Laser Processing of Polyimide on Copper

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(ABSTRACT)

While work using a laser for processing a polymer dielectric is currently being studied, the purpose of this thesis is to present an effective and economical approach using laboratory equipment that is most commonly used and available for the processing of materials including polymers and metals. The use of a laser allows for a more cost effective and flexible method for processing polyimide over other wet and dry processes.

This thesis represents the results of research on the laser processing of polyimide on copper. The research examines the effect of the laser processing parameters using a CO_2 laser. The parameters examined include the pulse width, repetition rate, and number of pulses. The processed samples include freestanding Kapton with no adhesive layer, freestanding Kapton with an adhesive layer, and Kapton with adhesive layered on copper. The laser processing used a single laser shot with the parameters being varied over a series of shots fired. The effect of the parameters was observed over large and small ranges. The characteristics of processed freestanding samples were graphically presented along with captured images. The results demonstrate that the laser processing of polyimide is strongly dependent on the laser pulse width and that the optimum value from these experiments suggest the use of a pulse width of 60μs for using a CO_2 laser. From these results, further considerations for the laser processing of polyimide on copper were given.

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Chapter I Introduction

1.1 Importance of Polyimide in Electronic Packaging

Polymers in electronic packaging have a variety of uses including overmold, underfill, conductive adhesive, and polyimide dielectric. Polyimide plays an important role in the area of electronic packaging because of its mechanical strength, thermal stability, and dielectric properties. This material provides protection for thin film metals and allows for easy processing in microelectronics applications. Polyimide films can be used as stress buffers to protect thin film metals and oxide on silicon chip surfaces and helps prevent damage due to stress and handling after encapsulation of the silicon chip. These films can also be used in flip chip bonding applications and can serve as a dielectric layer for thin film multichip modules (MCM-D's)[1]. Polyimide has useful applications that advance interconnect technology in electronic packages.

The development of ultra-high density flexible circuits by Chou *et al.*[2] demonstrates the use of a polyimide flex substrate in microelectronics as a viable option for a reliable, economic, and high density substrate that offers mechanical flexibility. Flex substrates can be used for MCM designs because of their interconnection densities. This high-density capability can be attributed to its multilayers, fine-line and microvia processing techniques. The work by Chou[2] uses a 355nm Neodymium Yttrium-Aluminum-Garnet (Nd:YAG) laser for the fabrication of microvias in flex substrates. The substrate is processed using a laser and then plasma etched with fluorocarbon (CF_4) and oxygen (O_2) gases to remove debris formed by the laser and enhance the adhesion of subsequent metallization[2].

More recent developments by Minari *et al.*[3] use Copper/Polyimide (Cu/PI) film as a high-density interconnect (HDI) circuit film in localizable stick-together (LST) technology for printed wiring boards (PWB). The interconnection between the layers was formed using a combination of chemical etching and laser drilling with a carbon dioxide (CO_2) laser. Figure I-1 shows the process flow diagram for the LST technology and Figure I-2 shows the multilayer structure of the PWB with the Cu/PI film. The CO_2 laser was used to form vias only in the adhesive layer. The laser drilling method used Cu pads as a drilling mask to shape the via hole instead of using a direct beam method where the via hole shape and size depends on the beam profile. The film was patterned using dry film photoresist technology and subtractive Cu patterning. After laser drilling, plasma cleaning using CF_4 and O_2 gases was performed to remove excess debris[3].

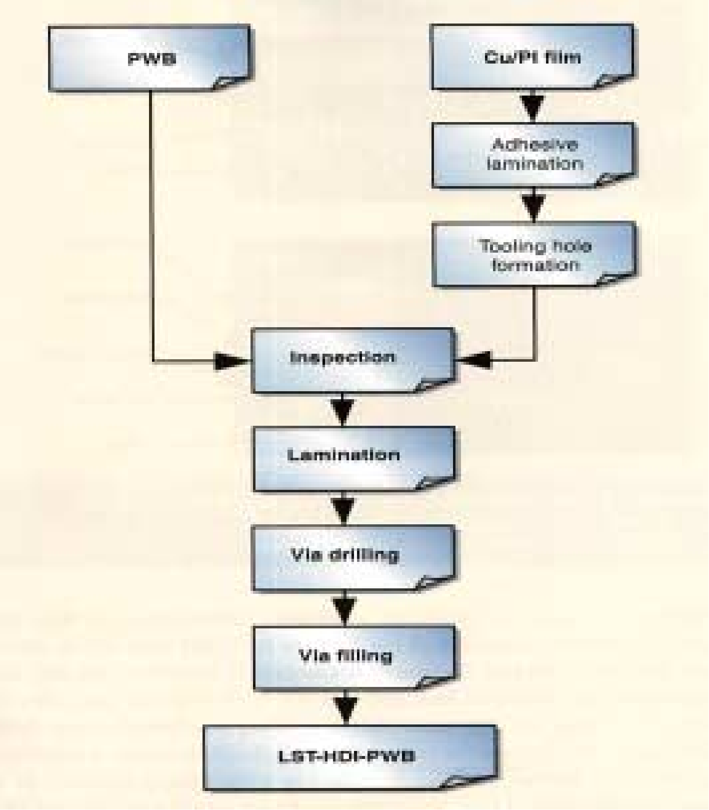

Figure I-1: Process Flow Diagram of LST-HDI-PWB[3]

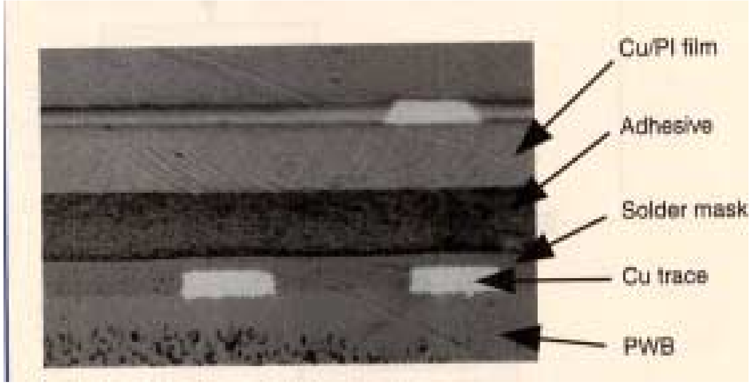

Figure I-2: Cross Section of LST-HDI-PWB[3]

The application of polyimide in electronic packaging as a dielectric layer can be seen in Figure I-3. Either mechanical punching or excimer laser drilling can be used for the formation of the vias in the dielectric layer in this application. The interconnections of the package were formed with copper.

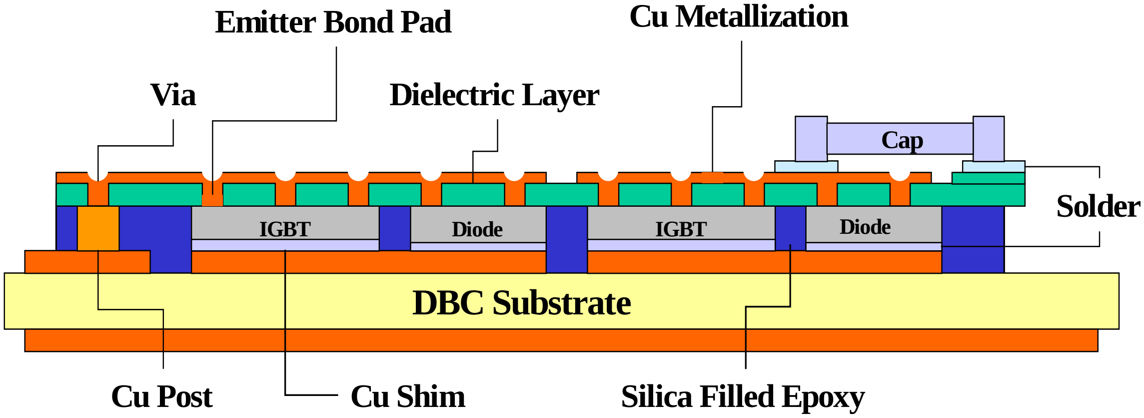

Figure I-3: GE's High Density Interconnect / Power Overlay Technology

The focus of this thesis is on the processing of polyimide dielectric on copper using a laser. The best method for processing is governed by the ratio of the via bottom dimension with the thickness (aspect ratio), via wall profile and the availability of tools for processing[4]. Common techniques for processing polyimide include wet etch, dry etch, and laser ablation[5]. The work in this thesis uses a direct beam from a CO_2 laser for processing that allows for effective vias. This technology leads to more economical and less complex methods for the formation of via holes in polyimide due to operational advantages of the laser. The analysis method uses images and graphical representations of the vias formed.

1.2 Overview of Existing and Developing Techniques of Polyimide Processing

1.2.1 Wet and Dry Etching of Polyimide

Polyimide is most commonly processed by etching or laser ablation. The wet etching process can be achieved using chemicals and the dry etching process can be achieved using plasma or reactive-ion etching. Wet-etching techniques produce coarse features whereas dry etching techniques and laser ablation allow for finer features such as smaller via dimensions[5]. Figure I-4 shows the established methods for wet etch, dry etch, and the use of photosensitive polyimide. A basis for which processing method to use can be formed by examining the process steps, quality of the material after processing, and the type of equipment available.

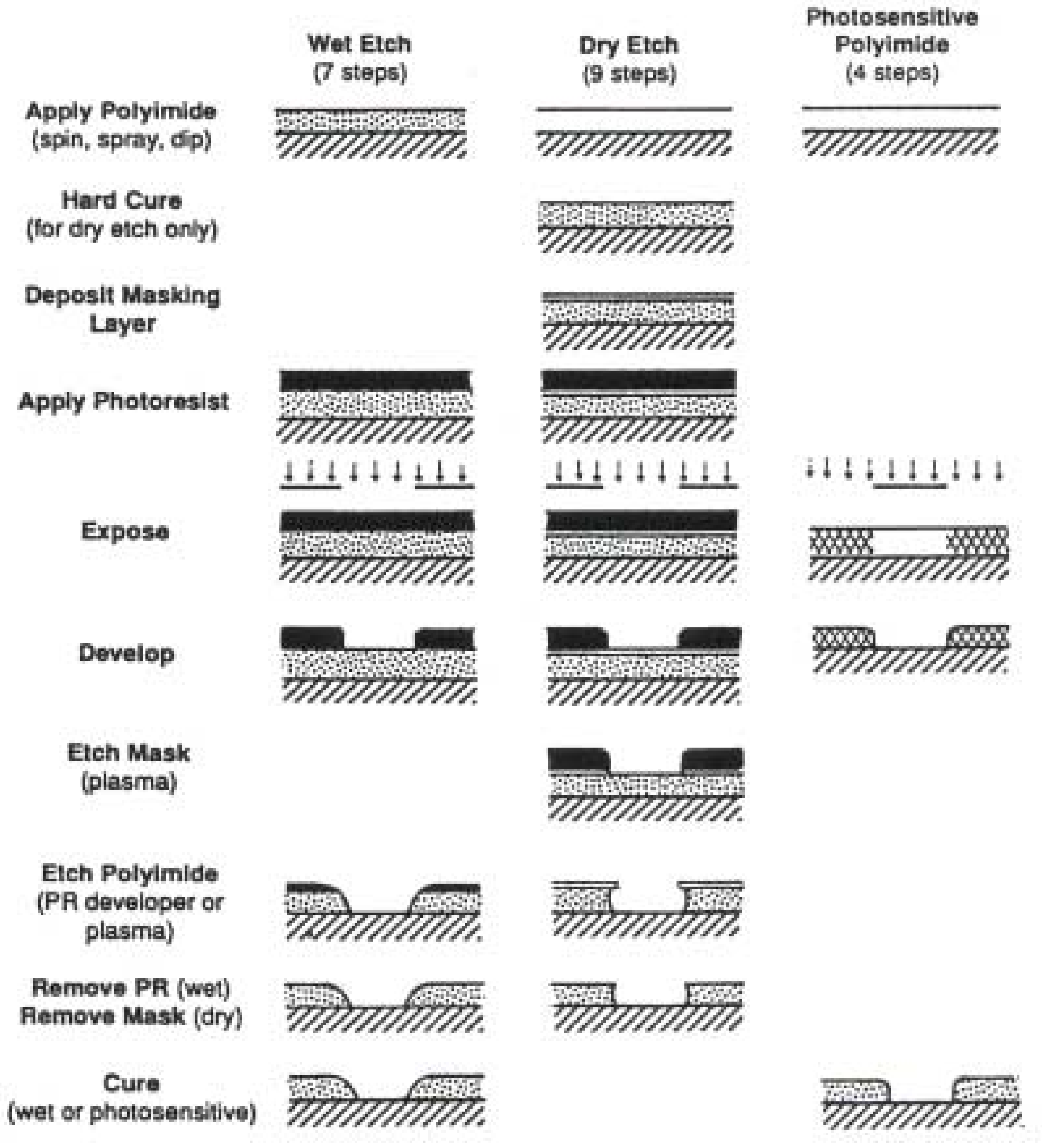

Figure I-4: Methods for etching polyimide[10]

The wet etch processing of polyimide uses wet chemistry along with a photoresist to define coarse features in the material with aspect ratios of 5 to 1 (via diameter to thickness). The photoresist is exposed on the polyimide and then developed. The developer etches the polyimide and afterwards the polyimide is rinsed away. The patterned polyimide is then fully cured to complete the imidization process and remove residual solvent[5]. A schematic representation of the imidization process where polyimide is formed from polyamic acid can be seen in Figure I-5. Chemical processing of polyimide is sensitive to temperature variations and limits the size and orientation of vias. This method is disadvantageous for the metallization vias where the vias are filled using electroless plating. Chemically etched vias can not support full metallization due to their shallow walled vias as seen in Figure I-6 where the via is not completely filled because of the structure of the profile[6].

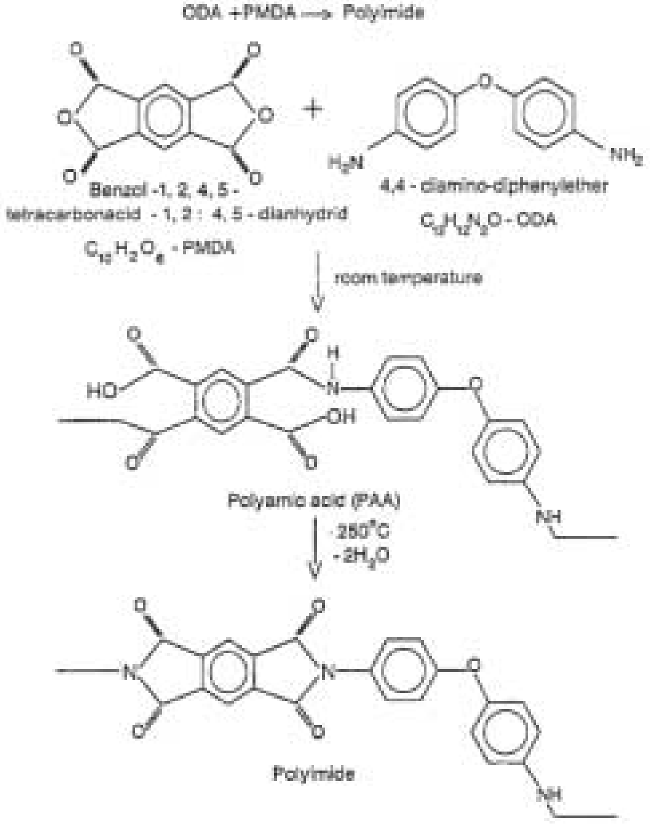

Figure I-5: Schematic of imidization of polyimide[7]

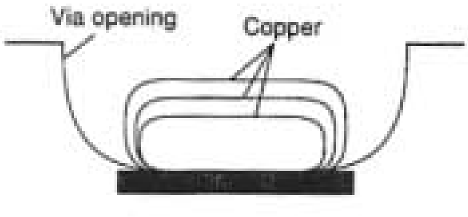

Figure I-6: Wet etching via wall profile[6]

The deposition techniques of polyimide allow for reactive ion etching or plasma etching for patterning the material. These techniques are dry etch methods that allow for finer feature sizes with an aspect ratio greater than 1 to 1. The dry etch methods begin with a hard cure of the polyimide. An etch mask such as thin film aluminum is then applied to the polyimide followed by the application of photoresist that is exposed and developed. The polyimide is then etched in a plasma or reactive-ion etcher. A mixture of CF_4 and O_2 gas is then used to etch the polyimide. The dry etch mask is then removed from the patterned polyimide[5]. Reactive ion etching as well as plasma etching has a combined effect of ion and chemical mechanisms that assist in etching by driving off hydrogen and partially oxidized carbon groups in polyimide. The concentration of O_2 and CF_4 gases can be adjusted to enhance the etch rate[7]. These dry etch methods allow for good adhesion for the metallization of the vias which have a tapered wall profile that can be improved by varying the composition of the gases. This method is not preferred due to the critical process steps involved[4]. An alternative method to dry etching is the use of photosensitive polyimide.

The use of photosensitive polyimide was developed as a way to reduce the cost of wet and dry etching. The processing of this material involves lithography where the film is exposed, developed, cured, and plasma cleaned. The use of this material is limited due to weakened mechanical and thermal properties[4]. Therefore, it can be seen as advantageous to use a laser to process polyimide.

1.2.2 Laser Processing of Polyimide

The use of a laser for the formation of vias has been developed for thin film electronic packages[8]. The most common application used by a laser is for material processing[9]. The process focuses on the controlled removal of material. A laser source that emits ultra-violet, visible, or infrared energy can be used to modify the surface of the polyimide for the formation of vias. The use of a wavelength greater than 200nm makes the process more economical from a design and manufacturing perspective[8]. Such sources that emit this type of radiation are the CO_2, excimer and Nd:YAG laser. A fraction of the polyimide removed is seen as debris. The amount of debris can be controlled with the processing atmosphere. The amount of material removed is a function of the number of pulses of the laser and the laser fluence that is the energy density of the laser and once it reaches a threshold value it causes material removal with each pulse delivered by the laser[8].

The use of a laser to form vias can be performed in four steps including the application of the polymer using an adhesion promoter, curing, ablation, and cleaning to remove excess debris[10]. Using a pre-cured polyimide with an adhesive layer can minimize these steps. By optimizing the laser processing parameters the cleaning step can be minimized or eliminated. The wall profile of the via formed with a laser as shown in Figure I-7 allows for full metallization and is not aspect ratio limited[4].

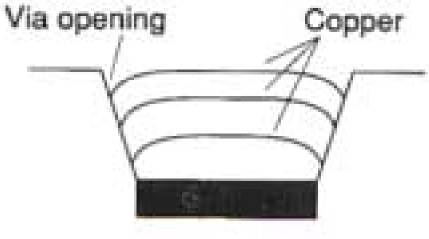

Figure I-7: Laser ablated via wall profile[6]

Most of the reported works on laser processing of polyimide dielectrics use excimer or Nd:YAG laser[11]. However, the instrument used in this thesis is the CO_2 laser because this equipment was readily available in the laboratory and has the ability to process a variety of materials. The CO_2

laser is shown to have high reliability, low maintenance, and quality output characteristics[9]. It has the ability to produce small feature sizes in thin materials[9]. The excimer laser allows for high-quality processing, but is uses toxic and corrosive gases, which lead to high running cost[11].

The quality of laser processed polyimide is governed by the physics of the interaction on the material surface[12]. The process of material removal at a specified wavelength involves two mechanisms, thermal degradation or chemical breaking of the bonds on the surface. Ultra-violet radiation causes photochemical decomposition of the polyimide[13]. This type of interaction is where direct bond breaking takes place without thermalization[14]. Infrared radiation promotes a thermal degradation of the polyimide that can be achieved using a CO_2 laser[13].

Early work was performed by Srinivasan[15] with a variable wavelength argon-ion laser in the ultra-violet range. The wavelength ranges from 300 to 330nm and from 350 to 380nm. His work supports a photokinetic mechanism for the laser interaction with polyimide instead of the ablative photochemical decomposition (APD) mechanism proposed for an excimer laser. APD is described as the etching of the surface of the polymer as a function of the wavelength of the laser, the absorptivity of the polyimide and the fluence of the laser. The photokinetic mechanism relates the cutting action of the laser as a function of the wavelength and movement of the laser spot. The samples used in his experiments are 25μm and 125μm Kapton film. He used surface profilometry, optical microscopy, and scanning electron microscopy to analyze the processed film. He suggests an optimum pulse width for the best results. The diameter of the laser processed area is a function of the pulse width, and experiments show that it increases as the pulse width increases. For pulse widths shorter than 500μs, the Kapton forms a tapered via wall. Srinivasan proposes the use of a CO_2 laser to heat the Kapton surface in order to lower the threshold for ablation[15].

Piglmayer, Arenholz *et al.*[16] discussed the ultra-violet laser interaction with polyimide according to the threshold for ablation. Their work uses an argon-ion laser with a wavelength of 302nm. Below the threshold, surface modifications and chemical degradations are shown to occur. Above the threshold, ablation or actual removal of material occurs. The effect of thermal and non-thermal mechanisms is still under consideration. Photochemical processes have been shown to depend on the intensity and pulse width of the laser where

$$\phi_0 = I_0\tau_l \tag{1.1}$$

ϕ_0 is the fluence, I_0 is the laser beam intensity and τ_l is the length of the pulse (pulse width). Thermal processes have been shown to depend mainly on the pulse width. The work by Piglmayer, Arenholz *et al.*[16] focused on the effect of a single pulse. Multiple pulses are believed to change the physical and chemical properties of the material. Experiments below the threshold showed hump formation on the surface of the polyimide due to polymer fragments being trapped within the surface. The threshold for ablation is considered to be a function of the pulse width. The results of the experiments support a thermal ablation mechanism for long pulses between 10ns and 50ms and a photochemical effect for shorter pulses. For thermal processes, the Arrhenius law is applicable[16].

According to the model proposed by Arnold[14], the Arrhenius law can describe the photothermal bond breaking on the surface of the polyimide. His research described the interaction of polyimide with an ultra-violet laser with nanosecond pulses. His model proposed that a critical density of broken bonds at the surface cause ablation to start. The experimental facts that motivated his model showed that ablated depth profilometry demonstrates ablation starts at the threshold fluence of the laser. The mass spectrometry reveals an Arrhenius tail during ablation and ablation results in the physical and chemical modification of the material. The observation of Arrhenius tails supports the thermal model of ablation. This model has a dependence on the laser repetition rate and pulse width. Arnold's[14] model focuses on volumetric decomposition of polyimide incorporating Arrhenius tails. Arnold uses the one-dimensional heat equation:

$$\frac{\partial H}{\partial t} = v\frac{\partial H}{\partial x} + \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) - \frac{\partial I}{\partial x} - L(1-n_{\mathrm{b}})k_0\exp(-T_{\mathrm{a}}/T) \tag{1.2}$$

where H is the volumetric enthalpy, v is velocity, K is thermal conductivity, k_o is a volume pre-exponential factor, I is the intensity, L is the enthalpy per unit volume, $(1 - n_b)$ is the fraction of virgin bonds and T is temperature[14]. This equation is used to calculate the temperature distribution that helps determine the Arrhenius factor. The volumetric enthalpy equation:

$$H = \rho \int_{T_0}^{T} c(T')\,\mathrm{d}(T') \tag{1.3}$$

where ρ is polymer density, c is specific heat and T_o is ambient temperature, is used to describe the thermally activated breaking of bonds. During ablation of polyimide it has the potential to lose up to 50% of its weight. The interaction with the laser causes breaking of imide rings and the release of CO molecules[14]. Figure I-8 shows a monomer of a polyimide chain where the broken bonds constitute CO molecules lost.

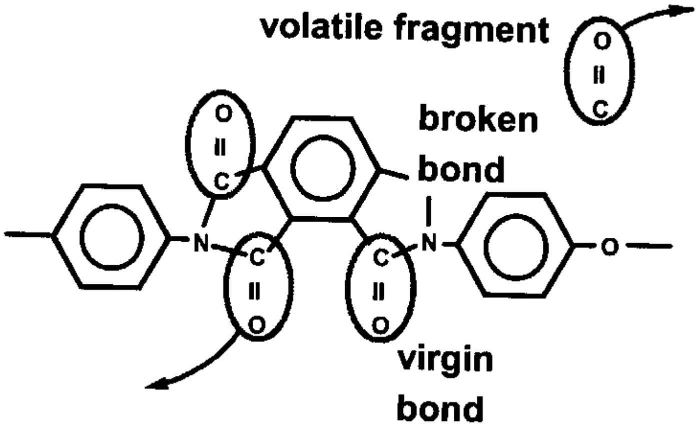

Figure I-8: Monomer of Polyimide Kapton™ [14]

The ablated depth of the polyimide is a function of the absorptivity and laser fluence. There is a logarithmic dependence on the depth, h, and the threshold fluence:

$$h = \alpha^{-1} \ln(\phi/\phi_{\mathrm{th}}) \tag{1.4}$$

where α is the absorptivity of polyimide, ϕ is the incident fluence and ϕ_{th} is the threshold fluence[14].

This supports the work by Tokarev and Marine[12] who stated that melt depth of polymers is dependent on the fluence and absorption coefficient of the material. They present a model for clean ablation using only a thermal mechanism. Their work focuses on the surface stability after laser processing. Tokarev and Marine[12] use an excimer laser in their research. The ablation of the material is described as surface melting with a temperature gradient through the depth of the material[12].

Haba and Morishige[11] presented a drilling technique for polyimide using an argon-ion laser at a wavelength of 515nm. They consider the use of a CO_2 laser disadvantageous due to the small hole sizes formed and propose the use of a visible laser. Their work involves a two-step process that includes laser material removal and ultrasonic cleaning. The samples used were 25μm thick polyimide layered on 18μm thick copper. Their process uses a single laser shot per drilled hole. The energy absorbed by polyimide generates a high temperature gradient followed by heat diffusion. The decomposition of the polyimide is due to the high temperature, which causes material to be removed as gas from the hole with some being deposited around it as debris. Tapered via walls were obtained due to thermal diffusion of polyimide and temperature gradient created by the copper layer. The minimum laser pulse width needed in order to reach the copper layer is governed by the polyimide thickness and heat diffusion. The greater the ratio of the polyimide thickness to the thickness of copper, the longer the pulse width needed to reach the copper layer. The use of pulse widths in the nanosecond range was not seen as an option to decrease the pulse width due to debris formation that could not be removed. Millisecond pulse widths can be used to drill holes in polyimide on copper, but is limited by the polyimide thickness[11].

1.3 Issues with Current Ways of Processing Polyimide

While work using a laser for processing a polymer dielectric is currently being studied, the purpose of this thesis is to present an effective and economical approach using laboratory equipment that is most commonly used and available for the processing of materials including polymers and metals. The use of a laser allows for a more cost effective and flexible method for processing polyimide over other wet and dry processes.

The equipment used drives the quality of the process, along with the cost[11]. Current ways of processing polyimide use an excimer or Nd:YAG laser because the processing is more efficient due to the strong absorption of the material by ultra-violet light. The CO_2 laser used in the experiments in this thesis has limits that are driven by the quality of the material after processing[13]. These limitations include charring and debris formation around the perimeter of the polyimide via and changes in conductivity and composition of the material [13,14]. Charring of the material occurs because of weak light absorption in the visible and near infrared region. This is the main disadvantage of using a CO_2 laser. However, cleaner ablation using a CO_2 laser can be achieved by adjusting the laser repetition rate. The CO_2 laser has the advantage of a larger beam size, larger pulse energies, higher laser efficiency, and use of nontoxic gases compared to the excimer laser[17].

Work by Brannon[17] supports the use of a CO_2 laser because of the operational advantages. At infrared wavelengths, the thermal mechanism of etching polyimide can be viewed as the amount of energy absorbed by the material. The absorbed energy is a function of the absorptivity and reflectivity of the material and fluence of the laser represented by this equation:

$$E_{abs} = \alpha(1-R)\phi \qquad (1.5)$$

where α is absorption coefficient, R is reflectivity, and ϕ is the incident fluence[17].

In order to improve the feasibility of using a CO_2 laser for the processing of polyimide it is necessary to examine ways to clean the surface of the material. Research performed by Coupland, Herman and Gu[13] demonstrated the use of a CO_2 laser dry cleaning process on 50µm thick polyimide. This process can be used to remove debris from CO_2 laser etched vias as well as debris generated by an excimer laser. Their work proposes a way to eliminate post-laser cleaning steps. Their study provides the first chemical evidence that supports photothermal mechanisms for CO_2 laser ablation. A wavelength-tunable CO_2 laser was used to effectively remove debris. Previous techniques of controlling gas flow and pressure used to remove excimer laser generated debris had little effect on minimizing the debris formed by a CO_2 laser because of the chemical and physical differences of the debris products. The CO_2 laser-generated debris was observed to maintain much of its original nitrogen, which is the key link in the monomer chain. Varying the laser wavelength and repetition rate optimized the debris removal process. The results at wavelengths of 9.220 and 9.250μm show effective laser cleaning with less than 100 pulses. The laser fluence was kept below the threshold for ablation to prevent damage of the polyimide. The laser cleaned surface did not appear charred or melted after using this cleaning technique, but there were ripples noticeable on the surface of the polyimide[13].

1.4 Objectives and Goals of Research Work

The work presented in this thesis presents a method for the processing of polyimide for improved surface-to-laser interaction. The objective of this research is to develop a procedure for obtaining quality via holes in polyimide (Kapton™) on copper. This procedure should minimize the debris caused by polyimide and laser interaction by using optimized laser parameters.

This thesis will demonstrate the use of a laser processing technique to drill holes efficiently and at low cost in polyimide for use in the process to build electronic packages. The processing of polymers with a laser will be explored along with the laser interaction with the polyimide. The mechanism that describes the CO_2 laser interaction with polyimide is not widely published and the work presented in this thesis attempts to identify the mechanism as the experiments support previous work published. A discussion on the dependence of the process on frequency, pulse width, and number of pulses will be reported.

The work in this thesis will provide a basis for determining how to set laser parameters for a CO_2 laser used to process polyimide in order to achieve quality and cost effectiveness.

1.5 Structure of Thesis

The first chapter introduces the research for this thesis and states the objectives and goals of this research, issues with current ways of processing polyimide, and advantages of the stated approach. It also presents a review of polyimide processing techniques, laser interaction with polyimide, and its application to electronic packaging. Chapter 2 presents techniques used to prepare samples, as well as laser processing techniques and laser processing parameters. Chapter 3 gives a quantitative and qualitative view of the results on the processing of different Kapton samples. Chapter 4 summarizes the work presented in this thesis and recommends future work.

Chapter II Experimental Procedure

2.1 Sample Preparation

This chapter describes the techniques, equipment, and processing steps for forming vias in polyimide on copper. In order to observe the effect of the laser parameters on the polyimide free-standing samples were prepared with Kapton on a frame. The two free-standing samples consisted of one with Kapton and one with Kapton with an adhesive layer.

2.1.1 Free-Standing Polyimide

The effect of laser interaction with Kapton was first analyzed using free standing samples of Kapton mounted on a metal frame as shown in Figure II-1.

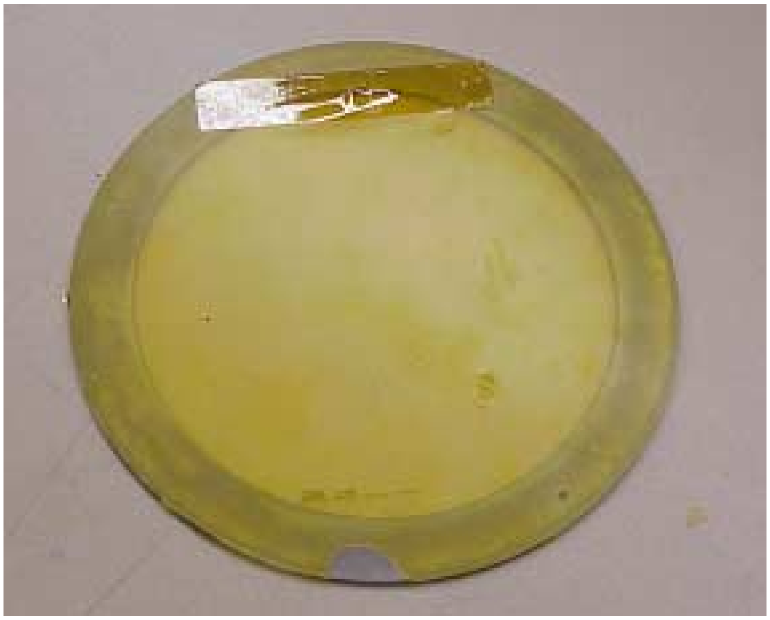

Figure II-1: Kapton^{TM} on metal frame

The samples consisted of a frame mounted with Kapton and a frame mounted with Kapton coated with an adhesive layer. The first sample of Kapton was mounted on a metal frame by using a sheet of adhesive film. The sheet was cut to fit the frame and a combination of heat and pressure was used to mount the material on to the frame. A laminating press was used to mount the Kapton on the frame as shown in Figure II-2. The temperature was approximately 250° C and a pressure of approximately 400 pounds per square inch was applied for 3 to 5 minutes. The adhesive is a thermoplastic polyimide that allows it to be reworked by reheating.

The processing of Kapton with an adhesive layer was processed in much the same way as the Kapton without adhesive. The only difference was there was no additional adhesive needed to mount the film on the frame.

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Figure II-2: Laminating Press

2.1.2 Polyimide Layering on Copper Procedure

The processing of polyimide is usually done over copper bond pads with the polyimide being deposited over the copper. For the experiments in this thesis, the focus is on the interaction of the polyimide and the laser for quality vias. To demonstrate the application of the processing method presented, polyimide film was attached to a copper substrate using a laminating press.

A single layer of Kapton with an adhesive layer was attached to the copper for one of the samples. The laminating press was used to bond the adhesive on the Kapton to the copper metal. The thickness of the copper substrate was measured to be 200µm (8 mils). The thickness of the Kapton was measured to be 25µm (1mil). The adhesive side of one layer of Kapton was placed over the copper. Once the laminating press reached a steady temperature approximately 250° C, the sample was placed between two parallel hot plates using thermal insulating gloves. Approximately 500psi were applied to the sample under the press. The sample was left for 2 minutes before being removed from the press and taken off of the hot plates. These steps were repeated until the desired layer thickness was reached. Figure II-3 shows the layering of polyimide with adhesive on a copper substrate. The number of layers chosen for the multi-layer sample was 10 in order to make the thickness of the polyimide greater than that of copper. Increasing the thickness of the polyimide would enable the aspect ratio to be increased for applications in microelectromechanical systems (MEMS).

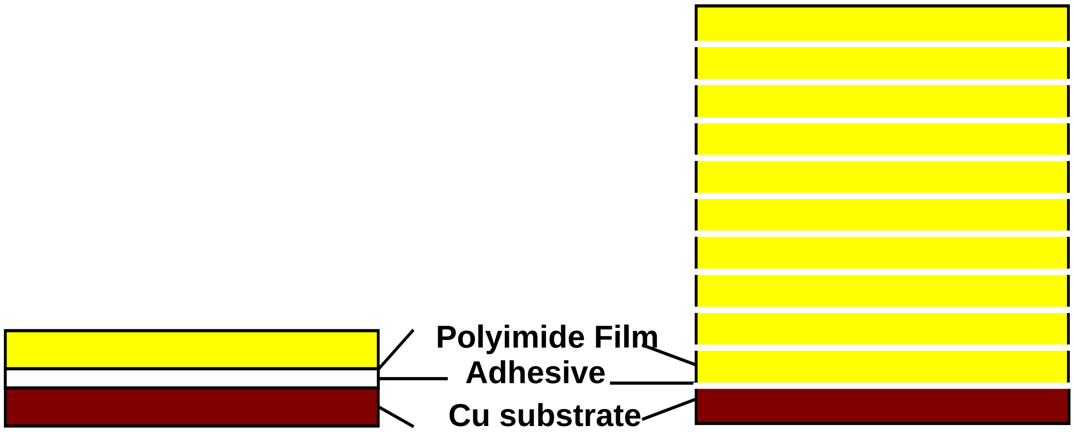


Figure II-3: Experimental Sample – Single Layer Polyimide   Multi-layer Polyimide

2.2 Laser Processing Technique

2.2.1 CO_2 Laser Setup [18]

The CO_2 laser shown in Figure II-4 is part of a materials processing system that outputs 100 Watts of power. It generates short, high intensity light pulses at a wavelength of 10 microns. This light source emits pulses of infrared light at repetition rates up to 20kHz. The pulses are directed by a beam delivery system that houses the enclosed beam.

Figure II-4: CO_2 Laser System

The CO_2 laser directs the light into the processing chamber as shown in Figure II-5 where it is focused through focusing lenses to increase the beam intensity at the material being processed. The material is removed by thermal mechanisms and an assist gas is used during processing to help cool the processed material locally and remove some debris generated during processing.

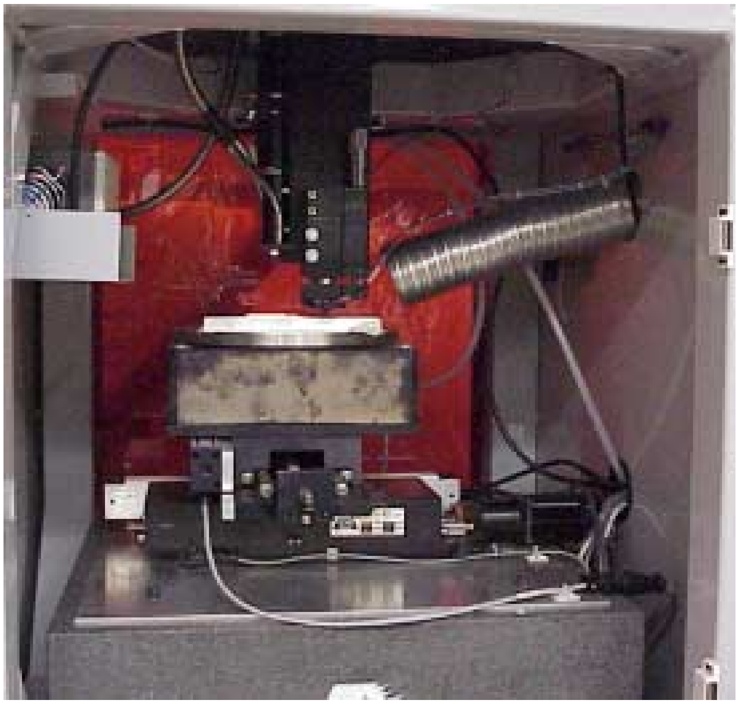


Figure II-5: Laser Processing Table

The CO_2 laser is an industry standard sealed system that allows the user to vary pulse width, repetition rate, stage speed and number of pulses. This flexibility allows for optimization of the material processing. Little maintenance is involved because it is a sealed system. All laser functions are software controlled and cooling water is used for the laser head.

The beam delivery system defines the optical path of the laser beam. It is fixed during operation, but can be adjusted. The output of the laser is directed away from the process chamber and steered back with the first and second turning mirrors. The long distance to the third mirror allows for beam divergence to make the initial beam grow to fill the final focusing lens for achieving minimum spot size on the target. Figure II-6 shows a schematic of the beam delivery system.

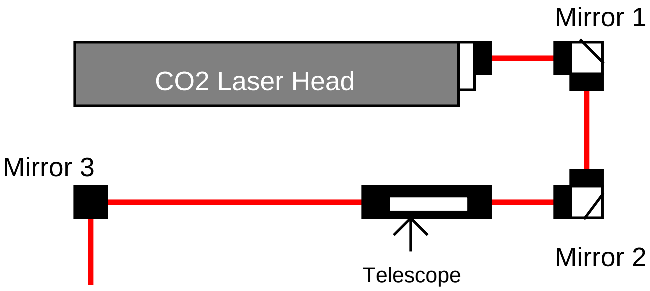


Figure II-6: Top View of CO_2 Beam Delivery System

The following is the procedure for standard operation of the CO_2 laser. It begins with the system startup, software control, and shut down. This procedure was followed for proper operation of the laboratory equipment. The system startup and system shut down procedures, as outlined in the laser operating manual, were used to power the laser system on and off. The software control was used to define the desired pattern and laser parameters for processing.

System Startup

1) Main disconnect switch is in ON position
2) Power up system by turning key and releasing emergency stop
3) Power up computer
4) Turn on water valve for CO_2 laser head
5) Choose CO_2 program and RUN
6) Test fire laser and verify proper functioning using software controls

Software Control

1) Home XY Stage
2) Calibrate Camera using scrap material
3) Focus laser by firing pulses onto thermal paper
4) Adjust set screw on focus head assembly up or down
5) Obtain smallest spot size for set laser parameters
   (For these experiments the repetition rate was 100Hz and the pulse width was 25µs for 10 pulses)

6) The smallest spot size was noted as 105μm
7) Measure height on Kapton on frame
8) Adjust setscrew up for difference in height from thermal paper
9) Place material for processing on stage
10) Load program file for processing
11) Run program file

Shut Down

1) Exit software
2) Power down computer
3) Press Emergency Stop
4) Turn key to off position
5) Leave main disconnect switch in ON position
6) Turn off water valve

2.2.2 Software Control

The software control determines the process parameters for each program developed. Pentawave PhotoMachining laser software is used to control the laser system. This program consists of operations that create processing and patterning files, control for the table on which the material is processed, and control of the laser operating parameters. The basic program concepts allow the user to home the motor controls, teach programming locations, calibrate the camera and laser locations, adjust the offset of the part to be machined, use reference points, compensate for beam radius, and adjust system parameters. The homing of the motion control system establishes the default origin of the system and is performed automatically at each startup of the laser. In order to program locations for patterning, the camera must be calibrated with the laser. This is the offset distance between the camera and the final focus lens. The reference points for processing the material can be changed by moving the table to the appropriate location and zeroing the x and y coordinates. The radius of the laser beam should be compensated for precision processing. This was not done because there were no set guidelines for the formation of vias. The software also allows for adjusting the system parameters such as the pulse width, repetition rate, xy-axis speed, and number of pulses that effect material processing. The software controls for Speed and

Pulse were used to program a series of pulses on the polyimide to observe laser processing quality. The Speed control allows the pulse width, repetition rate, xy-axis speed, and theta rotation speed to be chosen within the limitations of the equipment. The Pulse control allows the number of pulses, x-coordinate, y-coordinate, and theta rotation to be specified. The x and y-coordinates specified under this command are in relation to the user set origin[18].

2.3 Characterization

The effect of the CO_2 laser on the processing of polyimide is governed by the independent operating parameters that can be set using the software that controls the laser. These parameters include the pulse width, repetition rate, number of pulses and stage speed. The pulse width specifies the duration of the pulse output by the laser in microseconds. The repetition rate specifies the number of pulses per second output by the laser. The stage speed, which controls how fast the table moves on its x-y axis, was observed to have no effect on the formation of vias in the polyimide and it was not explored further.

The software was programmed to drill a series of pulses onto the Kapton samples. Each parameter was specified for a single laser shot. The parameters were varied for each successive run of the program and the quality of the holes was visually inspected. The visual inspection of the holes consisted of an examination using a microscope that allowed a magnification up to 7 times. Images were captured using a digital camera system attached to the microscope. The effect of the laser parameters was then noted.

The effect of the laser processing was further characterized by measuring the entrance diameter of the actual hole formed and the diameter of the heat affected area surrounding the hole formed on the polyimide surface. This information was plotted in a graph vs. the parameter being varied.

In order to represent the effect of pulse width, repetition rate, and number of pulses on via diameter, the diameter of each hole formed was measured and then divided by the largest hole diameter within the series of pulses fired. Each series formed eight to nine vias with varying process parameters. The measured data was analyzed in graphical form and compared with the visual results.

The quality of the via was quantified by measuring the diameter of the heat affected area surrounding the perimeter of the hole formed. The percentage of heat affected area was approximated using the following equation:

$$\text{Heat Affected Area} = (1-r^2/R^2) * 100\% \qquad (2.1)$$

where r represents the diameter of the hole formed and R represents the diameter of the total affected area. This data was graphed and verified with the visual results. The quality can be said to increase as the percentage of heat affected area decreases.

This quantitative analysis presented in Chapter 3 was used to form conclusions on the effect of laser processing on the polyimide.

Chapter III Results

3.1 Introduction

This section begins with the results on the laser interaction with polyimide. These results will include the interaction of precured polyimide with and without an adhesive layer. Once the effects of the laser parameters were established for controlled processing of polyimide with the CO_2 laser, the polyimide-copper (PI-Cu) samples were processed. The laser processing was performed in a closed atmosphere. A direct laser beam, with a measured spot size of 105μm at a repetition rate of 100Hz and pulse width of 25μs, was used with compressed air. This spot size is a function of the focal lens of the laser. Before the experiments were performed, the CO_2 laser was aligned following the procedure outlined in the operating manual.

3.2 Laser Processing of Kapton

3.2.1 Effect of Pulse Width

According to experiments performed using a CO_2 laser, the variation of the pulse width in the microsecond and millisecond range significantly affected the diameter of the via formed. A series of experiments varying the pulse width over short and long ranges showed an almost linear increase in via entrance diameter. This can be seen visually and by plotting the percentage of the largest hole diameter dependency on pulse width. The percentage of the largest hole diameter was determined by measuring the diameter of the hole formed and taking the ratio of the largest diameter. These experiments allowed for observation of the effect of pulse width variation given different number of pulses and repetition rate.

Over a range of pulse widths from 15μs to 1500μs, there was a trend of steady increase in the hole diameter formed during laser processing of polyimide. In deciding the best pulse width to use for laser processing, it is necessary to know the size of the via needed. The larger the via, the larger the pulse width needs to be. The effect of the pulse width was observed first over a small range of variance and then over a larger range and both were shown to have the same trend.

The heat affected area around the perimeter of the hole formed decreases as the pulse width increases. This trend was evident over large and small ranges in pulse width variation. The data presented shows the effect of varying the pulse width with a set repetition rate of 500Hz.

The picture taken of the actual sample in Figure III-1 shows the effect of increasing the pulse width on the hole diameter. The largest hole diameter in the picture is 478µm with 320 pulses. Figures III-2 and III-3 graphically represent the effect of laser processing of Kapton without adhesive by varying the pulse width.

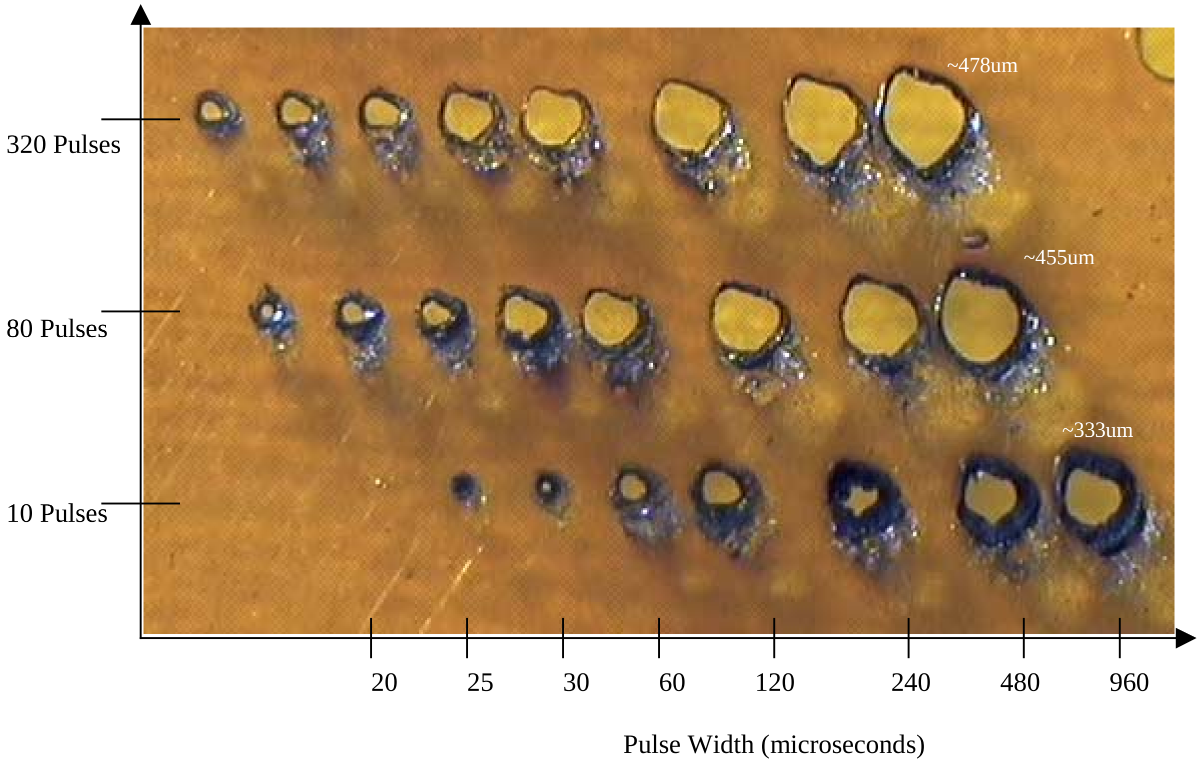


Figure III-1: Effect of Varying Pulse Width on Kapton™

Figure III-2 shows the increase in the hole diameter as the pulse width is increased. The effect of the pulse width appears to be linear. The greater the number of pulses the larger the ratio of the smallest hole diameter to the largest hole diameter. The energy density of the laser increases as the pulse width increases causing the hole formed to increase as well. The more energy that is absorbed by the material results in more material being removed.

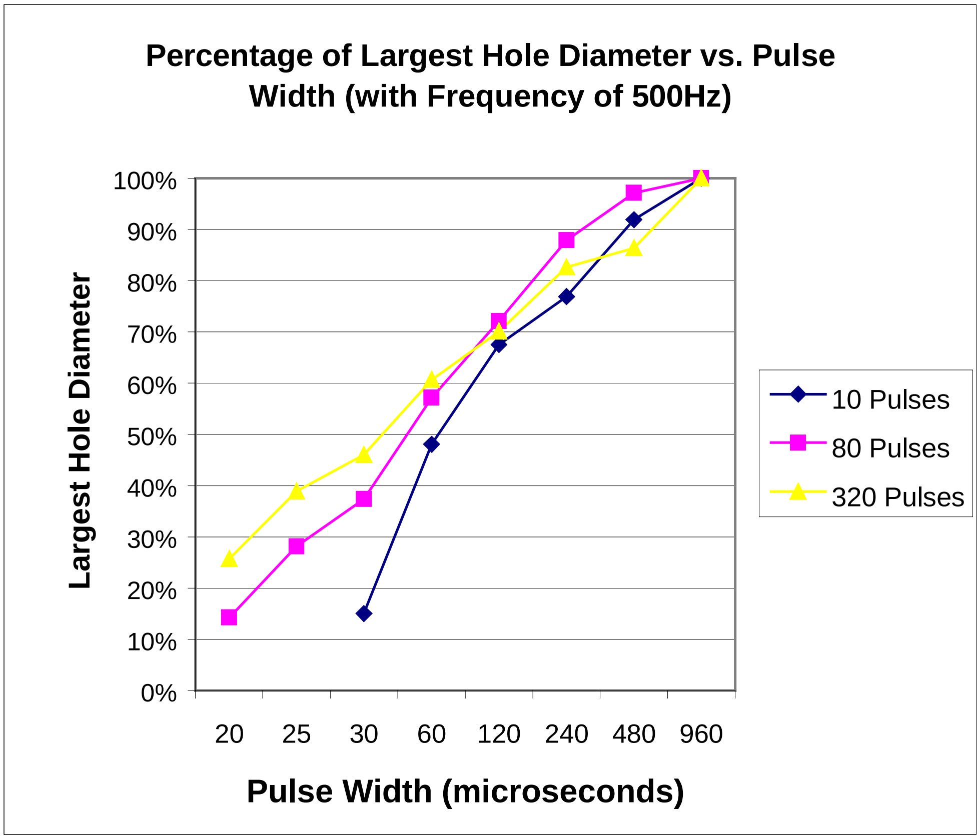


Figure III-2: Effect of Pulse Width on Hole Diameter

Figure III-3 shows a decrease in the heat affected area as the pulse width increases. This is most evident for larger number of pulses. As the number of pulses increase, there is evidence of less charring. Over the range of the pulse widths, the characteristic curve tends to approach an asymptotic value where a minimum percentage of heat affected area is reached. This asymptotic value is reached for pulse widths greater than 120µs.

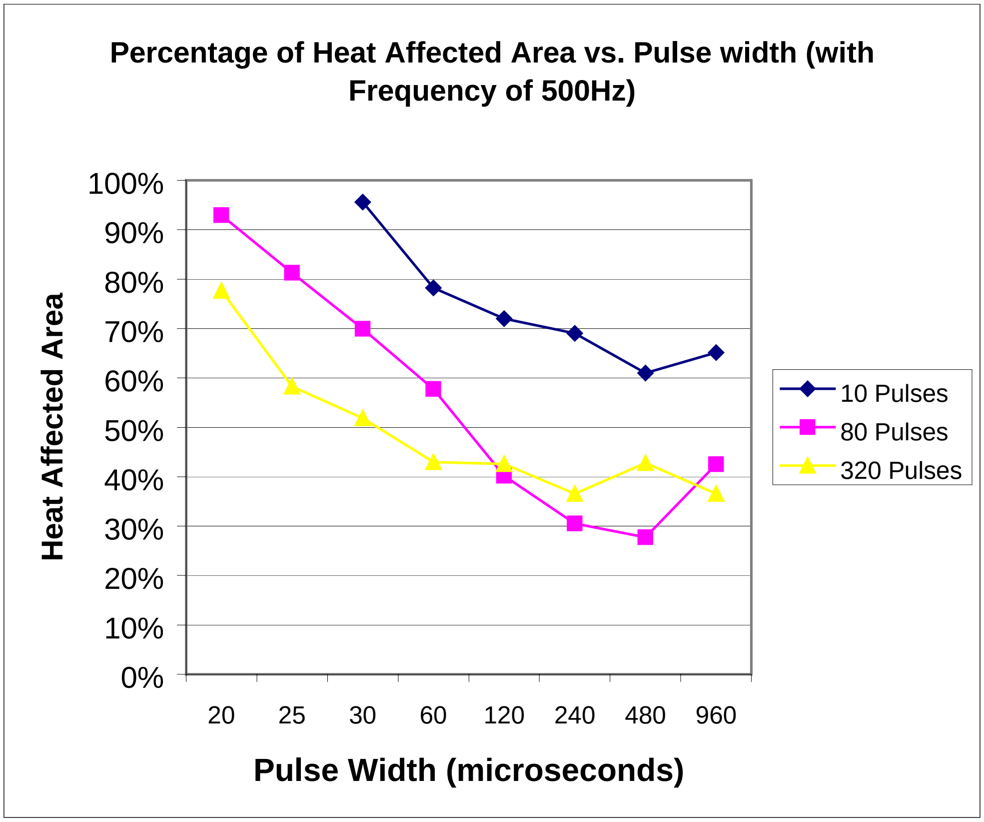


Figure III-3: Effect of Pulse Width on Hole Quality

The quality of the via was measured according to the equation (2.1) used previously. The percentage of the total affected area that is charred is plotted over the range of the pulse widths. The quality increases as the percentage of heat affected area decreases. The trend shows a decrease in charring with an increase in pulse width. This trend is also evident visually. There is an average of 40% decrease in charring as the pulse width was increased. The quality of the laser ablated via was observed using a microscope. Over the ranges of varied pulse widths, there was an obvious decrease in the amount of charring and debris as the number of pulses increased.

The appearance of more debris formation on the right side of the vias formed are indicative of the gas flow as the laser is directed onto the surface of the polyimide.

The results suggest a pulse width greater than 100 μs and using more than 100 pulses will create a via with a minimal amount of cleaning needed. Decreasing the repetition rate can minimize the charring and debris caused by laser processing.

3.2.2 Effect of Repetition Rate

The repetition rate was varied during laser processing in an attempt to minimize debris. The effect of varying repetition rate depended heavily on the number of pulses used. There was evidence that the diameter of the hole slightly increased as the repetition rate increased. The increase in hole diameter with increasing repetition rate does not have as great effect as increasing the pulse width. As the number of pulses increased, the hole diameter approached a more constant value.

The data presented shows the effect of varying the repetition rate with a set pulse width of 30 microseconds. By increasing the pulse width, there was not much difference noticed in the characteristic of the entrance diameter formed. However, the percentage of heat affected area was larger for shorter pulse widths. A shorter pulse width was chosen to minimize the processing time.

For a small number of pulses with frequencies above 500Hz there was not much improvement in the amount of charring and debris. As the number of pulses in the trials was increased it was more evident that the quality was better at the lower frequencies. The picture as shown in Figure III-4 of the actual processed sample of Kapton without adhesive by varying the repetition rate shows a strong correlation with the graphical data represented in Figures III-5 and III-6.

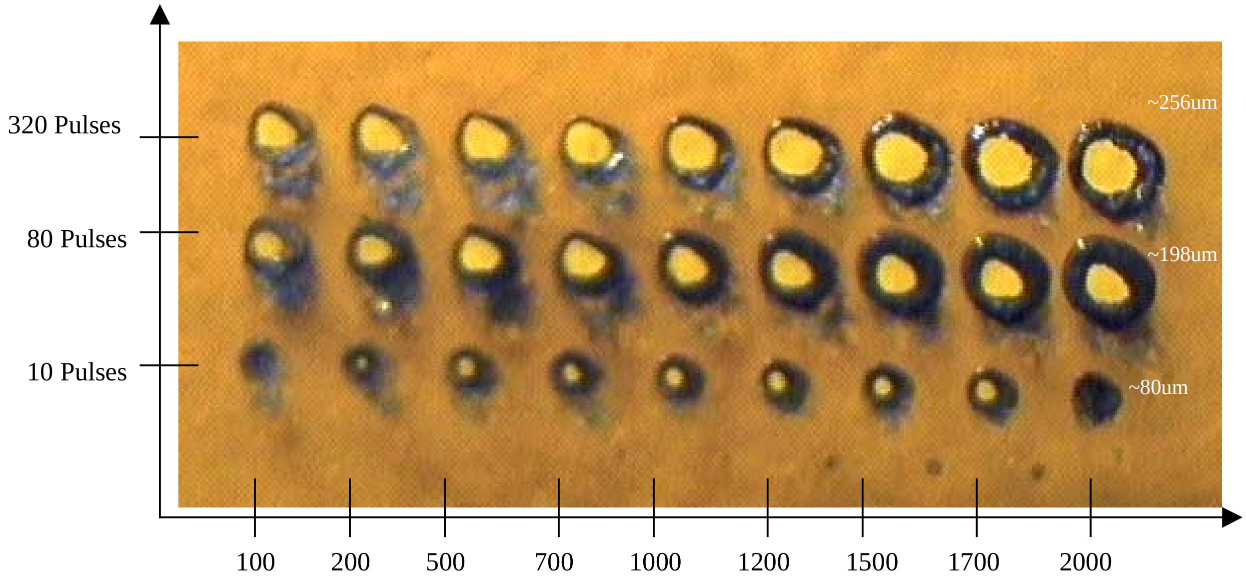


Figure III-4: Effect of varying Repetition Rate on Kapton™

Figure III-5 shows the graph of the dependency of the percentage of the largest hole diameter to the repetition rate shows a smaller entrance diameter for repetition rates less than 500Hz. For greater repetition rates, the diameter appears approximately constant. The repetition rate has little affect on the diameter of the hole formed.

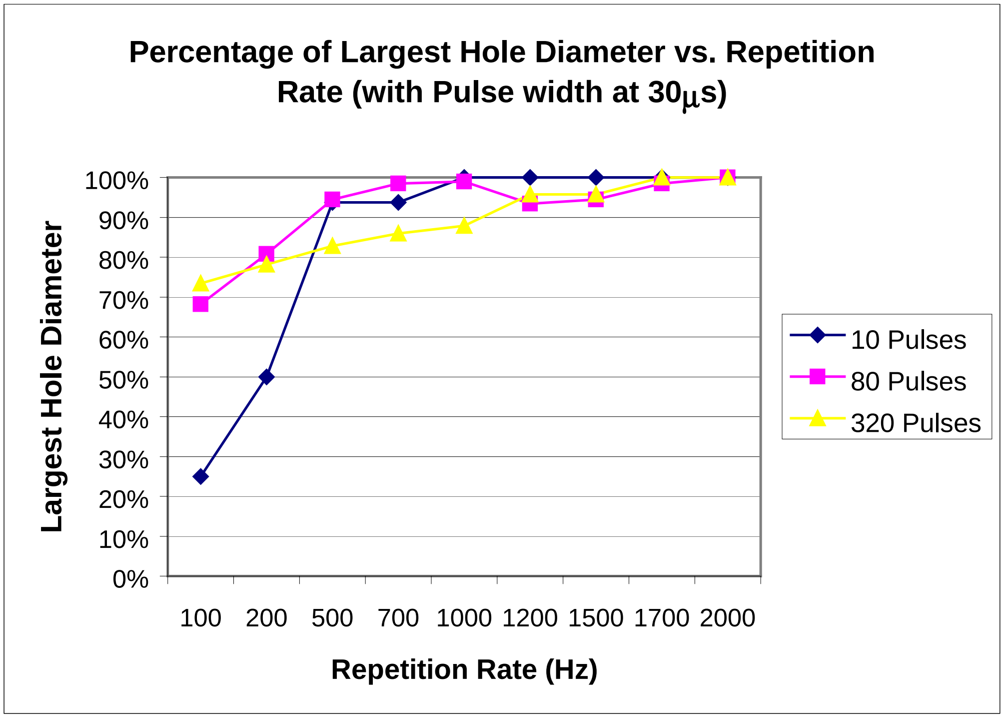


Figure III-5: Effect of Repetition Rate on Hole Diameter

Figure III-6 shows an almost constant amount of charring over the range of repetition rates. As the number of pulses increased, the trend shows a slight increase in charring for repetition rates over 1200Hz. The characteristic curves showed an increase in quality with an increase in the number of pulses. The constancy of the curves suggests that the repetition rate has little effect on the quality of the laser-processed polyimide. Lower repetition rates are demonstrated to have better quality.

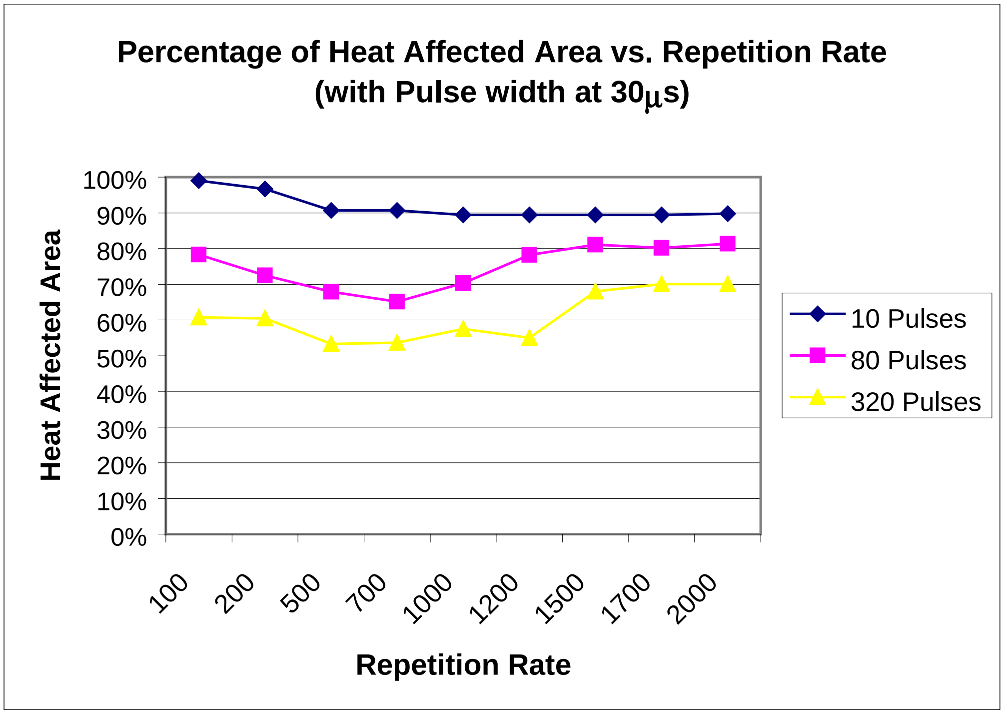


Figure III-6: Effect of Repetition Rate on Quality

The repetition rate was varied over a range from 100 to 2000Hz. Over the range of frequencies chosen, the maximum hole diameter was approached rather quickly which shows an almost constant hole diameter for frequencies greater than 500Hz.

The results demonstrate that better quality can be achieved using a frequency of 500Hz and a large number of pulses. From the results, the use of 320 pulses would produce good results. In order to determine the number of pulses for creating a good via, the effect of varying the number of pulses was observed.

3.2.3 Effect of Number of Pulses

The number of pulses was varied to determine their effect on the processing of polyimide. As the number of pulses increases over a set repetition rate and pulse width, the diameter of the hole increased until it approached its maximum value. This maximum value depended on the pulse width of the laser beam. The pulse width was increased for each successive run. As the pulse width increased, the number of pulses needed to form a via decreased. This can be seen by looking at one pulse over the pulse width variation and noticing the increase in diameter with the increase in pulse width. Over the range of pulses from 1 to 1280 the diameter showed a steady increase until it approached its limit. A visual inspection of the polyimide over the variation of the number of pulses showed the formation of no hole at small pulse widths (or a small hole at larger pulse widths) increasing to a relatively constant diameter.

There was noticeable improvement as the number of pulses increased. The trend showed a decrease in charring as the number of pulses increased. The best results were at longer pulse widths, lowered repetition rate and larger number of pulses. Figure III-7 shows the actual sample that corresponds with the graphs in Figures III-8 and III-9 that represent the effect of laser processing of Kapton without an adhesive layer by varying the number of pulses.

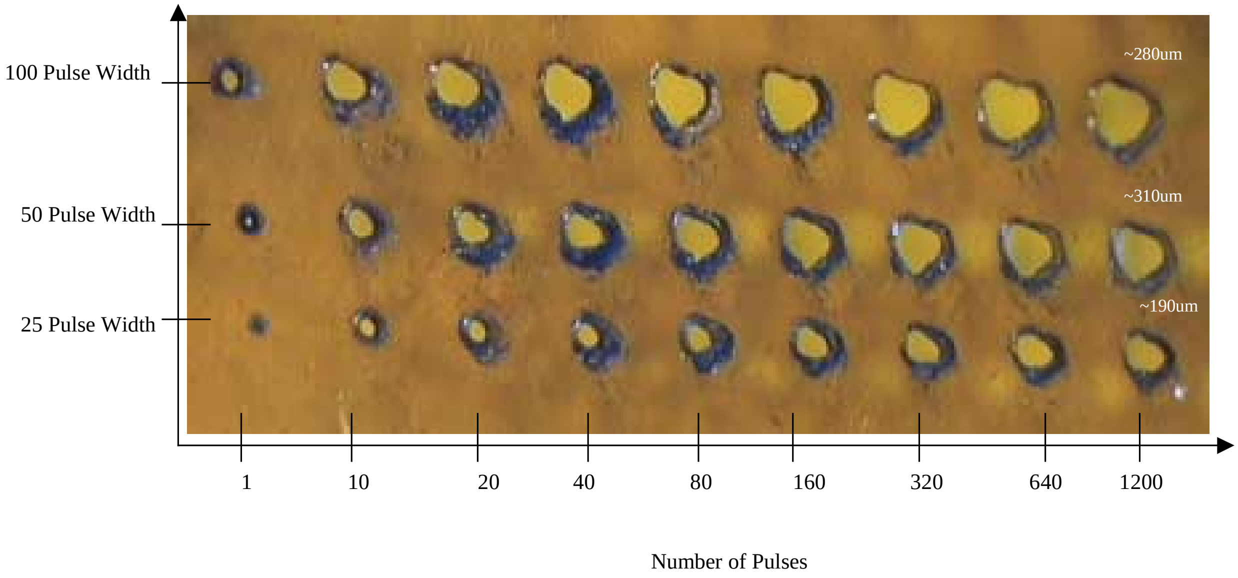


Figure III-7: Effect of varying Number of Pulses on Kapton^{TM}

Figure III-8 shows the entrance diameter of the hole increases almost linearly as the number of pulses increases until it reaches a maximum at 320 pulses. The diameter approaches a constant value beyond this point. As the pulse width increases, the ratio of the initial hole diameter to the final hole diameter slightly increases. For the three different characteristic curves shown, there is an overlap once the diameter approaches a constant value. The use of 320 or more pulses would produce a constant via diameter by laser processing with a CO_2 laser.

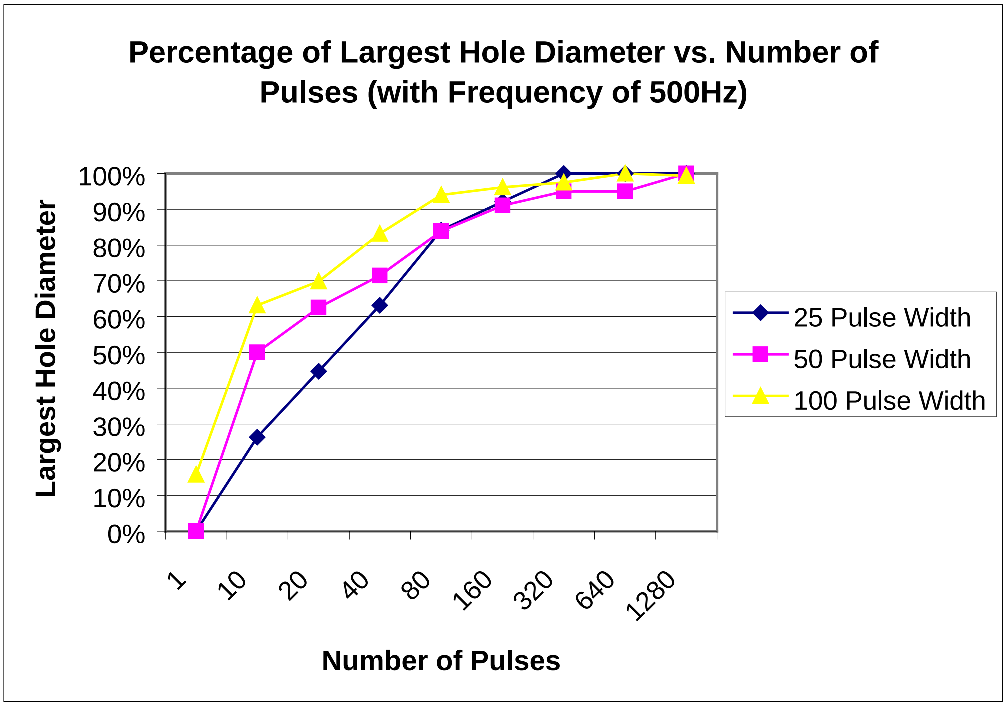


Figure III-8: Effect of Number of Pulses on Hole Diameter

Figure III-9 represents an increase in quality as the pulse width increases. The amount of charring decreases until it approaches a maximum around 320 pulses. There is less charring evident at longer pulse widths, but the process time increases.

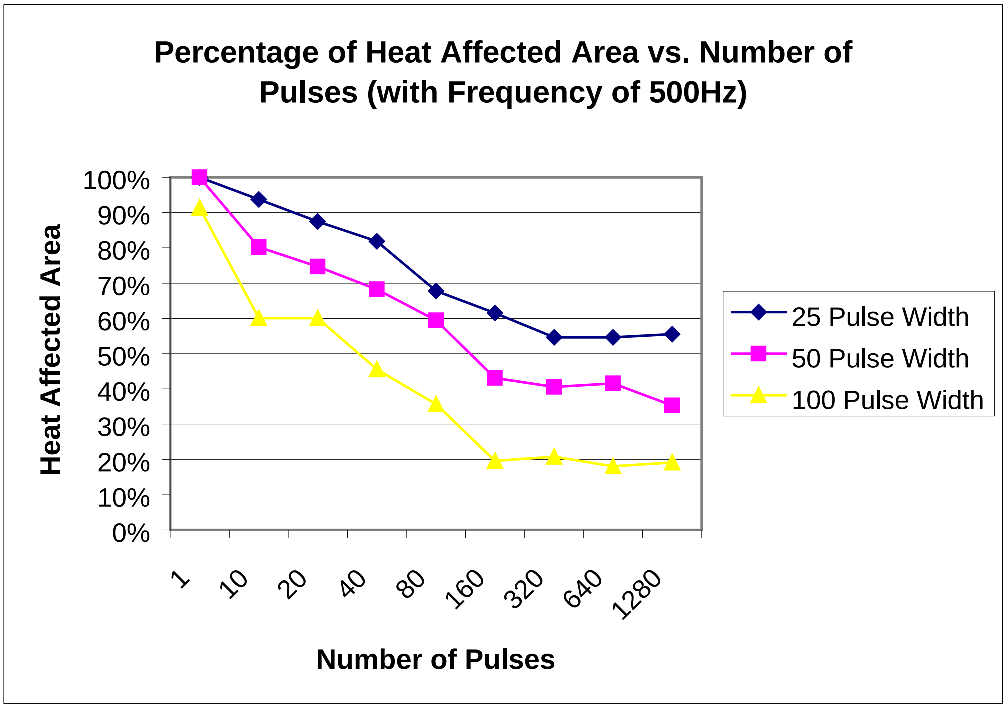


Figure III-9: Effect of Number of Pulses on Quality

The results suggest using 320 pulses for a constant diameter and a pulse width of 100µs to minimize charring and increase the quality of the hole formed. This would lead to an increase in processing time.

3.3 Laser Processing of Kapton with adhesive

3.3.1 Effect of Pulse Width

The laser processing parameters have a different effect on the polyimide when there is an adhesive layer present. The pulse width still has the effect of increasing the entrance diameter, but as the number of pulses varies this seems to have no effect on the characteristic curves. The addition of an adhesive layer increases the thickness of the polyimide and allows for cleaner laser processing.

The picture, as shown in Figure III-10, shows the actual processed sample and how it relates to the graphical data represented in Figures III-11 and III-12 on the effect of Kapton with adhesive by varying pulse width.

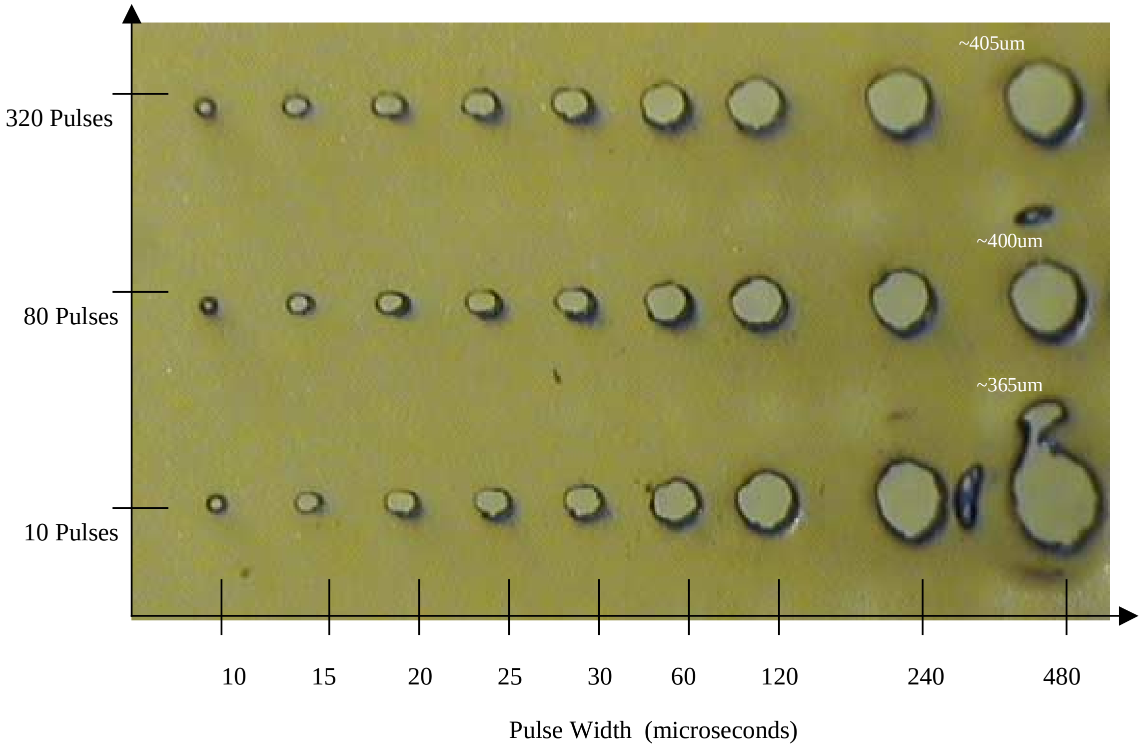


Figure III-10: Effect of varying Pulse Width on Kapton^{TM} with Adhesive

Figure III-11 shows an almost linear increase in entrance diameter with an increase in pulse width. By increasing the number of pulses, there was no significant effect on the hole formed as seen by the overlap of the characteristic curves for different number of pulses. Compared with the Kapton sample without adhesive, there is no distinction made for the number of pulses used. This would suggest that a smaller number of pulses can be used to achieve the same results as a larger number of pulses. Therefore, the process time can be minimized.

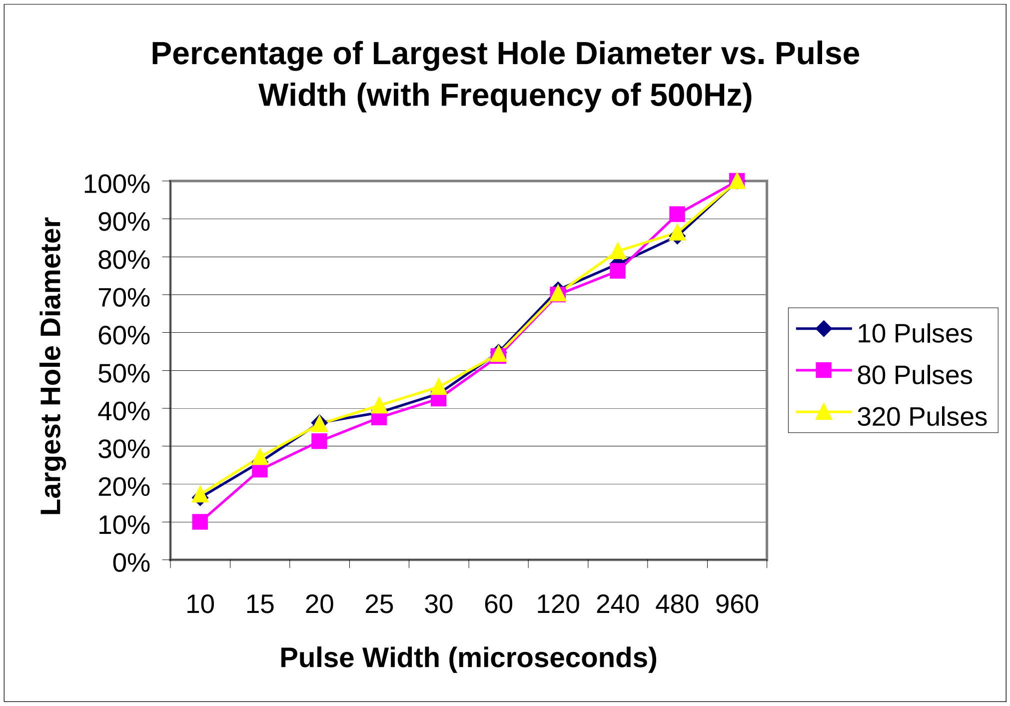


Figure III-11: Effect of Pulse Width on Hole Diameter

Figure III-12 shows the effect of varying the pulse width on the quality of the hole formed. Once again, the characteristic curves overlap. This suggests that the number of pulses have little effect on the quality of the Kapton. The quality of the hole increases as the pulse width increases. This corresponds with the data obtained without adhesive on the Kapton. There is a 40-60% increase in quality as the pulse width is increased.

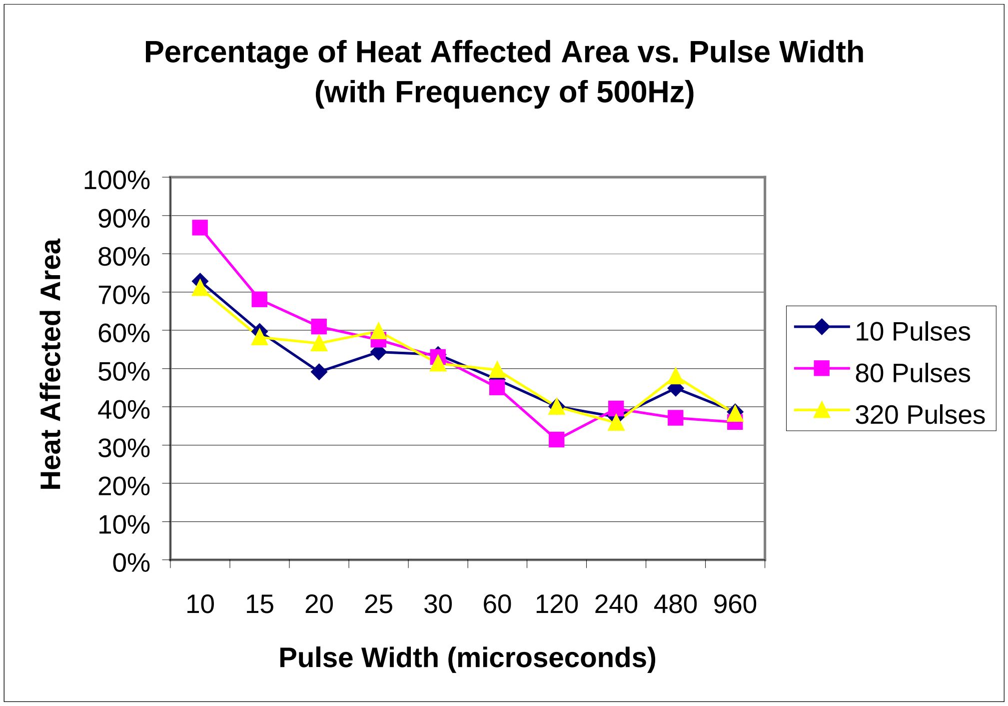


Figure III-12: Effect of Pulse Width on Hole Quality

The results suggest that the number of pulses used does not affect the entrance diameter. Longer pulse widths have less charring and better quality.

3.3.2 Effect of Repetition Rate

The repetition rate was varied with a set pulse width of 30 microseconds. There was a slight increase in hole diameter as the repetition rate was increased. As the number of pulses was increased over the series of holes formed, there was less charring and debris. The quality was almost constant over the variation of repetition rate.

The graphical representations of the results were used to analyze the sample shown in Figure III-13. The sample shows better quality at lower repetition rates and larger pulses. The appearance of more debris formation on the right side of the vias formed are indicative of the gas flow as the laser is directed onto the surface of the polyimide.

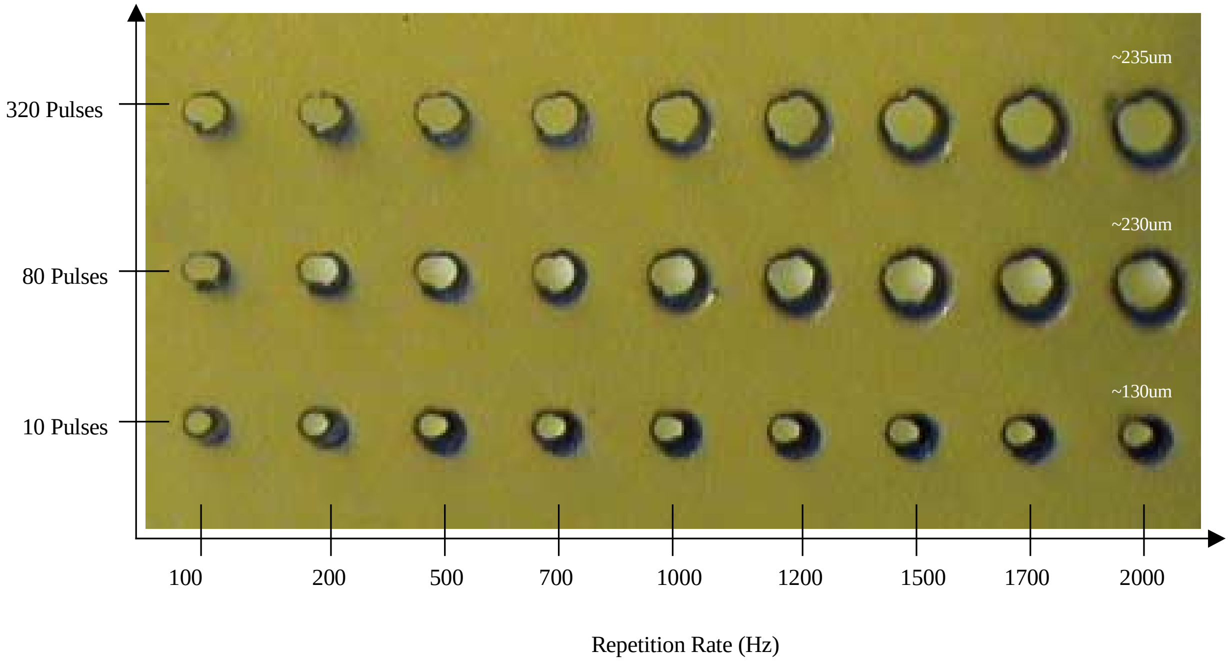


Figure III-13: Effect of varying Repetition Rate on Kapton^{TM} with Adhesive

Figure III-14 shows the graphical representation of the effect of varying the repetition rate on hole entrance diameter. For 10 pulses the diameter was relatively constant. There appeared to be a linear affect on the diameter for 80 and 320 pulses. The characteristic curves for 80 and 320 pulses overlap which reiterates the independence of the process parameters on the number of pulses.

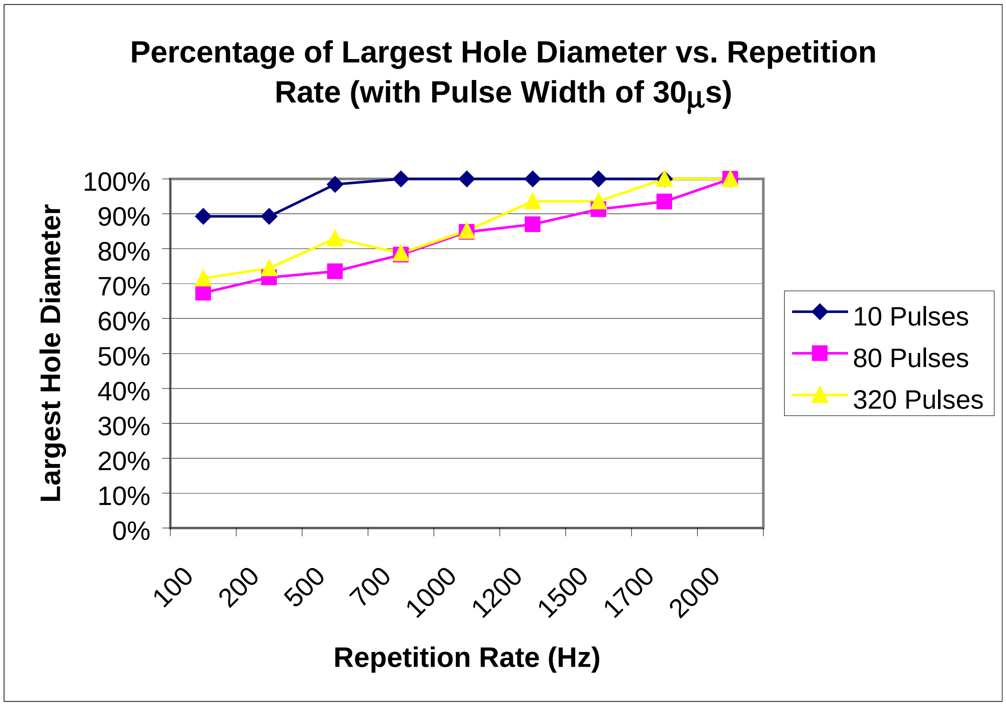


Figure III-14: Effect of Repetition Rate on Hole Diameter

Figure III-15 shows the relatively constant effect on quality by varying the repetition rate across a series of pulses. As the number of pulses increases, the quality is increased due to less charring. The best quality is achieved at lower repetition rates. The quality is relatively constant for variations in repetition rates for small number of pulses. For larger number of pulses, a lower repetition rate increases the quality of the material processed.

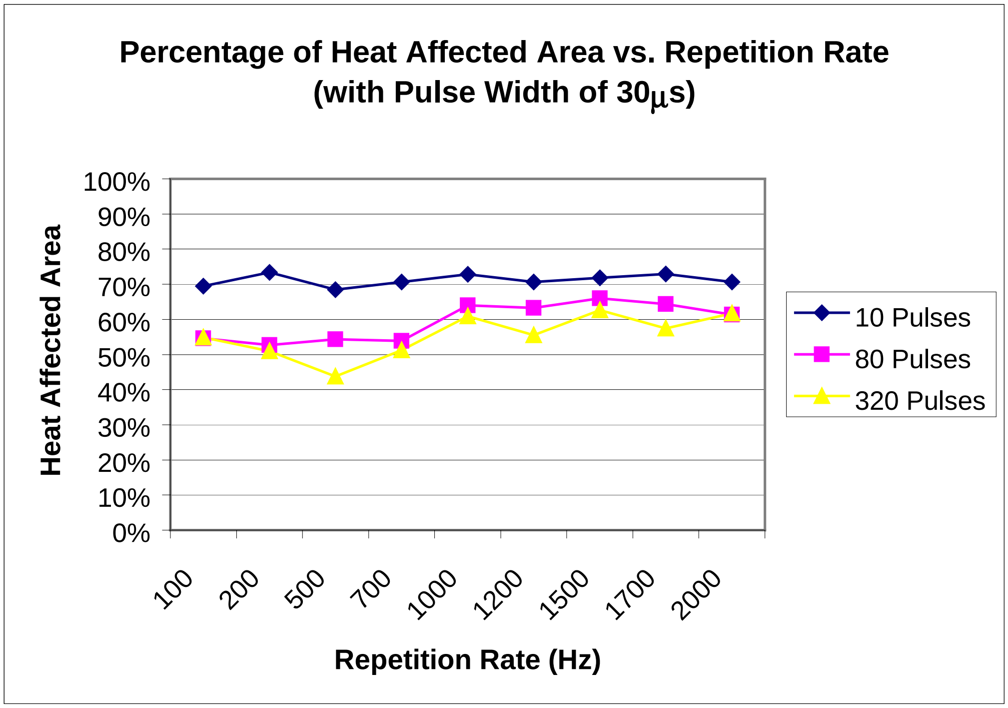


Figure III-15: Effect of Repetition Rate on Hole Quality

The results suggest using a repetition rate of 500Hz and 320 pulses to minimize the post processing cleaning. These results closely correlate with those on Kapton without adhesive.

3.3.3 Effect of Number of Pulses

The effect of varying the number of pulses on the Kapton with adhesive to increase the quality of the hole formed was studied. The study was conducted over a range of pulses from 1 to 1280 to observe the effect on the hole diameter and quality.

The actual sample shown in Figure III-16 has a strong correlation to the graphs that allow for quicker analysis of the results.

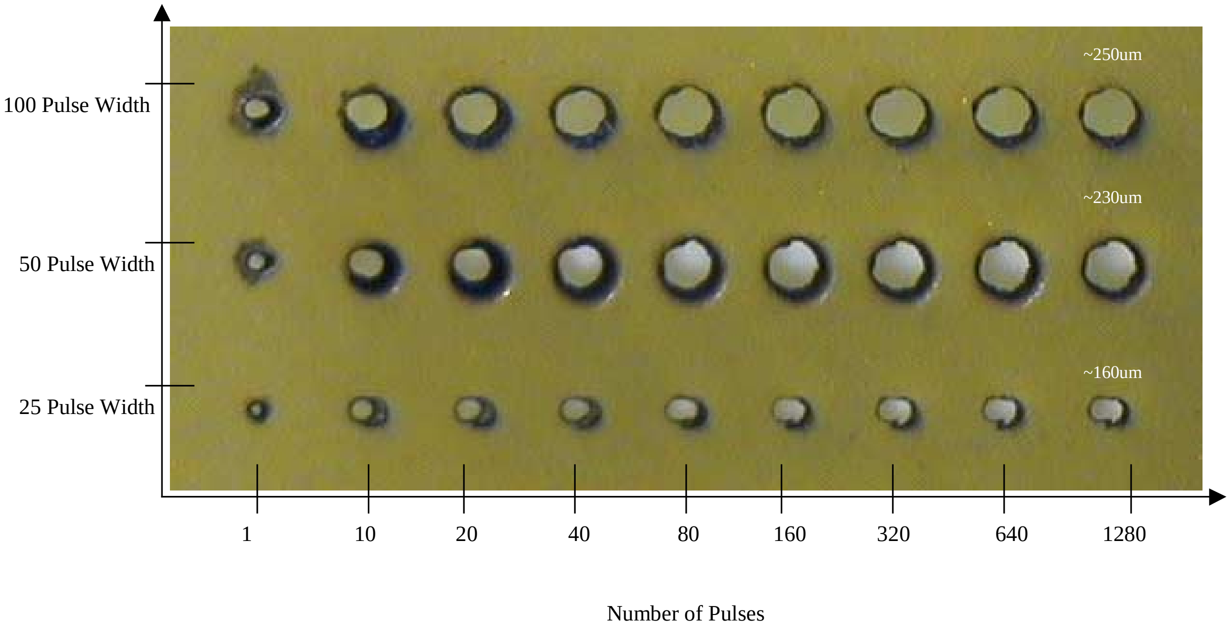


Figure III-16: Effect of varying Number of Pulses on Kapton^{TM} with adhesive

Figure III-17 shows the effect of increasing the number of pulses on the entrance diameter. The characteristic curves overlap for pulses greater than 40. For smaller pulses, the entrance diameter is a smaller percentage of the final diameter. For smaller pulse widths, the initial hole formed is much smaller than the final hole. The trend reveals an increase in the hole diameter formed up until 320 pulses. After reaching this point, the diameter appears to become constant. The use of 320 or more pulses will produce quality results for laser-processed polyimide.

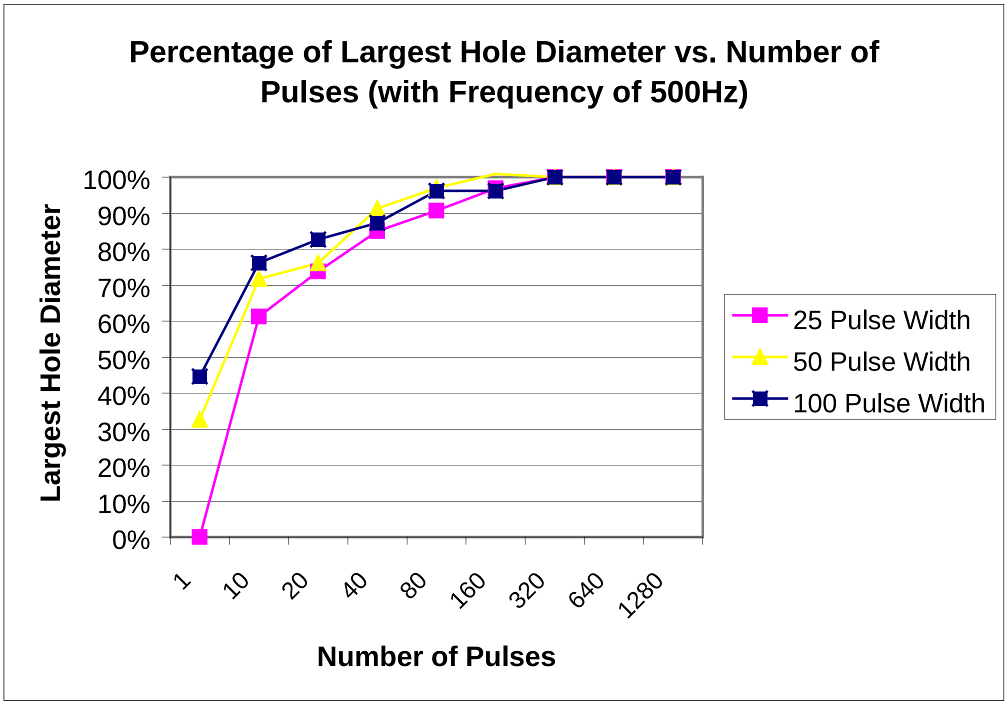


Figure III-17: Effect of Number of Pulses on Hole Diameter

Figure III-18 shows the effect of the number of pulses on quality. The trend shows a decrease in charring as the number of pulses increases. The curve reaches an asymptotic value at approximately 320 pulses. From earlier results, the quality of the hole formed is expected to increase as the pulse width increases. This is not the case as the pulse width increases from 25 microseconds to 50 microseconds. However, the expected results were as expected for a pulse width of 100 microseconds.

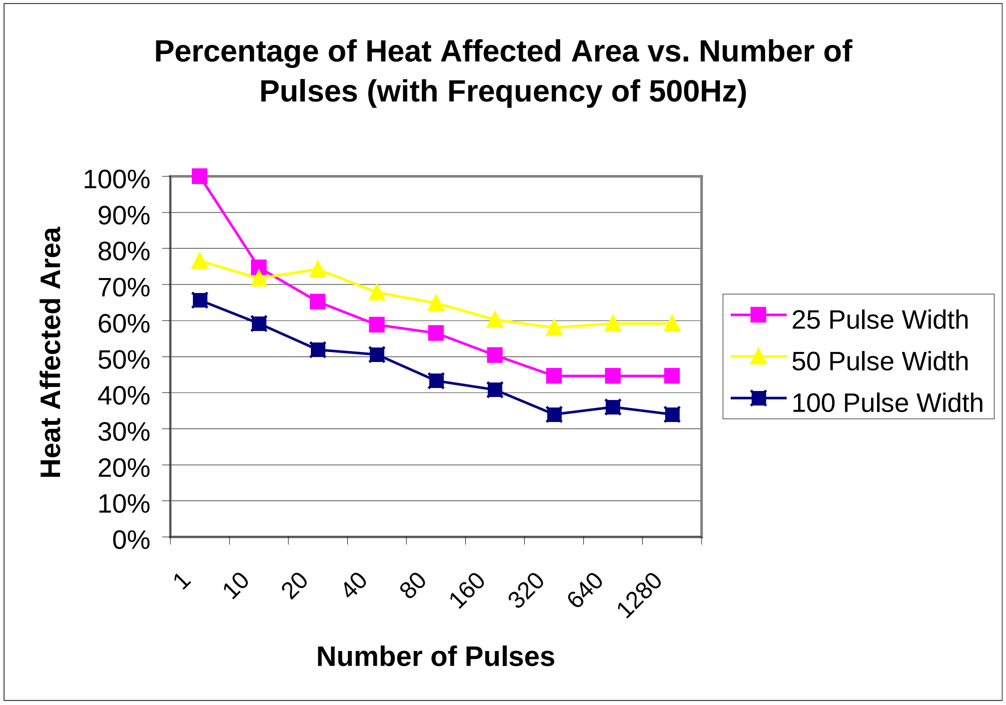


Figure III-18: Effect of Number of Pulses on Hole Quality

The results recommend using a large pulse width with a large number of pulses for the best quality hole.

3.4 Laser Processing of Kapton on Copper

3.4.1 Single Layer Sample

The laser processing of Kapton on copper was observed using results obtained from processing of the Kapton with adhesive samples. The work began with a single layer of 25µm (1mil) Kapton with adhesive applied to 200µm (8mil) copper layer. The effect of varying pulse width was observed on the PI-Cu sample. The results presented are only pictures of the processed samples. This is due to the limitations and the level of accuracy that can be obtained using the camera on the laser system to measure the diameter of the hole and the total affected area. The pictures may not clearly show that the Kapton was able to reach the copper layer due to the limitations of the digital camera setup.

The effect of varying the pulse width on a single layer of Kapton on copper was not easily characterized. By increasing the pulse width when processing Kapton on copper, the size of the affected area increases. The results were expected to be different than those achieved with free-standing Kapton due to heat diffusion caused by copper.

As shown in Figure III-19 the laser processed areas appeared to be badly charred. As the pulse width is increased, the charred area increases. It was not clearly evident that there was an actual hole formed on the surface of the Kapton because the reflection of the copper.

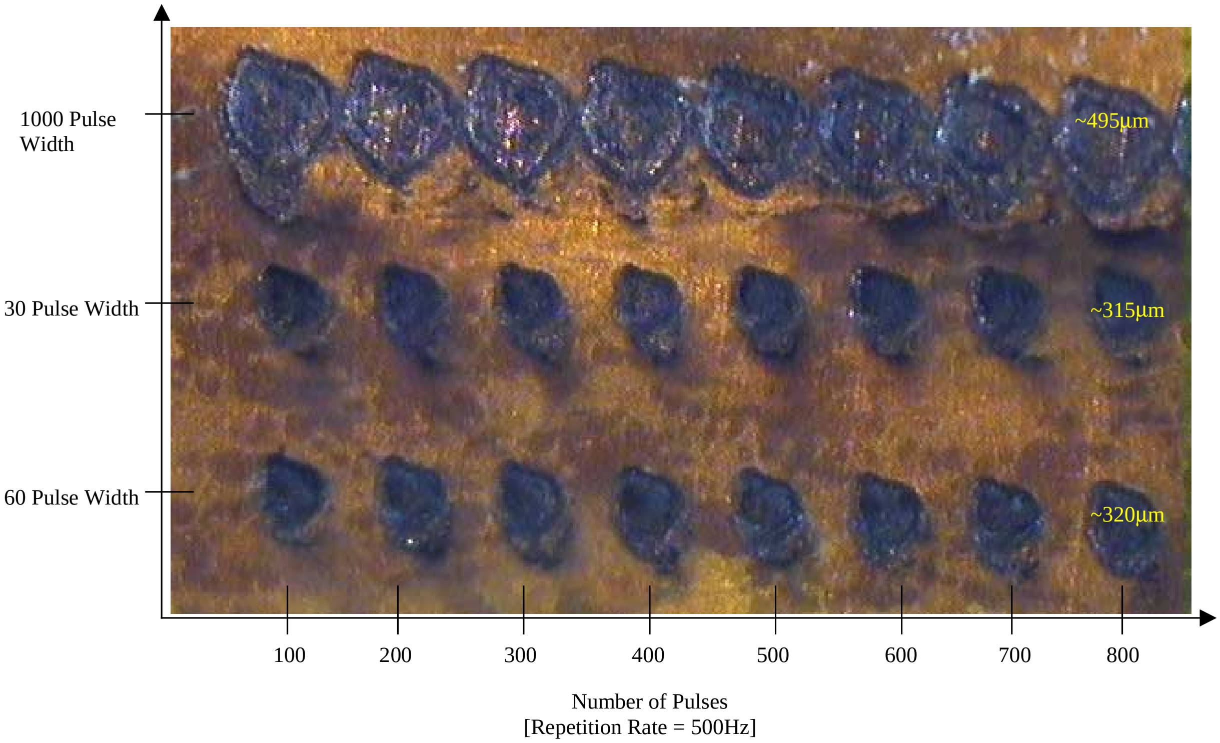


Figure III-19: One layer Kapton^{TM} on Copper

The Kapton with adhesive was removed from the copper to see the effects of the copper on forming a via. Figure III-20 shows that the copper layer was reached. There is a lot more charring and debris on the surface of the polyimide than that obtained with the free-standing Kapton with adhesive. An effective cleaning method is necessary to remove the debris generated by the laser processing. The diffusion of heat caused by the copper created material degradation but not ablation.

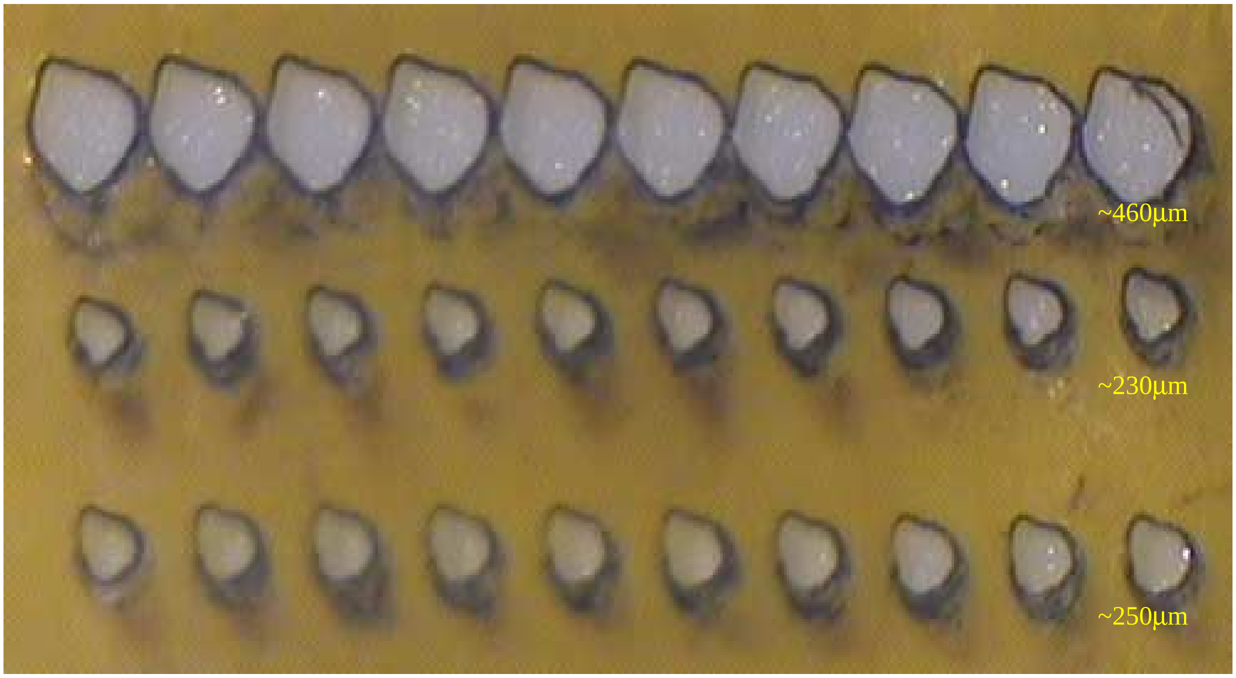


Figure III-20: Kapton™ removed from Copper

The surface of the sample was sanded to try to reduce the reflection of the copper, but this had no effect on the processing of the sample.

3.4.2 Multi-layer Sample

Due to the results obtained by varying pulse width on the one layer of Kapton on copper, it was decided to explore increasing the thickness of the polyimide to obtain better results. The thickness was increased to be thicker than the copper layer as suggested by Haba and Morishige's[11] work.

The pulse width and repetition rate was varied to obtain the least debris and to reach the copper layer. Figure III-21 shows where the polyimide clearly reaches the copper layer. It is not clear from the picture that this happens due to the depth of the via and lighting of the digital camera. Vias were formed down to the copper layer for each shot of the laser, but there was a lot of debris that made it difficult to visually see that the copper layer had been reached. The cleanness of the via formed increased as the number of pulses increased and the repetition rate decreased.

The pulse width was fixed at 60µs and the number of pulses was varied from left to right as the repetition rate was changed for each row.

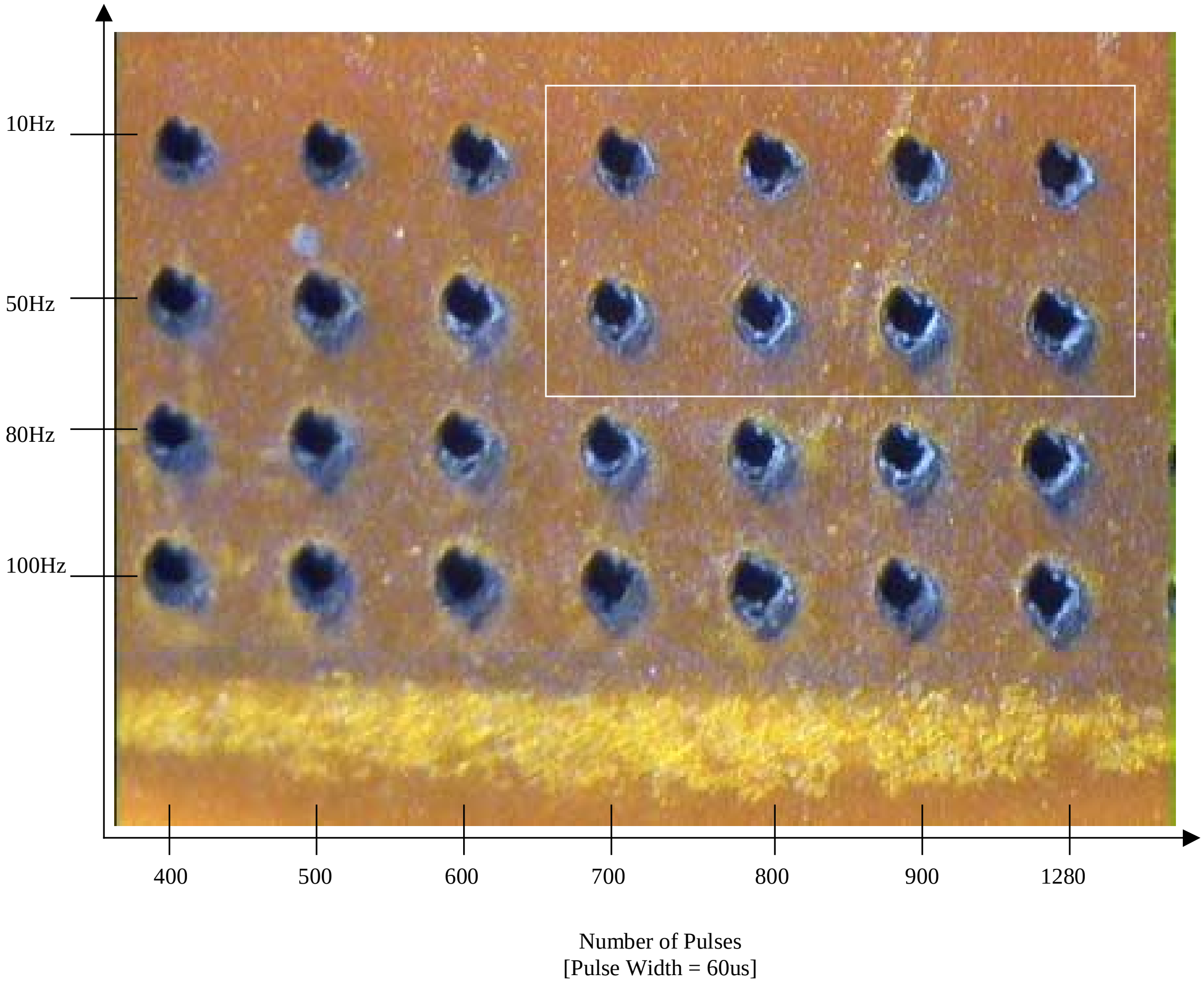


Figure III-21: Ten layer Kapton^{TM} on Copper

As the pulse width was increased for a set repetition rate, it took fewer pulses for the copper layer to be cleanly reached. For larger pulse widths, there was more charring and a larger via diameter. For pulse widths greater than 200µs, it took between 200 and 300 pulses to clearly see that the copper layer had been reached, but there was considerable charring and debris around the perimeter of the via. For smaller pulse widths, the quality of the vias formed was better, but it took more pulses to reach the copper. As well, the quality increased for lower repetition rates and appeared the best at 10Hz. As the repetition rate was decreased, it was noticeable that it took more time for laser processing. At this low repetition rate, the process time was several seconds long for each shot of the laser.

Figure III-20 is increased in the rectangular area to show where the best results were obtained. The best results are shown in Figure III-21 where the copper layer was reached with a pulse width of 60µs and repetition rate of 10Hz. However, it took 700 pulses before it was evident that the copper was reached.

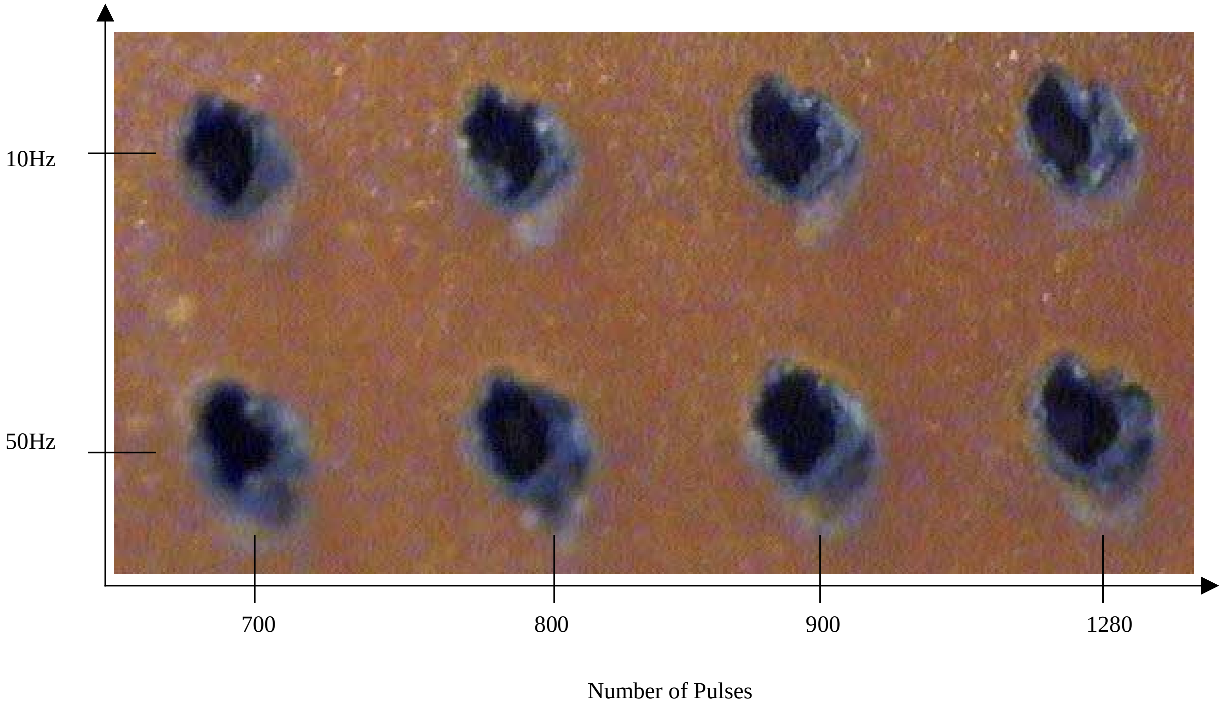


Figure III-22: Close-up of Figure III-20 best results

As the repetition rate was decreased below 100 Hz, there was less charring and debris evident around the perimeter of the via formed. Within the series of laser shots fired for a set pulse width, the copper layer could be reached sooner. The limitations of the laser allowed for a minimum repetition rate of 10Hz.

Once the Kapton with adhesive was removed layer by layer to observe the quality of the hole formed it was observed that the copper layer had been reached with each laser shot. Figures III-

23 and III-24 show the top layer and bottom layer, respectively. The diameter of the hole decreases through the thickness of the material. There is slightly less debris evident around the perimeter of the via formed on the bottom layer. However, there is noticeable debris on the surface of the material caused by removing previous layers.

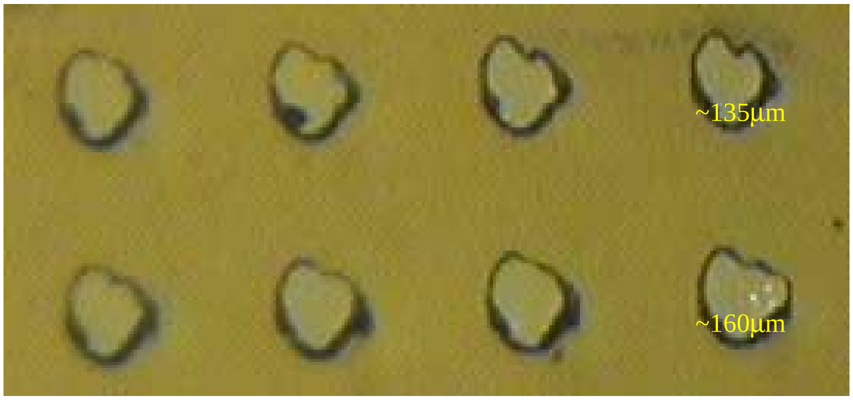


Figure III-23: Top layer of Kapton™ removed from Copper

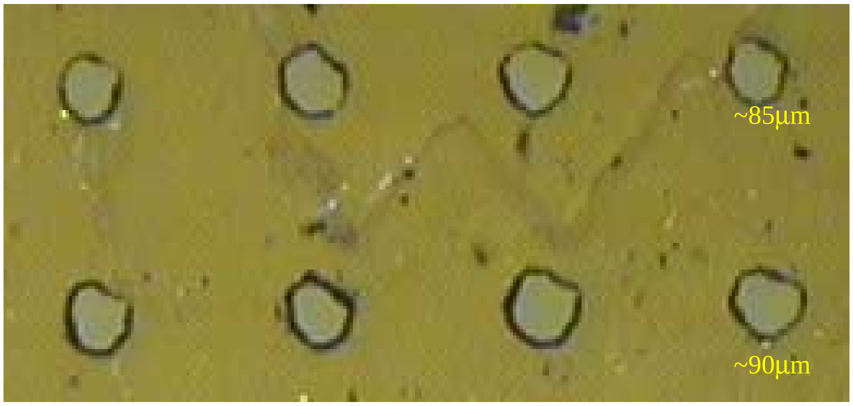


Figure III-24: Bottom layer of Kapton™ removed from Copper

The pictures presented in Figures III-23 and III-24 show an aspect ratio was approximately 2:1 (via dimension to thickness). This could lead to applications of laser processing in MEMS technology that requires high aspect ratio holes.

3.5 Discussion

The results presented were correlated after preliminary processing of Kapton. The effect of the parameters was examined. The values chosen reflect an optimum process where consideration was given to quality, minimal number of pulses, and relatively short pulse width. The use of a low repetition rate was used to help obtain better quality in the laser processing of polyimide on copper.

As well as improved quality with CO_2 laser processing, consideration should be given to minimize the process time that is affected by the pulse width, the number of pulses, and the repetition rate. A short process time can be achieved with short pulse widths, small number of pulses, and high repetition rates. However, to optimize the quality of the processed free-standing samples the pulse width should be long, the number of pulses should be fairly large, and the repetition rate should be low. For the PI-Cu samples, the pulse width should be short and the repetition rate vary low. The process time for best quality processing of polyimide on copper lead to a longer process time than the free-standing samples.

According to work by Srinivasan[15], the pulse width determines the diameter of the hole formed by laser ablation. As the pulse width increases, the diameter formed increases. The results from the experiments in this thesis support his conclusion.

According to previous work on laser processing of polyimide, scanning electron microscope and x-ray photoelectron spectroscopy were used to analyze the processed samples. The approach in this thesis concentrated on the effect of the laser parameters on the polyimide with graphical representation as well as captured images of the processed samples.

The study of the effect of the laser parameters on the processing of polyimide led to the improved processing of polyimide on copper. Work by Haba and Morishige[11] on the laser processing of polyimide on copper pointed out the limitations of drilling via holes down to the copper was determined by the polyimide thickness and the heat diffusion. Increasing the thickness of the polyimide, improved the ability to form vias down to the copper layer. Longer pulse widths in the millisecond range were used to drill holes down to the copper layer. In order to reduce the pulse width, it was suggested that a laser diode with a 0.8μm wavelength be used instead of the argon-ion laser (515nm) they used in their experiments. They suggested a wavelength closer to the thickness of the polyimide would yield better results[11].

An examination of the effect of the parameters on the laser processing of polyimide show that optimum parameters can be chosen to achieve the best quality. Figure III-25 shows that an optimum pulse width would be 60µs, where the two curves intersect for processing Kapton with Adhesive.

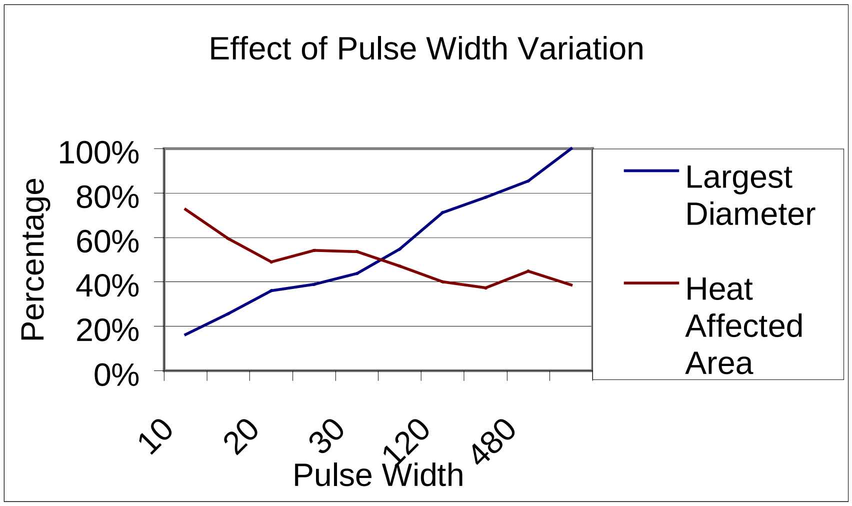


Figure III-25: Optimum Pulse Width

Figure III-26 shows that an optimum repetition rate would be less than 500Hz for processing Kapton with Adhesive. A relatively small repetition rate would create the best quality.

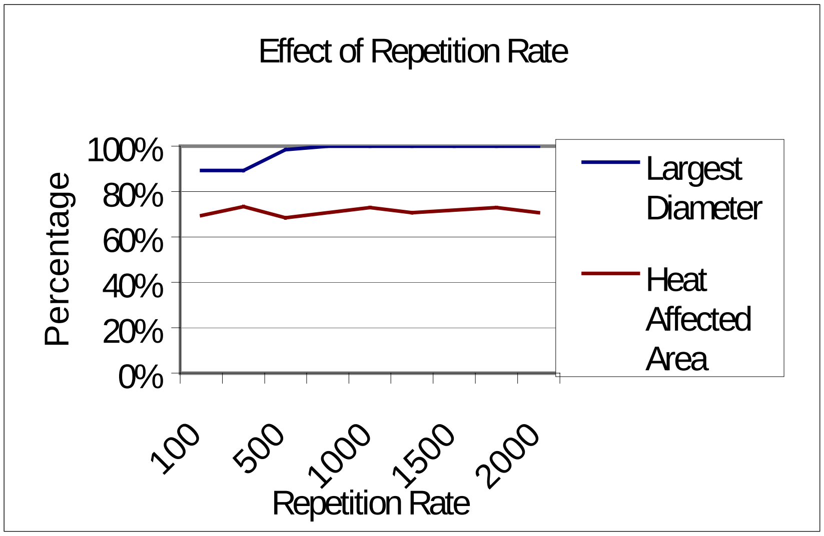


Figure III-26: Optimum Repetition Rate

Figure III-27 shows that an optimum number of pulses would be 320 for processing Kapton with Adhesive. At this value, the results are constant.

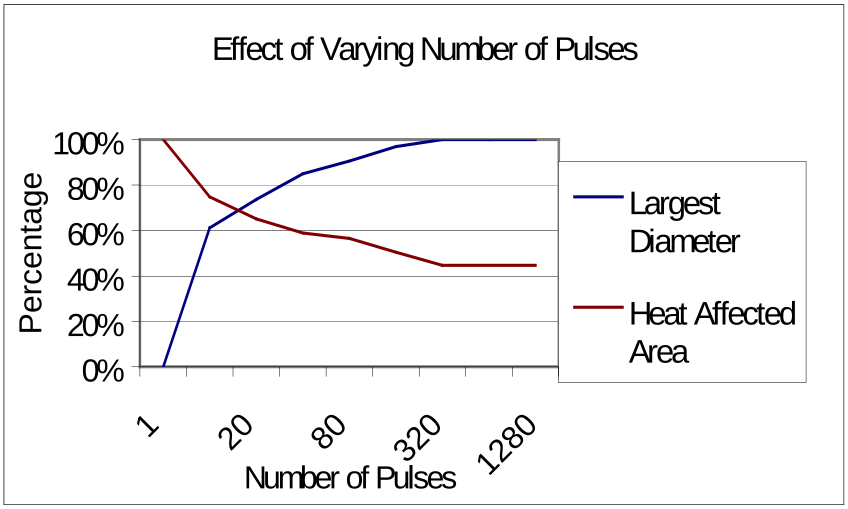


Figure III-27: Optimum Number of Pulses

The results presented on the laser processing of polyimide on copper demonstrate the ability to use a 10µm wavelength CO_2 laser to drill vias down to the copper with pulse widths in the microsecond range. The pulse width is shorter than that used by Haba and Morishige[11], which would allow for faster processing time. For improved quality, the process time would increase due to using a low repetition rate.

Chapter IV Summary and Conclusions

The approach to laser processing proposed in this thesis allows for consideration to be given to the laser process parameters including pulse width, repetition rate, and number of pulses. Each parameter was examined separately and their combined effect helped achieve the desired effect of improving the quality of CO_2 laser processed polyimide. The parameter seen to have the most effect on CO_2 laser processing is the pulse width. This parameter governs the diameter of the via formed by the process as well as amount of debris around its perimeter. The longer the pulse, the larger the total affected zone of the material. Using a pulse width larger than 60 microseconds can minimize the debris and charring evident around the perimeter of the hole. The number of pulses output by the laser also effect the diameter of the via formed. The more pulses, the larger the via. The use of more than 320 pulses was seen to improve the quality of the hole formed. The repetition rate or frequency has less of an effect on the via diameter formed. It affects the degree of charring, with lower repetition rates allowing for cleaner processing of polyimide. For freestanding Kapton samples a repetition rate of 500Hz was shown to produce the best results.

The PI-Cu samples yielded the best results for lower pulse widths than the freestanding samples. The heating effect of the single layer polyimide on copper hindered the formation of an effective via. The 10 layer PI-Cu sample showed the least amount of charring and debris around the perimeter of the via with a pulse width of 60µs, a repetition rate of 10Hz and more than 700 pulses. The copper layer beneath was also clearly exposed with these parameters.

Further research should explore the effect of current cleaning methods that would prove useful for post CO_2 laser cleaning. Previous work demonstrated that not all cleaning methods can be used to effectively remove debris from polyimide processed by a CO_2 laser. In order to optimize the CO_2 laser processing of polyimide the best cleaning method should be researched. Methods to minimize the heating effect on the surface of the polyimide should be considered. Future work should focus on minimizing post laser process cleaning by such methods as proposed by Coupland[13] who was able to minimize the repetition rate and increase the hole quality.

For the formation of vias for applications in electronic packaging, the use of a specified diameter may be of more use in controlling the process versus adjusting the pulse width. Increasing the aspect ratio by decreasing the via dimension and increasing the polyimide thickness can lead to applications in MEMS.

Appendix

Software Control Files for Pentawave PhotoMaching Software:

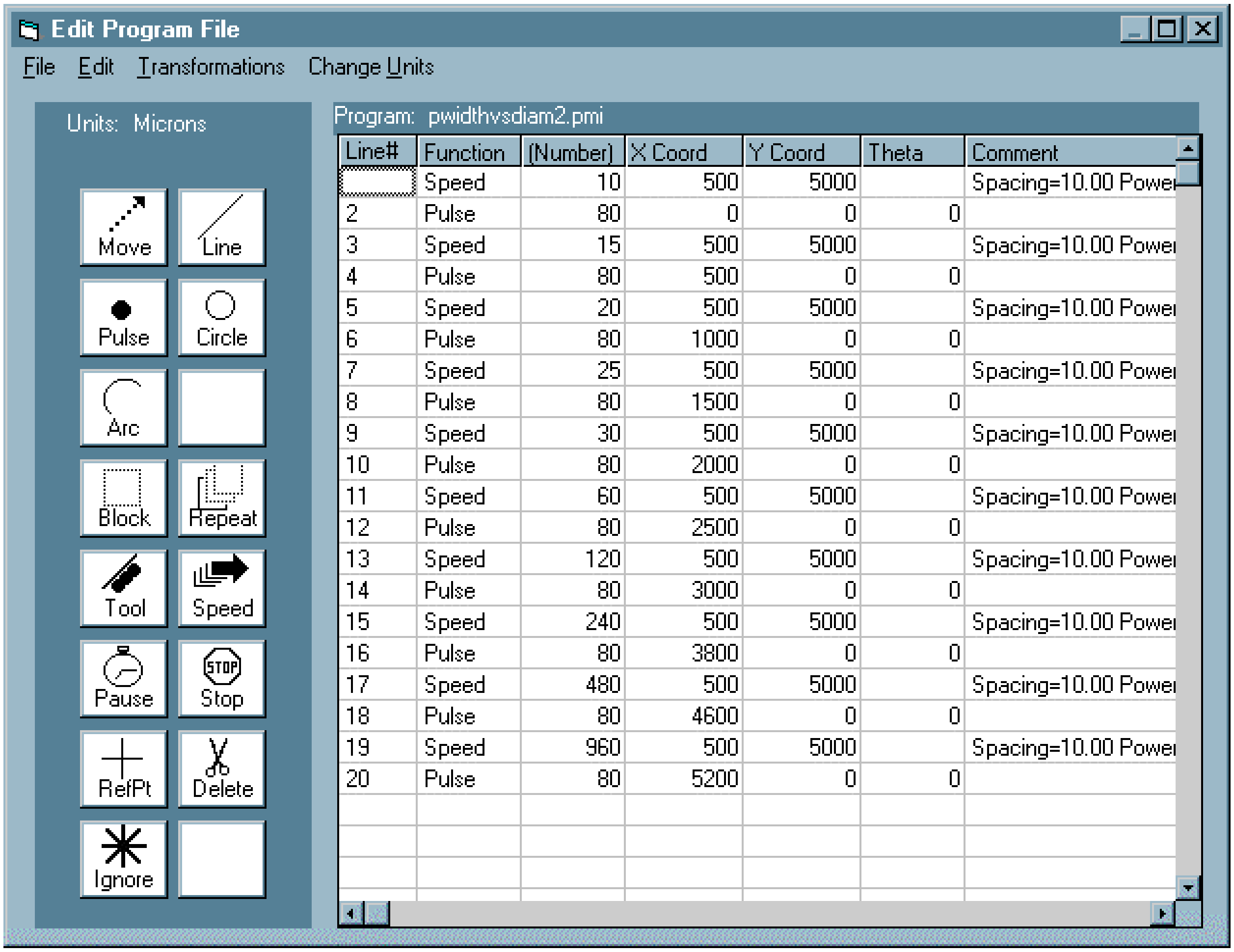
Pulse Width Variation

Pulse Width varies from 10µs to 960µs

Set Repetition Rate of 500Hz

Set Number of Pulses at 80

Set Stage Speed at 5000µm/s



Program: pwidthvsdiam2.pmi

Line#	Function	(Number)	X Coord	Y Coord	Theta	Comment
	Speed	10	500	5000		Spacing=10.00 Powe
2	Pulse	80	0	0	0	
3	Speed	15	500	5000		Spacing=10.00 Powe
4	Pulse	80	500	0	0	
5	Speed	20	500	5000		Spacing=10.00 Powe
6	Pulse	80	1000	0	0	
7	Speed	25	500	5000		Spacing=10.00 Powe
8	Pulse	80	1500	0	0	
9	Speed	30	500	5000		Spacing=10.00 Powe
10	Pulse	80	2000	0	0	
11	Speed	60	500	5000		Spacing=10.00 Powe
12	Pulse	80	2500	0	0	
13	Speed	120	500	5000		Spacing=10.00 Powe
14	Pulse	80	3000	0	0	
15	Speed	240	500	5000		Spacing=10.00 Powe
16	Pulse	80	3800	0	0	
17	Speed	480	500	5000		Spacing=10.00 Powe
18	Pulse	80	4600	0	0	
19	Speed	960	500	5000		Spacing=10.00 Powe
20	Pulse	80	5200	0	0	

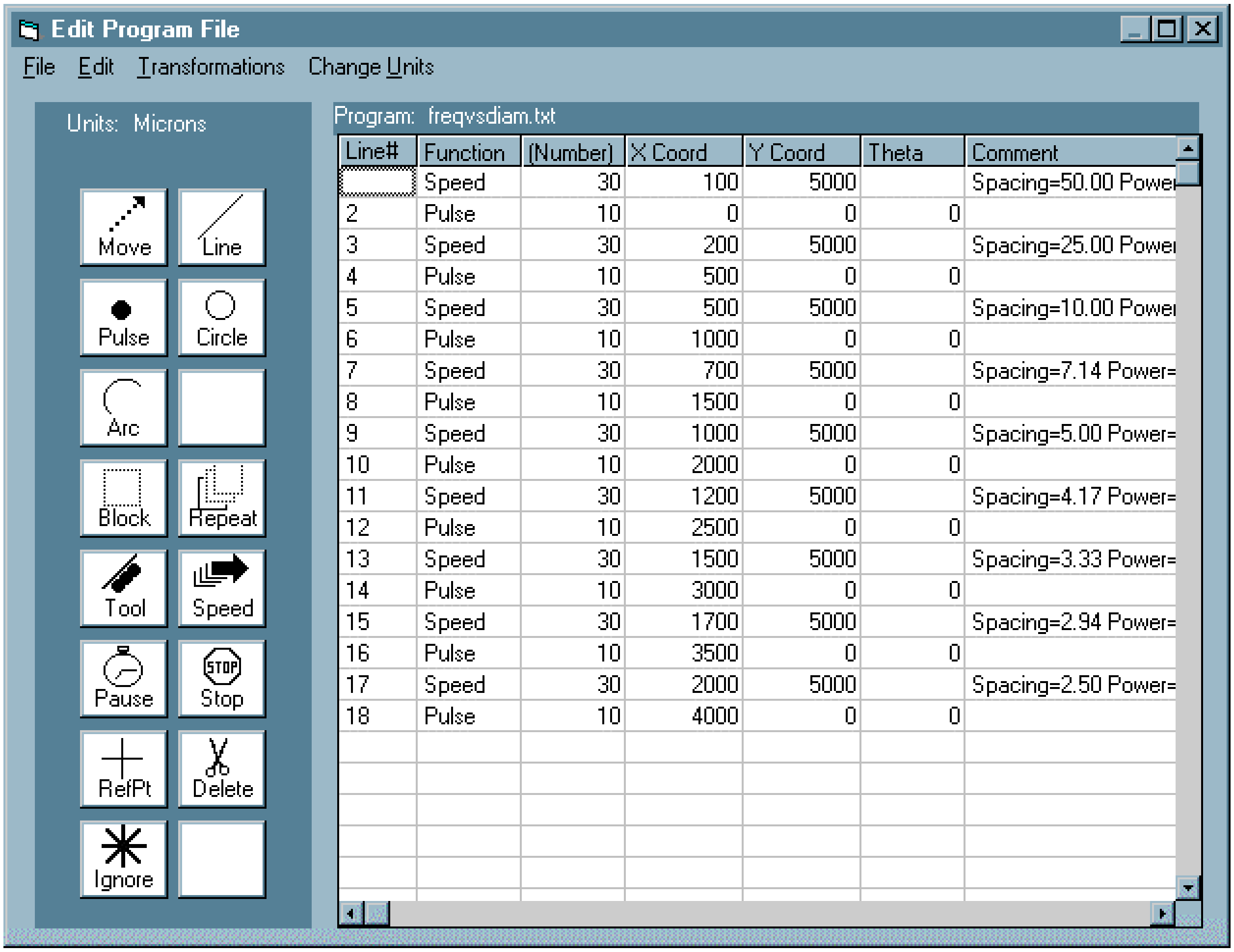
Repetition Rate Variation

Repetition Rate varies from 100Hz to 2000Hz

Set Pulse Width of 30µs

Set Number of Pulses at 10

Set Stage Speed at 5000µm/s



Program: freqvsdiam.txt

Line#	Function	(Number)	X Coord	Y Coord	Theta	Comment
	Speed	30	100	5000		Spacing=50.00 Powe
2	Pulse	10	0	0	0	
3	Speed	30	200	5000		Spacing=25.00 Powe
4	Pulse	10	500	0	0	
5	Speed	30	500	5000		Spacing=10.00 Powe
6	Pulse	10	1000	0	0	
7	Speed	30	700	5000		Spacing=7.14 Power=
8	Pulse	10	1500	0	0	
9	Speed	30	1000	5000		Spacing=5.00 Power=
10	Pulse	10	2000	0	0	
11	Speed	30	1200	5000		Spacing=4.17 Power=
12	Pulse	10	2500	0	0	
13	Speed	30	1500	5000		Spacing=3.33 Power=
14	Pulse	10	3000	0	0	
15	Speed	30	1700	5000		Spacing=2.94 Power=
16	Pulse	10	3500	0	0	
17	Speed	30	2000	5000		Spacing=2.50 Power=
18	Pulse	10	4000	0	0	

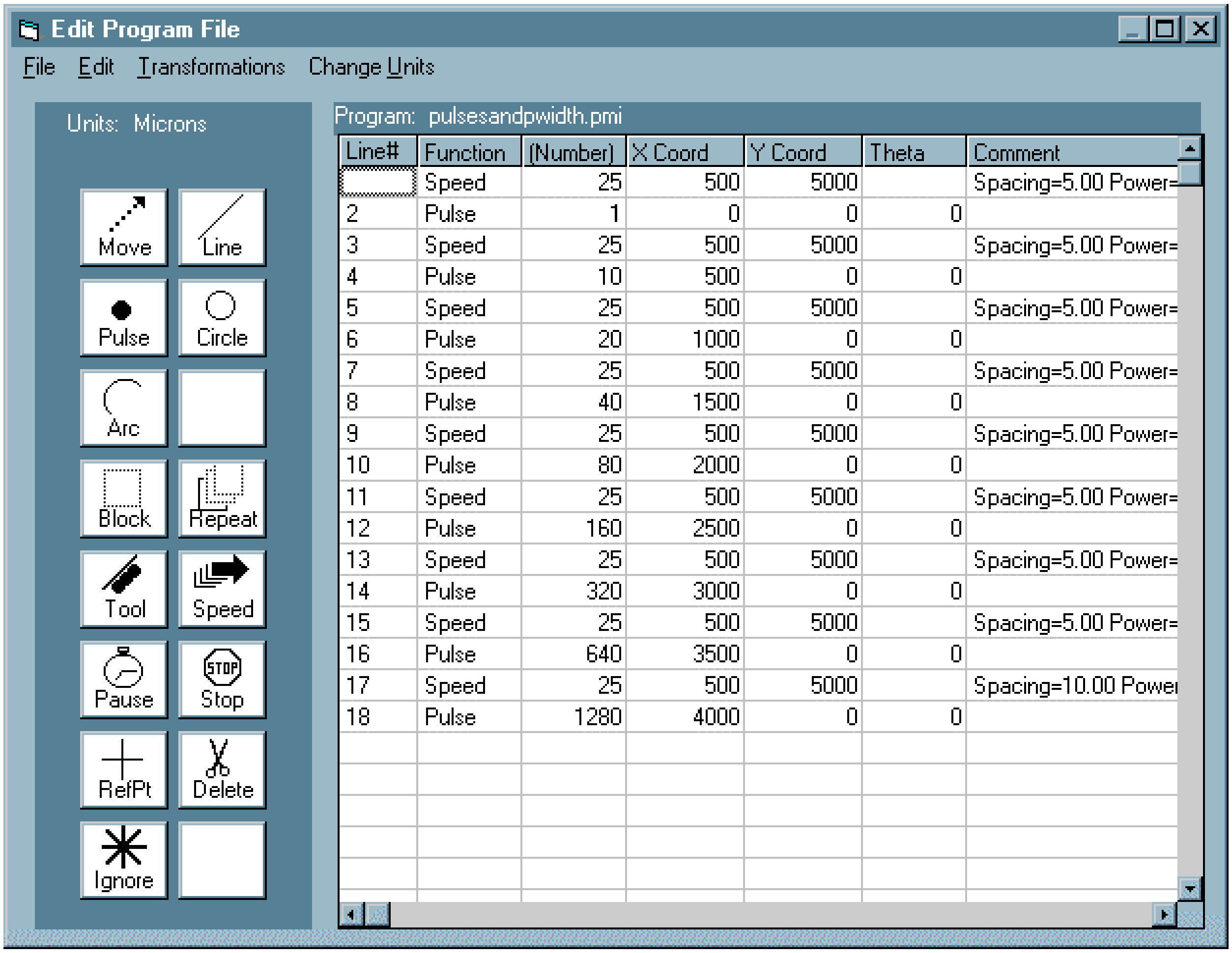
Varying Number of Pulses

Number of Pulses varies from 1 to 1280

Set Pulse Width 25µs

Set Repetition Rate of 500Hz

Set Stage Speed at 5000µm/s



Program: pulsesandpwidth.pmi

Line#	Function	(Number)	X Coord	Y Coord	Theta	Comment
	Speed	25	500	5000		Spacing=5.00 Power=
2	Pulse	1	0	0	0	
3	Speed	25	500	5000		Spacing=5.00 Power=
4	Pulse	10	500	0	0	
5	Speed	25	500	5000		Spacing=5.00 Power=
6	Pulse	20	1000	0	0	
7	Speed	25	500	5000		Spacing=5.00 Power=
8	Pulse	40	1500	0	0	
9	Speed	25	500	5000		Spacing=5.00 Power=
10	Pulse	80	2000	0	0	
11	Speed	25	500	5000		Spacing=5.00 Power=
12	Pulse	160	2500	0	0	
13	Speed	25	500	5000		Spacing=5.00 Power=
14	Pulse	320	3000	0	0	
15	Speed	25	500	5000		Spacing=5.00 Power=
16	Pulse	640	3500	0	0	
17	Speed	25	500	5000		Spacing=10.00 Powe
18	Pulse	1280	4000	0	0	

References

[1] HD MicroSystems, "Polyimide Properties and Applications Overview," http://www.hdmicrosystems.com/3tech/polyimid.html

[2] Chou, Bill, Solomon Beilin, Hunt Jiang et al, "Ultra-High Denisty Interconnect Flex Substrates," *High Density Interconnect*, pp. 14-21, December 1998.

[3] Minari, Naoto, Tadashi Kimura, Yoshihiro Okabe et al, "A Novel Localizable HDI-PWB Solution," *High Density Interconnect*, vol. 3, no. 12, pp.20-25, 2000.

[4] Prasad, Keshav and Eric Perfecto, "Multilevel Thin Film Packaging: Applications and Processes for High Performance Systems," *IEEE Transaction on Components, Packaging, and Manufacturing Technology*, vol. 17, no. 1, 1994.

[5] HD MicroSystems, "Basic Processing of Polyimide Coatings," http://www.hdmicrosystems.com/3tech.process.html

[6] Schammler, Gisela K.H., Veronica Shaw, and Gerhard Chmiel, "Comparison of the Metallization of Chemically and Laser-Etched Structures in BPDA-PDA Polyimide," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, Vol. 16, No. 7, pp. 720-723,1993.

[7] Popova, K. et al, "Reactive ion etching of vapor phase deposition of polyimide films in CF_4/O_2: effect on surface morphology," *Thin Solid Films*, vol. 274, pp. 31-34, 1996.

[8] Redmond, Thomas F., John R. Lankard, et al., "The Application of Laser Process Technology to Thin Film Packaging," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol.16, no. 1, pp. 6-12, 1993.

[9] Coffey, Valerie C., "Short CO_2 laser pulses target micromachining," *Laser Focus World*, vol. 37, no. 1, pp.54-58, 2001.

[10] Webster, James R. "Thin Film Polymer Dielectrics for High Voltage Applications under Severe Environments," Master's Thesis, Virginia Tech, 1998.

[11] Haba, Belgacem and Yukio Morishige, "Novel drilling technique in polyimide using visible laser," *Applied Physics Letter*, vol. 66, no. 26, pp.3591-3593, 1995.

[12] Tokarev, V.N and W. Marine, "'Clean' processing of polymers and smoothing of ceramics by pulsed laser melting," *Journal of Applied Physics*, vol. 77, no. 9, pp4714-4723, 1995.

[13] Coupland, Kristen, Peter R. Herman, and Bo Gu, "Laser cleaning of ablation debris from CO_2-laser-etched vias in polyimide," *Applied Surface Science*, vol. 127-129, pp.731-737, 1998.

[14] Arnold, N. and N. Bityurin, "Model for laser-induced thermal degradation and ablation of polymers," *Applied Physics A*, vol. 68, pp. 615-625, 1999.

[15] Srinivasan, R., "Etching polyimide films with continuous-wave ultraviolet lasers," *Applied Physics Letters*, vol. 58, no. 25, pp. 2895-2897, 1991.

[16] Piglmayer, K., E. Arenholz, C. Ortwein, N. Arnold, and D. Bauerle, "Single-pulse ultraviolet laser-induced surface modification and ablation of polyimide," *Applied Physics Letters*, vol. 73, no. 6, pp. 847-849, 1998.

[17] Brannon, J.H, J.R. Lankard, "Pulsed CO_2 laser etching of polyimide," *Applied Physics Letters*, vol 48, no. 18, pp. 1226-1228, 1986.

[18] Photomachining Inc. Laser Operation and Maintenance Manual, 1998.

Vita

Gustina B. Collins was born on February 25, 1977 in Spartanburg, SC. She earned her B.S. degree in Electrical Engineering from Clemson University in May 1999. While attending Clemson University, she participated in several organizations including Alpha Kappa Alpha Sorority Incorporated, National Society of Black Engineers and Society of Women Engineers. During her undergraduate tenure, she completed a cooperative education experience with Milliken Magnolia Finishing Plant in Blacksburg, SC and three summer internships with Sony Electronics in San Diego, CA. She currently participates in the Black Graduate Student Organization at Virginia Tech. Gustina joined the Center for Power Electronics Systems in the fall semester of the year 2000 and participated in Electronic Packaging research efforts. She was honored by receiving the GEM Ph.D. Fellowship in 2000 between her sponsoring company Texas Instruments in Dallas, TX and a GEM member university. Upon completion of the Master’s Program in May 2001, Gustina will be pursuing the Ph.D program at Virginia Tech.