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Volume 611

Laser Processing of Semiconductors and Hybrids

Edward J. Swenson
Chairman/Editor

Presented in cooperation with

American Association of Physicists in Medicine • Center for Applied Optics/University of Alabama in Huntsville
Center for Laser Studies/University of Southern California • Georgia Institute of Technology
Institute of Optics/University of Rochester • Laser Association of America
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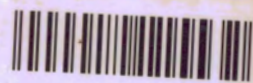
LASER PROCESSING OF SEMICONDUCTORS AND HYBRIDS

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Swenson

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LASER PROCESSING OF SEMICONDUCTORS AND HYBRIDS

Volume 611

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The third session dealt with laser processing of hybrid circuits. A technology review of high-speed, thick-film laser trimming was presented (611-01). A new approach of using lasers in production was before hybrid circuit laser trimming (611-02). An area of growing interest is laser assisted etching of electronic materials (611-09). Also of note is the work done to further the art of functional laser trimming of thin film resistors on integrated circuits (611-10).

The fourth session dealt with nondestructive testing using lasers. New techniques for defect diagnosis by scanning laser image generation were reviewed (611-11). And, the technique of inspecting solder connections with lasers was covered (611-12).

The breadth and depth of papers presented at this conference indicate the growing use of lasers in microelectronic production. Tools that are well suited to the constantly shrinking sizes and accuracies required and the flexibility and programmability needed in today's automated manufacturing environment.

Edward J. Swenson
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Precision laser micromachining

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Abstract

Lasers continue to enter many exciting new fields that have been traditionally the domain of other equipment. Lately, lasers and their associated precision positioning equipment have replaced the more conventional methods used in the micromachining area because of better control, repeatability and precision.

This paper discusses some of the latest applications of laser micromachining utilizing a medium-powered Nd:YAG laser. Topics will include machining ceramics, silicon and other materials as well as precise removal of thin films from various substrates.

Some of the techniques created to accomplish the required results will be shown as well as improvements over previous methods.

Introduction

Lately, more articles are being written discussing the acceptance of lasers for machining, drilling and shaping all types of materials. For the most part they have concentrated on industrial uses other than those in the microelectronics area. This paper is intended to demonstrate the many microelectronic applications available when a medium powered Nd:YAG laser operating at 1.06 micrometers (μm) (see Figure 1) is used to enhance previous production methods that have reached their limits to do the work correctly or efficiently. It will show this particular laser's outstanding characteristics for laser micromachining and hole cutting through silicon, ceramic, metals and other materials. Removal of thin films from various substrates to produce a desired electrical characteristic or geometric shape will also be covered. For template generation, the Nd:YAG laser can produce many different designs easily. These can be used later for screening or for laser marking using a higher-powered pulsed laser.

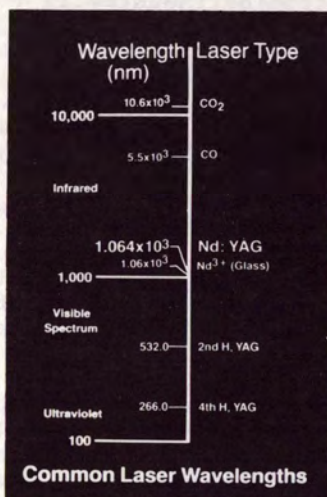


Figure 1. Nd: YAG Wavelength Chart

General Discussion

Even though the Nd:YAG laser has been around for many years, it continues to grow in microelectronic machining applications. For about 15 years it has been used to trim thick film and thin film resistors, on ceramic and glass substrates and silicon wafers. In these applications the beam has been moved around or positioned with either a rectilinear positioning system (Figure 22), driven by stepper or linear motors, or a galvanometer positioning mechanism (Figure 26). In the latter, the beam is scanned in an arc or scanned through a flat field objective lens where it is corrected so that the beam is perpendicular, or is close to perpendicular, to the part. With the rectilinear positioning system the beam is kept at a perpendicular angle to the work surface at all times. Both methods have their inherent advantages. The galvanometer offers greater speed because of

its light weight. While the rectilinear system can achieve greater precision over a larger area. The work that is discussed in this paper has been done with a precision rectilinear positioning system.

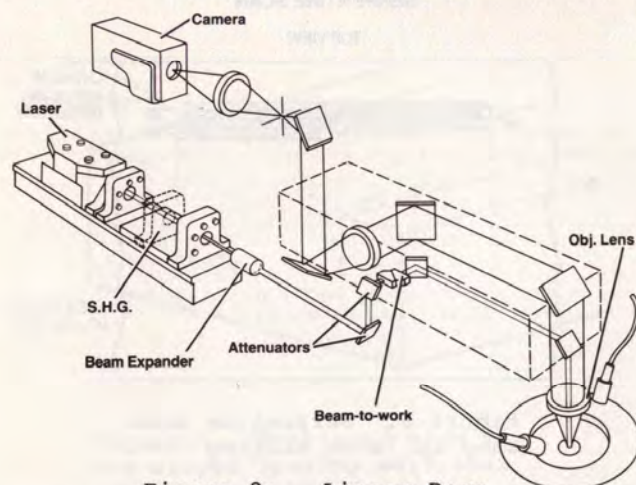


Figure 2a. Linear Beam Positioning System

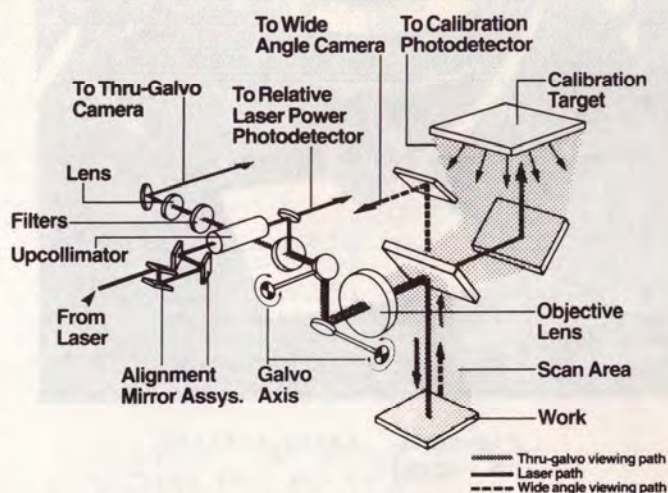


Figure 2b. Galvanometer Beam Positioning System

As tolerances became tighter, control of the laser energy and the positioning system had to become more precise to the point where the beam positioning system can now obtain accuracies of less than one micrometer (lum). Laser pulse-to-pulse stability control of $\pm 3\%$ and focused laser diameters in the three micrometer range are also being used in production. This led to the ability to repair dynamic random access and static random access memory devices (DRAMS and SRAMS) on silicon wafers and greatly assisted the advancement of the increased density of the current 256K and 1 Meg memories that are on the market today.

However, along with the advancements in laser trimming and laser memory repair, there are several other processing areas that have been enhanced with the Nd:YAG laser. Many of these have been small, specialized markets and, in some cases, strictly in-house operations. Others have become very large and cover many process areas of the microelectronics industry. Four areas are of particular interest. They include laser milling, hole drilling and cutting, removal of thin films from substrates, and laser marking.

Laser milling

This application involves modifying the shapes of various materials by using a Nd:YAG laser to vaporize portions and form extremely small, precision shapes. This usually cannot be achieved by mechanical methods because of dimensional restrictions or material hardness. Milling is one of the most common laser machining techniques.

In the laser milling area most of the emphasis is placed on ceramic processing. See Figure 3. It is used to replace slower, less accurate, conventional methods such as mechanical abrasive techniques. The laser offers more variety as to the minute shapes that can be cut into ceramic by being a non-contact tool, that has no bit to wear and be replaced. It also can be applied in places that are inaccessible to mechanical devices.

Conventional chemical etching techniques also present problems because of the set up and processing times as well as the handling of the chemicals themselves. There are also certain materials that are not affected by chemical etching processes which can be laser machined. Another milling technique that is seeing competition from the laser is ion milling. These systems require a vacuum chamber and costly capital equipment outlay. In cases where the laser is applied rather than ion milling it offers the advantage of being easier and less expensive to operate as well as being able to operate in a more ambient environment without the need for a vacuum chamber.

The benefit of using the laser for milling is that it raises the temperature of the material to the point of vaporization using the highly controlled infrared radiation. The laser causes the material to reach this point very quickly. The vaporized material also helps to carry the heat away and because of the very rapid heating only the immediate area is subjected to the high temperatures. Going through the operation of milling a simple rectangular area step by step will point out some considerations that must be taken into account to obtain clean symmetrical results.

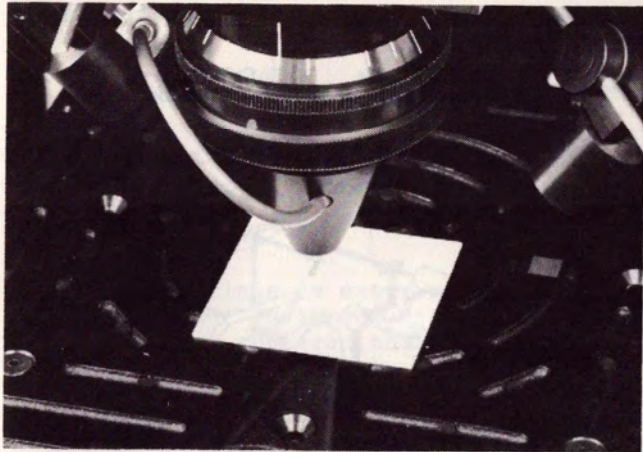


Figure 3. Laser milling on ceramic

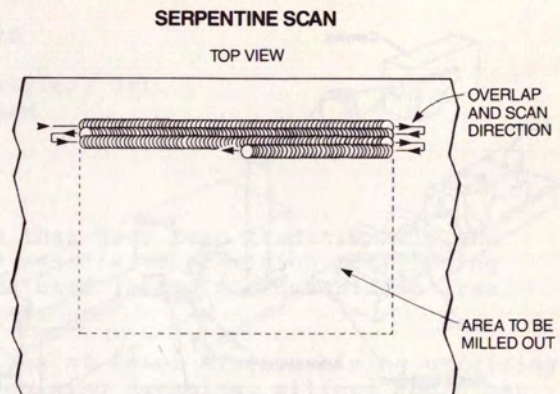


Figure 4. Serpentine scan used in laser milling

A simple operation is begun by scanning the focused laser beam over the desired area back and forth making parallel cuts to form the size and shape desired. The laser is gated on and off at the beginning and end of each scan but not during the incremental movement that determines the kerf overlap. See Figure 4. The proper speed, laser q-switch rate, power and beam diameter, are set to reach the desired depth and smoothness on the bottom.

This looks quite simple and, indeed if this were done, an area could be milled away with a fair amount of precision. In actual practice however there are several conditions that are changing throughout the procedure. One of these is what is taking place as the milling process is being initiated by the laser.

Quality of the edges and bottom of the area are the major concerns since the laser operates differently than machining or etching techniques. The beam can not be shaped in the same manner as a drill bit for each specific design requiring exact dimensions. It is also not possible to remove entire precision patterns as with standard chemical or ion etching processes. All dimensions are controlled through the use of proper laser parameters, computer controlled motion system and the correct use of a jet of air to assist in removing the vaporized material. Let us first consider the walls of the milled area.

If no modifications are made to the operation described above, the leading vertical wall of a laser machined area will differ considerably from the trailing vertical wall. The leading wall is the one formed as the laser is making its first scan. The trailing wall is the one formed by the last scan. When it is beginning a pattern, the laser is required to remove a strip of material that is the full width of the beam. It is the only place where this is required. All other scans will have had some of the material removed by the previous scan. As a result, the full depth is not reached on the first scan. Only after the first two or three scans are made is the full depth reached. This results in a gradual slope down to the desired depth as subsequent scans are made. See Figure 5. The sloped wall is usually not desired, cannot be well controlled and is actually determined by how well the laser energy is absorbed into the material.

In a condition where all four walls do not have to be as vertical as possible, or where there is only three walls, such as with an open-ended pattern, this scanning method may be the best one to use. See Figure 6. The aspect ratio of the area will determine which scanning direction will result in the fastest throughput. A slight rounding of the bottom of the open edge occurs in this case but it is usually not significant.

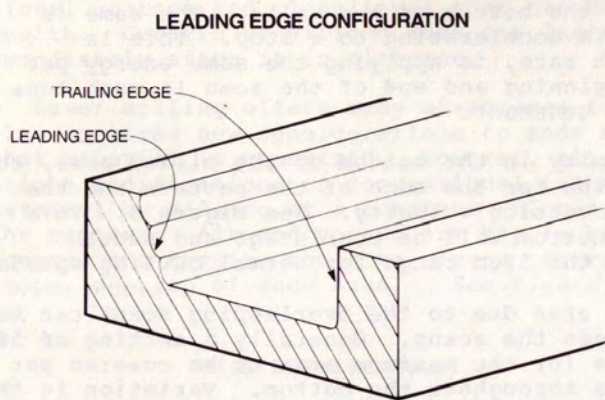


Figure 5. Sectioned view of the sloped leading wall that results when the laser scanning is begun at the outer edge

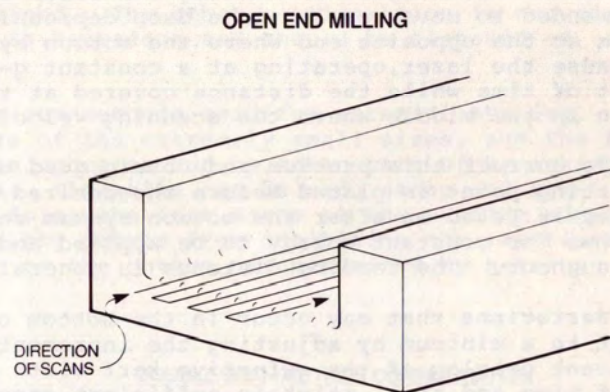


Figure 6. One method of laser milling that can be used for an open-end operation

One method that has been tried to correct this condition is to reduce the speed the laser is moving for the first few scans while maintaining the same q-switch rate. This effectively increases the laser energy per unit area so that a greater amount of material is removed where it is required. However, it is very difficult to achieve the laser parameters needed to obtain the same depth on the first scan as is needed for all the subsequent scans. Especially since the vaporized material must be blown out of the initial narrow groove.

A different method, but one that offers better control of the leading edge and greatly reduces this problem is to divide the area in two and begin the milling operation in the center of the area and move toward the outer wall, or what is normally the starting point. The outside wall is then the location of the last scan and the most vertical slope will be obtained. The second part of the area is completed by overlapping slightly from where the first scan was begun and incrementing over in the opposite direction. When the second part is completed, depending on the amount of overlap used, a shallow groove or slight ridge is the only artifact that will remain and is usually not significant to the overall function of the part. See Figure 7. This groove can be kept to less than 5um in width and less than 3um in height.

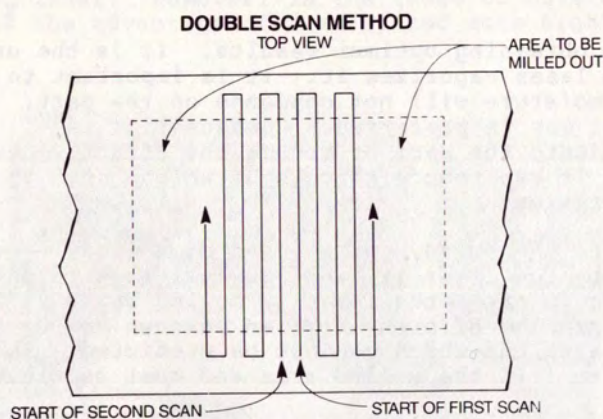


Figure 7. Double-Scan method used to obtain vertical leading and trailing walls

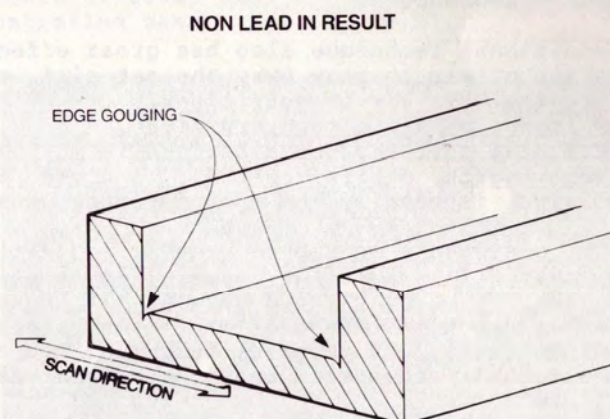


Figure 8. Sectioned view showing the gouging effect from not using a lead in

Another condition to be concerned with is what happens where the laser begins and ends its scan. See Figure 8. Gating the laser on at the same time the motion system is commanded to move results in a deep depression at the bottom of the walls. The same is true at the opposite end where the motion system is decelerating to a stop. This is because the laser, operating at a constant q-switch rate, is applying the same energy per unit of time while the distance covered at the beginning and end of the scan is much less than in the middle where the scanning velocity is constant.

To correct this problem and obtain good uniformity in the bottom of the milled area, the starting point is placed before the desired location for the edge of the pattern and the laser is gated on after the motion system reaches cutting velocity. See Figure 9. This allows for constant energy to be applied and the bottom will be consistent and smooth throughout. The leading distance is generally in the 50 μ m range for normal cutting speeds.

Serrations that may occur in the bottom of the area due to the overlapping scans can be kept to a minimum by adjusting the increment between the scans. Generally a setting of 50 percent overlap of the effective kerf width allows for the maximum area to be covered per unit time and still maintain sufficient smoothness throughout the bottom. Variation in the bottom can be kept to about two micrometer. The 50 percent overlap also works well to maintain straightness and obtain maximum slope of the walls where the laser starts and ends its scan. An edge variation of less than 2.5 μ m with a wall slope of about 5 degrees is typical.

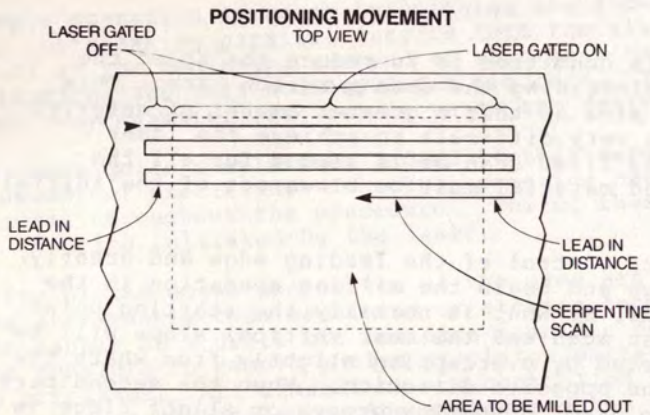


Figure 9. The movement of the positioning system including laser gate on/off sequence

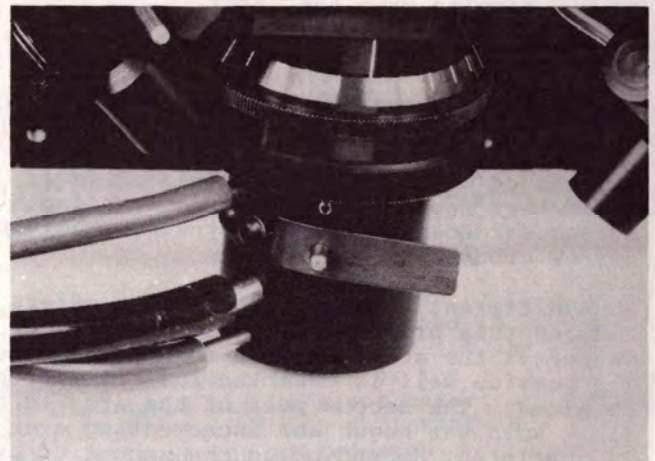


Figure 10. Close-up of air and laser nozzle

An additional technique also has great effect in obtaining optimum results. It is the use of a jet of air to blow away the material as the laser vaporizes it. It is important to assure that the air is sufficiently dry so that moisture will not condense on the part. If this is not possible then dry nitrogen or similar gas is preferred. Condensation is detrimental to the process because it may contaminate the part or reduce the effectiveness of removing the debris created. In either case, it can reduce throughput which, next to precision, is usually the most important consideration.

The assistance in debris removal is critical to the speed, quality and dimensional control that will result. As material is vaporized by the laser it tends to fall back into the area that is being cleaned out as well as the virgin areas the laser is moving toward. Material deposited ahead of the laser creates a problem of presenting an unknown and excessive quantity of material that must be penetrated and which can not be predicted. The material that redeposits behind the laser tends to fill the milled area and must be cleaned out later.

With a nozzle properly directing the flow of air at the laser cut and away from the direction of travel the redeposition of material is greatly reduced and the depth is better controlled. See Figure 10. Another reason for directing the ablated material away from the laser is to reduce the plume that forms above the cut being made. The plume acts as a shield to inhibit the laser from reaching the surface of the part. See Figure 11.

It is also advisable to have a vacuum system to carry the airborne particles completely away from the immediate area. The vaporized material that is blown away can fall onto another area of the part that is to be machined will fall onto the entire surface of the part

not only in the area that is milled. Except for metals, these particles usually do not adhere to the surface and can be cleaned off later. However, they can reduce the dimensional control and cleanliness that can be obtained. The other consideration is one of health. Ceramic or silicon dust for instance, is hazardous and should be disposed of immediately after it is airborne.

Laser milling offers many advantages to previous methods used for material shaping. It also requires new considerations to be made because of the extremely small sizes, and the fact that material is vaporized. However, all of the concerns can be taken care of by making slight modifications to conventional techniques. The walls can be made steep and symmetrical by milling at a constant velocity and doing the last scans at the outside edges of the pattern. Air and vacuum are key in keeping the debris from inhibiting the vaporization process and keeping the area clean. Serrations on the bottom are minimized by setting proper overlap of each scan. See Figure 12.

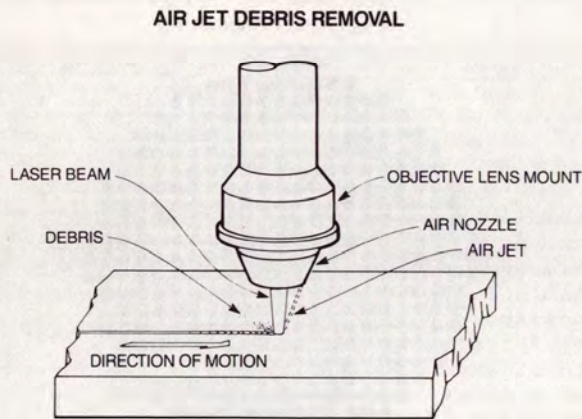


Figure 11. Drawing of air jet debris removal technique

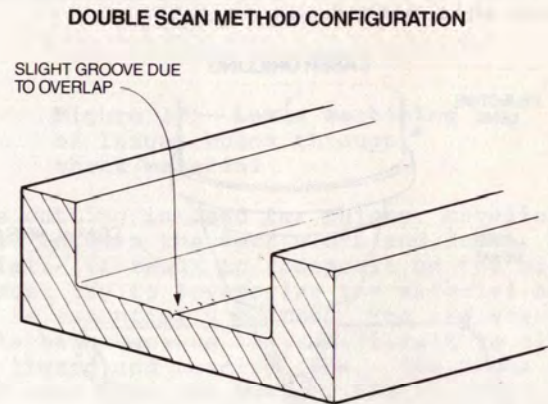


Figure 12. Symmetrical milling by double scan method

Laser hole drilling or cutting

These applications involve using an Nd:YAG laser for a variety of microelectronic drilling and cutting techniques in silicon, ceramic and some metals. The methods used for silicon and ceramic materials are similar to each other. Metals require slightly different parameters because of their highly reflective nature. Holes are generally round or rectangular but almost any irregular shape can be generated for particular applications. Many of the drilling techniques written about in industry trade journals discuss the use of a CO₂ laser. However, in the range of hole diameters of 0.005 inch and below, the YAG laser has the advantage of a small and more highly-controlled beam. See Figure 13.

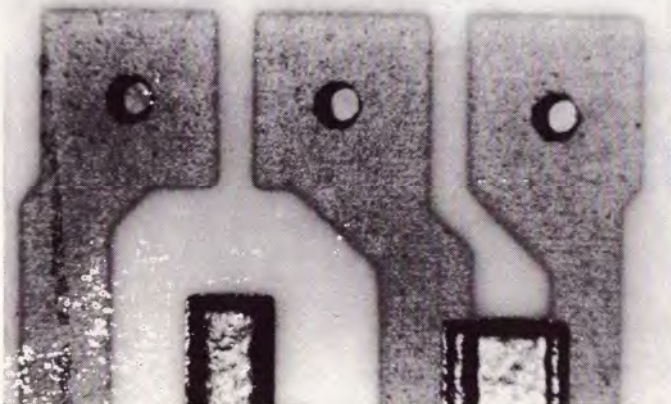


Figure 13a. Holes machined by laser through metal pads on thick film ceramic circuit allow for wire connections.

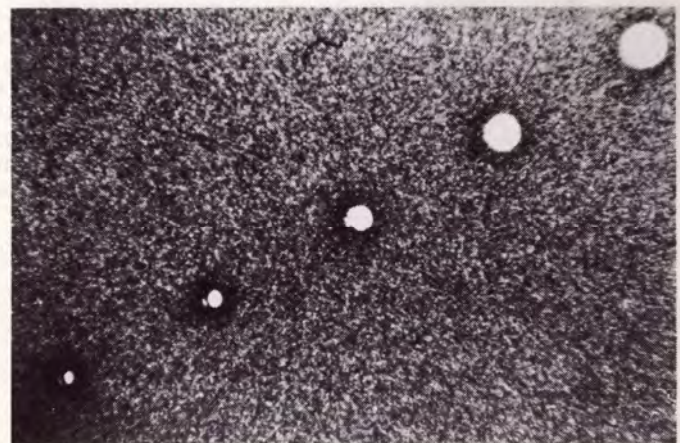


Figure 13b. Holes of different diameters "cored" through silicon. Hole diameters are from 5-25 mils, wafer thickness is 15 mils

The Nd:YAG laser is proving to be a cost effective solution to these applications. Holes are being cut through silicon wafers that are as thick as 0.070 inch, with hole diameters as small as 0.002 inch. A matrix of 0.005 inch diameter holes less than 0.01 inch apart can be cut in silicon or ceramic without causing fracturing or material degradation. This is possible because the laser's minimal effect on the surrounding area maintains part integrity. See Figure 14.

Two methods can be employed to cut holes. The first, drilling, is done by sequentially firing the laser in a stationary position as in Figure 15. A jet of air or dry nitrogen should be blown onto the work surface coaxial to the laser beam. This helps to remove vaporized materials from the laser path immediately, which increases the speed at which the laser will penetrate the material. The hole size is then determined by the beam diameter at its focused waist. Depending on the material thickness and the optics used, hole sizes can vary from 0.0005 inch to as large as 0.0015 inch. The taper in this case is generally greater than 10 degrees and hole roundness is not easily controlled. For materials covered in this paper, a thickness of greater than 0.01 inch will probably not be penetrated by using this method.

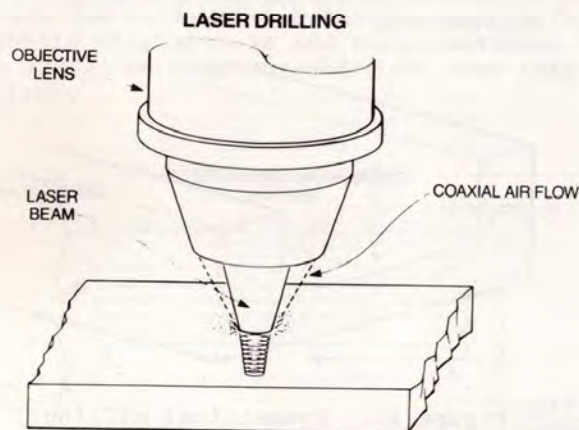


Figure 14. Successive laser pulses in a stationary position used to drill through a substrate

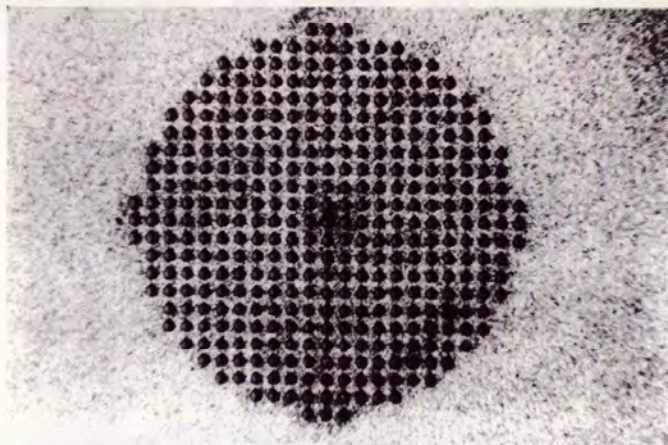


Figure 15. Matrix of holes cut in silicon by laser

The second method is machining. Two variations of the same process can be employed. The decision as to which one is based primarily on the thickness of the material to be penetrated. Thinner materials are often "cored out". See Figure 16. The laser is commanded to outline the geometric shape. Depending on the material thickness more than one pass is usually required in order to make a clean consistent cut. The air assist in this case serves several purposes. The first is to rid the cut of vaporized material as with laser milling. Another is to keep the material from redepositing behind the laser and forming bridges. And a third purpose is to blow out the core. The smallest of bridges can hold the core in place and lengthen the time to complete the process. A final pass after the core is out is effective in producing a smooth clean wall. However, continual passes will not completely reduce the taper since it is difficult to cause the laser to be absorbed in the vertical walls of the cut hole. Also, once the material has been penetrated, attempting to enlarge the hole is usually not successful unless a large enough bite is taken to result in significant vertical heating and vaporization.

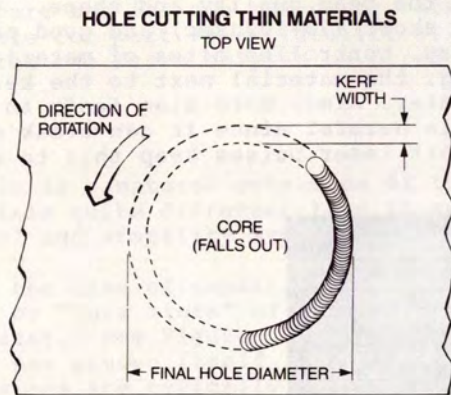


Figure 16. Laser machining of larger holes through thin material

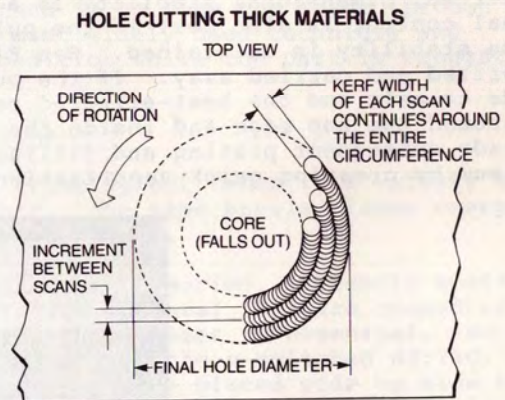


Figure 17. Laser machining of larger holes through thick material

The second variation of laser machining for hole cutting is used for thicker materials. See Figures 17 and 18. The greater the aspect ratio between the kerf width and depth, the more difficult it is to remove the vaporized material. It tends to redeposit on the sides and behind the path of the laser. The laser then must try to revaporize the material again and again. The result is that the cutting process is essentially halted. The assistance of air to remove the vaporized material is of little help because it is difficult to blow the material out sufficiently before it cools to a liquid and resolidifies. The plume of vaporized material can not successfully be directed away from the path of the incoming beam so it also inhibits the continual vaporization of new material. The result is the forming of a pool of material deep in the kerf that is repeatedly revaporized and redeposited.

To take care of this process problem the laser is controlled to form successively smaller concentric shapes creating a wider kerf. This allows for the removal of vaporized material immediately after it is airborne. The combination of air assist to remove the debris from the laser path and a vacuum system to draw the debris out of the kerf is recommended on this case. The essential cutting parameter to faster throughput is kerf width. Generally, for materials that are thicker than 0.01 inch and for holes that are less than 0.01 inch in diameter, it is recommended to remove all of the material as in a milling process. For larger diameters it is recommended to maintain an aspect ratio of part depth to kerf width of about ten to one. The fastest throughput and best overall dimensional control will then be obtained. Beam diameters used are in the order of 0.0015 inch. When the kerf is widened, as described above, to cut out patterns in thicker material an overlap of 30 to 50 percent is used in the series of concentric passes.

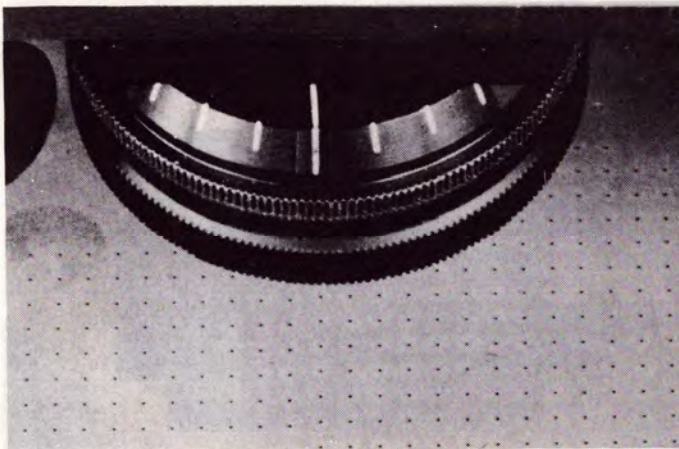


Figure 18. Photo of laser machined holes

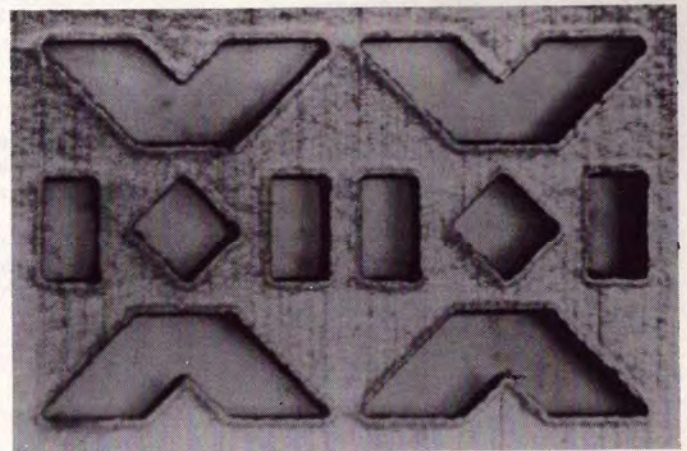


Figure 19. Untouched pattern cut through copper with the Q-switched Nd:YAG laser. Entire pattern is 30 mils X 40 mils

In all cases the mode structure of the focused laser beam is TEM₀₀. This results in precise control needed over the laser energy per unit area. When such small dimensions are concerned, dimensional stability is a direct result of the beam quality and shape. Dimensional control is also best if the pulse width is kept short (70-100 nsec) and good pulse to pulse stability is maintained. See Figure 20. This way, controlled bites of material are vaporized and carried away. If the pulses are too long, the material next to the kerf tends to melt and the heat-affected region becomes greater. Also, more slag tends to build up around the top edge and inside the hole. The slag is harmful since it can break off and degrade subsequent plating and filling operations. Short laser pulses keep this to a minimum by creating quick vaporization of the material.

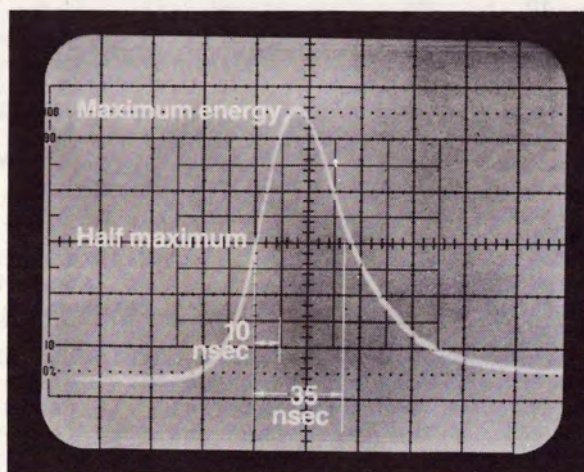


Figure 20. Q-switched laser pulse

In summary, hole drilling, like laser milling, is finding applications in a wide variety of applications. By using the laser many different sizes and shapes can be cut out very precisely. For thicker materials, generating a wider kerf to assist in the removal of debris increases throughput tremendously. And, the use of a jet of air and vacuum to keep the vaporized material out of the path of the laser also increases throughput and allows for a clean operation.

Laser marking

Laser marking is also an area that is included in micromachining. It involves, in many cases, the accurate generation of very small machine readable characters. More and more manufacturers want traceability of their assemblies through production and after they are in the field to provide for complete analysis throughout the lifetime of the part. These assemblies take on many shapes and sizes. In many cases, parts handling can be the most difficult part of the equipment and has as much to do with whether a laser system should be used or not. The application includes all types of packaged devices used today in the microelectronic industry.



Figure 21a. Laser marked connector.



Figure 21b. Laser marked packaged device.

Two common methods are used. One is to write out the character or symbol with the positioning system. This has the advantage of easily employing serialization techniques and each part has its own number or mark. The faster method is to fire the laser through a template for part value identification. This is the most widely used technique and requires the laser only to be fired in a stationary position while the part is brought under it.

Removal of thin films

This is a natural extension of thin film resistor trimming but takes in a variety of materials quite different than those used for resistors. The same precise laser energy control and stability are required to do this task successfully.

In the case of repairing dynamic and static random access memories, extremely small lines or "fuse links" of deposited polysilicon, a silicide or metal link are opened with the laser. See Figure 21. The control of all aspects of the laser is essential. No other laser has proven itself in a production environment as much as the q-switched Nd:YAG. Link dimensions are typically 1 to 2 μm wide and 0.5 μm thick and are placed side by side to create a pitch of 5 μm or less. Precise laser output power is required as well as laser focus to consistently vaporize the link without damaging the underlying layer of oxide and maintaining circuit integrity. Energies in the order of 1 to 2 microjoules and pulse durations of 40 nanoseconds or less are used. Beam diameters less than 5 μm are produced to be able to successfully open a selected link without effecting an adjoining link.

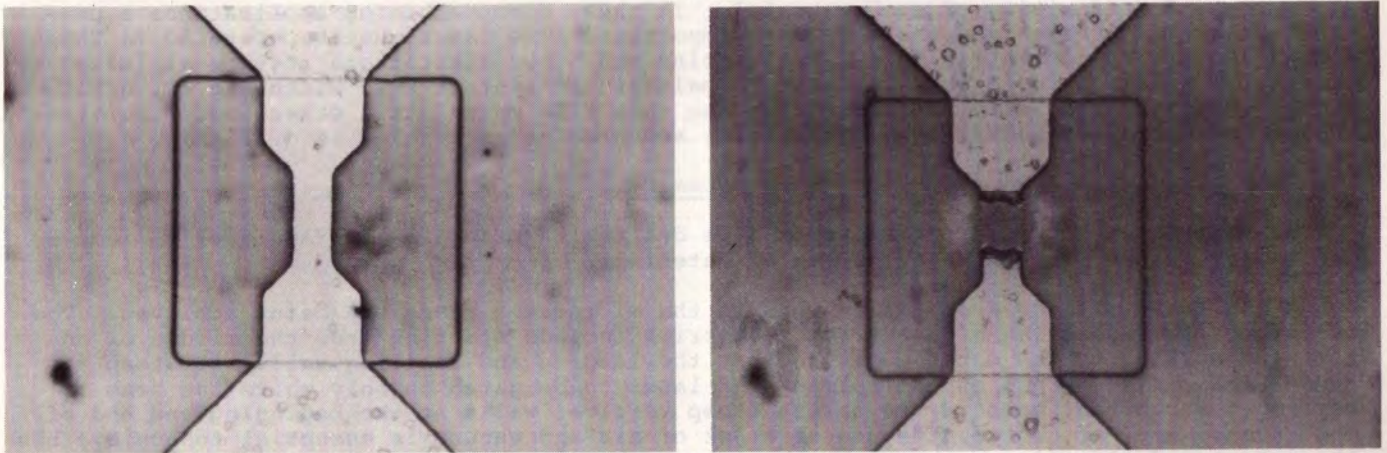


Figure 22. Metal unblown and blown links

Other combinations include removing deposited metals, such as copper and gold on ceramic substrates. Another involves removing chrome and iron oxides from glass substrates to generate photomasks used for thin and thick film circuits. Copper-Nickel films are being removed from mylar or epoxy films to balance strain gauges. And, finally, the removal of Indium-tin oxide can be accomplished to carefully create isolated conductive patterns. This application allows for the easy creation of patterns that are changed and redone under program control.

The removal of thin films from various substrates takes on a wide variety of laser powers, rep rates and beam movement velocities. For instance, to remove deposited 4 μm thick copper from a fired ceramic substrate, an average laser power of 800mwatts, a q-switch repetition rate of 3000 pulses per second and a scanning speed of 3mm/sec results in clean removal of the copper. See Figure 23. The same parameters work well for deposited gold on ceramic. While the power used to remove chrome from a glass substrate is about 40mw. The speed, in this case and q-switch rate are 10mm/sec and 8000 pulses per second respectively. An accurate and repeatable positioning system is obviously essential to do this type of work.

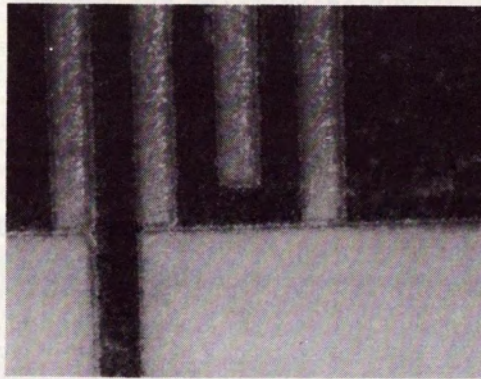


Figure 23. Removal of 4 μ m thick copper from ceramic substrate, conductor width is 2.5 mils wide

Laser energy

Laser energy is a very important parameter to consider in all of the applications where the Nd:YAG laser is used. Considerations must be made for the heat of vaporization, conductivity and diffusivity of each material. In these micromachining applications a controlled laser spot size and shape is very important. The laser must be operated in TEM₀₀ mode structure to accomplish this. Astigmatism and other aberrations must be minimized to be able to obtain a round gaussian beam to maintain consistent kerf widths in all directions. This is especially true when removing thin film materials. Otherwise, fine lines cannot be controlled under those conditions, and precise patterning is difficult.

Summary

The major areas covered in the paper have dealt with using the Nd:YAG laser to remove and modify shapes through vaporization of material.

In the laser milling area, dimensions in the micrometer range are being achieved. The techniques to accomplish high quality geometries include starting from the middle of an area and working to the outer edges so that the leading and trailing walls are steep and symmetrical. The method of controlling the laser to be gated on only while the beam is moving at a constant velocity to ensure steep vertical walls at the beginning and end of each scan. And, of course, the use of a jet of air and vacuum is essential to achieve the throughput and cleanliness that make the process valuable and safe in production.

For the hole cutting and drilling areas, the ability to cut out very small holes and patterns with extremely small kerf widths brings this technology down to dimensions never before possible. And using concentric passes with the laser to cut very small holes in thicker materials opens even more applications for the Nd:YAG laser. The use of a jet of air and vacuum improves the safety of the operation and also increases throughput and cleanliness.

The ability to generate patterns in real time with the laser by removing thin layers from various substrates, opens up exciting new processes such as laser generated photo-masks, to be considered which reduce the time it takes for a product to go from design to production. And, finally, laser marking has become a very large market in the micro-electronics industry for easier traceability throughout the lifetime of the device.

Laser micromachining would not be possible if not for the Nd:YAG laser's flexibility and ruggedness to work in production. But also important in the equation is the computer controlled system used to position the laser beam. This combination will result in a wider variety of applications in the future.

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