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Fundamentals of mega hertz femtosecond laser ablation and its application in interconnection via drilling

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**FUNDAMENTALS OF MEGA HERTZ FEMTOSECOND
LASER ABLATION AND ITS APPLICATION IN
INTERCONNECTION VIA DRILLING**

by

Senthilnathan Panchatsharam

Bachelor of Engineering (Mechanical)

Ryerson University, Toronto, Ontario, 2007

A Thesis

presented to Ryerson University

in partial fulfillment of the requirement for the degree of

Master of Applied Science

in the program of

Mechanical Engineering

Toronto, Ontario, Canada, 2009

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ABSTRACT

FUNDAMENTALS OF MEGA HERTZ FEMTOSECOND LASER ABLATION AND ITS APPLICATION IN INTERCONNECTION VIA DRILLING

Senthilnathan Panchatsharam, Master of Applied Science, 2009

Department of Mechanical and Industrial Engineering, Ryerson University

With the ever increasing demands on electronics and its portability, speed and function, the need for lighter and faster processing chips is always there. 3D stacking of chips is enabled through Inter-chip connections or Interconnect vias, which is used to create the electrical connections that facilitate the stacking. Interconnect vias provide the connectivity between the layers of the physical design, resulting in short connection lengths, which improve performance and decrease power consumption significantly.

This thesis proposes a high repetition rate, high power femtosecond laser drilling technique for surpassing the quality and throughput demand posed by the current market. A systematic study of the influence of the laser control parameters such as the repetition rate, pulse energy, intensity, wavelength, pulse duration, ablation threshold, quality and throughput rates is analyzed in detail. Decreasing via diameter and increasing via depth at high repetition rate are noted. A smallest via of 8.39 μm and a deepest via of 121 μm were obtained at 13 MHz and 4.33 MHz respectively. Minimal debris accumulation and exceptional surface qualities were noted at high repetition rates. Theoretical and experimental studies of shockwave effects during laser ablation on via surfaces were analyzed. Systematic process of learning the propagation of shockwaves and generating raised rims in ablated crater is analyzed. Analyzing surface temperature of the target revealed presence of small molten liquid layer at 13 MHz. Newly termed observations, primary

and secondary rims, were observed and analyzed under the influence of various laser parameters. Rim line width spacings were seen increasing at higher pulse width and higher power density. Gas assisted ablation showed decreasing line width spacing due to forced convection. Hence, with the successful results from the studies, the laser system shows the capability of meeting and surpassing the current market demands and considered for commercial applications.

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Finally, I am ever grateful to the grace of God for all the blessings.

DEDICATION

The author hereby would like to dedicate this thesis to his parents, Dr. V. S. Panchatsharam and Mrs. Aruna Panchatsharam and brother, Pranav Panchatsharam, for their continued support and help through the troubled times. Above all, the author would like to dedicate this thesis to his loving grandmother, Mrs. Chokkammal Vittal, for all the efforts she has taken to see him succeed at a graduate level study.

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NOMENCLATURE

ns	Nanosecond (10^{-9} s)
ps	Picosecond (10^{-12} s)
fs	Femtosecond (10^{-15} s)
μ s	Microsecond (10^{-6} s)
ms	Millisecond (10^{-3} s)
μ m	Micrometer (10^{-6} m)
cm	Centimeter (10^{-3} -m)
in	Inches
MHz	Megahertz (10^6 Hz)
kHz	Kilohertz (10^3 Hz)
nm	Nanometer (10^{-9} m)
mm	Micrometer (10^{-6} m)
W	Watt
GW	Gigawatt (10^9 s)
eV	Electron Volt
K	Kelvin
Deg	Degree Celsius
J	Joule
μ J	Micro-Joule (10^{-6} J)
2D	2 Dimensional
3D	3 Dimensional
UV	Ultra violet
T_e	Electron temperature
T_i	Lattice temperature
$I(t)$	Laser intensity at time t
α	Absorption coefficient
k_e	Electron thermal conductivity
I_0	Intensity
t	Time
τ_L	Laser pulsewidth
τ_e	Electron cooling time

τ_i	Lattice heating time
F_a	Ablation fluence
F_{th}, ϕ_{th}	Threshold fluence
l_s	Skin depth
D	Heat diffusion coefficient
E	Energy deposited inside target per unit mass
ρ	Density
P	Average power of the laser pulse
R	Reflection coefficient
r	Reciprocal of pulse interval
I_{th}	Threshold intensity
F	Laser fluence
T_0	Temperature at time $t = 0$
T_i	Initial temperature
ω_0	Radius of the laser focal spot
λ_0	Wavelength of the laser beam

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO INTERCONNECT VIAS

The current market in miniaturization of technology is lagging behind in meeting future demands for several applications. For example, embedded applications for communication (such as mobile phones and other hand-held devices) and driver assistance systems for automobiles require chips fabricated in conjunction with other technologies (i.e., sensors, actuators, analog, memory) with low-power high-performance processing capabilities, which proves to be very complex and expensive. Currently, the global buses, which connect these subsystems arranged on a 2D chip area, limit performance and power consumption. The solution to this problem is the concept of 3D stacking, for which, mixed technologies integrate the system by stacking several dies. In this approach, each layer of this chip stack will be manufactured using an optimized standard technology such as CMOS, and additional processing steps will also be implemented to prepare the individual dies for stacking process. Inter-chip connections or interconnections, which compose a 2D arrangement on both sides of the stacked dies, create electrical connections that facilitate the stacking. Interconnect vias provide connectivity between layers of the physical design, resulting in short connection lengths, which improve performance and decrease power consumption significantly. Furthermore, as a result of current market trends in compact technology, future 3D chips will be characterized by very high interconnection density with finer lines and spaces, smaller chip packaging homes and decreasing thickness as depicted in Figure 1-1. To gain more landing pads for small footprints components, the use of micro-vias becomes a must. Currently, many have reported having achieved micro-via sizes of 25 μm diameter and

above [1–4]. However, with the ever increasing demands on electronics and its portability speed and function, researchers are pushing this limit to achieve vias of less than $25\ \mu\text{m}$ and much smaller. But to obtain micro-via formations of such sizes requires techniques that are beyond the capability of conventional mechanical drilling, as shown in Table 1.

Figure 1-1: 3D stacking of chips with interconnection layers

Table 1: Characteristic comparisons of conventional drilling to micro-via laser formations in silicon wafer [5]

	Conventional Mechanical Drilling	Micro-via Laser Drilling
Landing Pad Area (in ²)	18	4.5
Number of Layers	6	4
Layout Efficiency	25%	80%
Wiring Density (in/in ²)	59.7	119.3
Via Pad Size (in)	0.027	0.014
Via Density (per in ²)	100	400
Channel Width (in)	0.100	0.050

Hence, optical/laser drilling is a preferred technique and has already been established for high volume production of blind vias and micro-vias and is strongly growing. Due to its high processing speed resulting in high throughput, the costs can be significantly lower than conventional mechanical drilling. As smaller via diameter and higher accuracy is required, UV laser processing is considered. UV lasers, such as nanosecond and femtosecond lasers, can currently produce micro-vias below 25 μm . In the current trend, laser processing of materials can be described as investigating new modalities in which the laser fluence may be delivered to a workpiece, specifically the ways in which the pulse duration, wavelength or pulse-shape give significant new control over the laser-material interaction. Lasers offer the parameters of fluence, intensity, wavelength, and pulse duration as factors which afford control over essential aspects of material interaction.

1.1.1 ADVANTAGES OF INTERCONNECT VIA

Various factors of interconnects have an integral role in deciding for 3D packaging. A few are listed below with their effects.

1.1.1.1 SIZE AND WEIGHT

By replacing single chip packages with a 3D device or by stacking chips, substantial size and weight reductions are achieved. This is simply done by stacking of chips with interconnections between chips. Thus, the magnitude of these reductions and interconnections depends on density, accessibility, thermal characteristics, and robustness which are required for 3D packaging. It has been reported that 40 to 50 times reduction in size and weight is achievable using 3D technology compared to conventional packaging. Also, it is evident from tests and

reports that a 5 to 6 time's reduction in volume is possible over Membrane Multi-Chip Module (MCM) technology and a 10 to 20 time's reduction over discrete packaging technology. Moreover, a 2 to 13 times reduction in weight is also achievable compared to MCM technology and a 3 to 19 times reduction compared to discrete components. All of these reductions result from eliminating the overhead weight and size associated with conventional technologies [6, 7].

1.1.1.2 SILICON EFFICIENCY

One issue concerning the packaging technology is the chip footprint, which is the printed circuit board area occupied by the chip [7]. In the MCM case, the footprint is reduced by 20–90% because of the use of bare dice. Three-dimensional packaging results in an even more efficient utilization of silicon real estate, which is referred to as “silicon efficiency”. Silicon efficiency can be defined as the ratio of the total substrate area in a stack to the footprint area. Consequently 3D technology exceeds a 100% silicon efficiency compared to other two-dimensional (2D) packaging technologies.

1.1.1.3 DELAY

Delay refers to the time required for a signal to travel between the interconnect wires in a system. In high speed systems, the total delay time is limited primarily by the time of flight, which is defined as the time taken for the signal to travel (fly) along the interconnect [8]. The time of flight, t , is directly proportional to the interconnect length. So reducing the delay requires reducing the interconnect length which is the case when using 3D packaging. The resultant reduction in interconnect length, results in a reduction of the interconnect associated parasitic capacitance and inductance, hence reducing signal propagation delays.

1.1.1.4 NOISE

Noise in general can be defined as unwanted disturbances superimposed upon a useful signal, which tend to obscure its information content. In high performance systems, noise management is a major design issue. Noise can limit the achievable system performance by degrading edge rates, increasing delays, and reducing noise margins, and can cause false logic switching. The noise magnitude and frequency are closely tied to the packaging and interconnect scheme used. In a digital system, four major sources of noise can be identified as:

- 1) Reflection noise
- 2) Crosstalk noise
- 3) Simultaneous switching noise
- 4) Electromagnetic interference (EMI)

The magnitude of all of these noise sources depends on the rise time of the signals passing through the interconnect. The faster the rise time, the worse the noise. The role of 3D technology in reducing noise is in the reduction of interconnection length, and hence reduction of the associated parasitics which translate into performance improvements. On the other hand, the noise could be problematic in a system if the used 3D technique does not address the noise. For example, if the interconnections don't have uniform impedance along the line or its impedance does not match the source and destination impedance, there is the potential for reflection noise. Furthermore, if the interconnects are not paced enough there is also a potential for crosstalk noise. Simultaneous noise is reduced because of the shortened interconnects and consequent

reduction of the associated parasitics, so producing less simultaneous noise for the same number of interconnections.

1.1.1.5 SPEED

The power saving achieved using 3D technology can allow the 3D device to run at a faster rate of transitions per second (frequency) with no increase in power consumption. In addition, the reduction in parasitics (capacitances and inductances), size and noise of a 3D device, allow for higher transitions per second which would increase the overall system performance.

1.1.1.6 INTERCONNECT USABILITY AND ACCESSIBILITY

The use of a 3D packaging configuration provides access to 116 neighbours within an equal interconnect length to a centre element in the stack, in contrast to eight neighbours to the centre element in the case of 2D packaging technology. Hence, reduction of the interconnect length in the stack results in reduction of propagation delay between chips. Furthermore, the available vertical interconnection results in maximum utilization of the available interconnects in contrast to traditional packaging technologies where such utilization is limited by physical structures such as vias or by previously routed interconnects. The accessibility in case of 3D packaging technology depends on the type of vertical interconnection employed as it is proportional to the available vertical interconnect density—which is defined as the number of signal layers per average wire pitch [9]. So, area interconnection provides the most accessibility and usability in contrast to peripheral interconnections, where the usability and accessibility are limited by the periphery length of the stacked element.

1.1.1.7 BANDWIDTH

Interconnect bandwidth, especially memory bandwidth, is often the performance limiter in many computing and communications systems. Thus low latency (delay) and wide buses are very desirable. For example, in the well known Intel Pentium, the CPU and Level 2 cache are packaged together in the same multi-cavity Pin Grid Array to obtain a large memory bandwidth.

1.2 TECHNIQUES USED IN MICRO-VIA FORMATION

Micro-vias, as opposed to through holes, with diameters below 200 μm are used to interconnect adjacent layers of printed circuitry. Different technologies are available such as mechanical drilling, laser via formation, plasma etching, photo via formation, etc. However, the two most common processes, mechanical and laser drilling are compared.

1.2.1 MECHANICAL DRILLING

Mechanical drilling is a proven technology that covers a large range of via diameters with high aspect ratios (depth to width). It is most economical for through vias and blind vias larger than 200 μm in diameter. To bridge the gap to micro-vias, special techniques are used to achieve depth controlled drilling of small via sizes. High speed spindles are combined with different kinds of depth sensors. Extremely precise blind via formation can be achieved with Electric Field Sensing (EFS).

Other techniques, such as Numeric Control (NC) drilling are also used in forming. However, NC drilling is technically limited to via sizes of 200 μm and up. Although smaller

holes may be possible, these would come at the cost of significant productivity. In addition, blind vias are virtually impossible where typical dielectric, like silicon, thickness is 50 μm or less.

From a cost perspective, mechanical drilling of micro-vias offers a great standard in forming micro-vias using existing mechanical drill equipment. Some of the depth control systems are even available as upgrades for existing machines. With very limited capital cost, the cost model for mechanical drilling is very simple and is reduced to the cost of operation.

While the costs are low for large via diameters, they rise with declining via diameter since the drill bits become more expensive and have to be replaced more frequently. There is a significant increase in costs when going down to via diameters of 150 μm and smaller. Therefore, operating costs are very expensive in high volume production of micro-vias especially for small via diameters.

Hence, most mechanical drilling is not suitable for forming micro-vias of less than 100 μm diameters. Also mechanical drilling of holes of this small diameter presents greater problems since coolant fed drills cannot be used on dielectrics. For such requirement, laser drilling – the fastest growing emerging tool for micro-via formation is considered.

1.2.2 LASER DRILLING

Laser via formation has already been established for high volume production of blind vias and micro-vias and is strongly growing. Due to its high processing speed resulting in high throughput, the costs can be significantly lower than with mechanical drilling. However, capital

costs for laser via formation can be considerably higher. Depending on the application, required accuracy and via diameter, different laser types and techniques are applied.

CO₂ lasers are more commonly and more efficiently used for blind via formation in various dielectric materials. With wavelengths between 9.6 μm and 10.6 μm , they are available with high peak and average power and achieve high ablation rates. For instance, conformal mask processing uses chemical etching to open the copper over the capture pads. The dielectric is then drilled with CO₂ laser, using the opening in the copper as a conformal mask. Laser systems for drilling unclad material use a mask in the laser beam to define via size. Either way, state-of-the-art CO₂ systems achieve net drill rates of 20,000 vias of 100 μm diameter per minute. However, there are limitations in via diameter and accuracy related to this process. Due to the wavelength, CO₂ lasers are limited to via sizes larger than 75 μm . This technology is therefore applied for low margin, mass production products such as handheld devices (cell phones, pagers, etc.). These products are typically manufactured in South East Asia to take advantage of the low labour costs. As smaller via diameter and higher accuracy is required, UV or hybrid laser processing are considered.

UV lasers can produce micro-vias down to 25 μm , due to their short wavelength. Industrial, diode-pumped, solid-state UV lasers are able to deliver stable output, combined with maintenance cycles, of some thousand hours. Good beam quality ensures a minimum focus diameter and maximum depth of focus, resulting in well-defined vias with small taper angle.

To achieve blind vias with desired diameter, the UV laser is used like a milling tool to ablate dielectrics. Starting from the center of the via, the laser spot ($\sim 25\text{ }\mu\text{m}$) is moved in concentric circles or spirals until the desired via diameter is achieved. It is obvious that this procedure takes more time with increasing via diameter and material thickness.

Hybrid laser systems feature both a solid-state UV laser and a CO_2 laser. These systems combine the best of both systems. The UV laser is only used for the most precise ablation, followed by the CO_2 laser for fast and efficient dielectric drilling. This way, dual laser via formation combines the advantages of high drilling rates (due to the CO_2 laser) with minimum via size down to $25\text{ }\mu\text{m}$ and highest accuracy (due to the UV laser). Therefore, an overall comparison between currently available machining methods and their characteristics are shown in Table 2.

Table 2: Comparisons of available machining methods and their characteristics

Type of Drilling	Practical Resolution Limit	Attainable Aspect Ratio (Depth : Hole size)	Taper	Side Effects
Excimer Laser	$75\text{ }\mu\text{m}$	$>100:1$	Yes	Recast Layer
CO_2 Laser	$75\text{ }\mu\text{m}$	$100:1$	Yes	Recast Layer, Burring, Thermal
Nd:YAG	$25\text{ }\mu\text{m}$	$100:1$	Yes	Recast Layer, Burring, Thermal
EDM	$100\text{ }\mu\text{m}$	$20:1$	No	Surface Finish
Chemical Etch	$250\text{ }\mu\text{m}$	$1:1.5$	Yes	Undercutting
Mechanical	$100\text{ }\mu\text{m}$	$10:1$	No	Burring

1.2.2.1 TYPES OF LASERS USED FOR MICRO-VIA FABRICATION

There are four basic types of laser media, Table 3. They are gas, solid state, semiconductor and liquid dye. Only gas and solid state lasers are practical for most industrial machining applications.

Table 3: Common laser used in industry

Type of laser	Medium	Wavelength
Gas Lasers	Excimer	193 – 351 nm
	CO ₂	10 μ m
Solid State Lasers	Nd:YAG	1064 nm
	Nd:YLF	1047 nm

1.2.2.1.1 CO₂ LASER

A carbon dioxide laser uses a gas mixture of CO₂:N₂:He. The CO₂ molecules constitute the active lasing medium, the N₂ gas serves as an energy transfer mechanism and the He atoms enhance the population inversion by depopulating the lower energy states. The population inversion and lasing transition in a CO₂ laser is established between vibrational and rotational energy states. Most CO₂ lasers are pumped by a gas discharge. Different types of CO₂ lasers currently employed are shown in Table 4.

Characteristics of CO₂ laser:

- Most common laser in industry
- Inexpensive
- Wide range of power output capabilities

- High efficiency
- Oscillating frequency is 9.4 – 11.0 μm (infrared)
- Long penetration depth (5 - 20 μm or more)
- Machining is a thermal process – the beam performs its cutting and drilling functions by overloading the target surface thermally
- Usually used in focal point machining mode except for CO₂ Transverse Electrical discharge in gas at Atmospheric pressure (TEA) lasers

Table 4: Types of CO₂ Lasers

Type	Beam	Delivery Method	Applications
Continuous Wave	Lower order mode Gaussian	Focal spot	High speed profile cutting; seam welding; cladding; engraving
Gate pulsed	Lower order mode Gaussian	Focal spot	Cutting and drilling in metals; spot welding
Enhanced pulsed	Lower order mode Gaussian	Focal spot	Cutting and drilling in IR reflective materials
TEA	High order multi-mode	Near-field imaging	Marking in thermally insensitive materials; wire stripping; flex circuits

Important CO₂ machining characteristics:

- Material interaction via thermal overload and vaporization
- Penetration depth is 5 to 10 μm
- Ultimate feature resolution ~ 10 μm
- Practical feature resolution ~ 75 μm
- Inert gas used to limit oxidation in process area

1.2.2.1.2 SOLID STATE LASER

Most solid state lasers are constructed by doping a rare earth element or metallic element into a variety of host materials. The most common host materials are $\text{Y}_3\text{Al}_5\text{O}_{12}$ (YAG), LiYF_4 (YLF) and amorphous glass. The Nd:YAG and Nd:YLF lasers are the most common solid state lasers in industry. Different types of Nd lasers currently employed are shown in Table 5.

Characteristics of Nd laser:

- Typical solid state lasers are pumped optically by arc lamps or flashlamps. Arc lamps typically are used for continuous wave (CW) pumping; flashlamps are used with pulsed lasers
- Solid state lasers are electronically excited. The atoms of the active medium become excited when an electron jumps to a different orbit around the nucleus. In Nd:YAG and Nd:YLF lasers, the neodymium ions (3^+) constitute the active medium
- Nd lasers are easy to pump. All Nd lasers (Nd:YAG, Nd:YLF, Nd:Glass) are four-level laser systems with numerous absorption bands above the upper lasing energy states $^4\text{F}_{3/2}$. Atoms at these states readily decay to $^4\text{F}_{3/2}$ making it easy to establish the required population inversion
- Emission wavelength of Nd doped lasers varies somewhat with different host materials. Some host materials have a less defined lattice structures than others. The energy linewidths in these materials are “broadened” such that the transition wavelengths are different
- Nd laser outputs can be frequency doubled, tripled or quadrupled through harmonic generation

- Nd lasers respond well to Q-switching

Table 5: Types of Nd Lasers

Type	Beam	Delivery Method	Applications
Continuous Wave (CW)	Lower order mode Gaussian	Focal spot	Profile cutting; seam welding; cladding; engraving
CW pumped; Q switched	Lower order mode Gaussian	Focal spot	Cutting and drilling in metals; spot welding
Flashlamp pumped, pulsed	Lower order mode Gaussian	Focal spot	Cutting and drilling in metals; spot welding

1.2.2.1.3 EXCIMER LASER

Excimer laser is a form of UV laser. It typically uses a combination of inert gas and a reactive gas. The wavelength of the excimer laser depends on the molecules used. Different types of excimer lasers currently employed are shown in Table 6.

Characteristics of Excimer laser

- Resonator cavity configuration produces a beam ideal for near-field imaging
- High peak power of the laser beam permits ablation of the target material with little or no heat affected zone
- The 191 – 351 nm optical wavelength permits generation of high resolution ($\sim 1 \mu\text{m}$) features on target surface
- The shallow absorption depth permits tight control of feature depth by controlling the number of pulses applied
- Large beam cross-section accommodates a large imaging mask for near-field imaging

- However, contains toxic laser gases and is corrosive

Table 6: Types of Excimer Lasers

Mixture	Wavelength	Gas Lifetime	Average Power
F₂	157 nm	~ 10 ³ pulses	< 5 Watts
ArF	193 nm	~ 10 ⁶ pulses	30 Watts
KrCl	222 nm	2(10 ⁶) pulses	30 Watts
KrF	248 nm	10 ⁷ pulses	50 – 100 Watts
XeCl	308 nm	2(10 ⁷) pulses	50 – 150 Watts
XeF	351 nm	10 ⁶ pulses	< 50 Watts

1.3 CURRENT AND FUTURE TREND IN INTERCONNECT VIA

Micro-via industries are currently equipped with nanosecond lasers for fabricating micro-vias for the current markets demands. Hence, issues associated with nanosecond laser drilling such as low throughput and expensive post processing steps are currently restraining the rapid growth in interconnect vias [10]. Compared with conventional nanosecond (ns) laser drilling, ultra-fast femtosecond (fs) laser pulses are particularly advantageous in high precision laser ablation, which can lead to improved surface morphology and a reduction in the extent of the heat-affected zone (HAZ) [11]. The quality difference of machined substrates with different laser pulse durations, in terms of collateral damage of the substrate along with mechanical and electronic properties, has been studied by *Xu et al* [19]. Furthermore, many have shown that laser material processing in the ultrashort pulse regime offers numerous advantages compared with longer pulses. Improvements in surface morphology, absence of thermal degradation, and reduced threshold fluence for polymers and dielectric materials are reported by [12, 13]. Ultrashort lasers offer high intensity to drill, to modify and to process surfaces cleanly by

aggressively driving multiphoton, tunnel ionization, and electron-avalanche processes [14, 15]. Also, nanosecond lasers are proven to have low power, throughput, threshold fluence and redundant debris and recast layer when compared to femtosecond laser [16 – 19]. Studies in femtosecond laser fabrication have been reported at low power and low repetition rate (< 1 kHz) [20 – 23].

Presently, the smallest micro-via size that is commercially fabricated is $50\text{ }\mu\text{m}$ in diameter and the demand is to fabricate in sub-10 micron ($< 10\text{ }\mu\text{m}$) vias in coming years [24]. According to the International Technology Roadmap for Semiconductors (ITRS), micro-via diameter will reach $18\text{ }\mu\text{m}$ by the year 2012 [25]. Current conventional high power kilo hertz repetition rate lasers are able to ablate $50\text{ }\mu\text{m}$ deep vias. However, this seriously hinders the throughput rates of industrial requirement. *Hermann et al* reported picosecond laser ablation of stainless steel and silicon substrates at a high power of 10 W and at a low repetition rate of 100 kHz micro-vias at a throughput rate of 1000 vias/sec [2]. Hence, femtosecond lasers with high power, high repetition rate have been investigated to surpass the industrial demands. Furthermore, with the advancement of fiber amplification technique, high repetition rate femtosecond laser becomes cheaper and give high average power. In principle, it has the potential to become an attractive tool for micro-via (less than $10\text{ }\mu\text{m}$) formation.

So far, researchers have tested and developed several methods for 3D integration. One such concept is the stacked silicon-on-insulator (SOI) technology, which embeds several silicon layers in silicon dioxide layers [26]. In a different approach, chips are either bonded to or become embedded in specific carrier materials. These carriers carry the required interconnect

structures and compensate for mechanical stress [27, 28]. A way to avoid SOI and carrier technology is to stack chips directly on top of each other, back to face [29, 30]. Critical steps include aligning the vias and fabricating reliable solder joints. After CMOS processing, the interconnect vias are etched and metalized from the front side of the wafer. A carrier is attached to the processed wafer, followed by a mechanical thinning process and a chemical-mechanical polishing step. Finally, the chips are soldered into a 3D stack. To avoid deep front-side etching that can cause an unfavourable aspect ratio for metallization, it is possible to etch vias from the back side after the thinning process, so that they reach contact pads in the first metal layer [31, 32].

1.4 RESEARCH OBJECTIVES

Researchers in femtosecond laser studies have resulted in low power kilo hertz repetition rates which are able to ablate vias of 50 μm deep. However, with the current micro-via industries demands of below sub-10 micron levels for 3D chips, the low power kilo hertz repetition rate femtosecond lasers hinders the progress of the industrial requirement. Hence, the main objective of this thesis is to study the high repetition rate, high power femtosecond laser system and its effects on micro-via drilling.

In this research, with an aid of a direct-diode-pumped Yb-doped fiber oscillator/amplifier femtosecond laser system, the potentials of using a high power-high repetition rate laser system in forming micro-vias using novel techniques are explored. With the capability of this laser system, the following are outlined as the objective of this study:

- Study the unique capabilities of the proposed femtosecond laser system and its advantages in micro-via drilling to suit the needs of the current market demands through analyzing various laser parameters like repetition rate, fluence, intensity, wavelength, pulse duration and throughput rates and evaluate the influence of these parameters on depth and quality of vias.
- Study the mechanisms of shockwaves and evaluate the substrate surface under various laser parameters and external effects such as polarization and gas assisted environment.

CHAPTER 2

FUNDAMENTALS OF LASER ABLATION

2.1 INTRODUCTION TO LASER ABLATION

Laser ablation in general is a materials-processing technique that has been known since the invention of laser in the 1960's. Immediately after the first lasers became available, there was a flood of theoretical and experimental studies on the ablation process, and a few years later it was demonstrated that intense laser radiation could be utilized in thin-film deposition. This application of laser ablation is called pulsed laser deposition (PLD). Over the next decade or two, however, laser ablation was mainly used for the analysis of various materials and further development of PLD. Ever since the discovery of high-temperature superconductivity, the research interest in PLD has increased dramatically. In addition to PLD, interesting applications of laser ablation include mass spectrometry, UV lithography, and production of free atoms for laser spectroscopy, and inertial confinement fusion research in the future [33].

The principle of laser ablation is to exploit high-power laser pulses, e.g., from a Nd:YAG or Excimer laser, in order to evaporate a small amount of matter from a solid target. In a broader sense, as the laser pulse hits the target, photons are immediately absorbed in a surface layer by electronic processes. The absorption depth depends on the optical penetration depth of the material, which can be in the order of a few nanometers at the vaporisation temperature. The absorbed energy is transferred into the material either by electrons (in metals) or by phonons (in non-metals). The energy relaxation time in metals is very fast, $\sim 10^{-14}$ s, whereas it is much

slower, $\geq 10^{-12}$ s, in non-metals [34]. However, compared with the laser pulse duration, the absorbed energy is rapidly converted into heat. Therefore, the surface is heated beyond the melting temperature of the target material and the surface melts. The melted surface starts to vaporise and the high temperatures generated at the target surface (up to several thousand degrees Celsius) cause the emission of molecules of the target.

A number of different interactions are involved in a laser ablation process. Not only the interaction between the laser and the target has to be considered, but also laser-vapour, vapour-target, laser-plasma and plasma target interactions play an important role in the ablation process. Also, another important laser ablation parameter is the laser-pulse energy density or laser fluence (J/cm^2), on the target surface. When the fluence is sufficiently high, rapid evaporation of material occurs in a thin surface layer, which is necessary for stoichiometric transfer of material from a multicomponent target. This introduces another characteristic feature of laser ablation, the existence of a laser ablation threshold, i.e., for all materials, there exists a threshold laser power density below which ablation, measurable material removal, is not possible. This threshold power density may be lower for non-metals than for metals, which is due to the poor energy transfer in non-metals giving rise to higher surface temperatures during the ablation process. Above the ablation threshold, the ablation rate increases nonlinearly with increasing laser power density. For optimum laser deposition, the laser power density should neither be too low nor too high. If the power density is too close to the ablation threshold, the material removal is low and non-stoichiometric transfer of target material is possible for multicomponent targets. If the power density is too high, however, a large amount of the laser energy is wasted in plume heating and ionization instead of being used for heating the target surface. However, the physics of laser-

matter interaction that leads to material breakdown and ablation differ with short and long pulses, which are emphasized in the next section.

2.2 ABLATION PROCESS

The first step in laser ablation is the absorption of laser energy by the target material. This is accomplished by linear or nonlinear processes. The material in the focal region is heated to melting temperature and, depending on laser intensity and pulsewidth, subsequently to vaporization temperature. For non-UV wavelengths, the absorption mechanisms are different for absorbing materials such as metals, semiconductors and dielectric materials such as glasses and plastics. The absorption mechanisms also depend on laser intensity, hence on laser pulsewidths for a given laser fluence. For metals and semiconductors, while linear absorption is the main absorption mechanism at long pulsewidths with low intensity, nonlinear absorption can become dominant at ultrashort pulsewidths with high intensity. For dielectric materials, absorption has to come from nonlinear processes through laser-induced optical breakdown.

Laser-induced breakdown is a process where a normally dielectric material is first transformed into absorbing plasma by the strong laser pulse. Subsequent absorption by the plasma of the laser energy causes heating that leads to irreversible damage to the host material. The nonlinear processes causes breakdowns are avalanche ionization and multiphoton ionization.

2.2.1 LONG PULSE LASER ABLATION

The avalanche ionization process is illustrated in Figure 2-1. In a dielectric material, the bound valence electrons have an ionization potential or bandgap greater than the laser photon

energy. The bound electrons do not absorb the laser light at low intensities. However, in any material there are always some free or conduction electrons present, and they are the seed electrons for avalanche ionization. These seed electrons can come from metallic impurities, thermal or linear optical ionization of shallow energy levels of inclusions. A free electron, when simply wiggling in the oscillating laser field, does not gain energy when averaged over an optical cycle, thus does not absorb the laser energy. However, the free electron can absorb laser energy when it collides with the bound electrons and the lattice through dephasing. This is the Joule heating process, also known as inverse Bremsstrahlung. The seed electron can be accelerated enough that its kinetic energy exceeds the ionization potential of the bound electron. Therefore the next collision with a bound electron will result in an ionization event if the free electron transfers nearly all its energy to the bound electron, resulting in two free electrons with low kinetic energies. This is called impact ionization. This process will repeat itself, leading to an avalanche where the free-electron density grows exponentially from the very low seed electron density. When enough bound electrons are ionized by this avalanche process, plasma with a critical density is created, and the dielectric material is broken down and becomes absorbing (the absorption by the initial seed electrons is negligible due to the very low density). This critical density is customarily taken to be 10^{18} cm^{-3} for nanosecond or longer pulses, since this is considered the density at which significant optical absorption occurs for irreversible damage to take place. For shorter pulse durations, the real plasma critical density for the laser wavelength, defined as (in cgs units) $n_c = m_e \omega^2 / 4\pi c^2$, where m_e is the electron mass and ω is the laser frequency. This is the plasma density at which the plasma oscillation frequency equals the laser frequency. Laser-induced breakdown is accompanied by emission of acoustic waves and optical plasma radiation (a spark) from the focus.

Figure 2-1: Schematic of electron avalanche by collision impact ionization

2.2.2 SHORT PULSE LASER ABLATION

When the laser field strength is very high, as in the case of ultrashort pulse laser–matter interaction, bound electrons of the dielectric material can be directly ionized through multiphoton absorption. This process is schematically shown in Figure 2-2. A bound electron can be lifted from its bound energy level or valence band to the free energy level or conduction band by simultaneously absorbing m photons in the laser pulse such that $m h \nu \geq U_I$, where $h \nu$ is the energy of the photon, and U_I is ionization potential or bandgap. This is called multiphoton ionization. As this is an m th order process, the cross section is extremely small. Only at very high field strength is multiphoton ionization significant. Therefore, for long pulsewidths where the field strength at breakdown is lower, the multiphoton ionization contribution is negligible, and laser-induced breakdown is dominated by avalanche ionization. However, at ultrashort pulsewidths, multiphoton ionization plays an important role, i.e., it determines the breakdown threshold behavior.

Figure 2-2: The multiphoton ionization process

The laser-induced breakdown process takes time to build up and depends on the laser field strength. It exhibits a threshold behavior, i.e., at a given laser pulsewidth, only when the laser field strength exceeds a certain threshold can the plasma density grow to the critical value where irreversible breakdown takes place. The threshold is customarily expressed as a laser fluence threshold as a function of pulsewidth. A large body of work has been carried out to study the laser-induced breakdown mechanisms for various materials [35, 36]. It has been shown that for pulsewidths from few tens of picoseconds, the breakdown mechanism is avalanche ionization, started from initial seed electrons [37]. Experimentally, it has been shown that the fluence breakdown threshold for this pulsewidth regime scales as the square root of the pulsewidth. Recently, some work on breakdown threshold for ultrashort pulsewidths has been performed [38, 39], and deviation from the pulsewidth square root scaling law has been observed. More importantly, the large statistical variation of breakdown events near the threshold at long pulsewidths has disappeared at ultrashort pulses. The breakdown fluence threshold is defined as the fluence at which there is a 50% probability a laser pulse with this fluence will

cause breakdown. For long pulses the threshold has a large deviation, some pulses with fluences way below the threshold value can cause breakdown, while some pulse with fluences far above the threshold will not cause breakdown. However, the situation changes drastically when ultrashort laser pulses are used.

2.3 CHARACTERISTICS OF LONG AND SHORT PULSE LASER ABLATION PROCESS

The difference between the long and short pulse breakdown indicates that different physical mechanisms are involved at ultrashort pulsewidths. The large statistical scatter for long pulses is mainly attributed to statistical variations of the seed electrons. For a normal material, the seed electron density due to impurities, etc., can be in the range of $10^8 - 10^{10} \text{ cm}^{-3}$. The volume of the laser focus of a $10 \text{ }\mu\text{m}$ spot is on the order of 10^{-9} cm^3 . Therefore, the number of seed electrons in this volume can be on the order of unity, and the actual number can vary greatly from site to site due to statistical variations. The avalanche ionization that leads to breakdown for long pulses thus will exhibit large fluctuations, since the seed electrons only come from those that are already present. On the other hand, for ultrashort pulses with very high field strength, multiphoton ionization can directly generate free electrons, they do not need to rely on the impurity seed electrons. Studies [38, 40] have shown that down to approximately 100 fs, the role of multiphoton ionization in the breakdown process is to supply the seed electrons. The breakdown is still completed by avalanche ionization, starting from the seed electrons density generated by multiphoton ionization. In this case, however, the seed electron density can be quite high and does not exhibit large statistical fluctuation. Consequently, the laser-induced

breakdown threshold at ultrashort pulsewidths becomes more deterministic. In other words, the breakdown threshold becomes precise at ultrashort pulsewidths.

Once the plasma of free electrons generated by avalanche ionization reaches a high enough density, typically the plasma critical density for the laser wavelength, irreversible material breakdown and ablation begin. The electrons absorb laser energy by collisions with ions and are heated to high temperatures. At the same time, the electrons transfer energy to the ions and the lattice, and the material is heated up. The amount of energy transfer, hence the heating, during the laser pulse depends on the pulse duration and the energy coupling coefficient. The absorbed energy also leaves the laser focal volume by heat conduction due to thermal gradient, therefore a larger volume than the focus is heated. For long pulses, the energy transfer from electrons to ions during the laser-matter interaction is strong, and heat diffusion can involve a much larger volume than the focus. The electrons and ions can be in thermal equilibrium or quasi-equilibrium, and the peak temperature is low. For long laser pulses, a large volume around the laser focus can be melted, but only a relatively small layer of material reaches the vaporization temperature. As the pulsewidths decrease, the laser field strength increases, and the interaction time gets shorter. The electrons are driven to much higher temperature, and the ion or lattice temperature is much lower than the electron peak temperature. The electron temperature can reach a few to tens of electron volts ($1 \text{ eV} = 11\,600 \text{ K}$) during the laser pulse duration, while the ions remain relatively cold. Subsequent electron-ion energy transfer, mostly taking place after the laser pulse is over, will then rapidly heat the ions to much higher temperatures compared to the long pulse cases. A large fraction of the material in the interaction volume is vaporized, going through a melt phase very quickly. The heat-affected volume due to conduction

is also much smaller because of the short interaction time. For ultrashort pulses, it can actually become smaller than the focus when the laser fluence is at or just above the threshold value.

For absorbing materials, such as metals and semiconductors, there is a large density of free electrons and valence electrons with an ionization potential less than the photon energy. For long pulses, linear absorption dominates, and the material is heated through Joule heating. When melting or vaporization temperature is reached, the material is considered broken down and damaged. The breakdown is also accompanied by acoustic waves and optical plasma radiation. The rate of heating is determined by the rate of laser energy absorption and the rate of energy loss from the focus, mainly through thermal conduction away from the focus. The rate of laser energy absorption is approximately constant before the breakdown. The energy is deposited in a surface layer whose thickness is given by the absorption or penetration skin depth $l_s = 1/\alpha$, where α is the absorption coefficient. Another characteristic length is the heat diffusion length during the laser pulse, which gives the heat penetration depth due to thermal conduction. This diffusion length is given by $l_d = (D\tau_l)^{1/2}$, where D is the heat diffusion coefficient and τ_l is the laser pulsewidth. For long pulses, $l_d > l_s$, and the volume of the material heated by the laser pulse, hence the temperature, is determined by the heat diffusion length during the laser pulse. Therefore, for long pulses, the fluence breakdown threshold varies with laser pulsewidth as $F_{th} \propto (\tau_l)^{-1/2}$. However, as the laser pulsewidth decreases to a value τ_c such that $l_d = (D\tau_c)^{1/2} < l_s$, the skin depth determines the heated volume during the laser pulse, not the heat penetration depth. The breakdown threshold becomes independent of the pulsewidth [41]. The above argument also applies to dielectric materials once significant absorption due to plasma generation occurs, and it has been used to explain the observed $(\tau_l)^{-1/2}$ scaling of the breakdown threshold [42].

For long pulses where the heat diffusion length is larger than the skin depth, a large volume is heated and melted, the ablation and material removal is accomplished through melt expulsion driven by the vapor pressure and the recoil of the light pressure. This is a very unstable process, since the fluid dynamics of the fluid phase and the driving vapor conditions are quite complicated. In via drilling and cutting applications, the resolidification of the melt after the ablation can lead to very irregular shapes in vias and cuts. On the other hand, for ultrashort pulses, the deposited laser energy is limited in a layer with thickness l_s . The localized energy heats the material very quickly past the liquid phase to the vapor phase with high kinetic energy (way above the vaporization temperature). The material removal is by direct vaporization away from the surface (into vacuum or air). Most of this is accomplished after the laser pulse irradiation is finished. The material is still heated by the heat diffusion over a longer time scale. However, the resulting melt layer thickness will be small because most of the heated material reaches vaporization temperature, and there is rapid cooling due to the steep temperature gradient. The heating of the material by heat diffusion is further reduced by the fact that a large amount of the absorbed laser energy is carried away by the direct vaporization. Because little liquid is involved, ablation and material removal become highly precise, in contrast to the long pulse case. This is the basis of precision micromachining with ultrashort pulses.

2.4 SUMMARY

In summary, laser ablation is the process of material removal upon the irradiation of the laser beam on the surface. Aspects of laser-matter interaction are elaborated through the differences between short and long pulses. With long pulses such as nanosecond lasers, material removal process is through phase explosion where due to thermal accumulation over the surface,

heat affected zone and cracks occur making it less desirable results. In ultrashort pulses such as femtosecond lasers, the ablation mechanism is mainly direct solid to vaporization state of materials. Hence, with precise breakdown thresholds and negligible thermal diffusion, ultrashort pulses are ideally suited for precision micromachining applications.

CHAPTER 3

EXPERIMENTAL DETAILS

3.1 INTRODUCTION

Understanding the capabilities of the laser system and its parameters are most essential for the micro-via fabrication process. This chapter gives an overview of the laser system used for the research, provided with the experimental setup and some of the important parameters considered for the laser ablation. All experiments were conducted using a high power high repetition rate femtosecond laser in the Micro and Nano Fabrication research lab at Ryerson University, Toronto, Canada.

3.2 EXPERIMENT SETUP

Experiments were conducted using a Clark-MXR IMPULSETM direct-diode-pumped Yb-doped fiber oscillator/amplifier femtosecond laser system, as illustrated in Figure 3-1. The system is capable of generating repetition rates of 208 kHz to 26 MHz with a maximum output power of 20 W at a repetition rate above 2 MHz.

The laser central wavelength is 1030 nm and pulse duration of 214 fs was adopted in forming micro-vias. Altering various pulsewidth during an experiment was adopted by changing the compressor grating position within the system and calibrated using an autocorrelator. However, the selection of pulsewidth and repetition rate was limited by the range availability of the laser system and was controlled internally with computerized preset selections.

Figure 3-1: Schematic of experimental setup for laser micromachining with a femtosecond laser. AOM, L, WP, M, D, GS, TL, Si and TS denote acousto-optic modulator, lens, quarter (zero order) waveplate, mirror, diaphragm, galvoscaner, telecentric lens, silicon substrate and translation stage, respectively

The laser system's output beam has a linear polarization which was changed to circular polarization by aligning a quarter waveplate with the beam. Optical waveplates, or commonly known as retardation plates, are used for manipulating the polarization of the laser beam. Polarization of the laser beam has a significant effect on the shape of the micro-via formed and has been previously studied [18].

The output beam of the laser measures approximately 4 mm in diameter which was expanded to 8 mm in diameter using a combination of UV fused silica plano-convex coated lens of 100 mm and 200 mm focal length. A galvoscaner was used for high speed beam positioning in x-y axis. An electronic driver, controlled by a computer, controls the movements of the galvoscaner. The use of galvoscaners is preferred over a translation stage due to its precision

and high scanning speeds. The galvoscaner used in this research has the capability of attaining speeds of upto 3000 mm/sec which is highly implausible with a mechanical translation stage. An acousto-optic modulator (AOM) was used, in conjunction with the galvoscaner, to diffract the zero order beam such that the substrate is not machined when the galvoscaner moves from one via to another. A telecentric lens with effective focal length of 100 mm was used to focus the laser beam onto the substrate's surface for machining.

The samples used in this research were of 250 μm thick single-side polished P type Boron doped silicon wafer with orientation of $\langle 100 \rangle$. The silicon wafer was mounted on a vacuum chuck secured by a two-axis translation stage. The two-axis precision translation stage has a smallest resolution of 1 mm and a range of 15 cm is used to locate the laser irradiation spot on the sample surface. Various dwell times for each repetition rate were obtained using EzCAD[®] software. All laser power readings were obtained using a power meter prior to beam entering the galvoscaner.

An average power of 11.5 W was delivered consistently to the substrate with minimal loss of power in mirrors and lens absorbing energy. Pulse energy decreases proportionally with increasing repetition rate thus maintaining the average power constant [4]. The processed microvias were all ablated well above its minimum threshold. The samples were examined under Scanning Electron Microscopy (SEM) for evaluating via diameter, depth, ablation rate, cross-section profile and top surface quality. The results are presented and discussed in the following sections.

3.3 PARAMETERS

Various parameters need to be better understood for processed micro-vias obtained with the experimental setup discussed previously. These include dwell time, spot size, and measurement errors obtained during the experimental process. These parameters and other aspects pertaining to the experiments performed will be discussed in detail in the subsequent sections.

3.3.1 DWELL TIME

Dwell time refers to the time taken for the beam to stay at one point. The dwell time is entered manually in the EzCAD[®] Software which in turn works parallel with the acousto-optic modulator and the galvoscaner. For generating micro-vias, dwell time is given to machine the sample for a particular given time before moving onto the next point. The galvoscaner used in this research moves the beam from one point to another. However, during the machining process, the acousto-optic modulator diffracts the beam giving the galvoscaner some time to accurately relocate to another point before the beam is diffracted back to the galvoscaner and starts machining at the new point. Therefore, the results discussed in the latter chapters do not include this mechanical time taken during the machining process.

3.3.2 LASER SPOT SIZE

Laser's spot size refers to the minimum diameter of the Gaussian beam focused upon the substrate. Experimentally, one can find the spot size by machining on a thin metal film with the pulse energy well above the material threshold. The machined spot can be analyzed under the

SEM and measuring the size. However, theoretically, the spot size value of the tightly focused laser beam can be calculated using Eqn. 3-1,

$$\omega_0 \approx 0.635 \frac{\lambda_0 f_1}{D} \quad \text{Eqn. 3-1}$$

where λ_0 is the wavelength of the laser beam (1030 nm), f_1 is the effective focal length of the scan lens (100 mm) and D is the diameter of the laser beam at the input of the galvo-scanner (8 mm). The spot diameter was calculated as 8.2 μm . During the experiment the spot size may be bigger due to scatter and misalignment.

3.3.3 MEASUREMENT ERRORS

Each set of samples contained 200 points or vias with same laser parameters. However, when analyzed under SEM, 5 samples were obtained out of 200 for experimental analysis. Therefore, in the latter chapters, the analyzed results represent an average values obtained with SEM samples. Also, SEM samples were further analyzed with Adobe Reader[®] for measuring diameters, depths and spacing. For example, a sample obtained at a repetition rate of 2 MHz at a dwell time of 1 ms has 5 SEM images of the sample. Therefore, the analysis of the via diameter refers to an average via diameters of 5 samples obtained. Hence, all the results discussed hereafter have an average $\pm 5\%$ measurement error included within the results unless otherwise stated.

3.4 SUMMARY

Micromachining process invariably depends upon the laser system used and the laser's parameters control the effects it has during the process. Therefore, for this research, the high

power high repetition rate femtosecond laser system is analyzed. The experimental setup was modeled for appropriate silicon processing in specific applications. Hence, the laser parameters need to be better understood for their role in pulse-to-substrate interaction.

CHAPTER 4

EFFECTS OF REPETITION RATE

4.1 INTRODUCTION

Laser ablative micro-via formation has been widely accepted as an effective manufacturing method for interconnect via formation. Current conventional nanosecond laser micro-via formation has reached its limit in terms of minimum via diameter and machining quality. In this chapter, the femtosecond laser has been investigated intensively for its superior machining quality and capability of producing much smaller features. However, the traditional femtosecond laser has very low power and is thus unable to meet the throughput requirement. This chapter studies the ablative micro-via formation using femtosecond lasers at megahertz repetition rates.

4.2 RESULTS AND DISCUSSION

4.2.1 EFFECTS OF REPETITION RATE ON ABLATION THRESHOLD

The laser ablative material removal process is very complex and very material dependent as well as highly dependent on laser parameters such as wavelength, pulse duration and laser fluence. For all materials, there exists a threshold power density below which ablation, i.e., measurable material removal, is not possible. Thus, minimum ablation thresholds were determined for silicon substrates at various repetition rates for comparative analysis [43]. Results are presented in, Figure 4-1a and 4-1b.

Figure 4-1: (a) Minimum threshold energy and, (b) Ablation threshold energy comparison of silicon at various repetition rates

Figure 4-1a illustrates that threshold energy decreases linearly then saturates with the increase of repetition rates. Figure 4-1b gives the actual pulse energy used for the present experiments. To form micro-vias at a reasonable throughput, the applied pulse energy should be kept well above the ablation threshold. Figure 4-2a and 4-2b, illustrates samples ablated at a repetition rate of 4.33 MHz (pulse energy of 2.65 μJ) and 26 MHz (pulse energy of 0.44 μJ), respectively. The total pulse energy delivered is constant for both repetition rates aforementioned. At lower repetition rate of 4.33 MHz, the pulse energy is sufficient and well above the damage threshold, which is evident from Figure 4-1b. However, for higher repetition rate at 26 MHz the ablated via is very shallow, less than 50 μm . The pulse energy at 26 MHz is slightly above the damage threshold and hence it is considered as surface ablation [3]. Further studies have shown to have similar effects upon threshold energy with increasing and decreasing effects of repetition rates [44, 45]. The deformities seen on either side of the via in Figure 4-2a, is subjected to mistiming of shutter closure. The laser power could not be completely turned off when the beam relocated from point to point. The residual laser power created the ripple

structure. This can be eliminated by employing a shutter with higher on-off frequency correlating with better galvoscaner control.

Figure 4-2: (a) Sample ablated at 4.33 MHz (2.65 μ J) and, (b) 26 MHz (0.44 μ J) with a dwell time of 100 μ s

4.2.2 EFFECTS OF REPETITION RATE ON VIA DIAMETER

Figure 4-3, illustrates the diameter of via obtained at various dwell times for various repetition rates. It is evident, that via diameter is smaller with lower dwell times and higher repetition rates. With higher repetition rate, as aforementioned, the pulse energy is low therefore only a small portion of Gaussian beam close to the intensity peak has enough energy to ablate the material, therefore results in smaller via diameter. Figure 4-4 shows the smallest via diameter of 8.39 μ m attained at 13 MHz (0.88 μ J) repetition rate, for a dwell time of 100 μ s. In contrast, increasing dwell time is shown to have increase in diameter, this is due to the higher number of pulses arriving hence opening the via wider. Also, heat incompletely dissipated on a nanosecond time-scale may account, in part, for enlargement of hole diameters by 1 – 5 μ m larger than the diameter of the focused laser beam. For fluencies well above threshold, ablation also extends

appreciable into the weaker edges of the Gaussian beam. The slight decrement in via diameters at 2.5 ms for most of the repetition rates could be due to the arrival of subsequent pulses accumulating heat over the via entrance thus creating a small amount of liquid silicon. This liquid layer flows back towards the entrance of the via and reducing the via diameter slightly and cools off rapidly with the termination of pulses. The surface temperature of the substrate is elaborated in detail in the latter chapter.

Figure 4-3: Via diameter obtained at various dwell time's for various repetition rates

Figure 4-4: Samples ablated at 13 MHz (0.88 μJ) with a dwell time of 100 μs

Micromachining of metals using a high repetition rate at high fluencies is observed to produce a near-circular region (bright white color) surrounding the entrance of the via, which we attribute to cumulative heating effects [46]. This region is characterized by exploiting the outer edges of the Gaussian beam. Figure 4-5 illustrates this heat accumulation region on a sample ablated at 13 MHz (0.88 μJ) repetition rate, for a dwell time of 500 μs . The arrow and dashed circle approximately represents the zone's width and zone's region respectively. Figure 4-6a and 4-6b shows SEM images and graphical representation of the change in heat accumulation zone width for various repetition rates. The total energy delivered is same for all repetition rates. Indication of increasing cumulative heating is noted at increasing repetition rates, where the width of the zone increases substantially although the via diameter is decreasing at higher repetition rates, evident from Figure 4-6b. Figure 4-7a and 4-7b shows SEM images and graphical representation of the change in heat accumulation zone width for 8.67 MHz repetition rate at various number of pulses. Similar trend, for increasing number of pulses, is noticed in conjunction with aforementioned phenomenon. Increasing number of pulses depict a slow growth in zone width in cumulative heat region. From Figure 4-6b, the zone width is highest at 13 MHz and higher number of pulses. In conjunction with previous studies, this phenomenon is correlating [47, 48].

Figure 4-5: SEM representation of heat accumulation zone on a 13 MHz repetition rate

Figure 4-6: (a) Heat accumulation zone at 100 μ s for 2 MHz, 4.33 MHz, 8.67 MHz, and 13 MHz respectively

Figure 4-6: (b) Heat accumulation zone width and via diameter at 100 μ s for various repetition rates

Figure 4-7: (a) Heat accumulation zone for 8.67 MHz repetition rate at 0.8×10^6 , 2.2×10^6 and 4.3×10^6 pulses respectively

Figure 4-7: (b) Heat accumulation zone width for 8.67 MHz repetition rate at various number of pulses

4.2.3 EFFECTS OF REPETITION RATE ON VIA DEPTH

The depths of the via hole obtained at 8.67 MHz repetition rates and dwell times are plotted in Figure 4-8. The ablation depth increases, for a given repetition rate, with the increase of dwell time. Although the pulse energy is constant at 1.32 μJ , increasing the dwell time increases the number of pulses, hence creating deeper vias for a given repetition rate. This phenomenon was observed at all the repetition rates. Also, beyond certain a dwell time, ablation depths seem to have reached a saturation point, which could be partially due to the fixed focal depth of the focal point [49].

Figure 4-8: Depths of via obtained at 8.67 MHz repetition rate at various dwell times

At a 4.33 MHz repetition rate, the ablation depth is observed to be highest at 121 μm for a dwell time of 1 ms (4.3×10^6 pulses), and a via etch rate of 1,000 vias/sec is attained. Similarly, at a 26 MHz repetition rate the ablation depth is observed to be lowest at 50 μm for a dwell time of 1 ms (26×10^6 pulses) and a via etch rate of 10,000 vias/sec. Lower pulse energy at higher repetition rate phenomenon plays a major role in determining the ablation depth. Threshold energy, from Figure 4-1b, decreases linearly then saturates with the increase of repetition rates. At a higher repetition rate of 26 MHz, the threshold energy is marginally above the damage threshold, hence the maximum depth is around 50 μm . Even with increasing number of pulses, the ablation depth has reached a saturation point where the consecutive pulses arriving will not further increase the depth.

Via drilling below the depth of 50 μm can be considered as surface ablation, where the molten material can be easily ejected from the bottom of the via. Therefore, the via depth mainly

depends on the penetration depth which is determined by the wavelength and pulsewidth. When via is shorter than 50 μm , the pulse energy plays a little role in determining the final depth of the obtained micro-via. For deeper vias, it is difficult for a molten material to escape from the ablated cavity. Higher pulse energy is more capable of ejecting the molten droplet out of the via bottom, therefore, penetrating deeper into the material and producing deeper vias [3]. So, at a high repetition rate, where the corresponding pulse energy is low, the via depth is shallow even at large number of pulses, while at low repetition rate, where the pulse energy is high, the via depth is increasing linearly with increasing number of pulses.

4.2.4 EFFECTS OF REPETITION RATE ON ABLATION RATE

In conjunction with ablation depth, effects of repetition rate on ablation rate are studied. Ablation rates, determined by dividing via depth by total number of pulses applied, for varying repetition rate with constant dwell time and vice versa were plotted in Figures 4-9 and 4-10 respectively. A common effect is observed in both analyses, decrease in ablation rate irrespective of increase in neither the repetition rate or with the dwell time. However, the rate at which these curves decrease is to be noted. A sharp decrease in ablation rate is observed when increasing dwell time. Increasing dwell time ablation depth ceases to ablate any further once it reaches saturation. Similarly, in Figure 4-9, an exponential curve or a slow decrease in ablation rate is observed with increasing repetition rate. However, in this case, the effect is due to the inverse proportionality between repetition rate and pulse energy. As repetition rate increases, pulse energy decreases hence the slow decrease in ablation rate.

Figure 4-9: Ablation rate obtained for various repetition rate at 2 ms dwell time

Figure 4-10: Ablation rate obtained at 13 MHz repetition rate at various dwell time

4.2.5 EFFECTS OF REPETITION RATE ON QUALITY OF MICRO-VIA (SIDEWALL, DEBRIS AND SHAPE)

Quality of micro-vias is an important factor in determining the reliability of the device. Sidewall profile, debris accumulation and circularity of vias are some of the major criteria in determining such reliability. Micro-vias formed by laser ablation are subsequently metalized to form electrical connection. If the qualities of vias are not equal to the required specification, it will certainly result in void during metallization, thus, failure of the device.

For conventional long pulse ablation, a lot of molten material will be spattered out from the irradiated area, contaminating the surrounding area and re-solidification of molten material are harder to remove even with aggressive removal. Due to its short pulsewidth of femtosecond laser, it is not viable for heat to be conducted away from the volume of focus, the deposited energy is limited within the shallow layer at the material surface. The highly concentrated energy heats the material quickly past the melting phase to the vapour phase. Hence, the material is vaporized away from the surface. Thus, results in a much cleaner finish. However, thermal effect is account for part of the ablation process even at femtosecond pulse duration. Therefore, the thermal defects usually associate with laser ablation is reduced but not completely eliminated.

Top surface quality of various repetition rates at constant dwell time is studied. At a dwell time of 1 ms, the repetition rate varied from 2 MHz to 26 MHz. Debris accumulations on the surface is more noticeable at higher repetition rates forming a thin film of debris. Debris in large balls, seen in Figure 4-11b, are formed at higher repetition rates, irrespective of dwell

times. Prominent heat accumulation effects, which results in shorter melt depth and hence the molten slugs form re-solidified material. However, the presence of molten material is not observed at lower repetition rates that have higher pulse energy.

Figure 4-11: Top surface of micro-vias drilled at 8.67 MHz for a (a) dwell time of 0.1 ms, (b) dwell time of 0.5 ms, and (c) dwell time of 2 ms

Also, the effect of increasing dwell time on the top surface quality is studied. Contrary to other studies [3], increasing dwell time has an adverse effect on debris accumulation. Figure 4-11a, b and c shows the top surface of micro-vias drilled at 8.67 MHz for a dwell time of 0.1 ms, 0.5 ms and 2 ms respectively. The SEM images show that increasing dwell times, for all repetition rates, has an increase in distribution of debris over a wide area. With increasing dwell time, subsequent pulses are not able to vaporize the material due to lower pulse energy, hence an increase in debris accumulation. Also, Figure 4-6a and Figure 4-7a also show that the balls grow in size and amount with the increase of repetition rate and number of pulse. This could be explained by the heat accumulation at high repetition rate ablation. With the increase of repetition rate and number of pulse, the thermal energy deposited by successive pulses must diffuse out through a larger volume of heated material. Since the thermal conductivity is lower in the heat accumulating region, the thermal energy is not effectively carried away hence resulting in more heating around the region. As a result a larger volume melts, resulting in growth in size

of the balls [48]. Similar occurrences are observed in [50, 51] where the effect of repetition rate and number of pulses are investigated upon the growth of large balls in the heat accumulation region. Also, studies have shown to reduce this effect through pulse trains or multiple burst of pulse trains with longer diffusion time between the pulses to allow for cooling [4, 50].

Various regions of cross-sectional profiles of various vias are studied. Effects of bubble formation in the necks of vias are evident in vias, to the best of our knowledge this phenomenon has never been seen before. SEM images of top and middle regions of the cross-sectional profile of vias at various repetition rates are seen in Figures 4-12 and 4-13 respectively. At increasing repetition rates, two observations are made. The steepness of the side walls and the bubble formation are analyzed. From Figure 4-12, the walls of drilled holes depend on the fluence (and on the numerical aperture of the optical system). At high fluence or low repetition rate, steep holes are created; with decreasing fluence or high repetition rate, the wall steepness diminishes. This effect can be compensated by choosing a beam path of appropriate numerical aperture. However, the second observation on bubble formation, a novel finding in femtosecond lasers, is seen more clearly in SEM images of Figure 4-13. Depending upon the ablation via drilling below 50 μm can be considered as surface ablation, in which case the molten material is easily ejected from the bottom of the via. This is evident in Figure 4-13c, where the repetition rate of 13 MHz with a depth of 47 μm has no bubble formation. For deeper vias, as seen in Figures 4-13a and 4-13b, for repetition rates and ablation depths of 4.33 MHz, 121 μm and 8.67 MHz, 75 μm experience unusual amounts of bubble entrapment. However, in comparison between repetition rates of 4.33 MHz sample and 8.67 MHz sample, the latter sample is seen to have more bubble formation. Pulse energy along with ablation depth of vias could explain the reason to this

phenomenon. High pulse energy at 4.33 MHz sample could play an integral role for lower bubble formation. The ablation depth is higher at 4.33 MHz (2.65 μJ) sample, but at this repetition rate the pulse energy is two times the amount of 8.67 MHz (1.32 μJ) repetition rate. Thus, at 4.33 MHz, the pulse energy is able to ablate much deeper vias and vaporize the molten materials while escaping. Hence the reason for lower amounts of bubble formation at lower repetition rates.

Figure 4-12: Top section of the cross-sectional profile of vias at (a) 4.33 MHz, 0.25 ms, (b) 8.67 MHz, 1 ms and (c) 13 MHz, 2 ms respectively

Figure 4-13: Middle section of the cross-sectional profile of vias at (a) 4.33 MHz, 1 ms, (b) 8.67 MHz, 2 ms and (c) 13 MHz, 2.5 ms respectively

Via shapes, such as taper angles and parallelism, are one of the major decisive factors in reliability. An inclined or a straight sidewall minimizes gas bubble entrapment and allows liquid to flow smoothly during metallization and electroplating processes [3, 4]. Figure 4-14 illustrates

SEM images of cross sectional profile of vias at different repetition rates. Diamond tip scribe was used in chipping the samples for SEM analysis, hence the uneven edges. At increasing repetition rates, the angle at the top section of vias is seen to have an increasing inclination. An angle of less than five degrees is observed in Figure 4-14a at lower repetition rates. Dependence of threshold energy at outer edges of the Gaussian beam, which causes the inclination of via entrance, helps ablate more efficiently at lower repetition rate with high pulse energy.

*Figure 4-14: Cross-sectional profile of micro-vias drilled at (a) 8.67 MHz, dwell time of 1.5 ms
(b) 13 MHz, dwell time of 2.5 ms*

4.3 SUMMARY

The femtosecond laser is an attractive tool for micro-via formation due to its superior machining quality. However, the low average power of the femtosecond laser hinders its application in industrial where throughput is the decisive criterion. The recent development of the femtosecond laser with relative lower pulse energy but Mega Hertz repetition rate has opened up a new opportunity for the industrial micromachining application of femtosecond lasers. In this research, a high repetition rate femtosecond laser was, for the first time, demonstrated for drilling

vias less than 10 μm in diameter in silicon substrates. A via diameter as small as 8.39 μm and a depth as great as 121 μm was obtained in preliminary experiments. Via etch rates of more than 10,000 vias/sec are achieved at a 13 MHz repetition rate with an ablation depth of 50 μm and similarly 1,000 vias/sec achieved at 4.33 MHz repetition rate with ablation depth of more than 120 μm . Laser parameters were studied for process optimization. In conclusion, the high repetition rate femtosecond laser has been demonstrated to be a promising tool for forming interconnection vias for next generation microdevices.

CHAPTER 5

STUDY OF SHOCKWAVES DURING ABLATION

5.1 INTRODUCTION

The rapid development of femtosecond lasers over the last decade has opened up a wide range of novel applications in industry which includes from material science to medicine [3, 52]. One important physical effect is material removal or laser ablation by femtosecond pulses which can be used for the deposition of thin films and micro-machining which was discussed in the earlier chapters. Also, a number of different interactions are involved in a laser ablation process. Not only the interaction between the laser and the target has to be considered, but also laser-vapor, vapor-target, laser-plasma and plasma-target interactions play an important role in the ablation process. It is in this context that many have reported to have observed the generation of shockwaves. In the vapor cloud through time resolved shadowgraphy models [53-55] many have analyzed and simulated shockwave generation during laser ablation of various materials. For instance *Arnold et al.* reported on a model of plume expansion in ambient atmosphere and deriving the internal and external shockwaves [56]. A study of the gas dynamics for the vapor plume generated during laser ablation was conducted including a counter propagating internal shockwave was reported by *Wen et al.* [57]. And a theoretical study of interaction between laser-induced plasma plume and gas background during film deposition was studied by *Bulgakov et al* [58]. However, shockwaves have seldom been observed in the ablated features. Hence, this chapter focuses upon the theoretical and experimental study of the vapor plume and shockwave propagation generated during femtosecond laser micro-via ablation. An experiment was carried out using the setup demonstrated, along with a blank silicon substrate to ablate the samples in an

ambient air and helium assisted environment. The cause for the raised spherical rims around the central ablation regime within the crater is better understood through the interaction of the internal and external shockwaves. Furthermore, the analysis of the raised spherical rim formation is explored in detail.

5.2 MECHANISM OF SHOCKWAVE FORMATION

The mechanism of shockwave generation during laser-material interaction is a complex process in which knowledge of density, pressure and temperature distributions within the plasma expansion stage needs to be understood. Numerous simulations have been provided to better conceptualize this complex phenomenon. *Predtechensky et al.* used the conservation laws to evaluate the terminal size of the vapor plume during laser ablation [59]. *Arnold et al.* also used this approach to calculate the trajectories of the contact surface between the compressed background gas and the high temperature vapor plume [56]. Furthermore, a more detailed study on the external shockwave and the contact surface, the dynamics of the internal shockwave within the vapor plume and the reflection mechanisms of the internal shockwaves have been reported by *Wen et al* [57]. For a better explanation of these experimental results, the mechanism of shockwave generation is summarized here.

Interaction of successive laser pulses with the target surface induces a vapor cloud with compressed pressure and extreme high temperature which is known as the vapor plume. As the vapor plume expands, a recoil pressure creates different regimes of shockwaves. As illustrated in Figure 5-1a, after the first pulse, the recoil pressure induced by the vapor plume generates a new region known as the internal shockwave. With relatively high enough pressure and temperature,

this internal shockwave surrounds the plume and expands along with the plume hence generating yet another region termed as the external shockwave. As the plume dissipates and before the arrival of next pulse, the fast-outward propagating internal shockwave gets reflected off of the slow-outward propagating external shockwave in the ambient background gas. The reflected internal shockwave propagates towards the center of the ablation region and strikes the sample surface. This process is illustrated in Figure 5-1b.

Figure 5-1: Laser irradiation (a) immediately after first pulse and (b) before the arrival of next pulse

Thus, with the arrival of successive pulses, the process of generating the internal and external shockwaves continues and engulfs the previous internal and secondary shockwaves until the termination of laser irradiation. During this process, the material goes through a molten stage under the repetitive irradiation of the laser pulse, forming a thin layer of liquid on the wall of the ablated crater. Hence, the reflected internal shockwave and the slow propagating external shockwave transmit into the liquid layer of the ablated material and form rim patterns. As the molten layer cools off rapidly upon the termination of laser irradiation, the rim patterns freeze on the wall of the ablated crater, resulting raised rims surrounding the central ablation region.

5.3 RESULTS AND DISCUSSION

5.3.1 INTERACTION OF SHOCKWAVES AND ABLATED SURFACE

Figure 5-2 illustrates crater ablation samples ablated at repetition rates of 8.67 MHz to 26 MHz with a dwell time of 0.5 ms. It was noticed that at 13 MHz and 26 MHz, raised rims with periodical spacing were observed within the ablated craters. But no similar rims were present in craters ablated at lower repetition rates.

Figure 5-2: Repetition rates of (a) 8.67, (b) 13 and (c) 26 MHz respectively

Laser induced periodical structures have been investigated in depth previously. A well accepted theory is that these structures can be explained by the interference between the incident light and a surface wave generated by scattering. Normally, these periodic surface structures appear as ripples orthogonal to the direction of the electric field vector of the incident light and show a period in the order of the wavelength of the generating light [60, 61]. However, the rim structure that was observed from the ablated crater does not correlate with the established surface modification theories.

Therefore, this chapter emphasizes the observances of such rim structures in the ablated features and the effect of repetition rate in the formation of the rim. It is also interesting to note

such formations of rims are generated within the craters of the ablated material, but not at the surrounding of the crater. Similar observances were reported through shadow-graphic images of laser-induced shockwave propagation from ablation in the craters by *Zeng et al.* [62].

It can be deduced that the formation of rims in the crater is due to repetitive laser ablation which influences the properties of the laser-induced plasma plume and the coupling of energy into the target. These changes lead to increased temperature of the target, stronger laser plasma absorption, and reduced mass ablation rate. Ablation at Mega Hertz repetition rates, such as those used in the present experiments, and low pulse energy is observed to produce a near-circular region (crater area) which was attributed to cumulative heating effects [4]. Also, at higher repetition rates, the time between laser pulses is less than the time span long enough for the heat to diffuse away completely, resulting in an accumulation of residual heat in the focal volume. If the pulse energy is sufficient, the substrate near the focus is melted and, as more laser pulses are absorbed, this melted volume increases in size. This molten region is characterized by exploiting the outer edges of the Gaussian beam which is illustrated on an ablated sample in Figure 4-2a and 4-2b. Also, earlier, it was reported that cumulative heating effects were increasing with increasing repetition rate, where effects were also noted to increase substantially at 13 MHz and 26 MHz. Hence, it is reasonable to construe that at 13 MHz and 26 MHz with successive pulses at low pulse energy keep the sample in a molten state. When the laser pulse is terminated, the melt rapidly cools into a structure with the alterations caused by shockwaves frozen in it. Furthermore, at higher repetition rates, with gradual decrease in energy, but still at high enough fluence values, the central region of laser-target interaction melts completely whereas the adjacent surrounding area is partially melt. *Anant et al.* studied this clear central

ablation regime with a narrow surrounding melt region at higher repetition rate [63]. The phenomenon is, thus, substantiating the formations of rims growing within the craters of the samples but not around the surrounding area of the crater.

Effects such as plasma generation and bond breaking are known to take up most of the laser energy during successive pulse irradiation. However, a significant fraction of the heat remains in the irradiated region, which is diffusing into the bulk. Thus, with successive pulses, heat accumulates in and around the focal volume. Hence, substantial increase in the surface temperature can be observed with multiple-pulse ablation. Heat accumulation is more prominent at high repetition rates (kHz or MHz) since the time between laser pulses is less than the time span long enough for the heat to diffuse away completely.

It is well known that material removal induced by femtosecond laser irradiation is a “cold” ablation, characterized by nonthermal material breakdown and rapid cooling after ablated species ejection. It is believed that there is no residual heat accumulation even at high repetition rate [64]. However, a recent study found that, for femtosecond laser ablation, it is the ambient gas plasma formed by highly ionized air that plays a key role in the residual thermal coupling [65]. Dependent on the laser fluence, fifty to hundred percent of the incident light can be stored in the bulk material as residual thermal energy immediately after the laser irradiation. Since the pulse interval at Mega Hertz repetition rate is in the nanosecond regime, the deposited thermal energy will not diffuse more than 1 μm . Therefore, I can assume that before the next pulse arrives the residual thermal energy is stored in a thin layer of material surrounding the ablated the cratered and will significantly increase the transient surface temperature.

Using an equivalent light intensity to represent the residual energy stored in the material surrounding the crater, I further investigate the surface temperature at higher repetition rates through an analytical solution of the linear heat equation describing the pulsed-laser irradiation of a substrate. The analytical expression for solving the surface temperature can be given as [66]:

$$\Delta T = \frac{I_a \omega_o^2 \tau_l}{4\sqrt{\pi k t (Dt)^{1/2}}} \quad \text{Eqn. 5-1}$$

where I_a is the laser-light intensity absorbed by the bulk silicon after the laser irradiated material removal (it stores in the bulk material as residual thermal energy), ω_o is the radius of the laser focal spot, τ_l is the pulse duration, k is the thermal conductivity and D is the heat diffusivity of the metal target.

The light-intensity, I_a , can be estimated by the residual energy coefficient and reflection during ablation.

$$I_a = K(1 - R)I_i \quad \text{Eqn. 5-2}$$

where, I_i is the incident light intensity, P is the average power of the incident laser pulse and R is the reflection coefficient during the ablation. Experiments revealed that K is around 0.45 for metals at a fluence around one order higher than the ablation fluence [65]. Since silicon has similar properties as metals, I assume that the silicon has the same K values as metals. A prior study showed that the reflection coefficient of silicon during femtosecond laser ablation is 0.393

at a wavelength of 488 nm and 0.329 at a wavelength of 800 nm [67]. Therefore, it is reasonable to assume that the R is around 0.3 at a wavelength of 1030 nm.

The incident light intensity, I_i , is calculated from laser power and repetition rate, r , which is the reciprocal of pulse interval, t .

$$I_i = \frac{4P}{\tau_i \pi \omega_o^2 r} \quad \text{Eqn. 5-3}$$

Substituting Eqn. 5-2 and 5.3 in 5.1, I simplify the equation to:

$$\Delta T = \frac{K(1-R)P}{\pi \sqrt{\pi k t} \left(\frac{D}{r} \right)^{1/2}} \quad \text{Eqn. 5-4}$$

Therefore, for this research, I substitute 14.7 W as the average power. At a room temperature of 300° K, the thermal conductivity, k , and thermal diffusivity, D , are 155 W/m.deg K and $8.5 \times 10^{-5} \text{ m}^2/\text{s}$, respectively [68]. The resultant surface temperature rise at various repetition rates calculated from Eqn. 5-4 is plotted in Figure 5-3. Due to the simplifications and assumptions, the calculated temperature rise is expected to contain a large error. The values presented are not sufficient enough for a quantitative study. Figure 5-3 shows that, under multiple-shot ablation, the residual surface temperature after laser irradiation increases with the increase of repetition rate. Therefore, I can deduce that at a low repetition rate, there will be no molten liquid silicon present in the ablated crater during the interval between two laser pulses. At a certain point, the repetition rate is high enough to maintain the surface temperature above the melting point of silicon. Therefore, a small amount of liquid phase is certain to be present at the wall of the ablated crater. The liquid layer allows the shockwaves to transmit and attribute to the

raised rims frozen on the inner wall of the ablated crater. In this experiment, the threshold-like repetition rate is found to be 13 MHz. As the repetition rate increases further, the surface temperature will eventually reach a critical point. Hence, no liquid phase of silicon will be expected in the ablated crater and no rims will be present. The laser system used in this experiment does not provide repetition rate above 26 MHz. Hence, I cannot verify this hypothesis for repetition rates higher than 26 MHz. Also, previous studies in this area have not observed such rims in ablated craters solely due to their inability to carry out experiments at high repetition rate laser systems. Therefore, this study sets up a paradigm for observations of shockwaves within the ablated craters at high repetition rate laser systems.

Figure 5-3: Surface temperature evaluation at increasing repetition rate

Moreover, it has been reported that the laser-induced plasma formation in the craters has greater electron number density and is at higher temperature compared to plasma produced on a flat surface. The larger the crater aspect ratio, the greater the plasma temperature and electron

number density in the crater [69, 70]. Thus, a combination of crater formation and ablation process generates the rims within the crater and not on the flat surface surrounding the entrance of the crater.

5.3.2 INTERACTION OF SUBSTRATE-SHOCKWAVES

Figure 5-4 illustrates the two distinct features of rims generated in the crater of a sample ablated at 13 MHz with a dwell time of 0.25 ms. *Bulgakov et al.* reported a similar study in which two types of shockwaves, primary and secondary shockwaves, were predicted through simulation and analysis [57]. When the fast propagating internal shockwave collides/reflects off of the slow propagating external shockwave, the sudden impact causes the external shockwave to grate the molten surface thus raising the primary rim. Similarly, the reflected internal shockwave begins to move towards the central ablation regime, compressing the hot air within the internal shockwave. The compression of hot air and internal shockwave interact with the molten surface and as a result secondary rims are formed. Multiple-times reflected internal shockwaves collide with one another forming the numerous secondary rims which have smaller amplitudes and line spacing than those of the primary rims [56]. Finally, these formations of rims are noted to grow in between the primary rims until their growth is arrested by the termination of laser pulses. Also, the evaporated particles ejected from the molten pool amalgamate and establish the spherical balls surrounding the crater and the entrance of the via. The phenomenon for the formation of spherical balls surrounding the craters was previously studied and reported in the earlier chapter.

Figure 5-4: Illustration of primary and secondary rims observed at 13 MHz, 0.25 ms

5.3.3 EFFECT OF PULSE WIDTH

Figure 5-5 illustrates the primary rim line spacing obtained at pulse widths of 330, 600, 1000, 2000 and 5000 fs at a repetition rate of 13 MHz. It is evident, that primary rim spacing increases with the increase of pulse duration. This is primarily due to the laser energy being absorbed by the free electrons during the interaction of short laser pulses with the substrate bulk. From the results presented in Figure 5-5, the rims spacings can be roughly classified into regimes. In the lower regime, when the pulse width in the region of 330 fs – 1000 fs, the rim spacing is around 0.6 μm , and the spacing increases slightly with the increase of pulse width. In the higher regime, when the pulse width is in the region of 1000 fs – 5000 fs or otherwise 1 ps – 5 ps, the rim spacing is around 1.1 μm , and the spacing decreases slightly with the increase of pulse width. This phenomenon can be explained by the fact that the laser ablation mechanism at a femtosecond pulse width is different from that at a picosecond pulse width.

Figure 5-5: Primary rim line width spacing at repetition rate of 13 MHz

The difference between picosecond and femtosecond ablation has been extensively studied in recent years and can be explained qualitatively by considering the laser-solid interaction [71]. Upon impact of a laser beam on the substrate, the electro-magnetic energy is converted into an electronic excitation and then into thermal energy. That is to say, the laser-solid interaction process is the excitation of electrons from their equilibrium states to excited states by absorption of photons. A quasi-equilibrium situation is established by electron-electron scattering on the time scale of about 10^{-13} s. At this stage, the electron temperature is much higher than the lattice temperature. Then the high temperature electrons cool off by means of emitting phonons and transferring considerable energy to the lattice on the time scale of about 10^{-12} s. After photon relaxation, the thermal diffusion from the surface to the bulk follows on the time scale of about 10^{-11} s, which can transfer the energy into the bulk. Successive processes are of a thermal nature. When sufficient amount of thermal energy is transferred into the bulk, attaining the melting temperature, transition from the solid to liquid state takes place. Therefore,

the time of lattice heating by electron-phonon scattering, which is in the scale of 10^{-12} s and the time of thermal diffusion, which is in the scale of 10^{-11} s in silicon, are important characteristics to better understand the experimental results shown in Figure 5-5 [72]. The time of laser heating the substrate depends on the laser pulse duration in the laser-solid interaction. Therefore, the laser pulse duration also plays an important role in the initial laser energy deposition on the substrates surface. In Ref [72], the time scale of energy relaxation processes with distinguished regimes of thermal and non-thermal ablation have been studied.

Mechanisms leading to structural modifications using picosecond and longer laser pulses are to be thermal ablation in nature, which means, they take place on timescales longer than 10^{-12} s. In contrast, femtosecond laser pulses open up non-thermal processes that take place on a timescale shorter than 10^{-12} s, i.e., before thermal processes takes in effect. In particular, with femtosecond laser pulses, ultra-fast phase transition and ablation can occur, which is considerably different from thermal process.

In this experiment, the laser pulse duration in the femtosecond pulse regime (330 fs to 1000 fs) is shorter than the lattice heating time [73]. The equilibrium between electron and lattice cannot be established during the laser irradiation period and even the heat diffusion is not sufficient to transfer the energy away from the surface. The deposited laser energy results directly in a solid-vapor transition, which is followed by a rapid expansion on the surface in a very short time interval. During this process, thermal diffusion into the bulk can be neglected due to the ultra-short duration. In essence, the laser ablation is a direct solid-vapor transition and the non-thermal ablation occurs. Thus, accumulation of heat and the vapor plume dissipate much

quicker with reduced melt recast. The quicker cooling effect restricts the primary rim to propagate further from the central melt regime, thus, leading to a smaller rim spacing at a shorter pulse width. However, in the case of the picosecond regime (2 ps to 5 ps), the phenomenon is inversed. There is enough time to establish equilibrium between electron and lattice. And as mentioned previously, thermal diffusion takes place on a time scale of 10^{-11} s and most of the deposited laser energy is transferred from the surface into the bulk material via thermal diffusion. The absorbed laser energy will heat the silicon surface. With successive pulses, the temperature of the silicon surface reaches its melting point gradually. The surface gradually melts and a molten layer develops on the surface. Subsequent irradiation makes the surface temperature reach the evaporation temperature and silicon is vaporized eventually. Hence, laser ablation in this case is accompanied by thermal diffusion and evaporation occurs from the molten layer. Therefore, heat accumulates much faster on the silicon surface, thus allowing the plume cloud to keep expanding. With the heat accompany, the primary rims in the picosecond regime propagate much further than the femtosecond regime, which explains the wider spacing of the primary rims in the picosecond regime.

In Figure 5-5, an increasing number of pulses (longer dwell time) is observed to have a smaller line spacing at a given pulse width. The earlier chapter reports that an increasing number of pulses has a substantial growth of the central ablation regime with smaller growth of crater width. Hence, with the aforementioned phenomenon of generation of rims within the crater, the propagation of the primary rim is stunted due to the smaller crater width.

Figure 5-6 illustrates the secondary rim line width spacing obtained at pulse widths of 330, 600, 1000, 2000 and 5000 fs at a repetition rate of 13 MHz. It is noticeable that the spacing of the secondary rim varies randomly. Unlike the primary rims spacing growth, the propagation of secondary rims is restricted due to the enveloping slow propagating external shockwave. Also, as mentioned previously, the internal shockwaves reflect back and forth within the vapor plume until the vapor plume expansion slows down. Thus, the labyrinth graphical representation explains the instability of the internal shockwaves within the engulfing plume [74].

Figure 5-6: Secondary rim line width spacing at repetition rate of 13 MHz

5.3.4 EFFECT OF LASER POWER

Figure 5-7a plots the primary rim spacing obtained at varying average power with a constant dwell time of 0.25 ms and pulse width of 330 fs at a repetition rate of 13 MHz. Observation of the line width was noted at every 1 W decrement from the highest average power of 14.7 W. The graphical representation indicates decreasing line width spacing with decreasing

average power. In essence, as the power delivered to the substrate is reduced, the pulse energy keeps dropping. With lower pulse energy, the substrate no longer melts. Therefore, with no melt regime, the induced shockwaves have no influence on the substrate's ablated crater surface in forming the rims. This elucidates the reason, below an average power of 11.6 W, the formation of rims were no longer observed and thus falling below a barrier for the formation of rims. Figures 5-7b and 5-7c compare the craters ablated at 14.7 W and 11.6 W with rims caused by shockwaves noticeable in craters ablated at 14.7 W but nothing in craters ablated at 11.6 W.

Figure 5-7: (a) Primary rim line width spacing at repetition rate of 13 MHz at varying power

Figure 5-7: Illustration of primary rim line observance at repetition rate of 13 MHz at a power of (b) 14.7W and (c) 11.6 W with a dwell time of 0.1 ms

5.3.5 EFFECT OF ASSISTED GAS

The effect of background gas during the ablation process is examined. Figure 5-8a and 5-8b give SEM images of the craters created in the ambient background air and forced helium assisted gas. Table 7 depicts the values obtained at the 13 MHz repetition rate with varying dwell times for both gases. It is noticeable, with helium gas, the primary rim line spacing is shorter than that compared to ambient background air. This is due to forced convection or cooling assist during the ablation. The expansion of the vapor plume is constricted due to cooler surrounding gas. This cooling process conducts heat away from the surface of the material thus reducing the accumulation of heat and restricting the propagation of shockwaves. Also, the forced helium assisted gas behind the external shockwave effectively decelerates the expansion of the vapor plume [75]. However, when the ablation process was repeated with the same parameters with ambient background gas, the primary rim line spacing is seen to have increased substantially. With no forced convection during the ablative process, the vapor plume expands faster and provides less momentum drag for the shockwaves generated, thus enabling a wider formation of primary rim spacing.

Figure 5-8: Samples ablated at 13 MHz with a dwell time of 0.5 ms with (a) helium assist and (b) normal background air respectively

Table 7: Samples ablated with different gas assist

Background Gas	Time [ms]	Primary Rim Width [μm]	Secondary Rim Width [μm]
Helium	0.10	1.418	0.342
Helium	0.25	0.646	0.215
Helium	0.50	0.563	0.139
Ambient Air	0.10	1.582	0.253
Ambient Air	0.25	1.468	0.177
Ambient Air	0.50	1.127	0.127

5.3.6 EFFECT OF POLARIZATION

Adopting various polarizations during the ablation process was also examined. Table 8 depicts the values obtained at 13 MHz repetition rate with varying dwell times with circular, linear (S), and elliptical polarizations. It is evident that rim spacing is the widest for circular polarization. However, from Figure 5-9a, b, and c, it is noticeable that adopting various polarizations also has an effect on the shape of the crater ablated. *Tomita et al.* reported a similar study with polarization-dependent surface wave formation [76]. Similarly, the rims formed within the crater take the shape of the crater ablated, which is directly attributed to the incident laser beam's polarization.

Table 8: Samples ablated with different polarization

Polarization	Time [ms]	Primary Rim Width [μm]
Circular	0.25	0.646
Circular	0.50	0.563
S	0.25	0.532
S	0.50	0.494
Elliptical	0.25	0.532
Elliptical	0.50	0.394

Figure 5-9: Samples ablated at 13 MHz with a dwell time of 0.25 ms with (a) circular, (b) linear (S) and (c) elliptical polarization respectively

5.4 SUMMARY

In this research, I observed rim patterns raised by shockwaves generated during laser ablation of silicon at Mega-Hertz pulse repetition rate and a laser fluence well above the ablation threshold of the substrate. The rim patterns are classified into two distinct regimes, primary and secondary rims. And the formation of primary rims and secondary rims is reported through the interaction of shockwaves with the ablated surface. It is shown that vapor plume and shockwave mechanisms play an integral role in rim formation. Furthermore, this chapter further analyzes the rim patterns raised by shockwaves through the changes in laser parameters such as pulse duration, repetition rate, dwell time, and pulse energy, which are seen to have significant effects in the rim spacing. Gas assist and polarization were also analyzed to substantiate any evidence of change in rim spacing but only to show that external effects had very little effect.

CHAPTER 6

CONCLUSION

6.1 CONCLUSION

The objective of this research was to find novel techniques in forming micro-vias when compared to the current techniques used in micro-via industries. The current demand for micro-via industries using current techniques such as mechanical drilling and laser drilling were studied along with the advantages and restrictions of each of these techniques. With the current demand of producing vias below sub-micron levels, mechanical drilling poses a huge problem by limiting the production of vias to 100 μm , due to damages to the drill bits below this size. Hence, lasers are being used for its myriad functions and capability of producing micro-vias for the current demand in the industries. And due to the increase in demand for micro-vias, the femtosecond laser drilling technique was researched for its capability of achieving micro-vias below the sub-micron levels with high surface and inner wall qualities for metallization, along with minimal thermal damage to the substrate, hence giving it durability and endurance. Especially, lasers offer the parameters of fluence, intensity, wavelength, and pulse duration, which afford control over essential aspects of material interaction.

Micro-via industries are currently equipped with nanosecond lasers for fabricating micro-vias for the current market demands. However due to the issues associated with a nanosecond laser, it is currently restraining the rapid growth of interconnect vias. Although the femtosecond laser has been studied in the recent times for their advantageous uses in this industry, it has not

been implemented due to its high cost and insufficient experimental studies. Hence, a thorough knowledge of the fundamentals of a number of different laser interaction involved in a laser ablation process is studied to precisely machine the desired outcome.

Therefore, for this research, a high repetition rate-fibre amplified femtosecond laser capable of delivering high power was used. Experimental setups were modeled for analyzing various studies within the scope of this research. Laser parameters such as fluence, intensity, wavelength, and pulse duration, were optimized to study the influence and effects upon the micro-via qualities. Thus, the experimental studies were carried out in unison with femtosecond laser studies to enhance and deliver results to satisfy the current demand.

This research work investigates the influence of the varying repetition rates on the via diameter, via depth and ablation rate. Varying repetition rates were also investigated on the quality of micro-vias produced within the sidewalls, amount of debris accumulated and the formation of via shape. The following outlined are some of the major findings of this research which were never been obtained in femtosecond studies:

- Ablation threshold required to initiate laser micromachining process in a silicon substrate was studied to help understand the process of laser ablation at high repetition rates.
- A smallest via of 8.39 μm wide at a repetition rate of 13 MHz with a dwell time of 100 μs and a highest depth of 121 μm at a repetition rate of 4.33 MHz with a dwell time of 1 ms were noted.
- Analysis of via qualities machined under various laser parameters showed exceptional top surface and sidewall qualities with minimal or no accumulation of debris.

delays, methods to use short vertical interconnects have been developed to replace the long interconnects found in 2D structures. This technology can demonstrate a low-cost fine via hole formation and highly reliable via filling processes. However, due to lack of studies in the area, it has not been implemented on a large scale. As a future work, studies in this area will surely find various applications in the micro-devices industries.

As future work, gas assisted ablation could be tested to help cool the substrate while machining. It has been proven in some cases where helium and nitrogen gases help improve the quality of via's. Therefore, gases such as Argon, hydrogen and neon can be tested to either help reduce the thermal accumulation during the ablation or have a chemical reaction with the substrate to enhance the qualities of the interconnect via's. Also, vacuum chambers can be used to ablate the substrates within to help reduce the airborne particles hindering the ablation process hence aiding in higher repeatability and cleaner vias.

Furthermore, a wavelength of 1030 nm was assumed for all experiments carried out during this research. However, as a future work, lower wavelengths can be tested with the aid of second harmonics and third harmonics to form thin film deposition or even 3D patterns for micro and nano-structuring.

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