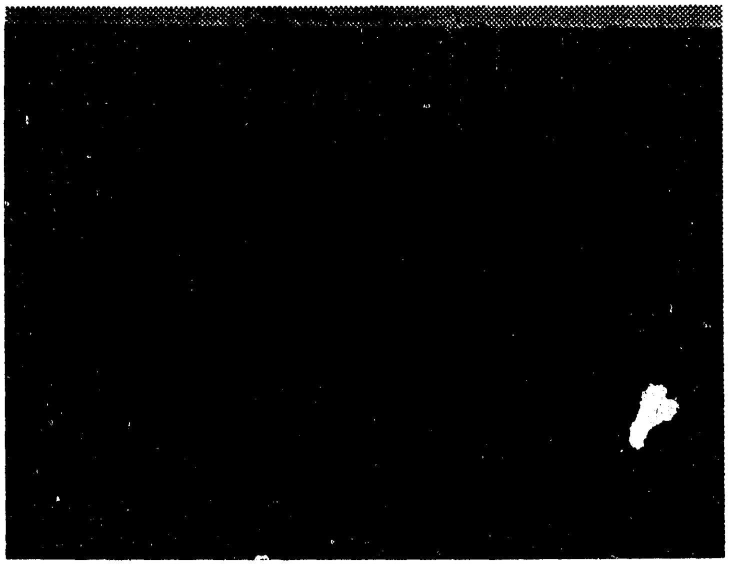


Figure 4. Via drilled at a lamp current of 10 amps creating a bore hole of ≅ 25 microns in diameter and then a second via drilled in the exact location with a lamp current of 17 amps creating a via of 100 micron diameter with little or no Si melt and minimal damage to the substrate around the via formation.

532nm Wavelength -

In order to investigate the increased absorbed energy densities to create more vaporization than melting, the Nd:YAG laser system was modified to accept a nonlinear frequency doubling crystal which changed the wavelength to 0.532 microns (532nm). This change offered a larger optical absorption coefficient in the Si (i.e. higher volumetric energy density deposition) and smaller potential spot size. The combination of these two factors creates more vaporization than melting. As we discussed provioussly, the absorbed energy density is a function of the absorption properties of the material (Si) at the specific laser wavelength. See Table 5. The characteristics of absorption, reflection and transmission in Si varied drastically from the fundamental wavelength to the second harmonic wavelength of 532 nm. Therefore, the energy density of a 532nm beam is significantly better than at the fundamental wavelength. In addition, the spot size will vary directly with wavelength as is indicated by the following equation for theoretical spot size, $s = (4\lambda/\pi)(f/d)M^2$. From this relationship it is obvious that as the wavelength decreases so does the focused beam spot size. Thus, at the second harmonic wavelength the beam area is reduced by a factor of four, producing an increase in energy density at the focused spot. Finally, the energy of each photon doubles as the frequency is halved. All three effects are combined in this change. The total effect from this one change increases the deposited volumetric energy density by at least two orders of magnitude, thus causing a change in the physical response of the material (i.e. vaporization rather than melting). The experiments conducted at this wavelength were conducted with two separate laser systems. One was the U.S. Laser System described in Table 1 and the other a Quantronix Model#114 power supply and laser head whose characteristics are shown in Table 6.

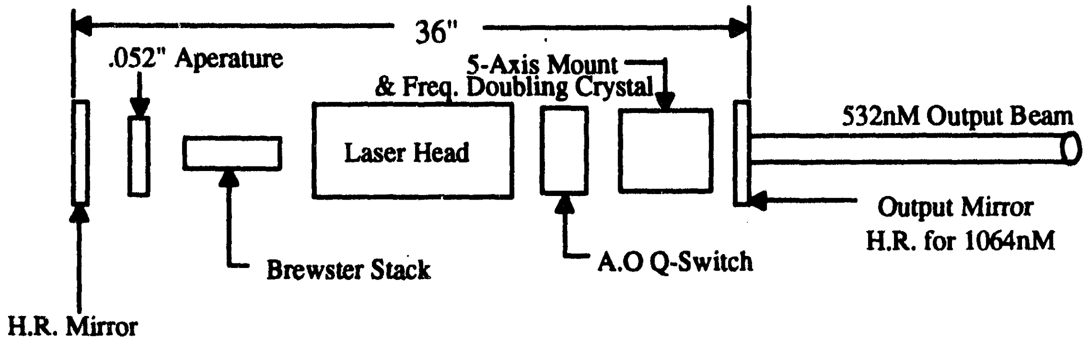
Table 6. Quantronix Model # 114 Characteristics

Quantronix Model#114 Power Supply and Laser Head - C.W. Pumped Q-Switched Nd:YAG Laser in a U.S. Laser Class I enclosure.

Wavelength -	532nm
Pulse Length -	150ns
Laser Mode -	TEM 00
Pulse Energies -	1.25mJ
Pulse Frequency -	3kHz
Exposure Time -	7 seconds
Optical Accessories -	Tre-pan Assembly

All experimental information was obtained using intra-cavity frequency doubling. Two different nonlinear frequency doubling crystals were used. Beta Barium Borate (BBO) and Potasium Titanyl Phosphate (KTP). The BBO crystal produces a stable conversion of the frequency with less temperature sensitivity, however the conversion efficiency will be slightly less than the KTP. The KTP crystal has excellent conversion efficiency producing higher output power but output is unstable over time and temperature. The original experiments involved the U.S. Laser System with a BBO crystal intra-cavity. The standard cavity configuration consisted of spatial filters, brewster stack, Q-switch and doubling crystal. See Figure 5.

Figure 5. Optical Rail Set-Up for Frequency Doubling Operation



The initial set-up produced approximately 2 watts, at 532nm wavelength beam, with the standard configuration as shown in Figure 5. The nonlinear crystal was placed intra-cavity because the circulating power within the cavity of a Nd:YAG laser is up to ten times the extracavity power.[3] Also, the spatial aperatures were used to create a TEM_{00} mode. The TEM_{00} mode offers the highest energy density; because the conversion efficiency of the nonlinear crystal increases with energy density, this maximizes the output at 532nm.[4] The intracavity polarizer was used to provide a polarized beam. The 5-axis mount is then used to match the orientation angle of the nonlinear crystal to the polarization of the beam creating the frequency doubled output.

Once the system design was completed and functional, an experimental matrix was produced to verify system parameters and Si material response. (Test matrix shown in Table 7.) In order to compare the effects of helium on hole formation, no helium assist was run using the same lamp current and repetition rates as in Table 7. The original test matrix showed that the power level available at 532nm was capable of penetrating 625μm silicon, however the taper of the via was significant and the via diameter was extemely small. Entrance diameters were on the order of 25 microns and were approximately 12.5 microns at the exit. The interior walls did not exhibit as much silicon melt, but geometries looked very poor and a large amount of taper from entrance hole to exit hole was evident. Cross-section micrographs did not show conclusive evidence that helium was beneficial to the process. As seen with 1064, the addition of helium as a shielding gas showed no discernable difference. See Figure 6. Lamp current variances would vary spot size and consequently vary via diameters. However, at maximum current the largest via diameter was approximately 25 microns. This diameter was to small for the metalization subprocess requirements.

Table 7. Original Test Matrix for 532nm laser operation.

HELIUM		REPETITION RATES: 1 repitition	2 repetitions	3 repetitions	LAMP CURRENT
	20 CFH	X	X	X	13A
	40 CFH	X	X	X	15A
	60 CFH	X	X	X	17A

Figure 6A. and 6B. Micrograph of cross-sectioned vias drilled with original parameters set for 532nm.

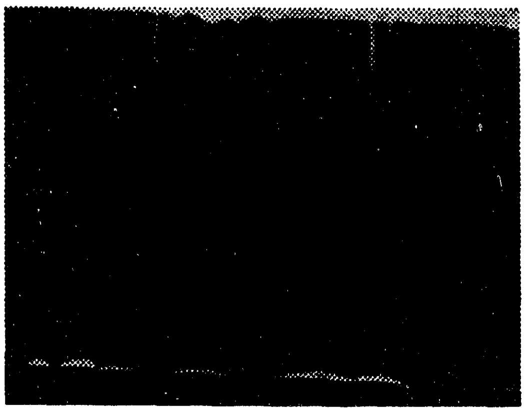


Fig. 6A. Micrograph shows extreme taper and very small diameter vias at 532nm compared to 1064nm. The entrance hole diameter is ≅ 25 microns (.001") and the exit hole has tapered to ≅ 12.5 microns (.0005") diameter.

Fig. 6B. Micrograph showing less Si melt and damage to the side walls compared to vias drilled at 1.064μm.

With initial data indicating that drilling Si at 532nm was promising, the project focused on optimizing the laser system for 532nm operation. A dedicated frequency doubled Nd:YAG laser, Quantronix Model#114 power supply, U.S. Laser Model# 3732-A laser head was enclosed in a U.S. Laser Class I cabinet. A KTP frequency doubling crystal was used to maximize the second harmonic output power of the system. The KTP crystal produces higher efficiency doubling and is less susceptible to crystal damage caused by thermal heating that could severely degrade performance. These improvements were specifically made to optimize the power density at the Si substrate surface. With the laser optimized for second harmonic operation a short focal length abberation free lens was obtained and the mechanism for material vaporization was in place. However, one significant problem had to be dealt with. Due to the smaller wavelength and TEM_{00} mode, the maximum via diameters were significantly less than what was required for the complete interconnect process. Maximum via diameters at maximum lamp current were measured to be 25μm at the entrance.

In order to produce larger diameters with existing laser system parameters, a technique called "tre-panning" was used. Tre-panning has been used extensively in mechanical fabrication. Tre-panning is the process of offsetting the beam from the normal axis of the optics and then scanning the beam in a circular motion around the normal axis to circumscribe a larger diameter circle which creates the required diameter hole. A tre-pan optical assembly was developed to fit the existing laser system. To accomplish this several design considerations had to be considered. First, the resolution of beam offset to the normal had to be very precise. Second, to maintain maximum power densities transmission losses had to be minimized. Third, not knowing an exact process parameter the circular motion had to have variable speed control. The final design utilized two BK7 glass 1° wedges mounted in an optical assembly designed to fit into the system beam path prior to the focusing lens. The assembly held both wedges independent of one another. (See Figure 7.) Thus maximizing the resolution of the offset beam to the normal. In addition, the wedges choosen were matched optically for angular displacement to maximize resolution of the entire tre-pan assembly. This was accomplished by passing a HeNe laser beam through a multitude of test wedges at a specific distance. Once the beam entered the wedge angular displacement was measured at a distance of 21'6" from the test wedge for greater angular displacement and subsequently better resolution to match this distance. This was done with a large quantity of test wedges to insure the best match. Once the precisely matched wedges were chosen, they were A/R coated for 532nm to minimize transmission losses. This matched set produced offset at the workpiece from 0.0 - 0.060" diameters (0.236 mm) using a 40mm F.L. lens. The last consideration was the variable speed motor to control RPM of the tre-pan assembly. The two piece wedge assembly was placed in a rotating housing and then placed in the beam path prior to the focusing lens. The assembly was rotated by a variable speed D.C. motor using a small drive belt. In the specially designed assembly, one wedge is held stationary and the second wedge rotates around the fixed wedge to create beam displacement. This allows for precise displacement and control of the beam off the normal axis. Then the entire assembly housing that incoporates both wedges is rotated from 0-110 RPM. The beam enters the tre-pan assembly on normal axis and will remain on normal axis when exiting the tre-pan assembly when both wedges are aligned perfectly with respect to each other as shown in Fig. 7. As you slightly rotate the free wedge with respect to the fixed wedge you create a displacement of the beam as shown in Figure 8. Amount of displacement is dependent upon wedge alignment and is completely operator controlled with excellent resolution.

Figure 7. Tre-pan Optical Wedge Design

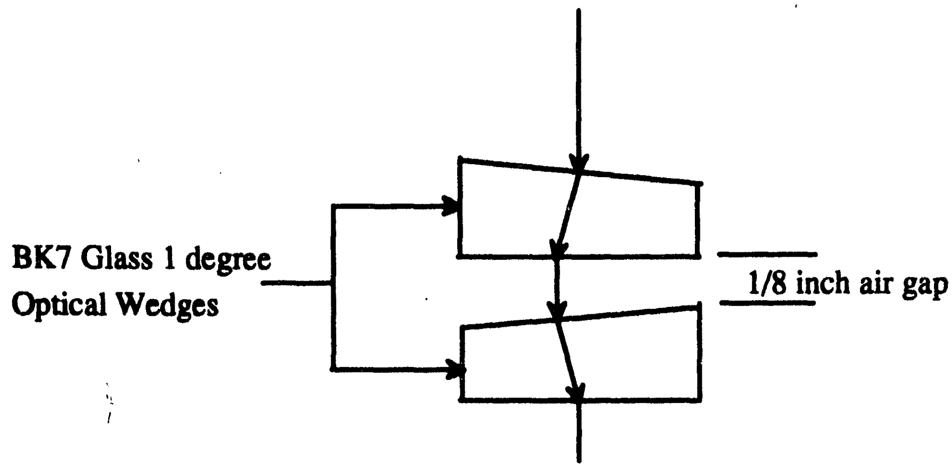


Fig. 7 - Wedges as shown the beam will deviate through each wedge and remain on the same optical path when exiting the tre-pan assembly.

Figure 8. Optical Tre-Pan Assembly

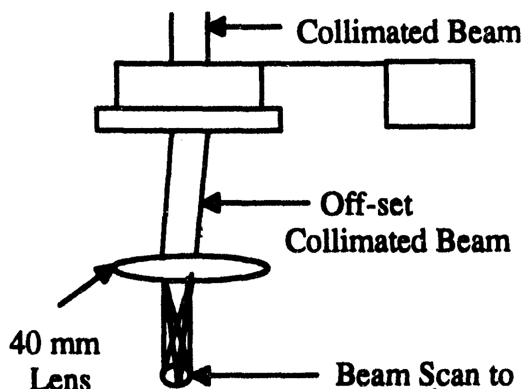


Fig. 8 Side view of tre-pan assembly and how the collimated laser beam is offset thru the focusing lens and then rotated from 0-110 RPM.

Once the complete system, including tre-pan assembly, was operational, multiple vias were drilled. The parameters that were varied, included lamp current, tre-pan RPM, and exposure time. The new system quickly demonstrated it was capable of drilling vias with the desired geometries and consistancy that was lacking in previous experimental designs. Preliminary optical inspection with light illuminating the via from underneath provided data that the via was very circular, with smooth interior wall surfaces and essentially no taper at the diameter desired. The initial vias were drilled with the following laser parameters: 532nm wavelength, 1 watt average power, 3khz pulse frequency, 40mm focal length lens, 5 second exposure time, 110 RPM tre-pan assembly rotation rate offset to produce a 0.005" (0.127mm) hole.

Further experimental matricies provided data to optimize via formation in Si with thicknesses ranging from 0.008" to 0.025" (0.203mm to 0.635mm). Vias produced exhibited excellent geometries, minimal taper, smooth interior wall surfaces and no damage to the substrate surrounding the via formation. (See Figures 9A-9F.)

The micrograph in Figure 9A shows a functional die with .037mm (.0015") diameter via in a .100 x .100 mm (.004" x .004") aluminum bond pad. With no damage to the bond pad as shown, there is no adverse affect to processing wire bond interconnects. Figures 9B and 9C show micrographs of cross-sectioned vias taken at 90° and 45° angles thru a functional die of .300mm (.012") thickness. The via diameter is ≅ .050mm (.002"). Fig. 9C shows vias in a functional die that is .375mm thick with no evidence of microcracking in and around the via as seen with vias produced with 1064nm wavelength. Fig. 9D illustrates good repeatability in the process. This optical photo shows a 9x9 matrix of .050mm (.002") diameter vias on .254mm (.010") centers with no damage to the Si substrate. Figs. 9E and 9F illustrate the diversity of the tre-pan assembly. Vias were drilled in the same substrate thickness as Fig. 9C, but the via diameter is .125mm and each via still exhibits no material damage in around the hole.

Figures 9A. thru 9F. Micrographs of vias drilled at 532nm utilizing optical tre-pan assembly for beam scanning.

Fig. 9A. Micrograph of via showing via diameter versus bond pad size. Bond pad is .100 X .100 mm square (.004" x .004")

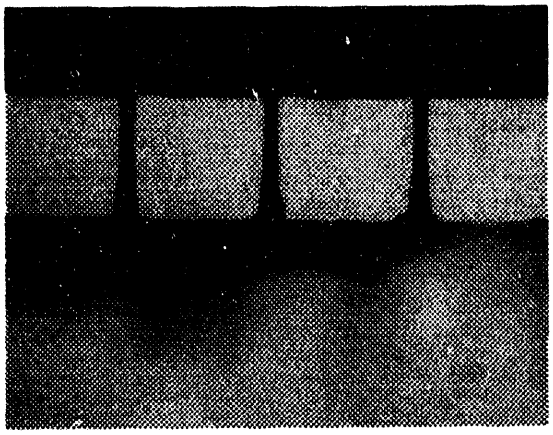


Fig. 9B. Micrograph of cross-sectioned vias in .375 mm thick Si substrate showing good geometries, minimal taper and excellent repeatability. Via diameter is ≅ 50 micron (.002").

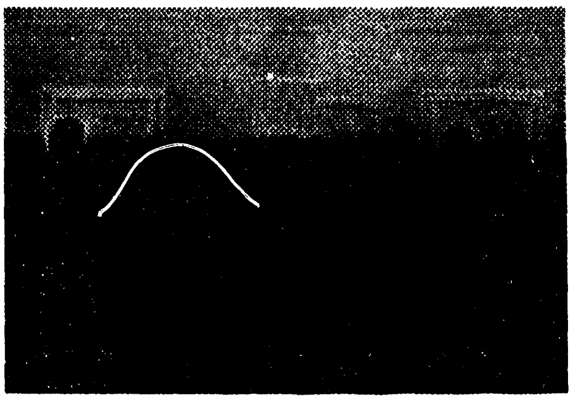


Fig 9C. Micrograph of cross-sectioned vias thru a functional die of thickness .425mm (.015"). The via diameter is ≅50 micron (.002").

Fig. 9D. Optical photograph showing 50 micron (.002") diameter entrance holes on 254 micron (.010") centers. Verifying consistancy of the frequency doubled Nd:YAG system design.

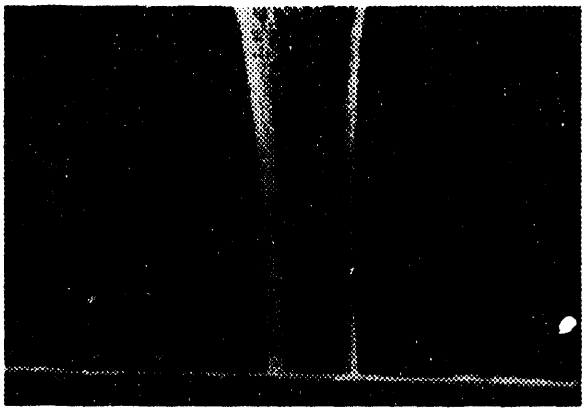


Fig. 9E. Micrograph of cross-section via that is ≅ .126mm (.005") diameter. The via was drilled in .375mm (.015") thick Si substrate illustrating the diverse capabilities of the system design.

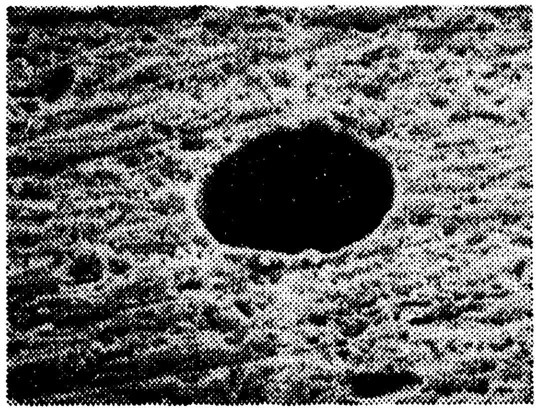


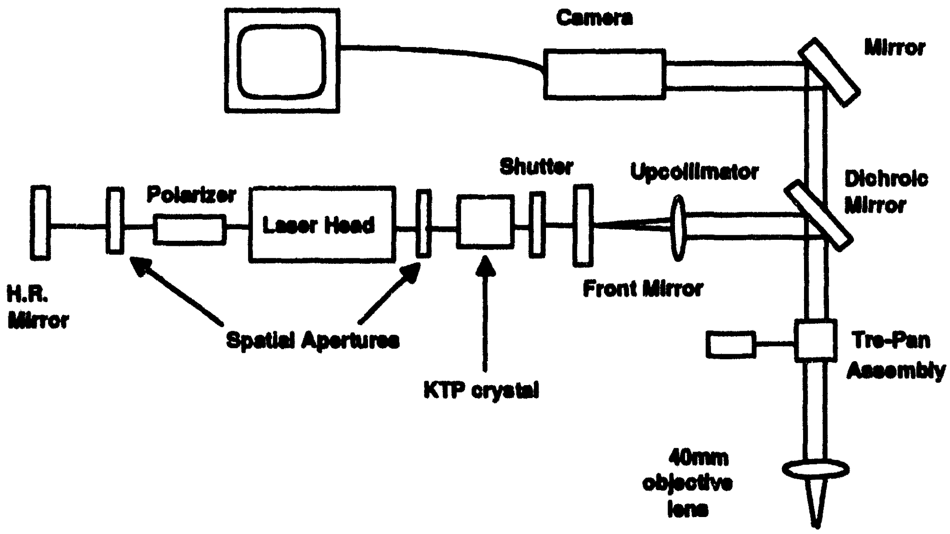
Fig. 9F. Optical photo of ≅ .126mm (.005") diameter via in Si substrate. Exhibiting excellent circular geometries with clean, smooth interior walls.

Summary of 532nm

It was obvious from our results using the lasers fundamental wavelength that energy densities needed to be increased to obtain better drilling results. In order to obtain the necessary energy densities, a frequency doubled 532nm Nd:YAG laser system was procured which offered improved absorption, a smaller focused spot size and increased energy of each photon. The energy of a photon at the 532nm wavelength is double that for a photon at the fundamental (1064nm) wavelength, as show earlier. Also, the optical absorption coefficient of Si at 532 nm is increased by a factor of forty and the area of the spot is reduced by a factor of four over the fundamental, creating higher absorbed power densities in the substrate. This was the key to optimize the drilling process at or near the vaporization/ablation region and produced significantly better results.

The final key element of the system design was the use of optical tre-panning apparatus to provide precise diameter control and hole morphology control. Using the Q-Switched, frequency doubled Nd:YAG laser with the optical tre pan assembly and a 40mm F.L. lens, has proven that vertical via technology is not only possible but practical in Si. The process has been proven to be repeatable and to meet the requirements for the metallization process to create vertical interconnects. This laser system design has also demonstrated excellent flexibility to changing technical requirements for a diversity of applications. The complete laser system configuration is shown in figure 10.

Figure 10. Frequency Doubled Nd:YAG Laser System

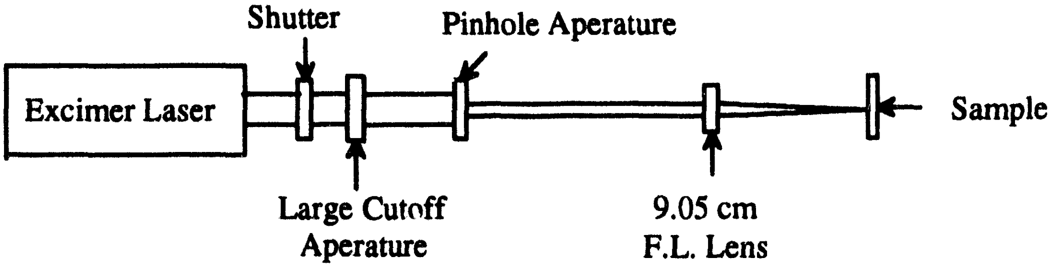


248nm Wavelength -

The final wavelength that was investigated for drilling silicon was 248 nm. This wavelength is produced by an excimer laser. An excimer laser is a inert-gas/halide, gas dynamic laser which produces high power, high efficiency, and high brightness as a coherent UV source.[6] Excimer lasers are capable of producing wavelengths from 193 nm to 360 nm, depending on the gas mixture and ratio. The major advantage that we saw in the excimer was that it was a coherent source of UV energy. The energy per photon at 248 nm is approximately double that of 532 nm and silicon's optical absorption increases from 8000 (cm^{-1}) at 532 nm to well over 1×10^6 (cm^{-1}) at 248 nm. These increases move the material removal process to an ablation regime and away from melting or vaporization. The ablation process removes the material without significant thermal energy input to the substrate providing better looking holes and more precise control of cutting action. Another advantage we saw in the excimer laser was the relatively short pulse lengths available, typically 15-20 nsec compared to 130-200 nsec for the doubled Nd:YAG system. These short pulse lengths decrease the amount of heat that goes to the substrate which significantly reduces the thermal impact on the substrate. A disadvantage to the excimer is its low frequency operation. Because it is a gas dynamic laser, it takes much more time for the popuation inversion to take place and the laser to lase. The excimer can only fire up to 250 times per sec. The Q-switched Nd:YAG can be set at anywhere from 1K to 50K Hz. If you use an excimer, this parameter lengthens the time it takes to cut a hole if you cut one hole at a time, which is what we are doing currently. However, because the excimer is a gas dynamic laser, a larger laser can be built to provide energy densities high enough to use the entire 1 inch by 2 inch beam without focussing the beam. By using a proper shadow mask, the larger laser could simultaneously drill many holes in that 1" by 2" area. Therefore, using this masking technique, many holes could be drilled in parallel, thus reducing the overall drilling time. This would speed up the cutting process considerably. The excimer laser is the only UV laser which has this potential since the Nd:YAG lasers dont lend themselves to parallel processing.

We had an opportunity to experiment with an excimer laser when we were graciously invited to do some collaborative research with Prof's. Rex Lee and Wilfredo Moreno at the University of South Florida's Center for Microelectronics Research in February 1992. They had recently purchased a Questek 2000 excimer laser which they were setting up with XeF and KrF to do damage studies on electronic devices. One objective of the trip was to investigate the excimer's suitability as a cutting tool for this work. We used the KrF gases which produces a beam at 248 nm. We experimented with various thicknesses of Si wafers ranging from 0.025" (0.625 mm) to 0.050" (1.27 mm). We also varied: repetition rates (rep rates), pulse energy (mJ), power (watts), the optical length (the distance between the pinhole aperature and the focusing lens), and where we placed the sample (at the image plane or the focal point). See system setup in Figure 11. We were limited in the type and quality of the experiments we could accomplish because some of the key optical pieces were either not available or being repaired while we were there. We kept the experimental matrix as simple as possible in order to obtain the best data possible with the simple setup being used. The via side walls looked very good with smooth interior wall surfaces with little or no material melt (See Figure 12.). However, the large taper (approx 2:1 through 0.025") and large via entrance diameter (approx. 0.005" - 0.008") were considered to be areas of concern. Another concern was the cutting speed which took a minimum of 30 seconds for the 0.025" wafers. These parameters would limit the utility of an excimer for drilling vias in substrates if they could not be improved. Two other key factors in determining the utility of an excimer laser are its large initial cost (anywhere from $250K and up) and the extensive ES&H requirements associated with putting it in a laboratory or manufacturing environment. Its operating cost are significant when you consider the cost of the rare inert gases and the frequency at which these bottles are changed. These factors will all have to be incorporated into the decision to use an excimer. More research will also be necessary to confirm the excimer's limitations and/or abilities for diameter, taper, and cutting speed control. The two days we spent with USF did not allow adequate time to investigate many of these parameters. It was unclear whether the excimer would be better than say a quadrupled Nd:YAG (at 266 nm). The power of the quadrupled YAG is significantly less than that of an excimer but its cost, frequency, and ease of operation may make it a better choice. We plan to investigate this possibility in FY93.

Table 11. Excimer laser and Optical Rail Set-Up



SUMMARY:

When we began to investigate the possibility of putting fine holes in Si substrates for vertical electrical interconnect (or vias) for Si Multichip Modules (MCM), laser drilling was just one of the possibilities. We were looking for processes that could produce holes in Si consistantly, with the necessary alignment and accuracy, would produce high quality hole geometries, and be compatible with typical clean room Si fabrication processes. Although, our initial results were not perfect, we did see the potential of laser drilling after some modification to the initial setup. Laser drilling, as we have defined it in this report, still has some drawbacks. Our best results, to date, are with the doubled Nd:YAG laser with the tre-pan assembly. However, with our anticipated need of approximately 400 vias per Si substrate, at least 4 substrates per six inch wafer, and 24 wafers per wafer lot, drilling 1200 holes per wafer at approx. 5 sec per hole will take almost 2 hours of drilling time (assuming an automated system, which has not been completed, yet). This serial process is, at this time, necessary, since no other laser system has the performance in Si of what we can do currently. We will be looking for the laser that can drill many holes simultaneously, maybe the KrF excimer or speeding up the drilling process. This is a serious limitation for the laser drilling process at the present time.

In this report, we have investigated three different laser sources; the fundamental wavelength of the Nd:YAG laser at 1064 nm, the doubled Nd:YAG laser at 532 nm, and the KrF excimer laser at 248 nm. All three sources produced holes in Si. The fundamental wavelength of the Nd:YAG proved that hole formation in Si substrates was feasible. We also learned that careful consideration of the laser parameters for the process was critical to produce the results necessary and that stability of the laser would be an important parameter if this process was to be used for production type of work. The fundamental wavelength's utility was limited by poor absorption of that wavelength in Si and hole diameter limitations caused by the power and beam characteristics at that wavelength. We were also limited by the hardware we had available. Via morphology was acceptable but not what we considered to be the best attainable.

The doubled Nd:YAG produced the best results at the dimensions we considered to be necessary for our applications. These improvements were obtainable through the combined effect of doubling the frequency of the laser light which increased the absorption, made possible smaller beam diameters, and doubled the energy per photon. We also improved the laser cavity to produce a consistant TEM00 beam and other laser parameters to produce a stable output for long periods of time which will be necessary for a production laser. In addition, we added some extra features to make the system give us better quality results by adding the tre-panning assembly. All these changes resulted in greater control and consistant high quality results. These results also showed that we could controllably drill sensitive electrically good die through the bond pads and not destroy the functionality of these die.

Finally we studied the use of an excimer UV laser at the University of South Florida's Center for Microelectronics Research. Although limited by the available optical setup that was current at USF while we were there, we were able to ascertain basic characteristics of the excimer by the results. Our initial assumptions about the drilling parameters of the laser were fundamentally correct. The short pulse lengths produced fine control of the cutting action. The substrate material showed no cracking and very good morphology of the resulting holes. What we were not expecting was the large taper and the length of time it took to drill each hole through the substrate. This was compounded when we realized that this was with a focused beam. These parameters discouraged us from exploring further into the excimer laser. In all fairness, a fully operational setup and more carefully thought through experiments should be accomplished to finally ascertain the utility of the excimer laser to this type of processing.

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[3] T.S. Gross, S.D. Hening and D.W. Watt, *Crack Formation During Laser Cutting of Silicon,* Journal of Applied Physics, Jan. 15, 1991
[4] Miller
[5] Miller
[6] Daniel J. Ehrlich & Jeffrey Y. Tsao, Laser Microfabrication (Academic Press, Inc., 1989)

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