SAND95-0797C

# Laser Micromachining of Through Via Interconnects in Active Die for 3-D Multichip Module *


Dahwey Chu
Sandia National Laboratories
P.O. Box 5800, M.S. 1082
Albuquerque, NM 87185-1082
Phone: 505-845-8148
Fax: 505-844-2991
Email: chud@smtplink.mdl.sandia.gov

W. Doyle Miller
Sandia National Laboratories
P.O. Box 5800, M.S. 1082
Albuquerque, NM 87185-1082
Phone: 505-844-7142
Fax: 505-844-2991
Email: millerwd@smtplink.mdl.sandia.gov



## Abstract

*One method to increase density in integrated circuits (IC) is to stack die to create a 3-D multichip module (MCM). In the past, special post wafer processing was done to bring interconnects out to the edge of the die. The die were sawed, glued, and stacked. Special processing was done to create interconnects on the edge to provide for interconnects to each of the die. These processes require an IC type fabrication facility (fab) and special processing equipment. It contrast, we have developed packaging assembly methods to created vertical through vias in bond pads of active silicon die, isolate these vias, and metal fill these vias without the use of a special IC fab . These die with through vias can then be joined and stacked to create a 3-D MCM. Vertical through vias in active die are created by laser micromachining using a Nd:YAG laser. Besides the fundamental 1064 nm (infra-red) laser wavelength of a Nd:YAG laser, modifications to our Nd:YAG laser allowed us to generate the second harmonic 532 nm (green) laser wavelength and fourth harmonic 266nm (ultra violet) laser wavelength in laser micromachining for these vias. Experiments were conducted to determine the best laser wavelengths to use for laser micromachining of vertical through vias in order to minimize damage to the active die. Via isolation experiments were done in order determine the best method in isolating the bond pads of the die. Die thinning techniques were developed to allow for die thickness as thin as 50 μm. This would allow for high 3-D density when the die are stacked. A method was developed to metal fill the vias with solder using a wire bonder with solder wire.*


## I. Introduction

There are several enabling technologies required in creating 3-D multichip modules (MCM). The main requirements are the thinning of die to a quarter of their regular thickness, the creation of through vias in die or MCM substrates, the isolation of these vias, and providing electrical conductivity from the front side of the die or MCM substrate to the back side.

To achieve high density through via interconnects in the die or MCM substrate for 3-D application, high aspect ratio via hole diameter to hole length is required. One way to achieve this rapidly and economically is to use laser micromachining/drilling techniques with a Q-switched Nd:YAG laser. Studies were conducted at three different laser wavelengths to determine which wavelength would minimize damage to the die or MCM substrate. Various techniques were tried to provide for via isolation in the die or MCM substrates. The final solution was laser micromachining/drilling with oxygen. Solder filling of the through via using a wire bonder and special solder wire was shown to be feasible.

## II. Die Thinning

To increase the density for 3-D MCM in the vertical direction, thinning the die or MCM substrate down to as small as one quarter of their original thickness needed to be demonstrated. The equipment used for die thinning is a Logitech PM4A precision lapping and polishing machine. Two other pieces of equipment used in conjunction with the Logitech PM4A are the Logitech VPB1 vacuum pressure bonding jig and the Logitech PP5GT precision polishing jig mounted with the Logitech PSM1 programmable sample monitor. Figure 1 shows the thinning equipment setup. The die are mounted onto 83 mm glass discs using quartz wax. The Logitech VPB1 system is then used to achieve a uniform bond between the sample and the glass disc. This glass disc is held on to the Logitech PP5GT jig by vacuum. The Logitech PSM1 which is mounted to the jig consists of two components: the sample monitor itself and the digital linear gauge. The Logitech PSM1 allows one to program in the amount of material to be removed and automatically stops the procedure when completed. The thickness of the die is measured by an Ono Sokki digital linear gauge.

# DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

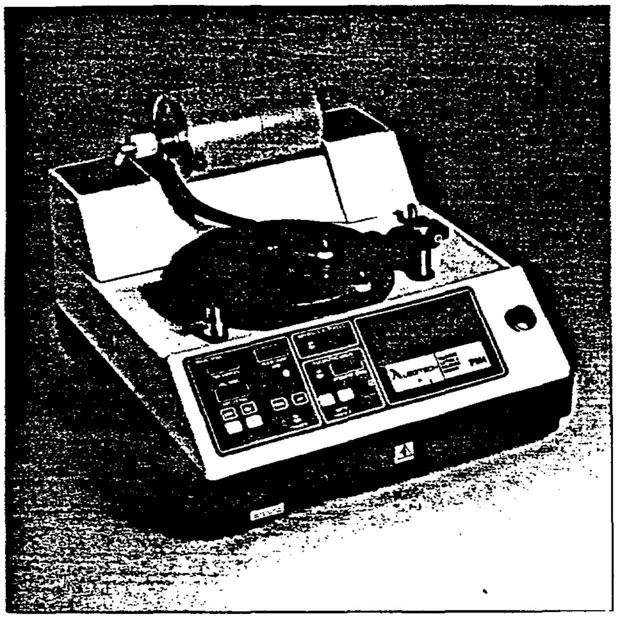

**Figure 1.** Logitech PM4A Thinning Equipment

Using the Logitech PM4A, the die or MCM substrate as large as 4" in diameter could be thinned down to 50 µm. Figure 2 shows the cross section of die at regular thickness of 625 µm, 150 µm , and 50 µm. After thinning has been completed, the die are carefully removed from the glass disc by dissolving the wax in hot limonene and cleaning in isopropyl alcohol. By conducting regular assembly packaging experiments on the thinned die, it was determined that the minimal thickness of a die should be no less than 150 µm. Die thinned to less than 150 µm have yield loss due to assembly handling of more than 25%.

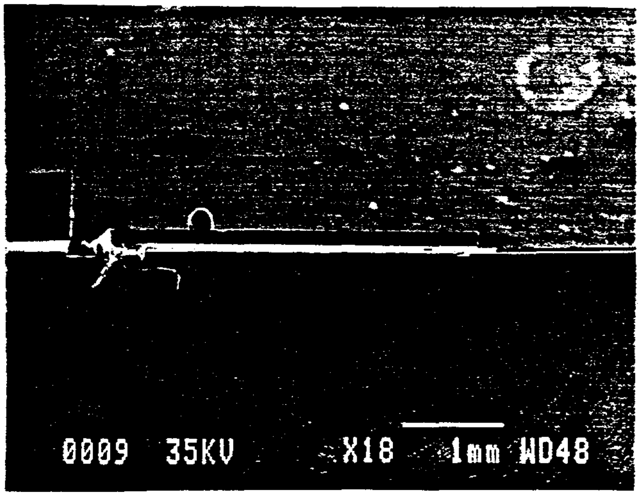


**Figure 2.** Cross Section of Thinned Die

### III. Back side isolation

After the die are thinned, the backs must be electrically isolated. This is accomplished by "painting" on an insulative material. Initially both spin on glass (SOG) and polyimide were tried. It was decided that polyimide was more suitable both for its isolation properties (tested by using probes/digital multimeter) and ease of handling. The procedure includes: placing the die face down on blue tape, applying the polyimide to the backs with a small paintbrush, air drying for one hour while still on the tape, removing from tape and curing in nitrogen for 1 hour at 175° C and 1 hour at 300° C. The polyimide used was Micro-Si SPI-115.

### IV. Laser Micromachining/Equipment

Laser through holes were created in Si substrates and active circuits utilizing a U.S. Laser Corp. Nd:YAG laser system. The fundamental system is Q-Switched @ 4 kHz. and produces an average power of 10 watts. The laser cavity is also configured with 0.060" apertures to produce a $TEM_{00}$ beam. Experimental trials to investigate the optimal through hole laser processes were made using the fundamental wavelength (1064 nm), the second harmonic wavelength (532 nm) and the fourth harmonic wavelength (266 nm).

The fundamental system was slightly modified to improve beam quality and thereby minimizing the focus beam spot size. The laser characteristics are as follows:

**Fundamental Wavelength (1064 nm)**

| | |
|---|---|
| Irradiance: | $2.32 \times 10^9$ watts/cm$^2$ |
| Q-Switch Rep. Rate: | 4 kHz. |
| Pulse Width: | 190 nsec |
| Laser Beam Mode: | $TEM_{00}$ |
| Focal Length Lens: | 40 mm |
| Beam Focused Spot Size: | ≅ 24 µm |

Second harmonic generation (SHG) was accomplished with a standard intracavity configuration. A non-linear temperature tuned crystal of lithium triborate (LBO) was added for SHG. Laser parameters at 532 nm are as follows:

**Second Harmonic Wavelength (532 nm)**

| | |
|---|---|
| Irradiance: | $5.8 \times 10^9$ watts/cm$^2$ |
| Q-Switch Rep. Rate: | 4 kHz. |
| Pulse Width: | 150 nsec |
| Laser Beam Mode: | $TEM_{00}$ |
| Focal Length Lens: | 40 mm |
| Beam Focused Spot Size: | ≅ 12 µm |

Fourth harmonic generation (FHG) was initially developed in conjunction with U.S. Laser Corporation. FHG was accomplished outside of the laser cavity by focusing the 532 nm output beam into a beta barium borate (BBO) non-linear angle tuned crystal. Additional optics were then required to separate the 532 nm and 266 nm beams. It should be noted that conversion efficiency at this wavelength is very small and is typically between 3 - 5%. Laser parameters at 266 nm are as follows:

**Fourth Harmonic Wavelength (266 nm)**

| | |
|---|---|
| Irradiance: | $1.77 \times 10^{9}$ watts/cm$^2$ |
| Q-Switch Rep. Rate: | 4 kHz. |
| Pulse Width: | 150 nsec |
| Laser Beam Mode: | $TEM_{00}$ |
| Focal Length Lens: | 40 mm |
| Beam Focused Spot Size: | ≅ 6 μm |

## V. Fabrication of Test Parts for Via Drilling and Isolation

In order to investigate via coatings for effectiveness in isolation, test parts were fabricated that could be manually probed with a digital multimeter. The test die consisted of four separate metal pads (125 mils each) in a square pattern. Parts were fabricated with two different types of starting material, p-boron .14 - .30 Ω/sq. and n-phosphorus 2 - 20 Ω/sq. Processing steps included thermal oxide plus deposited oxide for total thickness of 1.6 μm, followed by 1 μm deposition of aluminum silicon. The metal was photopatterned and etched.

Laser holes were drilled in the pads and then using the multimeter probes, pad to pad resistivity was measured. Initially the test die were to be used as a means of determining effectiveness of various via coating processes for isolation. Test plans included drilling a hole in each pad, coating the vias and then filling the coated vias with a conductive material. By probing pad to pad the via isolation could be measured.

### Die preparation for via coating

It is necessary to protect the wafer top surface during application of any material to be used for via isolation coating. A procedure was developed whereby the thinned die were mounted on a frame of blue tape prior to laser drilling. The tape was on the top side of the die and the laser drilling was done through the tape. The tape could then protect the surface during application of the isolation material. After application the tape was removed prior to drying/curing steps.

### Via isolation studies

The method developed for application of any via isolation materials utilized a vacuum chuck over which the die was placed, top side up. With the die in place, very small amounts of the material (spin-on-glass, polyimide, etc.) was dispensed over the laser holes using a manual dispense system (EFD, 2000XL). Vacuum was turned on to help pull the material through the holes. The die were then carefully removed from the chuck, the tape removed from the die and a drying/curing process done to complete the process

## VI. Laser Micromachining/Process for Via Creation

The first study done using test die included three methods of drilling the laser holes, and four via isolation splits. The material used for via isolation was SOG. Previous work with potential via isolation materials included polyimide and two types of SOG. Preliminary data had indicated that the SOG provided the best isolation. Testing of these first samples after via coat, before via fill, indicated all parts were shorted, i.e. low resistivity, in the 30-40 Ω range. These results pointed to a problem with the drill process. At this point, it was suggested that the problem was due to metal shorting to the silicon at the laser hole interface. Numerous etchants were then tried to possibly remove the shorted material. After many experiments it was decided that using an etchant was not appropriate because the etches that successfully solved the shorting also aggressively attacked the metal and capping material. Work effort was redirected to look at modifying the laser drill process to eliminate this shorting problem.

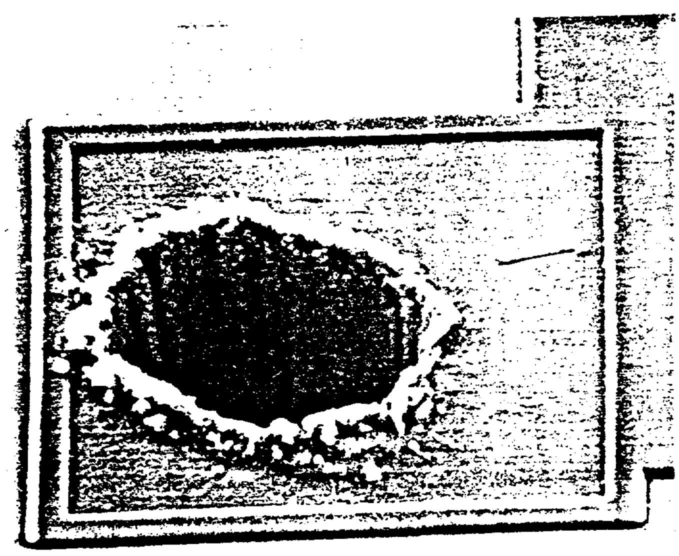

**Figure 3.** SEM Micrograph of through hole in 100mm X 100 mm contact pad.

The drilling of Si with a focused laser beam is a three-dimensional heat flow problem. The duration of the pulse determines the period of time for heating the material to a vaporization point1. This is why three separate wavelengths were utilized initially to determine optimum laser machined through holes. It was seen by cross section SEM micrographs (Figure 3 and Figure 4) that through holes processed with the 266 nm wavelength exhibited the cleanest side wall geometries with minimum residual Si debris for post processing steps such as solder bumping, filling and wire bonding. This is due to the absorption coefficient of this wavelength in Si being significantly greater than the fundamental and second harmonic wavelengths, thus creating a mechanism of material removal that includes vaporization and ablation. Consequently, what was thought to be optimized through holes machined through the metallized pads at this wavelength created isolation break down between contact pads when resistance measurements were taken between adjacent pads. It was shown there was almost a complete electrical short between measurement pads when through holes were laser machined at the 266 nm wavelength.

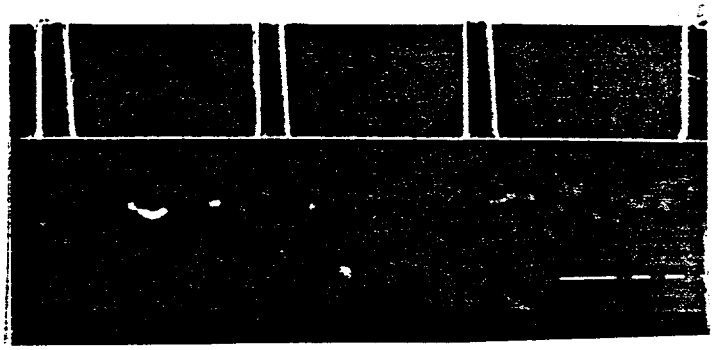

**Figure 4**. SEM Micrograph of cross-sectioned through holes in substrate.

Subsequently, through holes machined directly in metallized pads at 532 nm exhibit a break down in isolation also, but not the complete shorting that was seen at 266 nm. Resistance values typically ranged from 1 kΩ – 10 MΩ with great inconsistency. This was based on a sample size of 400 sites. Continued experimental trials allowed us to standardize on one process utilizing the fundamental wavelength within an $O_2$ environment. The process implementing $O_2$ minimizes the shorting effects seen at the fundamental, second and fourth harmonic wavelengths, while providing electrical isolation of the through-via without additional processing steps when processed at 1064 nm.

**Standard Laser Process for Through Hole Creation:**

| | |
|---|---|
| Laser Wavelength: | 1064 nm |
| Q-Switch Rep. Rate: | 4 kHz. |
| Average Output Power: | 10 watts |
| Optimum Through Hole Diameter: | 50 μm |
| $O_2$ Pressure: | 80 PSI |
| $O_2$ Flow Rate: | 120 SCFH |
| F.L. Lens: | 40 mm |
| Tre-Pan Assembly: | Rotating Optical Wedge |

It was known from previous experimental trials at the University of South Florida that "Laser created through holes near transistors were highly dependent upon distance from the device. Holes as close as 90 μm from devices yielded acceptable structure characteristics."[2] It was not anticipated that there would be a break down of isolation between contact pads due to laser processing through holes in contact pad metallization. Additional testing at the fundamental wavelength has shown that this shorting phenomenon between contact pads is very dependent on wafer starting material. Test die fabricated at Sandia National Laboratories were used to determine the relationship of break down resistance between contact pads and wafer starting material. P-boron and n-phosphorous starting materials were used for this experimental matrix.

The n-phosphorous starting material laser drilled with standard laser parameters exhibited isolation between contact pads measuring from 600 kΩ - 200 MΩ. This data was based on through holes in 200 metallized bond pad sites fabricated on n-phosphorous substrates.

P-boron substrates were laser drilled with standard laser parameters and measured for resistance between contact pads. It was found that resistance readings would range from 1kΩ – 200 MΩ. Data on resistance values is based on through holes in 200 metallized bond pad sites that were fabricated on p-boron substrates. It was illustrated that p-boron substrates were susceptible to consistent catastrophic shorts between contact pads when compared to n-phosphorous wafers. It was also determined that a high level of doping will decrease resistance slightly between adjacent pads, but does not result in the significant decrease in resistance observed when comparing phosphorous and boron doped starting wafers.

Additional experiments were run to determine what proximity a through hole can be placed to metallization in a p-boron substrate without degradation to isolation between contact pads. A total of 480 sites were drilled in p-boron test wafers that were fabricated with 150 $\mu m^2$ contact pads and 100 $\mu m^2$ metallization voids within the contact pads. This would allow for laser machining various through hole diameters within the pad to determine at what distance from the metallization the phenomenon creating shorting will occur in p-boron starting material. Data based on the 480 sites tested indicates > 25 μm from the metallization is adequate distance to insure no shorting phenomenon between contact pads. As the through hole approaches 25 μm or less to the metallization you begin to see a break down of isolation resistance between pads.

Results indicate that laser micromachining through holes in Si is very dependent on wafer type. Boron doped wafers represent worst case starting material and caution must be exhibited when processing within 25 μm of metallized regions to eliminate the phenomenon of electrical shorting from contact pad to contact pad. Phosphorous doped wafers do not exhibit this phenomenon. As shown, laser micromachined through holes can be placed directly through metallized regions without adversely effecting isolation from contact pad to contact pad.

### VII. Via Metallization/Solder Bump Attachment

In order to form the via metallization, solder bumping on top of the through via is required.

#### Solder bump formation

The solder bump attachment immediately follows laser drilling of the vias using $O_2$ to provide a thin dielectric layer on the walls of the via. To insure proper attachment, the die is inspected for cleanliness. Airborne debris such as dust and fibers, and surface contaminants including residual solvents and oil from fingerprints can have a significant impact on solder ball adhesion. If necessary, the surfaces are cleaned using a standard wafer cleaner (deionized water). The materials and equipment used in solder bumping include:

- Manual Thermosonic Ball Bonder (K&S Model 4124) equipped with Bumping Mode Logic hardware and Negative Electron Flame-off (P/N 4124-3000-000)
- 3% Ag, 97% Sn, 1.0 mil diameter solder wire (Tanaka P/N SB22)
- Bonding tool (Gaiser Tool P/N 1575-20-375M-20D or equivalent)
- Forming gas (5% H, 95% Ar) fed directly into the wire bonding equipment.

The following settings were used for the manual ball bonder in the bumping mode:

- Temperature of 205° C +/- 5° C
- Ball size dial setting of 3 to 4
- Static force of 20 to 30 grams
- Force dial setting of less than 1
- Time dial setting of 4.0 to 5.0
- Power dial setting of 6.0 to 8.0

The technique used in the process is thermosonic bonding under a forming gas atmosphere. Thermosonic bonding combines thermocompression bonding (compressing the wire onto the bond pad at elevated temperatures) and ultrasonic bonding (pressing the wire onto the bond pad while applying a burst of ultrasonic energy). By using both heat and ultrasonic energy, a good metallurgical contact between the wire and the pad is achieved.

A solder ball is first formed at the tip of the wire via a high voltage arc discharge (1200 V) to the solder wire in a forming gas atmosphere (Figure 5 (a)). The solder ball is then joined to the pad metallization by thermosonic bonding, also under a forming gas atmosphere (Figure 5 (b)). After bonding, the wire is then cut off by the clamp as the capillary tip is moved up (Figure 5 (c)). The 3% Ag, 97% Sn wire can be directly applied to Al bond pads as well as Au.

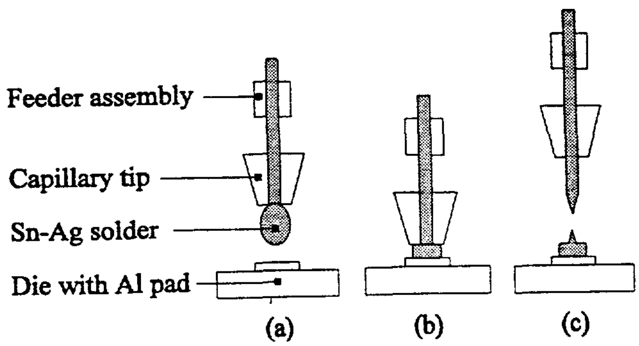


**Figure 5**. Thermosonic bonding. (a) Bonding head assembly and ball formation. (b) Contact is made while heat and ultrasonic energy are applied. (c) Wire is cut and process is repeated.

#### Via solder filling

Via metallization is done on a manual thermosonic ball bonder with bumping mode logic. Several different methods have been attempted.

The first method was to place a solder bump over the via and then align the device on to a Si mask which has slits in it. This was then placed on a heated vacuum chuck and the solder was reflowed through the vias under heat and vacuum.

The next method was to place the device on the heated vacuum chuck of the bonder and raise the temperature of the chuck to reflow the solder as the bump was applied to the via. This process formed small solder balls on the back side of the device. Then because the hole in the chuck was too small to fit all the vias over vacuum, the device was moved to another position to fill those vias but the small balls that were formed on the back side of the device were smeared across the back side shorting the vias.

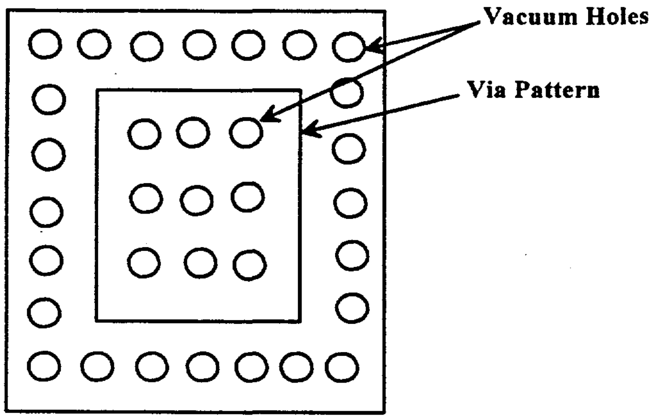


**Figure 6**. Top View of Si fixture for via filling.

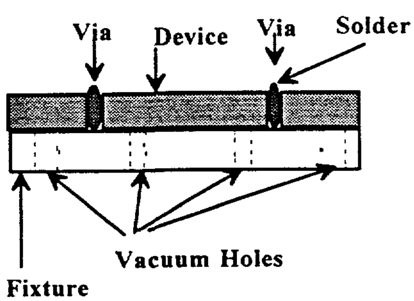


**Figure 7.** Cross-section view of Si Fixture for Via Filling.

The vacuum hole was then opened up to fit the entire device over vacuum. Now each via is over vacuum and the device does not have to be moved. This was more successful, filling approximately 60% to 70% of the holes. However, the small ball of solder formed on the bottom of the device made the device uneven. An attempt was made to remove the balls on the back side, but the solder in the via would come out when the ball was removed.

The final method to fill the via has been the most promising. A Si fixture (Figure 6 and Figure 7) was made to pull the solder through the via but stopping the solder at the fixture.

This fixture keeps the back side of the device even. Using this technique approximately 80% of the vias are filled completely. Figure 8 shows a cross section of a filled via.

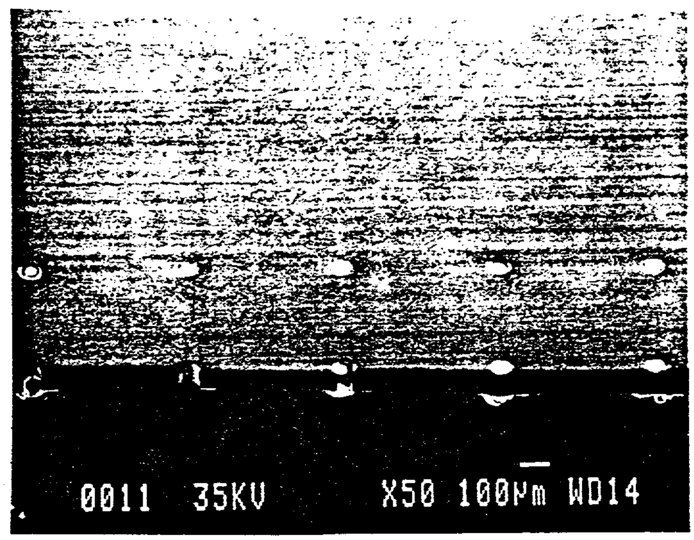


**Figure 8**. SEM Micrograph of Cross Section Via.

## VIII. Summary

At Sandia National Laboratories we have shown the capability to thin active integrated circuits to 50 μm while maintaining functionality. However, handling and assembly issues at this thickness reduce the yield rate tremendously. A die thickness of 150 μm represents optimum thickness to successfully address handling and assembly losses. Also noted, laser processing through holes in active circuits while maintaining isolation between contact pads is dependent on laser wavelength, atmosphere during processing, and wafer starting material. The optimum laser wavelength and atmosphere for through hole micromachining has been determined to be 1064 nm in a flooded $O_2$ environment. This allows for minimum degradation to isolation resistance between contact pads and creates a thin oxide layer within the through hole for isolation of through hole metal for z-axis interconnection. There is the need to further investigate the laser micromachining process in p-type starting materials to insure minimal break down of isolation between adjacent contact pads. As demonstrated, n-type wafers allow laser micromachining of through holes in metallization without catastrophic break down of isolation resistance between contact pads. Through hole filling has been demonstrated on standard assembly equipment. With the combination of these enabling technologies it has allowed the development of a 3-D MCM.


### Acknowledgments

The authors would like to thank Simone Smith for her work producing SEM micrographs, Melanie Tuck for the fabrication of test structures, John White for his support in laser micromachining experimental trials, Richard Paul for his support in via filling experimental trials and Nao Moore for her support in advanced packaging processes.


### References


[1] Rex A. Lee and Wilfrido A. Moreno, University South Florida and Richard A. Gassman and W. Doyle Miller, Sandia National Laboratories, "Excimer Vs. Nd:YAG Laser Creation of Silicon Vias for 3D Interconnects", Proceedings of Thirteenth (1992) IEEE/CHMT International Electronics Manufacturing Technology Symposium.

[2] Rex A. Lee and Dennis R. Whittaker, University of South Florida, "Laser Created Silicon Vias for Stacking Dies in MCM's", Proceedings of Twelfth (1991) IEEE/CHMT International Electronics Manufacturing Technology Symposium.



* This work was supported by the United States Department of Energy through Contract No. DE-AC04-76DP00789