Excimer laser machining of glass for high density substrate manufacture

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Metadata Record: https://dspace.lboro.ac.uk/2134/28103

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EXCIMER LASER MACHINING OF GLASS
FOR HIGH DENSITY SUBSTRATE MANUFACTURE

by

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PhD Thesis
Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

June 2009

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ABSTRACT

The widely growing market of miniaturized electronic devices demands for alternative substrate materials and manufacturing technologies on which fine pitch components can be mounted. Glass has been identified as a potential substrate material as it offers a number of advantages including a coefficient of thermal expansion closely matched to that of silicon that may reduce the thermo-mechanical stresses on the interconnects in the flip-chip assemblies. In addition to this, its dimensional stability and optically transparent nature facilitates alignment of multiple layer structures, enabling accurate drilling of microvias to capture pads and the potential for applications in optical interconnect.

Since glass is extremely brittle, micromachining of thin glass substrates to create vias and tracks is a significant challenge for which laser machining technologies offer a potential solution. This research work investigated the machining of microvias and tracks on thin CMZ glass sheets (100-50 μm thick) using an excimer laser operating at 248 nm. The effect of various process parameters including pulse energy, repetition rate and irradiation time were studied to optimise the machining. The process was optimised for 100 μm diameter microvias in 100 μm thick glass using a wide range of operating parameters. The through-hole drilling was successfully achieved at repetition rates as low as 20 Hz in 20 s. Through-hole microvias down to 40 μm entry hole diameter were successfully drilled in 50 μm thick glass. Subsequently machining of tracks (>200 μm wide) was optimised to achieve the desired depth of around 15 μm. The laser beam delivery system was characterised to understand the role of the individual optical elements to subsequently improve the laser beam profile and in turn the machining process. The attenuator device was successfully removed from the beam delivery system to increase the energy fluence at the work piece from 3 J/cm² to 4.5 J/cm² resulting in a minimum via taper of 14° with a 50 μm exit hole diameter for 100 μm microvias. Machined microvias and tracks were characterised using optical microscope and SEM analysis to investigate debris, recast layer and crack formation in machined features. Debris and recast layer formed around the microvias and tracks varied with process parameters. Debris was successfully reduced to a minimum level with a protective polymer layer coating on the glass,
however it was still difficult to remove recast formation. Microcracks were investigated in both tracks and microvias. Microcracks were found along the side walls in most microvias. While ablating tracks, microcracks were formed in unablated areas, mainly near the start and the finish of the tracks. Low fluence and high stage speeds caused unablated edges resulting in microcracks in that region.

Since defects such as debris, recast layer and microcracks were formed, and the stresses induced during the machining process reduced the strength of the glass, post treatments such as thermal annealing and tempering were investigated to try to minimise the internal stresses and improve the strength of the glass.

As reliability is an important issue in the substrate manufacture, machined glass was investigated for fatigue damage under three-point bend test and thermal cycling. Debris and recast formation affected the fatigue life of the glass and the thermal annealing treatment improved the fatigue life of the glass. No failure or additional damage was identified in any of the machined glass samples subjected to thermal cycling in the range of -20 °C to 125 °C for 500 cycles.

On the basis of the above investigation and optimisation of individual features, circuit patterns were machined suitable for double layer and single layer demonstrator devices.

**Keywords:** Glass substrates, Flip-Chip, Excimer laser, Glass machining, Microvia machining, Tracks machining, Microcracks, Debris, Recast formation.
ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr David Hutt and ex-supervisor Dr Karen Williams for their valuable guidance and support throughout my research study. I would also like to thank my second supervisor Prof Paul Conway for his kind support and guidance.

I am very grateful to the EPSRC for funding through the Innovative Electronics Manufacturing Research Centre (IeMRC) and for providing sufficient financial support to carry out this research. I would also like to acknowledge the collaboration of the industrial partners, GE Aviation Systems and Qioptiq for their technical support.

I also wish to thank Mr Peter Wileman for his valuable support and guidance in the laser system operation, together with Mr Andy Sandaver and Mr Jagpal Singh for their kind support and guidance during my experimental work.

I would like to thank my parents and in-laws who’s kind support made it easier for me to concentrate on my research study. Finally, I want to dedicate this PhD to my husband Mayur and little son Rishit, without their support this PhD would have been impossible.
PUBLICATION LIST

Conference Papers


Journal Papers


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2. Excimer laser machining of glass substrates for the manufacture of high density interconnect (Part I: machining of microvias).

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<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
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<tr>
<td>CSP</td>
<td>Chip Scale Package</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>DCA</td>
<td>Direct Chip Attach</td>
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<tr>
<td>DSC</td>
<td>Differential Scanning Calorimetry</td>
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<tr>
<td>FIB</td>
<td>Focussed Ion Beam Microscopy</td>
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<tr>
<td>FR-4</td>
<td>Fibre Reinforced composite, series 4</td>
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<tr>
<td>GMP</td>
<td>Gas-Microwave Plasma</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
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<tr>
<td>HDP</td>
<td>High Density Packaging</td>
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<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared light</td>
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<tr>
<td>I/Os</td>
<td>Inputs/Outputs</td>
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<td>LSI</td>
<td>Large Scale Integration</td>
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<td>MCM</td>
<td>Multi Chip Module</td>
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<tr>
<td>MOS</td>
<td>Metal Oxide Semiconductor</td>
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<tr>
<td>MSI</td>
<td>Medium Scale Integration</td>
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<tr>
<td>Nd:YAG</td>
<td>Neodymium Yttrium Aluminium Garnet solid state laser</td>
</tr>
<tr>
<td>PTH</td>
<td>Plated Through Holes</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PoP</td>
<td>Package on Package</td>
</tr>
<tr>
<td>PWB</td>
<td>Printed Wiring Board</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
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<tr>
<td>SiP</td>
<td>System in Package</td>
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<td>SoP</td>
<td>System on Package</td>
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<td>SoC</td>
<td>System on Chip</td>
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<td>SSI</td>
<td>Small Scale Integration</td>
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<tr>
<td>TAB</td>
<td>Tape Automated Bonding</td>
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<td>TMA</td>
<td>Thermo-mechanical Analysis</td>
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<td>TSV</td>
<td>Through Silicon Via</td>
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UV  Ultraviolet light
VLSI  Very Large Scale Integration
QFP  Quad Flat Pack
3D-ASSM  3D All Silicon System Module
SYMBOLS

d.o.f  Depth of focus
f  Frequency of the emitted photons
h  Planck's constant
I₀  Intensity of the laser light incident on the work piece
I  Moment of inertia
E  Young's Modulus
k  Boltzmann Constant
Kᵢ  Stress intensity factor
L  Gauge length
M  Bending Moment
Nᵢ  Population of the species in their lower energy state
Nᵢᵢ  Population of the species in their higher energy state
N.A.  Numerical Aperture
P  Applied load in the three point bending
T  Temperature
Tᵣ  Glass transition temperature
R  Reflectance of the laser light
α  Absorption coefficient
E  Photon energy of the emitted photons
η  Refractive index
λ  Wavelength of the emitted photons
μm  Micrometre
v  Speed of the emitted photons
π  Radians
Θ  Divergence of the laser beam
w₀  Spot size of the beam at the beam waist
w(z)  Spot size of the beam at the distance z from the beam waist
σ  Applied stress in the three point bending condition
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1 INTRODUCTION

The continuing trend in the miniaturisation of electronic devices demands for high density interconnection technology to reduce size, weight and cost of the package while also providing high processing speed and functionality. This can be achieved by increasing the level of silicon integration, which eliminates different packages for individual integrated circuits (ICs) and by using high density substrates. In miniaturised devices, flip-chip is a popular interconnection technology widely used for high density packaging systems both for the electronics and optoelectronics industry [1]. This is because both chip and substrate are directly bonded, which further enables fine pitch size, higher integration, efficient heat dissipation and effective self alignment. However, due to the direct bonding of the chip to the substrate, both are required to work at similar dimensional limits and tolerances. The relatively low cost manufacture and wafer bumping of semiconductor device I/Os even with extremely fine pitch size can be readily achieved, however the high volume production of substrates with matching features is still difficult with existing processes and materials [2]. To enable the further uptake of flip-chip interconnects, new materials and methods for high volume, high density substrate manufacture are required.

1.1 Limitations with Current Materials and Processes

With the advancement in chip scale electronics packaging systems, particularly flip-chip, substrate manufacturing processes are required to create fine features with high accuracy and dimensional tolerances to match with semiconductor die and provide reliable interconnection. The production of narrow copper tracks of the order of 50 μm width is relatively straight-forward, however, creating small size microvias and capture pads to produce fine pitches that can match semiconductor bondpad sizes is still a difficult process for high density substrates. The biggest challenge is in aligning the microvia holes with matching capture pads. Existing composite materials such as FR4 used for circuit boards possess limited dimensional stability, particularly for large panel sizes which further require the capture pads to be made significantly larger than the microvias.
to avoid breakout and this ultimately limits the overall pitch that can be achieved [3]. Since the semiconductor industry roadmaps predict further reductions in bondpad pitch and the move towards area array connections to reduce the die size, this will continue to present problems for substrate manufacture. Furthermore, currently used polymeric and composite substrates have a coefficient of thermal expansion (CTE) very different to that of silicon, causing a thermal mismatch and ultimately limiting the reliability of the flip chip interconnect.

With the increasing speed of the microprocessors, there is a growing demand for the use of optical waveguides within the PCB to replace electrical connections between components. At present, high rates of data transfer over electrical connections are limited by phenomena such as crosstalk, which can be overcome by using optical waveguides [4]. However, the integration of optical waveguides into substrates presents a range of challenges including material selection, combined optical and electrical design, and accurate alignment of light emitting and detecting devices. This requires substrate materials with superior optical properties and processing technology that promotes a high level of accuracy and reliability of interconnects.

1.2 Why Glass as a Substrate Material?

Glass has been identified as a potential substrate material which is able to meet the requirements of high density electrical interconnect and optoelectronics. Glass offers a number of advantages over conventional organic and composite substrate materials including:

- High dimensional stability that enables an accurate match to the features on the semiconductor chips.
- Since glass is optically transparent, it is possible to “view” capture pads and tracks during manufacture, which makes it possible to drill blind microvias accurately and inspect flip-chip devices. Not only this, alignment of multiple layers also becomes easier.
- Glass has high thermal stability, which makes it suitable for higher melting point lead free solders and harsh operating environments.
The thermal expansion coefficient of borosilicate glass closely matches with that of silicon (glass $3.5 \times 10^{-6} \text{ K}^{-1}$, silicon $2.8 \times 10^{-6} \text{ K}^{-1}$), which can potentially enable flip-chip attachment without the use of underfill and further reduce thermo-mechanical stress on flip-chip solder joints, thereby increasing the reliability of the interconnects.

Glass is optically transparent and hence can be used as a medium for transporting optical signals between devices within the same substrate for waveguide applications.

1.3 Overview of the Glass PCB Project

Glass substrate manufacture is a new emerging concept for electrical and optical interconnects [2, 5]. It involves using thin sheets of CMZ glass (a commercial grade with CTE similar to Si) of 100 µm thickness to build multilayer structures.

![Process route for the production of multilayer glass substrates.](#)
Fig 1.1 shows a potential process route for the manufacture of multilayer glass substrates. Glass sheets are laser machined to create features like microvias and fine tracks of the order of 50 µm to produce circuit patterns and subsequent metallization of these patterns using electroless and electroplating of copper/nickel is carried out. Further, multilayer laminates are then formed by a direct bonding technique with further machining and metallization steps. Optical waveguides can also be incorporated using such processes.

Glass laminates so formed are further mounted with components such as resistors, capacitors and transistors to form single or double layer devices or with flip chips to form electrical or optical interconnects. Figs 1.2 and 1.3 show schematic diagrams for such a device incorporating electrical and optical interconnects.

To investigate the above process, a research project was carried out which was aimed at investigating manufacturing processes for high density substrates using thin glass cover slips as a substrate material. This research project was EPSRC funded with collaborative industrial partners and was divided into three
individual research areas: laser machining of glass, metallisation of glass and lamination of glass sheets. Each area was undertaken by a PhD student.

1.4 Scope of the Thesis

Research work presented in this thesis is a part of the above mentioned project and focussed on laser machining of 50-100 μm thick sheets of glass to be used as a substrate material, using KrF excimer lasers. The main aim of this work was to optimise the process of machining microvias and tracks in the CMZ glass supplied by Qioptiq and investigate defects such as debris and microcracks.

This introduction chapter presented an overview of the whole Glass PCB Project. Chapters 2, 3 and 4 describe the literature survey carried out to investigate this research. Chapter 2 describes the current trends in electronics packaging and interconnection technology and various manufacturing processes used for microvia formation. Chapter 3 describes the micromachining of materials using excimer laser technology. The mechanism of laser generation, description of the excimer laser system, laser-material interaction behaviour and ablation mechanism with excimer laser is also discussed in this chapter. Chapter 4 discusses the general properties and structure of the glass, laser-glass interaction behaviour and laser ablation of glass. Further, research work related to laser micromachining of glass carried out by various authors is also covered.

Chapter 5 describes the methodology and experimental techniques used for this research. Chapters 6 and 7 describe the machining of microvias and tracks respectively. The effect of laser process parameters such as energy fluence, repetition rate, drilling time and stage speed on machining of these features is discussed and the process window for each of these features has been identified. Further, characterisation of machined features to investigate defects like debris, recast layer, microcrack formation and surface roughness of the machined features is presented.

Since microcracking is a major problem during machining, detailed investigation of microcracking is discussed in Chapter 8. To improve strength and reliability of the substrate, machined glass samples were subjected to post heat treatments, the initial results of which are also presented in this chapter. As
reliability is a major concern for substrates, two types of reliability tests, fatigue
cycling under three point bending and thermal cycling between -20 °C to 125 °C
were carried out for the machined glass samples. Chapter 9 describes the results of
these tests.

Chapter 10 covers the machining of different circuit patterns used for
developing single layer and double layer demonstrator patterns for electrical
interconnection. Finally, Chapter 11 gives conclusions drawn from the results
achieved in the current research and from which the scope of future work is
designed.

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Chapter 2: Electronics Packaging and Substrate Manufacture

2 ELECTRONICS PACKAGING AND SUBSTRATE MANUFACTURE

2.1 Introduction

In today's world, the electronics industry is considered one of the most important as it is a major driving force for science, technology, manufacturing and the overall world economy. Looking back in history, vacuum tubes were invented in the first half of the twentieth century which made possible the generation of electric waves that could be transmitted, detected and amplified enabling wireless communication [1, 2]. The foundation of electronics was led by the invention of the three electrode vacuum tube by Lee de Forest in 1906 and the further evolution in electronics continued in the second half of the century with the replacement of vacuum tubes with the transistor in 1947 and integrated circuit (IC) in 1958, leading to the great expansion of solid state electronics [1]. Initially, ICs were primarily based on bipolar transistors; however, since the mid 1970s, ICs were also composed of metal-oxide-silicon (MOS) field effect transistors as they reduced the size of the electronic device and offered high yield and low power dissipation. With further advancement in IC manufacturing technology, more transistors were incorporated into components leading to small scale integration (SSI), medium scale integration (MSI), large scale integration (LSI) and very large scale integration (VLSI) devices, which consist of more than $10^6$ transistors per chip.

This chapter discusses the different electronic packaging and interconnection technologies and current trends in miniaturisation and high density packaging. Since this research work focuses on flip chip interconnection, flip chip technology and reliability issues related to it are covered in detail. As discussed in the previous chapter, substrate materials and microvia formation technology play key roles for the reliability of the high density packages, so to highlight these issues, different electronic substrate materials and different microvia formation technologies currently used for electronics packaging are covered and the purpose of using glass as a substrate material and excimer laser technology for microvia formation is justified further.
2.2 What is Electronic Packaging?

Electronic packaging involves anything from discrete ICs and other components such as resistors, capacitors, and inductors to the entire electronic system. It encompasses four key functions in electronics: (1) Power distribution, (2) Signal distribution (3) Thermal management-Heat dissipation (4) Package Protection [3].

Packaging technology bridges the gap between the semiconductor manufacturer and PCB manufacturer. With time, different packaging technologies have evolved with the aim to improve speed, density and the functionality of the packages [4]. Fig 2.1 shows the typical microelectronic package, which consists of two or three levels of packaging hierarchy. In general, the IC chips, logic and memory are connected to the first level module packages by wire bond, flip chip and tape automated bonding (TAB) technology and further, this packaged device is attached either directly to a printed wiring board (PWB) or to another kind of substrate which is denoted as a second level of packaging. Alternatively, the packaged device can also be directly assembled to an intermediate vehicle such as hybrid circuit or multichip module [5].

![Diagram of microelectronic packaging hierarchy](image)
2.2.1 High Density Interconnections and Miniaturisation

Allan [6] has reported the trend in miniaturisation and high density packaging from conventional wire bond technology to current 3D packaging systems with evolution of new technologies and processes for system packaging. Fig 2.2 shows the miniaturisation trend from Quad Flat Packs (QFP) to Ball Grid Array (BGA), Chip Scale Package (CSP) and further package reduction with 3D integration.

Fig 2.2 Trends in miniaturisation [6].

With the increasing trend of miniaturisation in electronic devices, Chip Scale Packaging (CSP) and Direct Chip Attach (DCA) technologies play an important role, since they offer high functionality in a small area. Traditional CSP is defined as 1.2x die size, however nowadays 0.5 mm to 0.8 mm pitch ball grid array is also regarded as a CSP package. In Direct Chip Attach (DCA) as the name suggests, the chip is directly attached to the board or MCM [7].
Chapter 2: Electronics Packaging and Substrate Manufacture

With reduction in electronic package size, the requirement for high density interconnection increases and hence the chip and the board need to stack on top of each other in a 3D form. Wafer-level, SiP and PoP methodologies combined with Through Silicon Via (TSV) interconnection technology all together help to overcome IC miniaturisation challenges.

2.2.2 Current trends in packaging and interconnection technology

The trend in the miniaturisation of packaging systems has been an ongoing process for many decades. The increase in package level integration involves more challenges for electronics manufacturers. The electronic systems in today's world are primarily discrete systems performing various functions like computers for data computations, telecommunications and portable consumable products with audio, video and other functions. There is a new emerging trend for systems named as convergent systems which is characterised by the convergence of all the above product functions into one product. The next generation convergent systems include electronic products such as smart watches with cell phone, global positioning system (GPS), sensor and webmail access, and smart medical implants with wireless communication, sensing and imaging characteristics. There are four main approaches for these convergent systems, such as System on Chip (SoC), System in Package (SiP), System on Package (SoP) and Multi Chip Module (MCM) [8]. Fig 2.3 illustrates all four approaches as reported by Tummala [8].

2.2.2.1 System on Chip (SoC)

In SoC multiple function "systems" (digital, analog, mixed signal, radio-frequency functions) are all placed on one chip. This cuts the development cycle and increases the product functionality. However, chip designs and build cycles are long and require multiple passes to complete.

2.2.2.2 System in Package (SiP)

SiP consists of more than one IC in a single package. SiP can contain several chips such as a specialized processor, DRAM, Flash memory, combined with passive components such as resistors and capacitors all mounted on the same substrate. SiP technology can involve stacking of packaged ICs by traditional wire
bond, TAB or flip-chip technologies or stacking by through silicon vias (TSV) without using wire bond or flip-chip [9]. Fig 2.4 shows these categories for a 3D stacked package.

**Through Silicon Via Technology (TSV)**

Through Silicon Via (TSV) is a 3D packaging technology for semiconductor system integration in which three dimensional wafer/chip stacking is accomplished by vertical interconnection with through silicon vias rather than flip chip and wire bonding techniques. The concept of TSV has gained more importance recently through the development of important technologies such as deep silicon etching, wafer thinning and wafer/chip bonding that enabled the integration of highly complex systems efficiently [10-12].

TSV can be used for wafer stacking and chip stacking. Wafer stacking technology is based on complete wafer fabrication and bonding, for which the size of each wafer and chip are required to be the same to achieve alignment of multiple levels. Chip Stacking is a hybrid technology that involves through-via fabrication
by wafer processing and chip stacking and allows heterogeneous integration such as different size of substrates, wafer and dies [12-14]. However, challenges are still involved with the cost and reliability issues for TSV and stacked packages.

2.2.2.3 Multi Chip Module (MCM)

Multichip module is another highly sophisticated on-chip integration technique in which multiple integrated circuits, semiconductors and other modules are packaged to form a single device. Depending on the type of substrate used to support and interconnect the die, they are categorised as MCM-C (Ceramic substrate), MCM-L (multilayer laminated PCB substrate), MCM-D (deposition of the module on the substrate by thin film technology) [5].
2.2.2.4 System on Package (SoP)

System on Package (SoP) is the emerging technology, developed in the mid 1990s in the Packaging Research Centre at Georgia Institute of Technology, in which the entire system is placed on a single flip-chip size package with all needed system functions. SoC, SiP, thermal structures and batteries are considered as subset technologies of the SoP. It overcomes both fundamental and integration shortcomings of SoC, SiP and MCM that are limited by CMOS processing and cost, performance, size and reliability issues of current packaging systems [9].

2.2.3 Different interconnection technologies

The size and reliability of the package is significantly influenced by the interconnection technology used for it. There are four chip to package interconnection technologies used in the industry (fig 2.5): (1) tape automated bonding (2) beam lead (3) wire bond (4) flip chip, which are discussed briefly below.

Tape automated bonding (TAB) is a low cost high volume production process which uses automated gang bonding of inner and outer leads. This process is cheaper and faster than other processes and can produce reliable interconnections [1].

In beam lead technology, beam shaped wires of gold, known as beam leads are electroformed in the kerf region between two chips. Initially, a wafer is thinned by chemical etching and individual chips are then separated by etching the silicon kerf regions on the back side of the chips. The beam leaded chips are then gang bonded to substrates face down by a thermocompression joining method. Although this method produces reliable interconnection it is not popular since it is not compatible with the multilevel wiring on chips and also involves long and expensive wafer thinning and chip separation processes [15].

Wire bonded chip interconnection is done in two steps. In the first step, the back side of the chip is mechanically attached to either a lead frame paddle or to the die attached area of a substrate (ceramic or plastic) so if required, electrical connections can be made on the back side of the chip. In the second step, the bond pads on the circuit side of the chip are electrically interconnected to the lead frame.
or substrate by wire bonding. Wire bonding can be accomplished either by thermosonic or thermo compression ball-wedge processes using gold wire, or ultrasonic wedge-to-wedge process using either gold or aluminium wire.

Flip-chip bonding makes it possible to interconnect the chip and substrate directly face to face, enabling high density interconnection. Due to the direct bonding, the required volume for interconnection is reduced and also fewer connections are required. However, solder joint reliability is the major issue due to large thermal mismatch between organic substrate materials and silicon chips. Development of different processes using alternative substrate materials are underway to overcome these drawbacks [1, 16] and are discussed below.

**2.3 Flip Chip Technology**

In flip-chip technology, the chip is directly bonded to the substrate through a conductive bump with the chip surface facing towards the substrate. It is a leading technology for interconnection which offers high density packaging with high functionality and low cost.
Fig 2.6 shows a schematic diagram of a flip-chip interconnect with direct attachment of the silicon chip to the substrate through solder bumps. Other methods of attachment include thermo-compression, thermo-ultrasonic bonding and adhesive technologies [1]. Since the solder bump interconnection is very small, fatigue strains are easily developed during normal operation of the chip resulting in failure of the interconnection. Hence the air gap between chip and substrate is filled with an adhesive (underfill) that will reduce the overall stress and increase the life of the solder joint.

2.3.1 Flip-chip interconnection reliability issues

Various factors can cause failure of the flip-chip interconnects. However, the major cause is due to thermal mismatch between the chip and the substrate material which can result in failure at solder joints or cracking in microvias and substrate. Chip size also affects the reliability of the solder joint; fatigue life of the solder joint decreases with increase in chip size, which is due to increase in the shear stress with increase in edge dimension caused by larger expansion mismatch near the corners of the die. Flip-chip failure can also occur if the underfill is not applied correctly, which causes formation of voids and defects that further reduces the thermal cycle life of the interconnect. Solder joint geometry and composition along with interface metallurgy also affects the reliability of the interconnect [1].

Thermal mismatch is the major problem in flip chip assemblies of the current FR-4 series and organic substrates [17]. As reported by Lau [4], the thermal expansion coefficients for FR-4, silicon chip and solder bump are 18.5x10^{-6} K^{-1}, 2.8x10^{-6} K^{-1} and 21x10^{-6} K^{-1} respectively. This causes distortion of the flip chip assembly which further induces stresses on the corner edges of the solder joint. Fig 2.7 shows a schematic view of the deformation of solder joints in a flip-chip interconnected with an FR-4 substrate [18].

Due to local thermal expansion mismatch, stress concentration occurs at the corners of the solder bump. When such a distorted structure is subjected to a fatigue or thermal cycling load, it will cause rapid failure of the interconnect. Fig 2.8 illustrates the schematic model of solder joint failure due to deformation caused by thermal mismatch in the flip chip assembly.
Deformation or distortion due to thermal mismatch can be avoided using an underfill material. The underfill material that typically consists of an epoxy, filler, and anhydride hardener is placed around the edges of a flip-chip device and allowed to flow inside the space between the planar surface of the die and the substrate on which it is mounted. Underfill is mainly used to protect the die face from contamination and to provide structural strength to the interconnection by holding the chip and substrate. This helps in reducing stress concentration associated with the corner solder joints since the elastic modulus and coefficient of thermal expansion of the underfill (30 x10^{-6} K^{-1}) closely matches with that of the solder bump (21x10^{-6} K^{-1}), which enables them to act as a single-phase material between the chip and the substrate. Underfill can improve fatigue life by upto 20 times more than the unfilled interconnect [1, 4]. However, the underfill material applied should be free of defects or voids. Proper curing of material and the complete filling of the gap are the two major factors when using underfills.
Using alternative substrate materials and manufacturing process routes can overcome some of the drawbacks experienced with the current methods and substrate materials. The next section deals with the basic processes and materials involved in the manufacture of the substrates.

2.3.2 Substrate materials

Selection of substrate material is an important criteria to get high functionality and reliability of the interconnects. The need for higher frequencies and better functionality on the chips demands for high performance, high density, high Inputs/Outputs (I/Os) and low cost packaging systems/interconnects. For this, a substrate material requires the following properties [4, 18]:

- Low dielectric constant and high dielectric strength.
- Low moisture absorption, low dissipation factor.
- Low thermal expansion coefficient with high glass transition temperature, high thermal conductivity.
- High dimensional stability, good solvent resistance and chemical resistance and low flammability.
- Should be able to achieve good adhesion of the copper film.

For flip-chips, three kinds of substrates: organic, inorganic and composite laminate substrates are currently used. In inorganic materials, mainly ceramics are used. Ceramic is quite appropriate for flip chips considering reliability issues, since its thermal expansion coefficient is low and it has high thermal stability compared to organic substrates. However, alumina substrates have large coefficient of thermal expansion compared to silicon, which induces shear stresses causing failure of the flip chip, and require underfill to minimise stresses induced by thermal mismatch. Charles [1] has reported failure of solder joint assemblies after 1000 thermal cycles in one such flip chip interconnect using alumina substrate without underfill. Use of ceramic substrates has also not widely spread in recent years due to the high cost involved [1].

Organic substrates are used widely due to low cost, and also because they are available both in rigid or flexible form depending upon the application. The polyimide class of materials are widely used as a substrate material. Most of the
polyimide substrates are composed of aromatic diamine and dianhydride, substitutes of which can be changed to obtain a wide variety of properties. However, only a few of them such as Kapton are used for high temperature applications. The coefficient of thermal expansion of organic substrates is very different to that of silicon. In the case of polyimide during thermal cycling, expansion of the substrate is accommodated by stretching out and bending of joints [17]. Fig 2.8 illustrates the bending of a flip-chip assembly that commonly occurs with organic substrates.

![Diagram of Warpage during cool down of thermal cycling](image)

Fig 2.8 Warpage during cool down of thermal cycling, due to CTE thermal mismatch in organic substrates [19].

FR-4 is a fibre reinforced material composed of multiple plies of woven glass cloth impregnated with polyfunctional epoxy resin. Since its mechanical and physical properties satisfy the need for most of the electronic products, it is widely used. Other FR series materials include FR-2, FR-3, FR-5 with different fibre matrix composition. However, without underfill, the FR series material does not form reliable interconnection with silicon chips due to large mismatch of coefficient of thermal expansion and poor dimensional stability.

Since properties of most materials listed above are still not suitable enough to enable high density interconnects, there is a need for alternatives. As mentioned in the introduction chapter, glass has almost all the properties which make it suitable as a substrate material for high density interconnects. Table 2.1 compares the properties of commonly used substrate materials with silicon and glass. Silicon as a substrate material is an attractive option for the package substrates. Recently, a novel approach of 3D All Silicon System Module (3D-ASSM) has been proposed by a Global Industrial-Academic consortium of Georgia Tech, Fraunhofer IZM (Germany) and KAIST (Korea) which focuses on the miniaturisation of the entire
system using silicon for ICs, packages and boards [20]. However, silicon is not optically transparent and is also electrically conductive.

In addition to the selection of a suitable substrate material for high density interconnect, advanced manufacturing processes are also required, which can accurately form small size features of the order of 50-100 μm such as smaller diameter microvias with fine pitch and very narrow conductive tracks [22]. The production of copper tracks is relatively straightforward, however, creating fine pitch microvias and in particular microvia in pad architectures at the pitches matching those of the semiconductor bondpads is a difficult process [23]. Pitch sizes of the order of 100 μm with microvias of around 50 μm and aspect ratios of 1 are currently used for chip scale packages (CSP) and flip chip area array packages. The IC package road map predicts more complex board designs with finer microvias and pitch sizes as small as 0.7 mm [24]. This requires substrate manufacturing processes, especially microvia formation technology, which can enable drilling of small size microvias with fine pitch size at low cost in high volume. The following section discusses the various microvia formation processes used, reliability issues and the road map of microvia technology.

Table 2.1. Properties of currently used substrate materials and silicon compared with glass [1,4,21].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Silicon (borosilicate)</th>
<th>Glass</th>
<th>FR-4</th>
<th>Alumina</th>
<th>Polyimide</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE (x10^-6 K^-1)</td>
<td>2.8</td>
<td>3.3</td>
<td>18.5</td>
<td>8.1</td>
<td>55</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>94</td>
<td>70</td>
<td>22</td>
<td>300</td>
<td>3.2</td>
</tr>
<tr>
<td>Glass Transition Temperature(T_g) (°C)</td>
<td>500-600</td>
<td>130-170</td>
<td>1700-1750</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>11.8</td>
<td>4.6</td>
<td>4.3-4.7</td>
<td>9.0-9.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>0.2</td>
<td>0.28</td>
<td>0.21</td>
<td>0.35</td>
</tr>
</tbody>
</table>
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2.4 Microvia Formation

The relatively low cost manufacture and wafer bumping of semiconductor devices with high I/O counts and fine bump pitch are readily achieved, but the production of high volumes of substrates with matching feature sizes to support them is problematic [25, 26]. Therefore, microvia formation in the substrates plays a significant role in the substrate manufacturing process. In general, vias are the holes drilled in substrates with subsequent plating to connect different layers. Vias are divided into three types: Blind vias, Buried vias, Through vias as shown in fig 2.9.

![Vias in multi-layer PCBs](image)

**Blind Vias** – Blind vias are located on the outer layers of the circuit board to make contact with the inner layers.

**Buried Vias** - Buried vias are holes plated within the core of the circuit board without access to the surface on either side of the board.

**Through Vias** – Through vias cross the entire thickness of the board and are used as interconnect or mounting locations for electronic components.

The purpose of microvias is similar to conventional vias, except that the hole diameter is in the range of 50 to 300 μm. Microvias offer many advantages over conventional drilled holes in substrate materials [4]:

1. Very small via sizes enable higher pitch density and so higher interconnect density, which reduces the size and weight of the board and hence reduces the overall cost of the substrate/PCB.
2. Accommodates more chips in a smaller area of the substrate and enables high density packaging.
Electrical performance is improved due to the smaller via length and diameter. The inductance is reduced due to the shorter pathway of the plated through hole.

Microvia size and aspect ratio are the important parameters during the microvia formation process as they affect the reliability of the interconnect. Several processes are used for creating microvias with different capabilities in terms of size and aspect ratio (ratio of substrate thickness to hole diameter), which are discussed in the following sections.

2.4.1 Commercially used processes for drilling of microvias

There are five major processes used for fabrication of microvias [4, 27]:

1. Mechanical drilling
2. Laser via ablation using CO\textsubscript{2} laser, Nd:YAG laser, and Excimer laser
3. Photo-defined vias
4. Chemical etching
5. Plasma etching

The main commercial processes are: Chemical Etching, Photoimaging and Laser drilling [27].

2.4.1.1 Mechanical drilling

This is the most common process for generating holes on PCBs for holes of diameter \( \geq 200 \text{ \mu m} \). In general this process is more suitable for via drilling, however using innovative technologies of high speed spindle and numerical control can enable microvia drilling with the above size limit. As such the thickness of the dielectric is not important for through hole vias, but for drilling blind vias, the dielectric thickness is required to be above \( 50 \text{ \mu m} \). Microvias formed by this method are of a cylindrical shape. This method is appropriate for polymers and composites, but for hard materials like ceramics and glasses it is difficult since it causes cracking and chipping of the material [16].

2.4.1.2 Laser drilling

In this process holes are created by a high power laser beam leading to features as small as \( 50 \text{ \mu m} \). Laser drilling is compatible with both copper-clad or
unclad dielectrics, and reinforced or non reinforced substrates. It can be used for both blind vias and through holes. The main difficulty is the low production rate. Excimer, CO₂ and Nd:YAG lasers are used commercially for microvias [27].

2.4.1.3 **Photo defined microvias**

In this method microvias are produced using a modified liquid photoimageable dielectric (PID). The PID is applied onto the substrate as either a liquid or dry film followed by exposure to ultraviolet light through a mask, which after development leaves microvias that can be further filled with conductive ink and cured. Multilayer PCBs can be formed by repeating the process in the same manner on a thin dielectric layer. This technique is restricted to photoimageable dielectric materials only but is used for mass production [28].

2.4.1.4 **Chemical etching**

In this process a photoresist film is applied to the substrate material and patterned to create a series of openings. These then act as a mask in the subsequent chemical etching process producing microvias. As reported by Lau [4], hot KOH solution has been used as an etchant for the polyamide films. This technique is a mass production technique as all vias are formed at the same time regardless of number and diameter. This process is mainly suitable for blind vias.

2.4.1.5 **Plasma etching**

This process is also known as dry etching and has been used in the semiconductor industry for producing very fine features and is now being used for microvia formation in PCBs. In this process, base material is usually copper clad dielectric, where the copper layer acts as a mask for plasma ablation and is photochemically patterned by conventional techniques used in PCB manufacture. After this, gas-microwave plasma (GMP), which has been promoted by Dyconex of Switzerland, is used for microvia formation. This technique is also used for mass production as all microvias are formed simultaneously. Plasma etching can also remove organic contaminants and minimise undercuts in the holes with careful conditioning.
2.4.2 Comparing different microvia technologies

Different methods used for microvia formation have their own advantages and disadvantages; for example, photo defined and plasma etching methods are suitable for mass production, but these processes are limited by via size, dielectric thickness and dielectric material. Plasma etched microvias are likely to have undercuts. In contrast to this, laser drilling offers good quality and smaller size down to 50 μm or less, but involves high equipment cost and low drilling rates. Lau [16] has illustrated cross section images of microvias drilled with three different processes: plasma etched, photo defined and laser drilled.

![Diagram of microvia formation processes](image)

Fig 2.10 Range of microvia size formed by different microvia technology [16].

Today most electronics manufacturers use laser technology for microvia formation since it enables the formation of small size features with accurate positioning and high reliability compared to other methods. Fig 2.10 shows schematically the range of microvia sizes produced by different methods [4]. It can be seen that excimer lasers can produce fine size microvias down to 10 μm.
Nd:YAG lasers are also capable of producing microvias of the order of 50 μm and above, however the size of microvias drilled is limited to a narrow range. Photo defined and plasma etched microvias are produced over a wide range of diameter, but are not capable of producing very fine size microvias. Table 2.2 compares different features such as via size, aspect ratio, dielectric thickness requirement, geometry and surface morphology of microvias and machining rates of all these processes for fibre reinforced epoxy materials.

Table 2.2 Comparing features of different microvia formation technology for fibre reinforced epoxy materials [24, 30, 31, 18].

<table>
<thead>
<tr>
<th>Factor</th>
<th>Excimer Laser</th>
<th>Nd:YAG Laser</th>
<th>CO₂ Laser</th>
<th>NC Drilling</th>
<th>Photo Via</th>
<th>Plasma Etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. via size (μm)</td>
<td>2.5-100</td>
<td>25-50</td>
<td>300</td>
<td>200</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Laser wave length</td>
<td>157-308 nm</td>
<td>266 nm, 355 nm</td>
<td>10.6 μm</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>Approx. 1:1 to 2:1</td>
<td>~1:1</td>
<td>~1:1</td>
<td>10:1</td>
<td>0.5:1</td>
<td>0.5:1</td>
</tr>
<tr>
<td>Dielectric thickness</td>
<td>Important</td>
<td>Not so important</td>
<td>Important</td>
<td>Not so important</td>
<td>Very important</td>
<td>Very Important</td>
</tr>
<tr>
<td>Machining rate</td>
<td>600 vias/min</td>
<td>4500 vias/min</td>
<td>8500 vias/min</td>
<td>Limited by sequential drilling</td>
<td>All vias etch at same time</td>
<td>All vias etch at same time</td>
</tr>
<tr>
<td>Via is clean after process</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Via shape</td>
<td>Taper</td>
<td>Taper</td>
<td>Taper</td>
<td>Cylindrical</td>
<td>Taper</td>
<td>Taper</td>
</tr>
<tr>
<td>Special Needs</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

2.4.2.1 Microvia drilling using laser technology

The importance of laser technology for microvia drilling has increased in recent years with the current trends towards high density interconnection. As such, different lasers can be used depending on the type of substrate material; however, CO₂, Nd:YAG and excimer lasers are commonly used for micromachining of most materials. CO₂ lasers can operate in both continuous and pulsed mode, while the latter two systems give out pulsed laser light [32]. The CO₂ laser is the most widely used industrial laser as it offers high etch rates for via drilling, which makes it suitable for high volume production. However, as it operates at infrared
wavelengths, it is unable to produce high peak powers making it unsuitable to machine highly reflective and hard materials. Due to the longer wavelengths, the CO₂ laser also produces thermal damage around the machined features. The Nd:YAG laser after frequency tripling and frequency quadrupling can be used for machining most materials as it operates in the UV range and is suitable for rapid prototyping work. Due to the shorter wavelength it can drill through-holes in hard materials like glass, ceramics and metals like copper. However, it cannot offer etching rates as high as CO₂ lasers. The excimer laser also operates in the UV range and can drill features as small as 10 μm. It uses a mask projection technique which enables it to drill features with desired shape and size with high accuracy and also produces minimum thermal damage. The biggest drawback for this technique is the cost involved and etch rates are still lower than CO₂ and Nd:YAG lasers [33]. Overall, the Nd:YAG laser is a versatile microvia drilling tool used in most industries for high density interconnects since the operating cost is low compared to excimer lasers.

2.4.3 Reliability issues with microvia formation for high density interconnect

With the decrease in microvia size and pitch, reliability becomes a major concern for high density interconnects. Reliability of microvias depends on several factors such as the quality and geometry of the microvias, microvia size and aspect ratio, sidewall profile and the condition of microvias after drilling (cleaned or uncleaned). For reliable interconnection, microvias are required to be absolutely clean with no residue inside and should have smooth side walls without undercut and no perforation of inner layers [27]. Fig 2.11 demonstrates the various failure mechanisms in blind and through vias, which have been reported by several authors [34]. Defects like flaws and voids along the side walls can cause poor adhesion of the metallised layer, which further results in failure of the interconnect under repeated cyclic loading or thermal cycling conditions. Inappropriate geometry of the microvia can cause non-uniform thickness of plating across the microvia with subsequent failure. Joshi [35] has reported failure analysis of several microvias prepared using photo lithography, Nd:YAG and CO₂ lasers, in fibre reinforced laminates. According to this work, cleaning had a major impact on microvia
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reliability. Another important issue is stress concentration at the microvia-pad interface, which promotes crack initiation. Knadle [36] has also reported failure mechanisms in laminate substrates. He identified barrel cracks in plated through holes (PTHs), separation of the base in blind holes and at the microvia-pad interface.

![Fig 2.11 Different kind of failures of microvias in laminate substrates.](image)

2.4.3.1 Microvia Technology Roadmap

The advancement in electronics system integration and packaging involves great challenges for PCB manufacturers. High demand for array type components such as BGA, CSPs and flip-chip drive the need for creating smaller size microvias along with fine conductive lines on tight grids [37]. Improvements in existing processes and development of new microvia technology is necessary for further uptake of high density interconnects. Table 2.4 demonstrates the current and future trends in blind microvia formation [7].

Such small microvia size and pitch can be enabled using laser drilling technology and as a result, laser microvia drilling has taken hold of almost 75% of the world market since it is a cost effective process for high density interconnects.

<table>
<thead>
<tr>
<th>Table 2.4 Trends in blind via formation [7].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Via Size (μm)</td>
</tr>
<tr>
<td>Via Pitch (μm)</td>
</tr>
<tr>
<td>Blind Via Aspect Ratio</td>
</tr>
</tbody>
</table>
2.5 Summary

The road map for high density packaging technology further predicts a
decrease in the sizes of microvias and capture pads down to $\leq 80 \mu m$ with pitch
sizes of the order of $125 \mu m$. This involves great challenges for the substrate
manufacturers to produce reliable interconnects, since current substrate materials
are not capable to meet these requirements. Glass is a potential material to produce
high density substrates as it offers many advantages over the FR series and organic
substrates when the appropriate manufacturing process is applied. Since the
excimer laser can drill small diameter microvias with high positional accuracy and
tolerances with minimum thermal damage it is an appropriate tool for
manufacturing substrates for high density flip-chip interconnects [38].

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3 EXCIMER LASER MICROMACHINING

3.1 Introduction

Laser technology has played a leading role in the advancement of science and technology. Specifically lasers for material processing have truly brought a revolution in the microelectronics industry by replacing conventional substrate manufacturing technology. The ability of lasers to deliver high power in a small localised area made possible the fabrication of small scale features. Since it is possible to machine features down to $\leq 50 \, \mu m$ accurately with lasers, it is widely used for micromachining applications [1]. Laser microvia drilling technology has increasingly gained importance with subsequent reduction in chip size. As discussed in the previous chapters, three lasers are commonly used for via drilling: excimer lasers, TEA CO$_2$ lasers and Nd:YAG lasers. Due to the low cost of production, CO$_2$ and Nd:YAG are extensively used for manufacturing of conventional laminate materials like polyimide and FR4, but for hard materials like glass and ceramics, excimer laser can be used more efficiently. Since it operates in the ultraviolet range (351 nm-157 nm) and uses a mask projection technique, the excimer can produce extremely small features with desired shape and high accuracy [2]. This ability makes it potentially useful for manufacturing high density interconnects with fine pitch size and fine line circuitry and for creating waveguides and 3D structures. In addition, due to its flat top beam profile it is also suitable for a broad range of applications such as surface structuring, annealing and deposition [3].

This chapter reviews micromachining in different materials and its mechanism using excimer laser technology. The general concept of laser generation and the laser generation in an excimer laser is described. Furthermore the basic set-up of the excimer laser system, laser-material interaction behaviour and ablation mechanism with excimer laser is discussed in detail.
3.2 Concept of Laser Generation

Laser stands for light amplification by stimulated emission of radiation. The general set up of a laser consists of two mirrors, one fully reflecting and one partially reflecting which form an optical cavity, which contains an active medium, that may be solid, liquid or gas (fig 3.1). When energy is applied by an external source such as electrical current or flash lamp, atoms, ions or molecules are excited from the ground state (E_L) to a higher energy level (E_H) (fig 3.2a). Some of the excited molecules spontaneously drop back to the ground state emitting a photon with frequency \( f \), referred to as spontaneous emission. The photon so produced, can interact with the excited state of another species and causes it to drop down to the ground state emitting a photon of the same frequency \( f \), which is referred to as stimulated emission. The photons of the same frequency, \( f \), so produced are reflected back and forth to create a chain reaction that causes generation of coherent laser light.

![Fig 3.1 Schematic view of a laser cavity and laser generation.](image)

The photon energy of the emitted photon is given by the Planck equation:

\[
\Delta E = hf
\]

where \( h \) is Planck's constant, \( 6.625 \times 10^{-34} \) J-sec, \( f \) is the frequency of the emitted photon and \( \Delta E \) is the photon energy which is equal to the energy gap \( (E_H-E_L) \).

The frequency of the emitted photon is given by:

\[
f = \frac{c}{\lambda}
\]
where $v$ is the speed of electromagnetic waves in air and $\lambda$ is the wavelength of the electromagnetic radiation. The wavelength of the emitted photons can therefore be written as:

$$\lambda = \frac{h v}{E_H - E_L}$$  \hspace{1cm} (3.3)

Light amplification only takes place when the number of molecules in the excited state is higher than in the ground state. This is known as a population inversion. The ratio of the population of species in these levels can be obtained from the Maxwell-Boltzmann distribution, which is given by equation 3.4 [4].

$$\frac{N_H}{N_L} = \exp \left( \frac{(E_L - E_H)}{kT} \right)$$  \hspace{1cm} (3.4)

where $N_L$ and $N_H$ are the population in the lower and higher energy states respectively, $k$ is the Boltzmann Constant ($1.4 \times 10^{-23}$ Joules/Kelvin), $T$ is the temperature, $E_L$ and $E_H$ are the energy levels of the lower and higher energy states respectively.

For a simple laser system, the transition takes place directly between the ground state and excited state. Fig 3.2a shows the schematic presentation of a two level system in which the transition takes place between the ground state ($E_1$) and the excited state ($E_2$). However, in this situation it is impossible to get amplification as the excited species emits radiation easily and their number approaches that of the species in the ground state such that no further transition takes place. As a result, most of the lasers for commercial purposes are three level and four level systems.

As shown in fig (3.2b) in a three level system, excitation is achieved by pumping species from $E_1$ (ground state) to $E_2$ (excited state) which is followed by rapid non-radiative decay to the metastable state ($E_3$) with some loss of energy. This is followed by emission of a photon as a result of the transition of the molecule from a metastable state ($E_3$) to the ground state ($E_1$). For this, relatively high power is required for excitation, as more than half of the entire population of the species must be raised from the lower energy level. It is necessary for the species to stay longer in the $E_3$ state rather than dropping down to $E_1$ to build up and maintain the population inversion. However, the population inversion is difficult to achieve as the lower state is the ground state which requires high power for excitation every time to invert the entire population. Since a large amount of heat is generated
during rapid non-radiative decay, the system is required to be cooled before another excitation and so the output is limited to pulsed mode operation.

In the case where there is a lower energy level other than the ground state as shown in fig (3.2c), the laser transition occurs between the metastable state ($E_3$) and the lower energy state ($E_4$) after which rapid non-radiative decay to the ground state ($E_1$) occurs. This requires a lower threshold energy compared to the three level systems as it is not required to invert the entire population and can operate in continuous wave mode [4, 5].

![Diagram](image)

Fig 3.2 Photon emission mechanism in (a) Two level system (b) Three level system (c) Four level system [4, 5].

Since photons produced by stimulated emission have the same phase, frequency and polarisation, the laser light produced is coherent and monochromatic with low divergence and high brightness. In general, lasers operate in the range from infrared to ultraviolet wavelength within the electromagnetic spectrum as
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shown in fig 3.4. Laser light can either be in the form of continuous waves, a pulse or a train of pulses depending on the mechanism of photon emission.

![Electromagnetic Spectrum](image)

Fig 3.3 Electromagnetic Spectrum.

There are four basic components required to produce laser light:

1. **Active medium for light amplification** - liquid, gas or solid
2. **Source of excitation to maintain the population inversion.** This may be electrical pumping, optical pumping or chemical pumping.
3. **An optical cavity to provide optical feedback,** which can be a stable cavity where the beam converges and is confined to a narrow beam, or an unstable cavity where the beam diverges and is defocused as a result of reflection between cavities as shown in fig 3.4.
4. **An output device such as solid output coupler or scraper mirror.**
The type and the class of the laser are classified on the basis of the above components. In general, lasers for material processing have a stable optical cavity which can produce a beam with high power, high order of TEM modes (described below in detail) with peak central intensity at the centre.

### 3.3 General Laser Beam Characteristics

Laser beam light is monochromatic and coherent with low divergence and high brightness. The laser beam is characterised mainly by two types of modes: spatial mode and temporal mode. The spatial mode is determined by the laser beam intensity distribution, while the temporal mode is determined by the number of energy levels in the active medium and the source of excitation.

The spatial modes consist of transverse and longitudinal beam components. For the laser beam characterisation, the transverse mode is the most important and is denoted as the transverse electromagnetic mode (TEM). The longitudinal mode is a large number and generally not considered during laser beam characterisation since it has little influence on important beam characteristics and performance of the lasers. The TEM mode number gives the beam intensity profile on the plane perpendicular to the direction of beam propagation. Fig 3.5 describes the various TEM beam mode patterns [6]. The TEM mode structure depends on several factors such as the geometry of the optical cavity, its alignment and spacing, and properties of the active medium. Fig 3.6 illustrates the beam intensity distribution profile for different TEM modes. Fig 3.6a shows the Gaussian beam profile for TEM$_{00}$ beam mode, while fig 3.6b shows the TEM$_{10}$ beam intensity distribution with a central peak and an intensity annulus around it. Such a distribution is normally produced from an unstable optical cavity which is due to the nature of the scraper mirror used to extract the beam. Fig 3.6c shows the TEM$_{01}^*$ mode which is produced by an oscillation between two orthogonal TEM$_{01}$ modes and is used in most Sulphur Fluoride (SF$_6$) lasers [7]. Ion [4] has described the expression for the complex amplitude of TEM modes with different symmetry such as circular, cylindrical and rectangular [4]. The mode pattern affects the output energy distribution which may further affect the laser processing such as micromachining and surface treatments.
In general, high order modes cause power losses and poor focusability of a beam to a fine spot [4].

The temporal mode of the laser beam can be changed by incorporating various devices into the resonator. Simple pulsed output can be achieved by gating or chopping of the beam, either by using an attenuator or through modulation of the excitation power [7].

Fig 3.5 TEM beam patterns.

Fig 3.6 Intensity distribution of laser beam with different spatial modes (a) TEM_{00} (b) TEM_{10} (c) TEM_{01} [8].

3.3.1 Beam waist and beam divergence

The beam waist is the point where the beam spot size is a minimum along the beam axis. Fig 3.7 describes a beam with Gaussian intensity profile (TEM_{00}) where the minimum spot size is denoted as w_0 at the beam waist. The intensity distribution I(r) for a Gaussian beam in the plane of the waist is given by equation 3.5:
where \( r \) is the distance from the centre of the beam and \( w_0 \) is the distance from the centre at the beam waist.

\[
I(r) = e^{-2r^2/w_0^2}
\]  

Equation 3.6 gives the expression for the spot size \( w(z) \) of the Gaussian beam at a distance \( z \) from the beam waist:

\[
w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}
\]  

where \( w(z) \) is the spot size at distance \( z \) from the beam waist, \( w_0 \) is the spot size at the beam waist and \( \lambda \) is the wavelength of the beam. However, in the far field where \( z \gg z_R \) (Fig 3.7):

\[
\frac{\lambda z}{\pi w_0^2} \gg 1
\]  

This means that the beam starts diverging and the angle between the line of constant and the central axis is denoted as the angle of divergence and is given by eq 3.8 [7, 8]:

\[
\Theta = \frac{\lambda}{\pi w_0}
\]  

Where \( \Theta \) is the angle of divergence for the diffraction limited Gaussian beam. The divergence angle thus depends on the wavelength, beam diameter and mode structure of the laser beam. The Gaussian beam (TEM\(_{00}\)) has the lowest beam
divergence which is typically around 1 mrad, while multimode beams, such as those from the excimer laser, have divergence of around 2-10 mrad. While the initial laser beam characteristics are generally determined by the type of optical cavity, active medium and the devices and aperture in the optical cavity, they can be modified using different optical devices such as homogenisers, scanning mirrors, diffracting elements, polarizer and beam collimators.

3.4 Excimer Laser Generation Mechanism and Characteristics

The term excimer is derived from "excited dimer", where a dimer is a diatomic molecule formed by a chemical reaction after exciting one or both of the atoms. The term "Excimer Laser" is commonly used for the class of lasers where a rare gas halide (e.g. ArF, KrF, XeCl) is the active medium [4, 6].

3.4.1 Excimer laser generation

An inert gas (He, Ne, Ar, Kr, Xe) and a halogen (Cl, F, Br, I) are electrically excited to form positive and negative ions respectively and further react chemically to form an excited dimer. Since the rare gas halide so formed is unstable, it returns to the ground state within 5-15 nanoseconds, emitting a photon. The unexcited atoms in the ground state have less affinity for each other and are likely to strongly repel each other, which results in practically no atoms in the ground state. Hence the population inversion is readily formed in this case and the excimer laser belongs to the category of four level laser systems. Fig 3.8 shows the graphical presentation of binding energy verses internuclear separation for the KrF rare gas halide. Transition of the dimer occurs from the state B (excited state) to state X, (ground state) emitting the photon to generate laser light.

The upper laser level is an ionic charge transfer state of the positive rare gas ion Kr⁺ and the halogen negative ion F⁻. The excited excimer molecules are generated from the complex plasma reaction. Fig 3.9 shows the flow diagram of the reaction scheme for the KrF excimer laser. The formation of the excited rare-gas halide molecule is dominated by mainly two reaction channels: the ionic channel in which both rare gas and halide ions recombine in the presence of a third body which is a buffer gas such as He or Ne, and the neutral channel in which the excited
state rare-gas atom reacts with a halogen molecule (harpooning reaction). These reactions take place on a nanosecond time scale.

![Energy versus inter-nuclear separation](image)

**Fig 3.8 Binding energy versus inter-nuclear separation for rare gas halide molecules [6].**

Since the ground state is highly repulsive or only weakly bonded, so the emission of a UV photon from stage B (fig 3.8) occurs over a relatively wide wavelength band, for example, in the case of KrF gas where molecules are repulsive in the ground state, continuous laser emission is produced over a 0.4 nm wavelength spread. However, it requires high power densities of around 1 MW/cm³ to achieve the high excitation rates required to compete with fast loss processes, collisions and spontaneous decay.

![Reaction scheme](image)

**Fig 3.9 Reaction scheme for laser generation in KrF excimer laser [9].**
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The reaction kinetics of the photon emission in a KrF excimer laser system as described by Crafer [6] are reported below and defined by three different processes such as pumping, stimulation and losses.

**Pumping stage**

\[ \text{e}^+ + \text{Kr} \rightarrow \text{Kr}^+ + \text{e}^- + \text{e}^- \] (Positive rare gas ion)

\[ \text{e}^- + \text{F}_2 \Rightarrow \text{F}^- + \text{F} \] (Negative halogen)

\[ \text{Kr}^+ + \text{F}^- + \text{M} \Rightarrow \text{KrF}^* + \text{M} \] (M represents third body collisional partners He, Ne)

\[ \text{Kr}^* + \text{F}_2 \Rightarrow \text{KrF}^* + \text{F} \]

**Stimulated photon emission**

\[ \text{KrF}^* + \hbar \nu \Rightarrow \text{Kr} + \text{F} + 2 \hbar \nu \] (248nm)

**Losses**

\[ \text{KrF}^* \Rightarrow \text{Kr} + \text{F} + \hbar \nu \] (248nm) (spontaneous emission)

\[ \text{KrF}^* + \text{M} \Rightarrow \text{Kr} + \text{F} + \text{M} \] (collisional deactivation)

\[ \text{KrF}^* + \text{M} + \text{Kr} \Rightarrow \text{Kr}_2\text{F} + \text{M} \] (collisional deactivation produces Kr2F)

\[ \text{X} + \hbar \nu(248\text{nm}) \Rightarrow \text{X}^* \] (Laser Photon absorption, where X is an impurity molecule)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>F(_2)</th>
<th>ArF</th>
<th>KrCl</th>
<th>KrF</th>
<th>XeCl</th>
<th>XeF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>157</td>
<td>193</td>
<td>222</td>
<td>248</td>
<td>308</td>
<td>351/353</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>0.06</td>
<td>0.8</td>
<td>0.2</td>
<td>1.5</td>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>3</td>
<td>30</td>
<td>10</td>
<td>50</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>3</td>
<td>60</td>
<td>10</td>
<td>150</td>
<td>200</td>
<td>70</td>
</tr>
</tbody>
</table>

The wavelength of the laser beam depends on the electronic configuration of the rare gas and halogen atom. In general, the pulse duration varies between 10-30 ns. Table 3.1 lists the operating parameters for the commercially used excimer
laser systems such as KrF, F₂, ArF, XeCl, XeF, KrCl. For micromachining of most materials, the KrF excimer laser is an appropriate tool and is being widely used in practice.

3.4.2 Construction of excimer laser systems

In practice, most of the excimer laser systems operate in the pulsed mode with pulse duration ranging from 10 ns to 40 ns. However, ultra-fast excimer lasers with femtosecond pulses are also increasingly used nowadays for several material processing applications since they cause minimal thermal damage in the material compared to nanosecond pulsed systems [9]. An excimer laser uses a mask projection technique that can tailor the shape and size of the beam spot to machine small size features with high accuracy. Fig 3.9 shows the schematic layout of an excimer laser system, where the laser beam exiting the laser unit is projected on to the work piece mounted on motion tables through a beam delivery system. The beam delivery system mainly consists of several optical components for beam expansion, shaping, scanning, image projection and a mask holder.

Incorporating a mask in the beam delivery system offers various advantages over direct writing of the beam such as in the case of CO₂ and Nd:YAG lasers. Table 3.2 compares the mask projection technique with direct writing techniques [10].

3.4.2.1 Power source-high voltage system

In most of the commercially used excimer lasers excitation of the species is carried out using an electrical discharge with a voltage of 35-50 kV applied orthogonally across parallel electrodes. Self-sustained electrical discharge in the gas passes peak current densities of 1 kA/cm². Commercially available excimer lasers operate at 100-300 W power. There are storage capacitors which are DC charged to the working voltage and further pulse charged with matched or LC inverter circuits and small ceramic capacitors close to the electrodes through a thyratron. The secondary capacitors are in close proximity to the electrodes enabling low inductance pathway for current to flow through the gas and which in turn allows very fast rising high voltage pulses to be applied to the electrodes. Average life for
all the electrical components in the excitation system is predicted to be 1 billion pulses [6, 10].

Fig 3.9 Basic set-up of excimer laser system.

<table>
<thead>
<tr>
<th>Direct Writing</th>
<th>Mask Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited range of features are produced and only small area machined at a time</td>
<td>Flexible technique that can produce a wide range of structures with the same system and can machine large areas at a time</td>
</tr>
<tr>
<td>Optics are simple and inexpensive</td>
<td>Optics can be expensive</td>
</tr>
<tr>
<td>Can be used for serial writing and rapid prototyping of devices</td>
<td>Can be used for batch processes or volume production</td>
</tr>
<tr>
<td>Can operate at high repetition rates</td>
<td>Operates at modest repetition rates</td>
</tr>
</tbody>
</table>
3.4.2.2 Optical cavity

An excimer laser optical cavity consists of a stable resonator with plane-parallel UV transmitting mirrors. An input mirror with high reflectivity is made of aluminium or dielectric coating on materials such as fused silica glass, crystalline CaF$_2$ or MgF$_2$, and an output mirror with a reflectivity around 8% [6, 11]. In the course of laser operation, small particles are generated in the cavity due to sputtering of the material from the main discharge and pre-ionisation of the electrodes causing deposition of particles on the laser optics reducing the output and efficiency of the laser operation. To minimise this effect and also to keep dust and impurity levels to a minimum, electrostatic or particulate filters are used. The optics are required to be cleaned at regular time intervals to sustain the life of mirrors and efficiency of the process. The typical optics cleaning interval for such systems is between 50-100 million pulses.

3.4.2.3 Active medium

The resonator in an excimer laser is filled with a mixture of gases with 4-5 mbar pressure of halogen gas, tens to hundreds of mbar pressure of rare gas and then further pressurized to 2-4 bar with helium or neon as a buffer gas. The gas mixture is circulated in a sealed cavity by blowers through an electrode gap and water cooled heat exchanger. The halogen gases are highly toxic and corrosive, which may affect various components. To avoid harmful effects of these gases, it is diluted in 95% Helium. Prolonged exposure to short ultraviolet radiation causes defects in the lattice of the mirror substrate material. Fluorine and ozone can cause etching of the mirror surface, and so regular cleaning of the optics is required to minimise the effects of this.

3.4.2.4 Beam characteristics and beam delivery system

Most of the commercial systems produce a multi mode beam with a "top hat" profile. Fig 3.10 shows a schematic diagram of the excimer laser beam with top hat profile across the width and near Gaussian profile across the thickness, as described by Dickey [12]. However, since an excimer laser is a gas discharge laser, with time, as the gas fill ages, the gas chemistry also changes which further causes
changes in laser beam profile. Apart from this, the laser beam profile also changes if the resonator optics are dirty or if not accurately aligned. Hence, to maintain good quality of the beam, regular cleaning of the optics and checking of alignment is essential.

The raw beam coming from the laser device is of rectangular shape and inhomogeneous with an intensity variation of around 20-25%. Such an inhomogeneous profile cannot offer satisfactory performance in the ablation process. To make the beam homogenous with uniform intensity distribution, it is passed through the laser beam delivery system consisting of different optical components which further modify the laser beam profile before it is exposed to the work piece. The beam delivery system consists of several optical components such as beam expanders, beam homogenisers, beam multiplex, diffraction grating elements, image projectors/mask projection, scanning mirrors and plane parallel mirrors depending on the desired beam profile and material processing application [6].

The beam expander is used to expand the beam dimensions to further match it with the homogeniser and subsequent beam delivery optics. The beam homogeniser produces a very flat profile with uniform intensity distribution that can enable uniform machining at the work piece. Various optical devices are used in practice for homogenising the beam. Figs 3.11 and 3.12 illustrate the kind of beam expander optics and homogeniser optics used in general in industrial excimer laser beam delivery systems.

![Beam profiles](image)

Fig 3.10 Excimer laser beam profile [12].
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Beam multiplexers are used to split up the laser beam into several small beamlets of similar intensities, which can be performed either by beam splitters to divide the beam amplitude or small mirrors, prisms or lenses to spatially split up its wave front.

A mask projection or image projector tailors the shape and size of the beam and is an important component in an excimer laser system. The beam exiting the laser device has a poor mode distribution and a low beam quality, which cannot be focussed tightly on the workpiece. A mask is therefore incorporated in the beam delivery set up which defines the beam shape and size, and enables it to be focussed accurately with the projection lens. Secondly the excimer laser beam peak power is high enough to cause damage to the imaging optics even if not focussed down on the work piece, which can be avoided by the use of a mask that further reduces the size as well as power of the beam [2, 6]. A scanning mirror is a cylindrical lens used to reshape and homogenise the beam by scanning it across the mask.

![Beam Expansion Optics](image1)

**Fig 3.11 Beam Expansion Optics.**

![Beam Homogenising Optics](image2)

**Fig 3.12 Beam homogenising optics.**
3.5 Laser-Material Interactions

Lasers for material processing are used in a wide range of applications such as ablation, welding, cladding, melting, surface treatments, coating and deposition. The range of application varies mainly with the wavelength of the laser beam, power, beam characteristics and laser beam and material interaction. Absorption of the laser beam depends on the electronic configuration and bond energy of the materials such that different materials absorb at different wavelengths and with different absorption mechanisms.

3.5.1 Absorption in different materials

To enable absorption of the laser beam, the photon energy of the beam must excite transitions in the material that may be rotational, vibrational or electronic. The interaction depends on the electronic configuration of the material (related to the bonding) and the energy of the laser. The following sections describe the interaction of the laser beam with different categories of materials.

3.5.1.1 Absorption in metals

In the case of metals, the laser energy is absorbed by the free electron cloud which provides a large number of energy levels for electron excitation. Since different metals and alloys possess different electronic configurations, the absorption of the photon energy also varies accordingly. Transition metals have many unfilled orbitals which take part in energy absorption, hence they absorb in the visible range, while metals such as aluminium and magnesium have fewer energy levels and hence absorb poorly in the visible range. Metals and alloys processing is more efficient with ultraviolet wavelengths of light [4]. Fig 3.13 presents the mechanism of absorption in metals where an electron is excited to upper empty levels on photon absorption [13].
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3.5.1.2 Absorption in ceramics and glasses

Ceramics are crystalline or amorphous (glass) inorganic materials. Ceramics are ionically and/or covalently bonded and, due to this, there exists an energy band-gap in the electronic structure between the valance band and the conduction band. Photon absorption therefore only occurs if it is higher in energy than the band gap. Fig 3.14 shows the schematic diagram of the photon absorption in non-metals. Ceramics with ionic bonds absorb energy in the infrared region while those with covalent bonds need higher energies in the ultraviolet range. Photon energy is absorbed by resonance of bound electrons through coupling of high frequency optical phonons [13]. Absorption is weak over the visible range and increases rapidly in the ultraviolet region as transition of electrons takes place. Most glasses are covalently bonded and hence absorb energy in the ultraviolet range.

3.5.1.3 Absorption in polymers

Polymers comprise of either a linear or complex crosslinked structure of repeated monomer units. Atoms in chains and cross links are covalently bonded, but there is another weak force between these chains known as van der Waal's forces. Polymers have a band gap, but also absorb radiation through resonant vibration of molecular bonds and therefore absorb energy in the far infrared region as in the case of CO₂ lasers (10.6μm) [4].
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Fig 3.14 Mechanism of photon absorption in non metals [13].

Table 3.3 summarises the mechanism and wavelength of absorption of different materials with different bond type.

Table 3.3 Laser-material interaction for different materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of bonding</th>
<th>Mechanism for energy absorption</th>
<th>Strong absorption of the wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals and alloys</td>
<td>Metallic</td>
<td>Free electron cloud, empty energy levels</td>
<td>Near and far IR, Visible, UV</td>
</tr>
<tr>
<td>Ceramics and glasses</td>
<td>Covalent and ionic</td>
<td>Resonance of bound electrons through coupling to high frequency optical phonons</td>
<td>UV and IR</td>
</tr>
<tr>
<td>Polymers</td>
<td>Covalent, van der Waal’s force</td>
<td>Resonant vibration of molecular bonds</td>
<td>Far and near IR and UV</td>
</tr>
</tbody>
</table>

3.5.2 Excimer laser ablation mechanism

Since excimer lasers operate in the ultraviolet range, almost all materials can readily absorb the photon energy. Due to this, it is widely used for ablation.
processes. Laser ablation is the process of material removal in a controlled manner with the photon energy of the laser beam. Ablation processes depend on the laser type, power, beam characteristics and work piece material properties. With excimer lasers material is removed by two mechanisms (a) Thermal ablation (b) Athermal ablation, depending on the material characteristics.

In thermal ablation, the photon energy of the laser beam causes localised heating as a result of the thermal vibration of the lattice followed by melting and evaporation. This results in removal of the work piece material by heating followed by melt ejection. Fig 3.15 shows a schematic diagram of the thermal ablation process with removal of material due to melt ejection and vaporisation. Since material is removed by the melting process it is difficult to achieve clean ablation with defined edges. Depending on the laser beam characteristics and the material properties, during thermal ablation a region around the ablated feature is thermally modified due to the heat generated during the laser material processing and is defined as a heat affected zone (HAZ) [14].

In the athermal ablation process, the photon energy of the laser beam absorbed by the workpiece material causes direct breaking of the molecular or chemical bonds, as a result of which material removal takes place without any thermal effects. As such, there are three main mechanisms which are based on photoelectrical, photochemical and photophysical effects. With the excimer laser, athermal ablation occurs by either the photochemical effect, in which material removal takes place by the direct breaking of interatomic bonds, or by the photophysical effect, in which the material removal takes place by direct breaking
Chapter 3: Excimer Laser Micromachining

of the intermolecular bonds. Fig 3.16 illustrates the athermal ablation process in which material is removed in the form of fine debris which can be easily removed by appropriate cleaning methods. Since the material in the localised area is instantly vaporised when irradiated with the laser beam, melting and heating effects are avoided and it is possible to achieve clean ablation [4].

Ablation in different materials is defined by the minimum laser beam energy or fluence required to ablate the material which is known as the ablation threshold. Below the ablation threshold material removal does not occur since the energy is not enough to cause melting or vaporisation of the material and only localised heating of the material occurs. Table 3.4 describes the ablation threshold for different materials in the ultraviolet region. Fig 3.17 shows a graph of ablation rate as a function of fluence for different materials which were machined with excimers. It shows that the ablation rate for polyamide is very high compared to fused silica glass, alumina and shape memory alloys. It also shows that the ablation rate strongly depends on the laser machining parameters such as energy fluence, together with repetition rate, pulse duration and irradiation time.

Table 3.4 Threshold fluence of different materials [6].

<table>
<thead>
<tr>
<th>Material</th>
<th>Laser Wavelength</th>
<th>Threshold Fluence (J/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics and Polymers</td>
<td>193 – 308 nm</td>
<td>0.06 – 0.46</td>
</tr>
<tr>
<td>Glasses &amp; Ceramics</td>
<td>193 – 308 nm</td>
<td>0.8 – 15</td>
</tr>
<tr>
<td>Metals</td>
<td>193 – 248 nm</td>
<td>0.14 – 1.4</td>
</tr>
</tbody>
</table>
3.5.2.1 Nonlinear effects during ablation

The ablation process in different materials may ordinarily be either of thermal or athermal nature, but can also occur by both processes depending on the laser material interaction. The photon energy of the excimer lasers is in the range of 4-7 eV. Based on this, one can say that the material with a bond energy less than this value will experience material removal by direct breaking of bonds (athermal ablation) and in the case where the bond energy of the material is high compared to the photon energy of the laser beam, material removal takes place by heating and subsequent melting. In some materials where both the photon energy and average band gap are of a similar order of magnitude, ablation occurs by both mechanisms. In addition, the ablation mechanism depends on several factors such as laser operating parameters, average laser power, pulse duration and laser beam intensity distribution. However there are some other factors which also contribute in the ablation process.

In general, material responds linearly when irradiated with laser light and all optical phenomena such as absorption, reflection, refraction and scattering occur at the same frequency. However in some materials like quartz, or silica glass, when irradiated with high power lasers, non-linear effects are generated which are responsible for further ablation processes. Such effects include two photon and
multiphoton absorption, self focussing of the beam and impact ionisation which mainly enhance the ablation process.

The self focussing effect occurs due to a change in refractive index of the material when irradiated with a high intensity laser beam. The fact that the beam intensity is high near the beam axis causes the medium, whose refractive index increases with increase in electric field intensity, to act as a focusing lens placed in the beam path. If the refractive index increases with irradiance, the lens is converging and vice-versa if the refractive index decreases. This effect is more often observed in the interaction of femtosecond lasers with hard materials since a high amount of energy is deposited at the work piece due to the very short pulse duration. In general, two self focussing effects induced by plasma formation and the Kerr effect are usually observed in many materials [7, 14, 19].

In two photon and multiphoton absorption, more than one photon is absorbed simultaneously when the material is irradiated with a high intensity beam. Often, the presence of impurities causes defects such as electron and hole centres in the atomic structure, which can further act as free charge carriers and increase the absorption. When the photon energy is high enough it can also create electrons and hole centres in the structure that further causes two photon or multiphoton absorption. Hence this process depends on the density of defects in the structure which increase the number of free electron carriers to favour the above mechanism. Defects in the structure may be produced during irradiation with a high intensity beam or during the manufacturing process itself. This mechanism is more common in semiconductors and insulators such as glasses where non-stoichiometric valency ratios favour the above process.

In the case of impact ionisation when the material is irradiated with a high laser intensity, a highly energetic charge carrier looses its energy to create another charge carrier. In the case of semiconductors, this can result in avalanche breakdown in the presence of a high electrical field.
3.6 Summary

From this literature review it has been identified that since the excimer laser operates in the short ultraviolet range, it is suitable for machining almost all materials and especially suitable for hard materials like glasses and ceramics. In addition to this, the top hat laser beam profile and mask projection technique makes it a suitable tool for machining complex and fine features with a high level of accuracy. Since this research work deals with micromachining of glass substrates, the excimer laser was used for this purpose. However, the ablation mechanism in glass is a complex process compared to that in metals and polymers. To understand the laser-glass interaction, it is necessary to examine the glass structure and properties, which is discussed in the next chapter.

References


4 GLASS: PROPERTIES AND MICROMACHINING

4.1 Introduction

Since glass is brittle in nature, micro machining of glass is difficult with conventional mechanical techniques. As already discussed in chapter 3, glasses have stronger chemical bonding compared to polymers and metals, which makes fabrication with them difficult. Processes such as powder blasting, ultrasonic machining, chemical etching, mechanical grinding and polishing and embossing are used in practice for microfabrication of glasses. However, for high precision micromachining applications, laser technology is an appropriate tool. Since glass can strongly absorb laser light in the ultraviolet region, high power lasers like CO₂, Nd:YAG and excimer are used for machining of glass. However, the mechanism of ablation in glass depends upon the laser parameters and also the type of glass. Laser-glass interaction in the ablation process can produce certain undesirable effects such as microcracks on machined features, melt ejection and scattering of debris. However, it is still difficult to predict clearly the mechanism of glass and laser interaction [1]. This chapter deals with the properties of the glass and its interaction behaviour with the laser beam that are of prime importance to this research work.

4.2 Structure of Glass

The structure of glass and electronic configuration of glass play an important role in the laser material interaction behaviour [2]. The structure of glass can be considered as a frozen liquid, which has no long-range order. Glass is amorphous by nature and its atomic structure depends on the type and composition [3]. The basic structure of silica glasses consists of covalently bonded Si-O-Si. Fig 4.1 shows silicon from group IV of the periodic table bonded to four oxygen atoms forming a tetrahedron with the silicon atom at the centre and the four corners occupied by oxygen atoms.
The silicon atom has the electronic configuration 1s\(^2\)2s\(^2\)2p\(^6\)3s\(^2\)3p\(^2\), however hybridisation of the outer electron orbitals takes place to form four hybrid sp\(^3\) orbitals. Each hybrid orbital holds one electron and these are shared with four oxygen atoms, forming a tetrahedron. As oxygen has the electronic configuration 1s\(^2\)2s\(^2\)2p\(^4\), two more electrons are required to achieve a stable noble gas configuration, which is obtained by sharing with neighbouring silicon atoms as shown in fig 4.2a. This way oxygen forms a bridge between two silicon atoms (Si-O-Si) linking two silicon tetrahedra together as shown in fig 4.2b.

The O-Si-O bond angle in the tetrahedron is always constant and is around 109° 28', so short range order does exist. However, since the Si-O-Si bond angle varies over a wide range, long range order does not exist in glasses. Fig 4.3 shows...
the networking structure of pure silica glass [4]. Although long-range order does not exist in the glass structure, stoichiometry is still maintained.

![Diagram of network structure of pure silica glass](image)

**Fig 4.3 Network structure of pure silica glass.**

In reality, silicate glasses also contain other oxides, which can modify the structure of the glass and thus the properties. For example, oxides of boron, germanium and phosphorous are capable of forming similar network structures since boron, germanium and phosphorus atoms can substitute for silicon atoms. Such oxides increase the stability of the network and enhance the properties of the glass such as increasing the temperature of the softening point and increasing the chemical and electrical resistance. Alkaline earth oxides like sodium and calcium oxides occupy the interstices, causing the formation of non-bridging oxygen atoms that disrupt the network structure as shown in fig 4.4. Such oxides are termed as network modifiers and they reduce the stability, thus melting temperature,
viscosity, chemical stability and electrical resistivity are lowered. However, such effects facilitate the fabrication of glass at low temperatures [2].

4.4 Networking structure of soda lime silicate glass with sodium atoms occupying interstitial sites and forming non-bridging oxygen (NBO).

4.3 Viscosity of the Glasses

As glass is an amorphous material, it does not show a clear melting point, instead its viscosity changes with temperature. Fig 4.5 illustrates the variation of viscosity with respect to temperature for a typical soda lime glass as investigated by Zarzycki [5]. This viscosity regime predicts various useful points and ranges, such as the working range for micro fabrication and heat treatments. There are four key temperatures: Glass transition temperature, softening point, anneal point and strain point used in practice for the various applications.
4.3.1 Glass Transition Temperature (Tg)

This is the temperature at which glass transforms from a lower temperature glassy brittle state to a higher temperature supercooled liquid state and is denoted as $T_g$. The glass viscosity at $T_g$ is about $10^{13}$ Poise. The temperature range between the anneal point and the strain point is described as the glass transition range (fig 4.5) and the $T_g$ value falls within this range. $T_g$ is very useful in heat treatment of glasses since it determines the approximate temperatures for annealing and tempering.

4.3.1.1 Strain point

The strain point is the temperature at which the internal stress in the glass is substantially relieved in four hours.
4.3.1.1 **Anneal point**

The Anneal point is the temperature at which internal stress in the glass is relieved in 15 minutes. Most commercial glasses have an anneal point about 35-40°C above the strain point.

4.3.1.3 **Softening point**

The softening point is described as the temperature at which the glass will deform under its own weight. This temperature is useful for glass fabricators. Table 4.1 gives the $T_g$ values, anneal point and strain point for some of the glasses used in industry.

<table>
<thead>
<tr>
<th>Glass type</th>
<th>Glass transition temperature ($T_g$)</th>
<th>Anneal point</th>
<th>Strain point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borosilicate glass (laboratory purpose)</td>
<td>525°C</td>
<td>565°C</td>
<td>510°C</td>
</tr>
<tr>
<td>Lithium silicate glass (S-8070–SB)</td>
<td>465°C</td>
<td>481°C</td>
<td>459°C</td>
</tr>
<tr>
<td>Borosilicate crown glass (BK-7)</td>
<td>557°C</td>
<td>560°C</td>
<td>510°C</td>
</tr>
<tr>
<td>Fused silica glass</td>
<td>1200°C</td>
<td>1220°C</td>
<td>1125°C</td>
</tr>
</tbody>
</table>

A similar kind of viscosity profile as described in fig 4.5 is observed for most glasses. However, since viscosity strongly depends on the composition of the glass, the viscosity versus temperature plot varies depending on the concentration and the type of oxides present. Fig 4.6 shows the viscosity curves of various silica based glasses as a function of temperature. For the glasses with a stable network structure, such as fused silica, the viscosity curve is shifted to a higher temperature range while for the glasses with a disrupted network such as soda lime or the glasses with a high amount of sodium and calcium oxides, the viscosity curve is in a low temperature range.
Chapter 4: Glass: Properties and Micromachining

4.4 Laser-Glass Interaction

The Laser-Glass interaction is characterised by the absorption behaviour and depth of penetration of the laser beam into the glass. Thus, depending on the absorption behaviour of the laser beam, lasers with appropriate wavelengths and beam characteristics are selected for processing of glass.

4.4.1 Absorption of laser beam energy

Since glass is an insulator, unlike metals it will have a band gap in the electron energy levels between the valence band and conduction band as discussed in the previous chapter. The photon energy is absorbed by glass only if $E > \Delta E_g$, where $E$ and $\Delta E_g$ are the photon energy and band gap energy respectively. Generally in glasses, absorption of the laser energy takes place by the resonance of bound electrons through coupling to high frequency optical phonons. As discussed in the previous section, glasses consist of the network formers and network modifiers which affect the absorption properties of the glass. Even a small amount of impurities can affect the absorption behaviour since the impurity levels lie in the gap between the valence band and conduction band as shown in fig 4.7. This further reduces the band gap energy and makes the absorption easier even with low photon energies. As such, glass can absorb photon energies in a wide range from the infrared to ultraviolet region depending on its composition, but absorbs more strongly in the ultraviolet region [3, 10].

Fig 4.6 Typical curve for viscosity as a function of temperature for different glasses (a) fused silica (b) aluminosilicate (c) borosilicate (d) soda lime (e) lead borate [9].
In the case of linear optical effects, glass can transmit and refract the light and can also absorb the light at specific wavelengths, the intensity of the transmitted light decreases with increase in depth of penetration through the thickness of the glass. This is expressed in equation 4.1:

$$I = I_0(1 - R) \exp(-\alpha t)$$

(4.1)

where $I_0$ is the initial intensity of the light, $I$ is the intensity of the transmitted light, $\alpha$ is the absorption coefficient of the glass and $t$ is the depth of penetration of the beam, $R$ is the reflectance.

Different glasses have different absorption peaks depending on the band gap energy that varies with the composition and concentration of oxides in the glass. Pure silica glass, with no impurity states in the band-gap, requires very high photon energy and short wavelength in the ultraviolet range. With the addition of oxides like sodium and calcium, due to the formation of non-bridging oxides, the absorption range shifts towards longer wavelength. The addition of some transition metal oxides can cause an absorption in the visible range resulting in colouring of the glass. Beside this, doping of the glass can increase the absorption. Table 4.2 illustrates the effective band gap energy of different glasses depending on the type and amount of oxides present and the impurity level to create charge carriers [1, 4, 11].

---

Fig 4.7 Photon absorption in insulators with an impurity level within the energy band gap between valence band and conduction band.
When the glass is exposed to high photon energy in the short ultraviolet range, the laser-material interaction no longer obeys linear optical rules and non-linear optical effects come into existence. Different types of non-linear effects involved in laser material interaction have already been discussed in the previous chapter. In glasses, several non-linear effects such as two-photon absorption, multiphoton absorption, impact ionisation and self focusing of the beam can increase the absorption and thus the ablation dramatically.

4.4.2 Laser-ablation in glasses

Laser machining is capable of creating fine features in glass, but since the ablation mechanism is complex, defects like microcracks, debris and recast layer formation, along with thermal damage of the machined surface are produced, depending on the glass composition and the type of laser used. Several researchers have identified microcracks in the machined glass formed due to thermal stresses induced during the laser ablation process [1, 12-15].

Laser ablation in the glasses may be a thermal or an athermal process depending on the glass absorption characteristics and the photon energy of the laser beam. As shown in table 4.2 the effective band gap energy of most commonly used glasses lie in the range of 2 eV to 8 eV which is similar in magnitude to the photon energy in the ultraviolet and infrared range [1, 4]. Hence for glass ablation, three lasers: CO\textsubscript{2}, Nd:YAG (frequency tripled and quadrupled) and excimer are used commercially in most industries.

Since non-linear effects play a major role in ablation of glasses, mixed effects of both thermal and athermal processes are observed. Non-linear effects

<table>
<thead>
<tr>
<th>Glass type</th>
<th>Effective band gap (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused silica</td>
<td>7.5</td>
</tr>
<tr>
<td>Borosilicate glass</td>
<td>4.4</td>
</tr>
<tr>
<td>Soda-lime silicate glass</td>
<td>3.9</td>
</tr>
</tbody>
</table>
depend on the concentration and composition of the oxides and impurities present in the glass and the laser pulse duration. Hornberger [1] has described several non-linear effects occurring during ablation in silica glasses using excimer lasers. At high laser energy above the ablation threshold of glass, non-linear effects like multiphoton absorption occur which drastically increase the absorption coefficient of the silica glass, leading to explosive ablation of the material. Another such mechanism is impact ionisation, which occurs at very short wavelengths and high photon densities. This causes an avalanche of free electrons to occur, which results in the evolution of a dense plasma. Such non-linear effects are usually observed more significantly with femtosecond lasers due to the extremely short, high energy pulses.

In thermal ablation of glass, the laser energy causes heating up of the glass followed by melting and evaporation that forms a dense plasma cloud. This plasma cloud further interacts with the laser beam and absorbs part of its energy, which means that with the progression of the ablation process, the laser beam energy interacting with the glass surface continuously decreases and a limit is reached through the thickness of the glass below which further ablation does not take place [1, 12]. Melt ejection during thermal ablation causes a solidified layer to form around the periphery of the features and evaporation causes deposition of fine debris around it. Heating and melting causes the formation of a heat affected zone (fig 3.15 in chapter 3). In the literature, many researchers have reported thermal ablation in glass using CO$_2$ and Nd:YAG with a wavelength of 1 μm which causes a wide heat affected zone.

Along with the type of laser, the pulse duration also plays an important role in the laser ablation process. Usually lasers with nanosecond pulses cause thermal ablation in glass which further leads to the formation of a wide heat affected zone and also thermally induced stresses. However, in the case of laser ablation with femtosecond pulses, non linear effects have significant influence on the ablation behaviour. This is due to the rapid accumulation of the pulse energy for ablation that takes place before its diffusion or dissipation to neighbouring areas can occur. As a result of this, the thermal damage in the ablated areas is minimised and a heat affected zone is confined to a small region. Ben-Yakar and Karnakis [16, 17] have
investigated micromachining of borosilicate glass using 800 nm Ti-Sapphire lasers operating with femtosecond pulse duration (130 fs) and compared this with 255 nm UV lasers with nanosecond pulses (30 ns). The femtosecond pulses minimised the microcracking and gave a surface texture superior to the nanosecond pulse laser.

The use of F$_2$ excimer laser (157nm) for micromachining of glass is increasing since it provides high photon energy of around 7.9 eV that can efficiently machine very fine features (<10 μm) with a precise control.

4.5 Comparing Properties and Laser Micro Fabrication of Silicon with Glass

Since glass offers excellent optical and electrical properties it is often used in the microelectronics and opto-electronics industries [14]. Silicon is also widely used in the semiconductor industry and, as mentioned earlier, there is a move towards fabricating substrates with it. As a comparison, this section briefly reviews the laser machining of silicon.

Since silicon is a hard material, material removal takes place by thermal ablation during laser machining. However, the surface morphology of laser ablated silicon is quite different to that of glass that has also undergone thermal ablation. Chen [19] has compared the differences in morphology of silicon and glass as a result of excimer laser ablation. According to him, a corona or a ripple shape of recast near the edge of the ablated region is formed on the silicon, while in glass, the recast layer and debris are spread around the ablated area as particles. This is because the thermal diffusivity of glass is around 0.68 mm$^2$/s, which is very low compared to that of silicon at around 93 mm$^2$/s, due to which the ejected Si melt droplets merge together to form a liquid layer that solidifies with ripples around the edge of the ablated area.

The ablation rate of silicon is very low compared to glass as the thermal conductivity and thermal diffusivity of silicon is much higher and causes more photon energy to be conducted away, which results in less energy available for ablation. Another fact is that the melting temperature of silicon is 1410 °C, which is much higher compared to the borosilicate glass softening temperature of around 800°C. This indicates the requirement of high pulse energy and number of pulses.
Tseng [20] has reported such behaviour. Fig 4.8 compares the ablation morphology of borosilicate glass and silicon machined with an excimer laser at a fluence of 2.4 J/cm$^2$ and 250 pulses [20]. It shows clean ablation of a trench in glass with a depth of around 40 μm compared to that of silicon which was only around 8 μm with the same operating parameters. In addition, the HAZ in silicon was high compared to that of the glass.

![Fig 4.8 Ablation of trenches at 2.4 J/cm$^2$ and 250 shots in (a) silicon (b) borosilicate glass [19].](image)

### 4.6 Summary

Although glass is a potential substrate material for the high density interconnects, challenges are still involved in micromachining of the glass. Laser machining is identified as an appropriate technique for fabricating patterns and microvias in glass; however, the laser-glass interaction behaviour is still a complex phenomenon and further investigation of the ablation of CMZ glass to form microvias and tracks is required.

### References


Chapter 4: Glass: Properties and Micromachining


Chapter 5: Methodology and Experimental Techniques

5 METHODOLOGY AND EXPERIMENTAL TECHNIQUES

5.1 Introduction

As reviewed in the literature chapters, the low cost and high volume production of PCB substrates with very fine features closely matching those of the die or silicon chip and with reliable interconnection is still difficult with existing processes and materials. To enable the further uptake of flip-chip interconnects, new materials and methods for high volume, high density substrate manufacture are required. Glass was identified as a potential substrate material due to various advantages as discussed in the previous chapters, but machining of glass for high density interconnects is a difficult task since it is likely to produce defects like microcracks, recast layer formation and debris. This research was undertaken therefore to investigate the problems related to the excimer laser micromachining of 100-50 μm thick sheets of CMZ glass. Features such as microvias and tracks were machined using different mask sizes and shapes in order to identify a process window. This chapter describes the methodology employed in this research and the core experimental techniques and materials used. The research was grouped into different parts:

- Excimer laser machining and process optimisation
- Characterisation of the machined features
- Post treatments of the machined glass
- Reliability testing of the machined features
- Machining of the demonstrator device patterns

These areas are discussed briefly in the following sections.

5.1.1 Excimer laser machining and process optimisation

Machining of microvias and tracks in 100-50 μm thick CMZ glass was undertaken using a KrF Excimer laser machine (248 nm). The effect of various operating parameters such as pulse energy, repetition rate and irradiation time on
the machining process was investigated. In addition to this, laser system characterisation was also done to understand the system and its effects on the machining of the above features. Based on these studies, a process window for machining of microvias and tracks was identified. Different sized microvias and tracks were machined to explore the limitations of the smallest feature sizes in CMZ glass achievable with the given laser set-up.

### 5.1.2 Characterisation of the machined features

Once the operating window for machining of microvias was identified, investigation of microvias and tracks at the subsurface level using microscope techniques such as SEM and FIB was carried out. Defects like microcracks, recast layer formation and debris around the machined surface area were identified, and based on the qualitative and quantitative analysis of these defects, further process optimisation was done. Machining depth and surface roughness of microvias were measured using different metrology methods such as the Zygo white light interferometer and Talysurf CLI 2000.

### 5.1.3 Post treatments of the machined glass

Machined glass is weak since it contains thermal and physical stresses induced during machining and glass handling / cleaning. In addition to this, defects such as microcracks, debris and recast layer in and around machined features contribute to reducing the strength of the glass. Hence, to improve the fatigue strength of the machined CMZ glass it was subjected to post treatments such as annealing and tempering.

### 5.1.4 Reliability testing of the machined features

Reliability is of major concern for high density interconnects. In practice, for portable and hand held devices several reliability tests such as three or four point bending fatigue, thermal cycling and thermal shock resistance are used. In this research, reliability of as-machined CMZ glass and heat treated CMZ glass was investigated using three point bending fatigue and thermal cycling.
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5.1.5 Machining of the demonstrator patterns

After investigation of laser parameters and identification of an operating window for individual microvias and tracks, machining patterns were created using Q-basic software in order to follow the process flow chart for the manufacture of double layer and single layer circuits in coordination with subsequent metallisation and lamination processes.

5.2 Experimental Techniques: Excimer Laser Machining Setup

A KrF excimer Laser (203 EMG Lambda Physik model) operating at 248 nm wavelength was used as a machining tool for glass, this system produced 400 mJ maximum pulse energy with 34 ns pulse duration and 300 Hz maximum repetition rate. The beam exiting from the laser unit was rectangular (22 mm x 6 mm) with an inhomogeneous beam profile. To make the beam square and achieve a near “top hat” profile it was passed through a set of cylindrical lenses, which folded the beam in the vertical direction and the horizontal direction. After this it was projected onto the mask plane where it was passed through different size and shaped mask apertures which could tailor the shape and size of the beam at the work piece. Finally, the beam was passed through a projection lens with 1:15 reduction ratio. The mask plate rested on 15 x 15 mm square slot so in the absence of a mask, it delivered a beam of 1 x 1 mm spot size to the work piece. There was also a scanning mirror at the top of the optics head, which was used to homogenise the beam across the mask plane (fig 5.1).

The excimer laser was also equipped with an XYZ motion master table on which the sample was mounted. This consisted of motor driven XYZ tables having a resolution of 0.5 μm, 1 μm and 0.01 μm in the X, Y and Z directions respectively. The X and Y axes were mainly for movement of the work piece, while the Z-axis was for the adjustment of focus. Focusing was mainly accomplished by a laser range finder (an in-house built reflected diode laser beam and photodiode array detector). Movement in the X and Y direction and the laser shutter operation was controlled by MM2000 computer software for which a program was written in Q-basic and commands were accepted from a text file. Various machining patterns were developed using this software.
Since the initial laser beam was passed through several optics before impinging on the work piece, significant loss of energy occurred. Hence, to know accurately the energy of the beam at the work piece, a power meter supplied by Coherent was used which measured the pulse energy in the range of 5 mJ to 1 J. Pulse energy was measured for a fixed beam spot size area of 1 mm² (i.e. without a mask in place) from which the fluence (pulse energy per unit area) was calculated. The pulse energy was measured each time prior to glass machining to ensure that the fluence at the work piece was known for a fixed laser exit energy.

5.1 Beam delivery system.

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5.2.1 Role of the individual optics

The laser beam quality is an important parameter since it affects the machining quality of the features and depends on a number of factors such as the laser parameters, the type, spacing and alignment of the optics used, and the optical cavity. It was noted that with more optics, there was more energy loss since each optic also absorbs some of the beam energy. It was therefore necessary to understand and characterise the role of the individual optics to achieve excellent machined features with minimum defects.
5.2.1.1 *Attenuator*

The attenuator was located just next to the beam shutter as shown in fig 5.1. It helped to reduce the laser beam energy either by absorption or by reflection of part of the beam. Various types of attenuators are used commercially, which may either fully absorb or fully reflect or may be partially reflective / absorbing. For micromachining on soft materials like plastics and polymers where low threshold fluences are required, attenuation of the laser beam plays a major role.

![Diagram of Attenuator device in the laser beam delivery system.](image)

Fig 5.2 Attenuator device in the laser beam delivery system.

The effect of the attenuator in this system was evaluated. The attenuator was rotated back and forth around its central axis as shown in fig 5.2 and fig 5.3 shows the variation of pulse energy at the work piece as a function of position of the attenuator. The profile was obtained for three different pulse energies of the laser beam exiting from the laser unit: 250, 300 and 350 mJ. The pulse energy of the attenuated beam starting from point 961 (attenuator position reading) to 890 (attenuator position reading) was measured with the power meter at the work piece with a 1 mm² beam spot size. At 961 angular position, the pulse energy was partly attenuated, but this decreased with adjustment to around 920 that gave the minimum attenuation, after which further adjustment led to maximum attenuation at around 885. Since the power meter measured the pulse energy of the laser beam in the range of 1 J to 5 mJ, values below this range could not be recorded. It was noted that values of the positional readings were not consistent which may be due to some backlash in the control and care had to be taken during the characterisation.
Pulse energies were also measured without the attenuator in the path of the beam delivery system. The maximum attainable laser beam energy at the work piece increased from 30 mJ to 45 mJ on removal of the attenuator, indicating that about 30% of the beam energy was lost with the attenuator in the system. This is further discussed in chapter 6.

In addition to the fluence at the work piece, the laser beam profile also influenced the machining process. To identify the shape of the excimer laser beam intensity profile, the mask was removed from the laser beam delivery system such that the whole beam was able to impinge on a Perspex sample placed on the XY stage. Due to the ease of machining of the Perspex, this ablated a deep feature, the shape of which approximately represented the laser beam intensity profile. Fig 5.4 shows an optical microscope image of the ablated feature viewed through the surrounding transparent Perspex material. The figure shows a side view of the lower part of the feature: the hole is shown inverted, i.e. with the base of the ablated hole towards the top of the image. The base of the hole was not levelled and included a spiked structure indicating that there was some non-uniformity of the beam intensity profile.

![Graph](image.png)

Fig 5.3 Variation of pulse energy at the work piece with respect to the rotational position of the attenuator device in the laser beam delivery system.
Fig 5.4 Side view of a structure ablated in Perspex, without the use of a mask in the laser beam delivery system, to highlight the beam profile.

5.2.1.2 Optics train

The optics train consisted of cylindrical lenses LV1 and LV2 (fig 5.5a), which folded the beam in the vertical direction and LH1 and LH2 (fig 5.5b) that folded the beam in the horizontal direction. The distance between both horizontal and vertical lenses was fixed, as a slight change could affect the beam quality. For instance, if the distance between LV1 and LV2 increased, it caused a reduction in beam size and increase in beam intensity, which could cause damage to other optical elements in the path.

Fig 5.5 Ray diagram for cylindrical lenses in the optics train (a) Vertical lenses (b) Horizontal lenses.
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![Graph](image.png)

**Fig 5.3** Variation of pulse energy at the work piece with respect to the rotational position of the attenuator device in the laser beam delivery system.
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![Ray diagram for cylindrical lenses in the optics train](image)

(a) Vertical lenses

(b) Horizontal lenses

Fig 5.5 Ray diagram for cylindrical lenses in the optics train (a) Vertical lenses (b) Horizontal lenses.
5.2.1.3 **Scanning Mirror**

The scanning mirror was positioned on the top of the optics head as shown in fig 5.1. The scanning mirror (mirror 3) homogenised the beam by scanning it across the mask plane, which helped in uniform material removal at the work piece during the ablation process. Mirror 3 was equipped with a motorised and programmable system, which scanned the beam across the mask plane with desired scan length and scanning speeds. The maximum travel length of the mirror was 25 cm and maximum scan speed was 5 mm/sec, which were used for most machining applications. Positioning of the scanning mirror in different directions is illustrated in fig 5.6. The mirror was centrally aligned when in its idle position.

![Diagram of Scanning Mirror](image)

Fig 5.6 Beam at different position when scanning mirror 3 across the mask plane.

The effect of using the scanning mirror during the machining process is illustrated in fig 5.7. Fig 5.7a shows the optical micrograph of a rectangular feature in borosilicate glass machined without the use of the scanning mirror leading to uneven ablation with a small region of unablated material. In contrast to this, fig 5.7b shows the optical image of a rectangular feature in borosilicate glass machined with the use of the scanning mirror leading to uniform material removal and machining of features with regular geometry in close agreement with the mask shape. It was found that the scanning mirror was very useful for larger features where the inhomogeneity of the beam was most noticeable, however for features less than 200 µm the beam profile did not vary considerably and the mirror did not significantly improve the machining.
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Fig 5.7 Borosilicate glass ablated with rectangular mask (336 x 666 μm spot size) (a) Without the use of scanning mirror 3 (b) With the aid of scanning mirror 3.

5.2.1.4 Focus control

The focussing system at the work piece consisted of a diode laser beam and photodiode. The diode laser beam was reflected from the work piece at the working position onto the photodiode array detector, which provided the positional measurement in the Z-axis. Focus could be controlled manually or automatically depending on the type and the required quality of the machining process. To achieve good machining quality (features with clear edges and precise shape and size in close agreement with that of the mask), focussing of the beam needed to be very accurate. Fig 5.8 demonstrates the effect of changing the focus position of the work piece on the size and quality of the machined feature. Fig 5.8a shows the beam slightly out of focus in the upward/positive direction. The micrograph shows debris around the microvia holes and irregular edges with uneven removal of material. This was mainly due to the beam spot size slightly increasing at the work piece, but also due to energy reduction. Drilling with accurate focus control shows clear edges with clean ablation as shown in fig 5.8b. For the beam out of focus in the negative direction fig 5.8c this shows irregular machining across the microvia.
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5.2.1.5 **Mask projection**

The mask plane consisted of a 15 x 15 mm square slot which could be extended upto 20 x 20 mm. Masks of different material and fabricated with different methods were employed for machining of features in glass. The mask aperture shape and edge quality is important, since it causes scattering of the beam and affects the machining quality. Fig 5.9 shows optical microscope images of mask apertures in steel and brass fabricated with mechanical drilling and chemical etching respectively. The roundness and edge quality of the chemically etched brass mask was superior to the mechanically fabricated steel mask.

Fig.5.9 (a) 1.5mm diameter steel mask (b) 1.4mm diameter brass mask.

Masks with circular apertures as shown in fig 5.9 were mainly used for drilling microvias and sometimes for ablating tracks. The square and rectangular masks shown in fig 5.10 were largely used for ablating tracks. The chemically
etched brass mask showed curved corners but the edge quality was superior compared to the steel mask.

![etch_brass_mask][1]

(a) (b)

Fig 5.10 Different masks used for machining of tracks (a) Rectangular steel mask (b) Square brass mask.

5.3 Absorption Measurements of CMZ Glass

For this research investigation CMZ glass with 100 μm and 50 μm thickness, supplied by Qioptiq was used. The coefficient of thermal expansion for CMZ glass is around $3.6 \times 10^{-6} \text{K}^{-1}$, which is very close to that of silicon ($2.8 \times 10^{-6} \text{K}^{-1}$).

The absorption spectra of four different glasses: CMZ, CMG (a similar glass to CMZ, but with a CTE close to GaAs), borosilicate and silica glass were measured using a Hewlett Packard 8453A diode array spectrophotometer. Initially absorption measurements were done with reference to silica glass and finally with reference to air medium. Fig 5.11 illustrates the absorption curve for the CMZ glass as a function of wavelength, which shows complete absorption in the short and medium ultraviolet range from 190 nm to 357 nm. The absorption curve for CMZ glass is stronger than the other glasses as shown in fig 5.12, which compares the absorption properties of CMZ glass with the other glasses. It can be seen that the absorption range for CMZ and CMG glass is almost the same and absorbs ultraviolet wavelengths in a broader range from 190 nm to 357 nm compared to silica glass and borosilicate glass, which only absorb the ultraviolet light in a narrower range from 190 nm to 300 nm.
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5.4 Machining Process and Characterisation

Glass handling was critical since the CMZ glass sheets were very thin (50-100 μm) and damage could easily occur especially during cleaning. The following sections describe the protocols for laser machining, cleaning, sample preparation and characterisation.
5.4.1 Protocol for laser machining

CMZ glass samples supplied by Qioptiq were in the form of thin (100-50 μm) rectangular and square sheets of different dimension viz 75 x 75 mm, 60 x 20 mm, 30 x 20 mm, 30 x 10 mm, 40 x 10 mm, 50 x 10 mm. For the machining process optimisation, glass dimensions were chosen randomly with any size but fixed thickness since all sizes were easily accommodated on the sample holder. The following procedure was used for the excimer machining of the CMZ glass:

• Turn on the laser system and fill with fresh gases if required.
• Measure the pulse energy at the work piece with the power meter.
• Check beam-optics alignment and beam quality using fax paper.
• Clean the glass to be machined with acetone to remove any dirt or dust
• Since glass is optically transparent, it was difficult to see the position of the focus point on the work piece. To enable clear visibility of the beam focus point, black or blue ink, or a graphite aerosol spray was applied to the glass surface.
• The ink marked or graphite coated sample was mounted on the sample jig shown in figure 5.13a and 5.13b.
• For single features, manual adjustment of the beam focus was carried out using the photo diode array detector. For the machining of patterns, automatic focus control was chosen.
• In the case of manual operation for the machining of single features, the ON/OFF laser shutter switch was used to start and end the process for which timing was achieved using a stop-watch. For automatic control, the shutter operation was controlled by the program used for the individual pattern.
5.4.2 Sample preparation

5.4.2.1 Photoresist application

In some machining processes, especially for machining of the patterns, the glass was laminated with Ordyl Alpha 940 photo resist film. This was mainly used to reduce the adherence of debris directly to the glass as demonstrated in fig 5.14. For the photoresist lamination on the glass, a standard roll laminator was used and then it was exposed to ultraviolet light for 15 secs to harden it. A standard solution is used commercially for the removal of the photoresist film, but here, due to the small number of samples, acetone or methanol were used instead.
The quality of the photoresist film was significantly affected by the UV exposure time. Very low exposure times of around 5 secs caused poor adhesion of the photoresist film on the glass and higher exposure time led to hardening and strong adhesion to the glass which required high fluence and number of pulses during machining.

5.4.2.2 Sample Cleaning

The machined glass had loose and hard bound debris. A cleaning procedure as described below was therefore followed after laser machining:

- Soaking the machined glass samples with ink or graphite layer in isopropanol for 3-5 minutes to remove the ink / graphite. Glass laminated with the photoresist layer was soaked in acetone or methanol to remove the photoresist layer.
- Ultrasonic agitation of glass in isopropanol for 15-20 mins to remove debris using a standard ultrasonic bath.
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• Rinsing glass samples again with demineralised water and air-drying.
• In certain cases, glass samples were swabbed with acetone with the aid of lint free cloth to remove any dirt or dust particles on the glass surface.

5.4.2.3 Cross-sectioning.

Since CMZ glass is very thin and brittle, handling is critical, hence to look at cross sections of machined features the sample was carefully dissected with a diamond pen and this was then mounted with epoxy resin. Unfortunately, during further polishing, microcracks were induced, causing difficulty in identifying the original cracks. Hence, an alternative method was adopted in the later stages of the research that involved simply fracturing the sample across the machined features and mounting it vertically in a slotted SEM stub as shown in fig 5.15. This fixture was useful not only for investigating the cross-sectioned area under SEM, but also for side wall roughness measurements of microvias and tracks. In addition to this a Focussed Ion Beam microscope (FIB) was also used to produce stress free cross sections on a small area.

Fig 5.15 SEM slotted stud for looking through cross-sections in CMZ glass.

5.4.3 Investigation of debris and microcracks

Debris and microcracks are major issues in the manufacture of glass substrates since they can cause undesirable effects during subsequent processes. For investigating debris, Olympus and Nikon optical microscopes were used, but it was difficult to identify microcracks in the machined features, hence SEM analysis was used. Since glass is a non-electrical conductor, a thin layer of gold was deposited on the glass surface using a vacuum coater to make it conductive for SEM observation.
5.4.4 Ablation depth and surface roughness measurements

For measuring ablation depth of tracks and blind microvias, three kinds of equipment were used: TALYSURF 4, TALYSURF CLI 2000 and ZYGO white light interferometer. All these methods have their own merits and demerits. Initially, for basic measurements such as approximate depth measurements and average roughness, TALYSURF 4 was used, however, in the later stages of this research, the other two methods were more frequently used. As a normal practice, most of the depth and surface roughness measurements were carried out with the Zygo white light interferometer and were processed and analysed using the Talymap software in the CLI 2000 system.

5.4.4.1 TALYSURF 4

This technique used a thin probe to trace the variation in the depth of the sample across the length and the width and provided data on the average surface roughness. However, it did not give any information regarding 3D surface profile and the depth measurements were restricted to a small width of around 5 mm. Ablation depths of tracks with widths as small as 100 µm in 100 µm thick glass were measured successfully, but the ablation depth of blind microvias were difficult to measure due to their depth and taper profile. However, this method was useful for approximate measurements of depth in tracks or across steps.

5.4.4.2 ZYGO WHITE LIGHT INTERFEROMETER

The Zygo white light interferometer works on the principle of a traditional interferometer, where a pattern of dark and bright fringes occurs due to the optical path difference between a reference beam and sample beam. In this system, white light is split inside the interferometer; one beam goes to an internal reference and another to the sample, and after reflection, both the beams produce dark and bright fringes. It is a non-contact type of technique, which measures roughness and depth profile over a small area. It can also generate 3D surface profile maps. For more details refer to [1]. Since glass is optically transparent, it was difficult to measure ablation depth on the bare glass since most of the light was transmitted through. However, depth measurements in the machined glass with a thin gold coating were
successfully performed. This method was not appropriate for quantitative analysis of surface roughness and side wall roughness of features as it gave only average values for the selected region.

5.4.4.3 TALYSURF CL1 2000

This is a surface scanning topography instrument, which moves the work piece under a stationary gauge head. The CL1 is equipped with Talymap and 3D analysis software. With this it was possible to measure point to point roughness and depth across the sample. Again due to its optical transparency it was difficult to measure the depth of machined features in glass, however, it gave good profiles with gold coated samples. It was also possible to get depth profiles across a large area.

5.5 Summary

This chapter has explained the research methodology and the experimental techniques. The next four chapters will discuss the experimental results achieved through this defined route.

References

6 MACHINING OF MICROVIAS IN CMZ GLASS

6.1 Introduction

Microvias are a vital feature in the electronic printed circuit board. With the increasing demand for miniaturised electronics, the pitch size of the components is continuously decreasing and, in turn, array packages and flip-chips require substrates with extremely fine lines and small size microvias [1]. This requires reliable processes which can drill clean microvias down to 50 μm and below with high accuracy [2]. For machining of hard and brittle material like glass the excimer laser is an appropriate tool, as it operates in the ultraviolet range, in which these materials strongly absorb. However, machining of glass is still a challenging task due to microcracks and recast layer formation in and around the microvias during the machining process [3]. This experimental chapter deals with the machining of microvias in CMZ glass using a KrF excimer laser (248 nm). To produce microvias with the minimum amount of recast layer formation, debris, no microcracks and minimum sidewall taper, it is necessary to investigate the effect of process parameters and optimise and characterise the machined features.

6.2 Experimental Details

Microvias were machined in CMZ glass sheets of thickness 100 μm and 50 μm. Through-hole microvias of 100 μm diameter entry hole were machined to characterise the effect of variations in fluence (J/cm²), pulse repetition rate and irradiation time and to identify the process window for machining microvias. Further, to explore the process limits, different sizes of microvias were drilled to identify the smallest size achievable with the laser set-up. As mentioned in the previous chapter, pulse energy at the work piece was measured using a power meter. Since beam characteristics also influence the machining process, the effect of the beam profile on microvia drilling was also investigated. The machined glass samples were cleaned as described in chapter 5 and characterised using an Olympus optical microscope and SEM analysis. For ablation depth and sidewall surface
roughness measurement, a Zygo white light interferometer and TALYSURF CLI 2000 were used.

6.3 Results and Discussion

Since glass is a hard material, it requires high laser beam energy compared to other polymeric and metallic materials [4]. This means the ablation threshold (minimum energy required to ablate the material) for glass is higher than for other materials. The ablation threshold of 1.5 J/cm² for the CMZ glass was obtained by measuring the laser beam energy (mJ) per pulse at the work piece with the power meter and through visual inspection of samples, identifying at what power level machining of the sample commenced. The ablation threshold was also obtained from the experimental values by extrapolating a plot of ablation depth as a function of fluence on a semi-log scale. Fig 6.1 shows the plots of ablation depth in CMZ glass versus fluence, at different irradiation times and number of pulses: 5 s and 10 s for a circular spot size of 130 μm. There was little variation in threshold fluence values obtained with both plots, both were found to be in close agreement with the measured values. The ablation threshold value of the spot ablated at 5 s was 1.5 J/cm² which was the same as the measured value, while that for 10 s was 1.27 J/cm² showing 15% deviation from the measured value.

![Fig. 6.1 Variation of ablation depth with fluence for a 130 μm diameter hole in CMZ glass at 5 Hz repetition rate.](image-url)
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The above graphical relation is based on the Beer–Lambert law which is expressed in equation 6.1 [5].

\[ \Delta d = \ln\left(\frac{F_f}{F_0}\right)/\alpha \]  

(6.1)

Where \( \Delta d \) = ablation depth, \( F_f \) = fluence at work piece, \( F_0 \) = threshold fluence of the material, \( \alpha \) = absorption coefficient.

6.3.1 Process optimisation

While drilling through-hole or blind hole microvias in CMZ glass, entry holes were found to be in close agreement with the shape and size of the mask aperture. This can be seen in fig 6.2b and 6.2d which shows the images of entry holes of 100 \( \mu \)m and 93 \( \mu \)m microvias drilled with a 1.5 mm circular aperture fabricated mechanically in a steel mask (fig 6.2a) and a 1.4 mm circular aperture chemically etched in a brass mask (fig 6.2c) respectively. However, the shape and size of the exit hole depended on the laser beam characteristics and the laser process parameters.

Fig.6.2 Excimer laser drilled microvias in 100 \( \mu \)m thick CMZ glass (b) microvia drilled with 100 \( \mu \)m spot size with steel mask (a), (d) microvia drilled with 93 \( \mu \)m spot size with chemically etched brass mask (c).
To identify the operating window for the microvia drilling process, the effect of laser operating parameters: laser pulse energy /energy fluence, repetition rate and irradiation time were investigated. Through-hole drilling of 100 μm diameter microvias in 100 μm thick glass was successfully achieved at energy fluences as low as ~2.3 J/cm² at 30 Hz repetition rate and 40 s irradiation time. However, a tapered profile was identified in all the microvias irrespective of size. Fig 6.3 shows the cross section of a 100 μm microvia drilled in 100 μm thick glass at 4 J/cm² with an uniform tapered profile across the thickness.

The angle of taper in the microvias was evaluated using geometry and was also obtained directly from measured values of entry and exit holes as shown in fig 6.4. As reported by Crafer [6], during the microvia drilling process, diffractive effects at the edge of the hole are produced, resulting in a low fluence and ablation rate near the edges of the hole. Hence, with the progression of drilling through the thickness of the glass, a tapered hole is produced. Based on this, it is expected that with increase in fluence, the edge effect will reduce and so the taper angle will reduce. Fig 6.5 shows a graphical presentation of the taper angle of the microvias as a function of the fluence which shows a reduction in the taper angle with increase in fluence in agreement with Crafer [6].
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Fig 6.4 Taper angle measurement of through hole.

![Taper angle measurement of through hole](image)

Fig 6.5 Variation of taper angle of 100 µm microvias drilled in 100 µm thick CMZ glass with respect to energy fluence at 60 Hz repetition rate and 30 s irradiation time.

![Graph showing variation of taper angle](image)

Other factors such as the numerical aperture of the optics, beam divergence and shadowing effects also favour a tapered profile of the holes [7]. Since the Numerical Aperture (NA) varies with the depth of focus (d.o.f.) according to:

\[ d.o.f. \propto \frac{1}{NA^2} \]  

(6.2)
the smaller the NA value, the higher is the d.o.f., which will lead to a smaller taper angle. However, high beam divergence will lead to low depth of focus, which is likely to produce a bigger taper angle when drilling holes. This means along with laser fluence, the optical set-up of the laser system also plays an important role in the final profile achieved.

6.3.1.1 Effect of Energy Fluence

According to fig 6.5 as the energy fluence increases, the taper angle decreases, which means that the exit hole diameter of the microvia increases. Initially the maximum fluence achieved at the work piece with the standard beam delivery set-up was ~ 3 J/cm². Fig 6.6 shows a plot of exit hole diameter as a function of time and fluence for 100 μm entry hole diameter microvias at 20 Hz repetition rate and shows that the exit hole diameter increased with increase in fluence. Increasing the fluence from 2.3 J/cm² to 3.0 J/cm² also reduced the drilling time to produce through hole microvias from 20 s to 5 s. However, the maximum size of the exit hole diameter achieved with maximum fluence of 3 J/cm², along with repetition rates of ≥ 20 Hz and irradiation time of 30-50 s, was ~30 μm with a taper angle of 19°.

![Graph showing exit hole diameter as a function of irradiation time for 100 μm microvias machined in 100 μm thick CMZ glass for 20 Hz repetition rate and variable fluence.](image)

Fig 6.6. Exit hole diameter as a function of irradiation time for 100 μm microvias machined in 100 μm thick CMZ glass for 20 Hz repetition rate and variable fluence.
Since fluence is the main driving force to increase the exit hole diameter of microvias, trials were conducted to increase the fluence at the work piece and ultimately, the attenuator device, one of the optical elements in the beam delivery system was removed such that the fluence at the work piece increased from 3 J/cm$^2$ to 4.5 J/cm$^2$. With 4.5 J/cm$^2$ the taper angle limit reduced to 14° and the maximum achievable exit hole diameter increased to ~50 μm, as shown in fig 6.7.

The effect of the fluence on the microvia drilling process is clearly shown in fig 6.8, which compares microvia drilling at low and high fluences. Microvias drilled at 4.2 J/cm$^2$ had a bigger exit hole of ~40 μm compared to microvias drilled at 2.6 J/cm$^2$, which had an exit hole diameter of ~20 μm. Apart from this, the shape of the exit hole closely matched with that of the entry hole in the microvias drilled at 4.2 J/cm$^2$. In microvias drilled at 2.6 J/cm$^2$, the exit holes were very small with irregular geometry and also the edge quality of the holes was poor due to thermal damage near the edges, especially near the entry holes as shown in fig 6.8b. This is because, as described by Hornberger [8], at lower fluences, the heating and melting effect dominates as absorbed energy is converted to lattice vibration and is not enough to cause breaking of bonds and results in material removal by photothermal ablation.

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![Fig 6.7 Comparing the profile of exit hole diameter as a function of repetition rate of 100 μm diameter microvias at 3.0 J/cm$^2$ and 4.5 J/cm$^2$ fluence at fixed irradiation time of 20 s.](image-url)
Fig 6.8 100 μm microvias drilled in 100 μm thick glass at (a) 4.2 J/cm², 50 Hz and 20 s (1000 shots) (b) 2.6 J/cm², 60 Hz, 30 s (1800 shots).

Number of pulses per spot size

In the microvia drilling process, the number of pulses required to drill with a particular spot size can be obtained from equation 6.3:

\[ P_n = R \times t \]  

(6.3)

where \( P_n \) is the number of pulses, \( R \) is the repetition rate and \( t \) is the irradiation time.

For 100 μm entry hole diameter microvias, a minimum of 150 pulses were required to drill through holes even at maximum fluence of 4.5 J/cm². Fig 6.9 shows the plots of exit hole diameter and number of pulses for 100 μm entry holes for two different fluences of 4.5 J/cm² and 3 J/cm². These were obtained using
different combinations of frequencies and irradiation times. The exit hole diameter increased with increase in number of pulses, however a limit was reached depending on the fluence, beyond which no significant increase in size of exit hole diameter was observed. With increase in fluence, the number of pulses to drill a similar size of exit hole decreased.

Fig 6.9 Variation of ablation depth with the number of pulses per spot size at a fixed fluence for microvias with 100 μm entry hole diameter in 100 μm thick glass.

It was observed that the exit hole diameter was strongly influenced by the total number of pulses irrespective of repetition rates and irradiation times used. However, a wide variation in surface morphology and geometry of the exit hole was observed for the same number of pulses delivered with different combinations of repetition rates and irradiation times. It was therefore necessary to study the individual effect of both of these parameters.

6.3.1.2 Effect of repetition rate and irradiation time

The effect of repetition rate and irradiation time on the microvia machining process was also investigated. Figures 6.6 and 6.10 show the effect of the irradiation time with respect to different energy fluences and different repetition
rates respectively on the exit hole diameter for 100 μm diameter entry hole microvias in 100 μm thick glass.

Initially, increasing the irradiation time at fixed fluence and fixed repetition rate resulted in an increase in the exit hole size. However a plateau was reached where further increase in irradiation time did not increase the exit hole diameter, but increased the amount of debris and recast layer formation. As discussed earlier, the taper profile in microvias is affected by fluence and optical setup. According to this, a limit was reached beyond which further increase in laser irradiation time at fixed fluence did not increase the exit hole diameter. In addition to this, it is reported that during drilling a dense plasma cloud from an ionised material is likely to form which may absorb part of the beam energy resulting in less energy reaching the target causing excessive thermal damage around the holes [5, 8, 9]. Moreover, as described by Bogaerts [10], a nanosecond pulse duration, such as 34 ns used here, causes some energy loss by thermal dissipation and so less energy is available for the ablation. Fig 6.11 shows the optical images of entry and exit holes of 100 μm microvias drilled in 100 μm thick CMZ glass at three different drilling times: 5 s, 10 s and 20 s, at 4.5 J/cm² fluence and 60 Hz repetition rate. The exit hole size for 5 s drilling time is smaller compared to 10 s and 20 s. For 10 s and 20 s the exit hole size was almost the same around 50 μm, but in the latter case, a
greater amount of thermal damage around the hole was found. Fig 6.11c & e shows almost an equal amount of deposited debris around the entry hole of the microvia drilled at 10 s and 20 s irradiation time respectively; however, high thermal damage was observed around the exit hole of the microvia drilled at 20 s with a wider HAZ (fig 6.11f).

![Optical micrographs of 100 μm diameter microvias drilled at 4.5 J/cm² and 60 Hz repetition rate for different drilling times](image)

Fig 6.11 Optical micrographs of 100 μm diameter microvias drilled at 4.5 J/cm² and 60 Hz repetition rate for different drilling times (a) and (b) Front and exit hole of microvia drilled for 5 s, (c) and (d) Front and exit hole of microvia drilled for 10 s (e) & (f) Front and exit hole of microvia drilled for 20 s.

Fig 6.12 shows SEM images of 100 μm microvias where uneven removal of material along the sidewalls was identified in the microvia drilled at 5 s, but with increase in irradiation time to 20 s, uniformity along the side wall surface increased.
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Fig 6.12 SEM images of 100 \( \mu \text{m} \) diameter microvias drilled at 4.5 J/cm\(^2\) fluence, 50 Hz repetition rate and irradiation time of (a) 5 s (b) 20 s.

Fig 6.13 Optical micrographs of 100 \( \mu \text{m} \) diameter microvias drilled at 3 J/cm\(^2\) and 60 Hz repetition rate for different drilling times (a) and (b) Front and exit hole of microvia drilled for 5 s, (c) and (d) Front and exit hole of microvia drilled for 50 s.

In some cases, very long irradiation times such as 40 s or 50 s at higher repetition rates caused a reduction of the exit hole diameter of the microvia due to thick deposition of debris around the hole. Fig 6.13 shows the optical micrographs of exit and entry holes of 100 \( \mu \text{m} \) microvias drilled at fixed fluence of 3 J/cm\(^2\) and fixed repetition rate of 60 Hz and different drilling times of 5 s and 50 s. The exit
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hole diameter of the microvia reduced from 30 μm to 24 μm with increase in irradiation time from 5 s to 50 s along with thick deposits of debris.

At higher repetition rate it was possible to drill through-hole microvias with shorter irradiation times down to 5 s. With increasing repetition rate this produced clean ablation, however at high frequencies of the order of 100 Hz, microcracks were induced which are described in more detail in chapter 8. Intuitively, the same number of pulses delivered with the same fluence, should produce microvias with identical dimensions whether these are delivered at low rate for longer irradiation times or at high repetition rate over shorter periods. However, while dimensionally this was the case, it was found that the surface morphology and quality of microvias machined with these two approaches was different, especially in terms of debris deposition around the microvias and geometry of the exit hole. At lower repetition rates of ~30 Hz, undercuts in the exit hole were formed due to irregular drilling around the edges, while machining microvias at the higher repetition rates of 50 Hz or above, but with the same number of pulses, produced exit holes with good edge quality and precise hole geometry.

Wide variation in the quality of microvias and shape and size of the exit holes was identified when different machining parameters were used. These effects for 100 μm microvias are summarised in fig 6.14 with the basis that maximum...
fluence achievable at the work piece was 4.5 J/cm$^2$. From the overall investigation it was observed that microvias at repetition rates of the order of 60 Hz and 5 s (300 pulses) and maximum fluence of 4.5 J/cm$^2$ had maximum exit hole diameter (50 µm), minimum debris deposition and uniform side wall roughness.

6.3.1.3 Drilling smaller size microvias

Due to the tapered profile, through-hole microvia drilling was restricted to a particular size depending on the glass thickness beyond which it was difficult to achieve through-holes. This depends on various factors such as glass composition, the maximum fluence achieved at the work piece and laser beam characteristics. To explore this limit, different size microvias from 100 µm to 25 µm in diameter were drilled in the 50 µm thick CMZ glass. Through-hole drilling was successfully achieved down to 40 µm, but beyond this, only blind microvias were formed. Fig 6.15 illustrates the optical images of the microvias drilled in 50 µm thick glass with entry hole diameters of 50 µm and 40 µm. Maximum exit hole diameter achieved was around 20 µm and 9 µm respectively.

Fig 6.16 describes the theoretical capability with simple geometrical rules to achieve the smallest through-hole microvias in 100 and 50 µm thick glass on the basis of process optimisation results of 100 µm microvias in 100 µm thick glass discussed in the previous section. According to this, the smallest through-hole microvia size is limited to slightly above 50 µm and 25 µm in 100 µm and 50 µm thick glass respectively. Using this model, the exit hole diameter for different entry holes can be calculated using equation 6.4:

$$D_t = D_0 - 2t \tan(\theta)$$

(6.4)

where $\theta$ is the taper angle and $t$ is the thickness of the glass, $D_t$ is the exit hole diameter and $D_0$ is the entry hole diameter. For simplicity, $\theta$ is assumed to be 14 °, which is the minimum taper angle identified in 100 µm diameter entry hole microvias drilled in 100 µm thick glass.
Fig. 6.15 Optical images of different sized microvias drilled in 50 μm thick CMZ glass at 4.5 J/cm²: (a) & (b) 50 μm microvia drilled at 40 Hz and 20 s (800 shots) (c) & (d) 40 μm microvia drilled at 50 Hz and 20 s (1000 shots).

Fig. 6.16 Theoretical presentation of the smallest achievable through-hole microvia in 100-50 μm thick glass on the basis of process optimisation results of 100 μm microvias in 100 μm thick CMZ glass.
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An exit hole diameter for the given entry hole of different sized microvias was calculated using equation 6.4. Fig 6.17 compares the plots of microvia exit hole diameter as a function of entry hole diameter in 50 μm thick CMZ glass, for the model and measured values of microvias. With decrease in microvia size, the variation between theoretical and experimental values for the exit hole diameter increased, indicating that with decrease in microvia entry hole diameter, the taper angle increased. This difference in gradient may be because, with decrease in microvia size (beam spot size), the energy per pulse decreased and reduced the ablation rate [11]. In addition to this, several other factors such as plasma formation which absorbs part of the laser beam energy, laser beam scattering effects and laser beam characteristics can also contribute to reduce the laser beam energy with decrease in beam spot size. Hence the practical process limits were not as high as the theoretical assumptions.

From the above process optimisation, it was identified that microvia aspect ratios of the order of 1.25:1 (diameter to thickness) were the best that could be achieved in glass with the excimer laser used here.
6.3.1.4 Effect of laser beam quality on the microvia machining

The laser beam intensity profile also strongly affected the machining process. A poor beam quality or an inhomogeneity of the laser beam intensity profile caused problems during machining. Laser beam quality was influenced by several factors such as dirty optics, alignment of optics in the resonator and beam delivery system, and appropriate beam focus.

Effect of Dirty Optics

For the glass drilling, high energy fluence, high repetition rates and irradiation times were required, due to which the optics in the resonator became frequently dirty. The dirt on the optics caused either absorption or scattering of part of the beam resulting in an inhomogeneous beam profile with slightly lower pulse energy. Through-hole microvia drilling in 100 μm CMZ glass was almost impossible or required a very high number of pulses of roughly around 3000 shots with such a beam quality. Furthermore, the beam produced by dirty optics had low fluence compared to that of cleaned optics, which caused high thermal damage in the glass during microvia drilling.

Influence of optics alignment in the resonator and beam delivery system

Laser beam alignment is an important issue to be taken into consideration during laser material processing. This is because slight misalignment can cause dramatic changes in the beam profile and intensity distribution. Misalignment of the optics will result in the beam being projected slightly inclined to the surface which will lead to uneven taper profile of the machined feature. For example slight misalignment of Mirror 2 as shown in fig 6.18 produced microvias with an asymmetric taper as shown in fig 6.19 since the beam was projected slightly offset through the mask plane and the projection lens onto the work piece as shown by the dotted lines.

Effect of Laser beam focus on the microvia machining process

Beam focus was adjusted to the neutral point by moving the Z axis of the stage up and down either in manual mode or auto mode, the position of which was given by the photo diode detector. Movement of the Z axis was very sensitive hence fine focus adjustments were required. Changes in the work piece position slightly above or below the focal position of the beam caused a change in the shape
and size of the microvias. The effect of machining microvias in the glass slightly above and below the focal position of the beam has already been discussed in chapter 5.

Fig 6.18 Schematic diagram of the excimer laser beam delivery set-up showing the effect of misalignment of Mirror 2.

Fig. 6.19 Effect of laser beam misalignment on microvia drilling (100 µm entry hole) drilled in 100 µm thick glass at 2.5-3 J/cm², 20 Hz, and 20 s.

With change in the focal position of the beam spot, the beam intensity distribution and the spot size also changed, which has also been demonstrated by Bordatchev [12] using a Gaussian beam. This further caused changes in ablation rate and the size and shape of the microvia.
6.3.2 Microvia characterisation

For substrate manufacture, it is necessary to produce clean, defect free microvias with precise feature size and minimal sidewall roughness for reliable interconnection. Irregular sidewall and cross section profiles can cause void formation during metallisation, subsequently leading to failure of the device. Straight or inclined profiles enable uniform smooth metal coating of microvias [2]. As discussed in the previous section, a wide operating window was identified for microvia drilling in CMZ glass, which produced microvias with a tapered profile and with different size and shape of the exit hole. However debris, recast layer and microcrack formation are key issues during machining which are discussed in this section.

6.3.2.1 Debris and recast layer formation

As discussed in chapter 3, in excimer laser processing, material removal takes place mainly by two processes: (a) Photochemical (athermal) process in which the ablation occurs by direct breaking of the chemical bonds; (b) Photothermal (thermal) process in which ablation occurs by heating and melting of the material. Often one mechanism will be dominant depending on the laser wavelength and the material to be machined. For glass, ablation takes place with both mechanisms depending on the wavelength and process parameters [13]. Since a recast layer around the entry and exit holes was observed here, it can be assumed that at least some of the material was removed by thermal ablation.

While machining of microvias, a Heat Affected Zone (HAZ) was observed around the entry and exit holes. The width of the HAZ depended on the laser machining parameters and laser pulse duration. A long irradiation time produced a wider HAZ. Fig 6.20 a & b show SEM images of entry and exit holes of a 100 μm diameter microvia drilled in 100 μm thick glass, where the regions around the entry and exit holes show significant thermal damage.
While machining microvias in CMZ glass, a loose debris and recast layer was formed around the entry and exit holes. Recast layer formation around the holes and along the sidewalls of microvias was identified in almost all 100 μm and 93 μm through-hole and blind hole microvias in a wide operating window. However, the amount of recast layer formation depended on the laser parameters. With increase in fluence, the recast layer formation decreased as shown in fig 6.21, where the width of the recast layer around the entry holes reduced with increase in fluence from 2.6 J/cm² to 3 J/cm². Long irradiation time also increased the recast layer formation around the edges of entry and exit holes. This effect is shown in fig 6.22, which shows areas with re-solidified glass around the edge of the entry hole.

To remove the debris and recast layer formed around the microvias, glass samples were ultrasonically cleaned in an isopropanol bath (fig 6.23 b&c). Loose
debris around the microvias were easily removed by this method, however it was difficult to completely remove the hard crust of recast layer (fig 6.23b).

6.21 100 μm entry hole diameter microvias drilled at 40 Hz and 5 s (a) 2.6 J/cm² (b) 3 J/cm².

6.22 100 μm entry hole diameter of microvias drilled at 60 Hz and 2.6 J/cm² fluence (a) 5 s (b) 50 s.
In order to reduce the level of debris and recast layer attached to the surface, a method similar to that used by Kawamura [14] was used. This involved applying a protective polymer film to the surface of the glass such that debris would not be able to adhere directly to the glass surface. In this case, a dry film photoresist was used which was applied to both sides of the glass using a standard roll laminator (described in detail in chapter 5). After machining on this glass, the resist was removed by soaking it for a few minutes in an acetone or a methanol bath and subsequently, the glass was cleaned in an ultrasonic bath with isopropanol. This minimized the amount of debris and recast layer adhering to the glass, but it was still difficult to prevent it completely (Fig. 6.23c). It was observed that, with a high number of pulses, it was difficult to prevent the deposition of debris around the microvia. Fig 6.24 shows entry holes of microvias drilled at 4.5
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J/cm² on glass laminated with a photoresist film with 400 pulses (fig 6.24a) and 1600 pulses (fig 6.24b) for which the 1600 pulses sample showed a greater amount of deposited debris. This was because the ablation threshold of the photoresist material was much lower than that of the CMZ glass so that at a fluence of 4.5 J/cm² the laser beam spot instantly vaporised the photoresist film and subsequently for a high number of pulses, debris and recast layer formed during the machining process, adhered to the glass surface. The use of the photoresist layer was very effective for 100 μm diameter microvias drilled in the 50 μm thick glass, which showed clean microvias with almost negligible debris adhered (fig 6.25). This method was useful not only to reduce the level of debris, but also for the subsequent metallisation process which enabled selective plating on the laser machined glass.

![Fig 6.24 Optical images of 100 μm microvias drilled in glass that had been laminated with a photoresist film using 4.5 J/cm² fluence and 80 Hz repetition rate (a) 400 pulses (b) 1600 pulses.](image)

![Fig 6.25 SEM micrograph of 100 μm microvia drilled in photoresist laminated 50 μm thick glass.](image)
6.3.2.2 Side wall roughness of the microvias

As mentioned previously, the sidewall roughness of the microvia is an important aspect for the subsequent metallisation process and reliable interconnection. The roughness factor is of prime consideration for adhesion of the metal coating. Sidewall surface roughness of the laser machined microvias was measured using two techniques: Zygo white light interferometer and Talysurf CLI 2000 which are generally used for depth, surface roughness and surface profile measurements in different materials. CMZ glass samples machined with microvias were carefully cross-sectioned using a diamond pen, which allowed the glass to be broken across the microvia and were either mounted using epoxy resin or directly mounted on a SEM vertical stub (fig 5.14).

Roughness values were measured in two samples consisting of a single microvia drilled at 30 Hz and 60 Hz with a fixed fluence of 4.5 J/cm² and 20 s. Fig 6.26 shows the surface profile and 3D profile of a cross-sectioned area of the 100 μm diameter microvia drilled in 100 μm thick CMZ glass. In this case, the sample was gold coated and directly mounted on an SEM vertical stub.

![Fig 6.26 Surface profile and 3D profile obtained with Zygo white light interferometer of a 100 μm microvia drilled in 100 μm thick CMZ glass at 4.2 J/cm², 30 Hz, 20 s drilling time.](image)

Table 6.1 Roughness measurement along the sidewalls of a 100 μm microvia in 100 μm thick glass.

<table>
<thead>
<tr>
<th>Region</th>
<th>Roughness Value (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near entry hole</td>
<td></td>
</tr>
<tr>
<td>Central region</td>
<td></td>
</tr>
<tr>
<td>Near exit hole</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 shows the average roughness values (Ra) measured at different areas along the sidewall of 2 microvias machined with different laser parameters. In both the microvias, it was found that the area of the sidewalls near
the exit hole was smoother than other regions. A wide range of values were obtained and error limits were determined in one microvia drilled at 30 Hz and 20 s. However, in another sample drilled at 60 Hz and 20 s, it was difficult to determine many values which may have been due to non-uniform or a very thin gold coating.

Table 6.1 Sidewall roughness measurement in microvias with 100 µm entry hole diameter in 100 µm thick glass.

<table>
<thead>
<tr>
<th>Position along sidewall</th>
<th>Ra value (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microvia drilled at 30 Hz, 20 s and 4.2 J/cm²</td>
<td></td>
</tr>
<tr>
<td>Near entry hole</td>
<td>0.2 ± 0.04</td>
</tr>
<tr>
<td>Central portion</td>
<td>0.25 ± 0.05</td>
</tr>
<tr>
<td>Near exit hole</td>
<td>0.012 ± 0.04</td>
</tr>
<tr>
<td>Microvia drilled at 60 Hz, 10 s and 4.2 J/cm² (only single values measured)</td>
<td></td>
</tr>
<tr>
<td>Near entry hole</td>
<td>0.28</td>
</tr>
<tr>
<td>Central portion</td>
<td>0.19</td>
</tr>
<tr>
<td>Near exit hole</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Sidewall roughness was higher at the higher repetition rate, the average value being 0.2 µm at 60 Hz and 0.16 µm at 30 Hz. However still, more investigation is required to analyse fully the effect of laser parameters on sidewall roughness. Roughness around the exit hole was less compared to middle and upper areas and this was also observed under SEM as shown in fig 6.27. The sidewall surface near the entry hole was rough due to thermal damage produced by the laser beam and glass interaction, which subsequently reduced further going towards the exit hole.

Fig 6.28 shows a typical profile as a function of microvia diameter that was measured along the sidewall of a microvia drilled with 30 Hz, 4.2 J/cm² and 20 s drilling time. From the sidewall roughness measurement in a few microvias, it was observed that the roughness values were within the range of 0.8 µm–0.3 µm.
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Fig 6.27 SEM image of 100 μm diameter microvia cross section drilled in 100 μm thick glass at a fluence of 4.2 J/cm², 30 Hz repetition rate and 20 s irradiation time.

Fig 6.28 Profile of the sidewall of a microvia drilled with 30 Hz, 20 s and 4.2 J/cm².

6.3.2.3 Undesirable defects produced during microvia machining of CMZ glass

Since glass is hard and brittle in nature it is likely to produce several undesirable defects such as microcracks, chipping and undercuts along the edges and void formation along the sidewalls of the hole. Microcracking was the major problem during microvia machining. There are several reasons reported in the literature for the microcracking of glass, which are discussed in detail in chapter 8. In most machined microvias microcracks were observed along the side walls as shown in fig 6.29 which shows a 100 μm diameter microvia machined at 4.5 J/cm², 50 Hz repetition rate and 20 s irradiation time in 100 μm thick glass. Voids were also observed in some microvias near the entry holes due to melting and ejection of
the material. Fig 6.29 shows a void of around 2 μm formed near the edge of the entry hole. Using very short drilling times of 5 s or less, at high fluence and repetition rates, such defects could be avoided.

Fig 6.29 SEM micrograph of 100 μm diameter microvia drilled in 100 μm thick glass at 4.5 J/cm², 50 Hz and 10 s.

Fig 6.30 Exit hole of 100 μm diameter microvia in 100 μm thickness glass drilled at 4.2 J/cm², 40 Hz, 20 s.
Chipping and undercuts near the edges of the entry and exit holes were also observed in many microvias (fig 6.30). However chipping and undercuts near the edges were avoided by using appropriate laser parameters such as high fluence and high repetition rates.

6.4 Machining of Microvias using a different Excimer Laser

Due to the failure of the excimer laser based at Loughborough University, microvia drilling in CMZ glass was also carried out using a different KrF excimer laser (248 nm) with slightly different features. This facility was based at the School of Mechanical, Aerospace and Civil Engineering (MACE) of Manchester University and was used for only two days mainly to machine pads and microvias in double layer bonded glass sheets with an underlayer of metallised glass. For this work, 75 μm diameter microvias were drilled in 100 μm thick glass using a steel mask with a circular aperture as shown in fig 6.31.

![Circular mask aperture of 0.75 mm size fabricated in the steel plate.](image)

6.4.1 Excimer laser system

The excimer laser used was a GSI Lumonics, IPEX 848, KrF operating at 248 nm with an average power of 80 W, 400 mJ maximum pulse energy with average pulse duration of 20 ns and maximum repetition rate of 200 Hz. The beam exiting the laser unit was of 28 mm diameter with a divergence of 2 mrad. A maximum pulse energy of 6.7 J/cm² at the work piece was delivered with this set up. For this work, a projection lens giving a 1:10 reduction ratio was used. A vacuum chuck
was used to hold the sample in place however, there was no device for fine and coarse control of the focus and therefore the focal point was numerically calculated and adjusted by trial and error.

6.4.2 Microvia machining in the glass

Through-hole drilling of 75 μm microvias in 100 μm thick CMZ glass was successfully achieved with this excimer laser. Fig 6.33 shows the optical images of the entry and exit holes of 75 μm microvias drilled in photoresist laminated CMZ glass at 5 J/cm², 40 Hz and 20 s that produced an exit hole diameter of around 34 μm in size with a taper of 12°. Dimensions of the microvia were in close agreement with the mask size, however, the shape of the microvias was found to be slightly distorted which was mainly due to poor focus control and, since only a few samples were machined and investigated, it is difficult to comment further.
6.4.3 Surface characterisation

Microvias produced without photoresist laminated film at 40 Hz, 20 s and 5 J/cm$^2$ showed a high amount of debris that was cleaned in isopropanol revealing a thick layer of remelt deposition around the front and the exit hole as shown in fig 6.34. This may be because of long irradiation time; however, further detailed investigation of the effect of laser parameters in a wide range was beyond the scope of this brief study.

Fig 6.34 SEM image of the 75μm microvia drilled at 20 s, 40 Hz and fluence of 5 J/cm$^2$.

Fig 6.35 SEM micrograph of 75 μm microvia drilled at 20 s, 40 Hz and fluence of 5 J/cm$^2$. 
Microcracks were identified along the sidewall of the holes as shown in fig 6.35. However, the sidewalls were comparatively smooth compared to those machined with the excimer laser based at Loughborough University.

6.5 Discussion

Through-hole drilling of microvias was successfully achieved with both of the KrF excimer lasers. The GSI Lumonics, IPEX 848, KrF 248 nm gave more fluence at the work piece (6.7 J/cm²-maximum fluence) and it was therefore possible to drill microvias with low taper angle of around 12 degrees or less. This result can be combined with the original plot shown in fig 6.5 of the effect of fluence on taper angle to give fig 6.36. This shows that the trend identified with the Lamda Physik laser was continued to higher fluence with the Lumonics laser. However, as shown in fig 6.34 and 6.35 a thick recast layer was observed in these microvias due to the high fluence.

In general, increase in fluence favours a large exit hole diameter of the microvias and higher aspect ratios in glass, however defects like microcracks, debris and recast layer cannot be avoided. Glass laminated with photoresist layer prior to machining minimised the adherence of debris and recast layer around the entry and exit holes, but microcracks were still formed.

![Fig 6.36 Variation of the microvia taper angle in 100 μm thick CMZ glass with fluence.](image)
6.6 Conclusion

- Microvias were successfully drilled in 100 μm thick CMZ glass using an excimer laser operating at 248 nm. 100 μm holes could be drilled in as little as 5 s. A process window was successfully identified for microvia drilling and by modifying the beam delivery system the fluence at the work piece was improved by 30% from 3 J/cm² to 4.5 J/cm² which improved the maximum taper profile from 19° to 14°. This enabled exit hole diameters up to 50 μm to be achieved in microvias with entry holes of 100 μm diameter in 100 μm thick glass.

- Process limits to drill the smallest microvias were explored and it was possible to drill through-hole microvias down to 40 μm diameter in 50 μm thick glass provided the maximum fluence at the work piece was 4.5 J/cm².

- Debris and recast layer formed around the holes, but it was possible to minimise debris deposition by laser drilling the glass laminated with a photoresist layer.

- Surface roughness along the microvia sidewall varied with the laser machining parameters and measured values were between 0.8 μm and 0.3 μm. However roughness increased with increase in repetition rate or number of pulses. Roughness near the exit hole edge was less compared to other parts of the microvia interior.

- Microcracks were identified along the sidewalls in the 100 μm microvias drilled at 100 Hz and 50 Hz and will be investigated further in a later chapter.

References


Chapter 7: Machining of Tracks in CMZ Glass

7 MACHINING OF TRACKS IN CMZ GLASS

7.1 Introduction

Micromachining of tracks/channels using laser technology is becoming a versatile approach since it offers many advantages such as the non-contact nature of machining, which eliminates tool wear found in conventional drilling processes and it can machine more precisely and accurately, producing small feature sizes of the order of 100 μm. Micromachining of tracks can involve a number of applications starting from microfluidic channels for lab on a chip, in biomaterials, waveguide fabrication and in electronic packaging for interconnection [1].

This chapter deals with machining of tracks/channels/grooves in the 100μm thick sheets of CMZ glass with an excimer laser to identify a process operating window by studying the effect of each process parameter, followed by characterisation of the machined features to investigate aspects such as debris deposition, microcracking and surface roughness of the tracks. The aim was to create tracks for subsequent metallisation with uniform and appropriate roughness to achieve good adhesion of the metallised layer and a laminated substrate with no microcracks and good mechanical strength for reliable interconnection.

7.2 Experimental Details

Tracks of width around 100 μm and 480 μm in 100 μm thick CMZ glass sheets were laser machined using steel and brass masks with circular, rectangular and square apertures. Fig 7.1 shows the different types of mask used for machining of the tracks, details of which are also discussed in chapter 5.

Fig 7.1 Different masks used for machining of tracks (a) rectangular steel mask (b) square brass mask (c) steel circular mask.
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A visual basic program with automatic beam focus was used to control the sample stage to machine tracks with the excimer laser. Effect of the process parameters such as energy fluence, repetition rates and stage translation speed on the ablation rate, roughness and track surface profile as a function of mask size and shape were investigated to identify the best operating window for machining of the tracks. The techniques such as Talysurf 4, Talysurf CLL, Zygo white light interferometer (methods described earlier in chapter 5) and SEM analysis were used to measure the depth and surface profile of the tracks. In most cases, since glass is optically transparent, it was difficult to measure the ablation depth of tracks on the bare glass, so the samples were gold coated to make them observable and enable depth and roughness measurements. In addition to this, to explore the process limitations, tests were conducted to machine tracks with the smallest possible width.

Machined samples were routinely cleaned ultrasonically in isopropanol. A few glass samples were machined with the CMZ glass laminated with a photoresist layer to compare the behaviour of debris and recast deposition around the tracks. Machined tracks were characterised using optical microscopy and SEM analysis to investigate the microstructure, deposition of debris and the microcracking behaviour. To look at cross sections of the tracks, vertical SEM stub holders were used to directly mount glass samples which were cross-sectioned using a diamond pen (fig 5.14), and conventional epoxy mounting methods were also used. The features were very fine and, especially for tracks, even cross sectioning with a diamond pen produced cracks in the sample, so to avoid such defects, some tracks were machined at the edge of the glass sample, so that they could be directly observed. Such samples were directly mounted on SEM vertical stubs.

7.3 Results and Discussion

7.3.1 Initial Observations

Compared to microvia drilling, machining of tracks in CMZ glass required a lower range of laser process parameters to produce tracks with a depth range of 5-20 μm. The shape and size of the tracks produced were in close agreement with
the mask shape and size. Close tolerances of around 10 μm or less were observed between the spot size and width of the machined tracks depending on the spot size. Fig 7.2 shows the optical image of a 100 μm wide track machined with a circular mask (fig 7.1c).

![Optical image of excimer laser machined 100 μm wide track in 100 μm thick CMZ glass.](image)

Fig 7.2 Optical image of excimer laser machined 100 μm wide track in 100 μm thick CMZ glass.

![Optical image of the cross section of a track machined in 100 μm thick CMZ glass using square brass mask at 3.2 J/cm², 15 Hz and 50 μm/sec stage speed.](image)

Fig 7.3 Optical image of the cross section of a track machined in 100 μm thick CMZ glass using square brass mask at 3.2 J/cm², 15 Hz and 50 μm/sec stage speed.

Although the tracks were machined with good accuracy, similar to the case of microvias, machined tracks were identified with tapered sidewalls. The geometrical profile of the tracks depended on the shape of the mask. Tracks produced with circular mask had U and V shape geometry across the width depending on the laser parameters used. This was because when machining with a circular mask, overlapping of the pulses occurs as the beam progresses for which the area of overlap in the central region of the spot is larger than that near the edges. This causes more ablation in the central region of the track than at the
edges, leading to the U or V shaped profile observed. With the square mask, machined tracks had a trapezium like shape with flat bottom and tapered sidewalls since the excimer laser produced a tapered edge profile similar to that observed when machining microvias as described in the previous chapter. Fig 7.3 shows the cross section of a track machined using the square brass mask (fig 7.1a) in the 100 \( \mu m \) thick CMZ glass sample mounted in an epoxy resin.

7.3.2 Process optimisation

The required ablation depth for the fabrication of tracks was around 5-10 \( \mu m \), which would enable a metal track of this thickness to be deposited without protruding above the surface. To achieve this, the process operating window was identified by studying the effect of parameters such as energy fluence, repetition rates and the stage speed. Samples were examined for the ablation depth and surface roughness.

7.3.2.1 Effect of Energy Fluence

It was possible to ablate 100-500 \( \mu m \) wide tracks down to 10 \( \mu m \) of depth with a fluence of 2.5 J/cm\(^2\) and a stage speed of 50 \( \mu m/sec \). With increase in fluence, the ablation depth of the tracks increased linearly. Fig 7.4 shows a plot of ablation depth measured at different fluence at fixed repetition rates of 9 Hz and 16 Hz for \( \sim 480 \mu m \) wide tracks machined with the square brass mask. In this case, ablation depth was measured using Talysurf 4. The ablation rate increased with increase in fluence for a fixed number of pulses.

At low fluence, ablation in the tracks was very non-uniform, but with increasing fluence this non-uniformity decreased. This effect can be seen from the depth profiles of the tracks measured across the width of the track with the Talysurf CLI 2000 as shown in figs (7.5a, 7.5b, 7.5c). These are 100 \( \mu m \) wide tracks machined at 2.7 J/cm\(^2\), 3.42 J/cm\(^2\), 4.2 J/cm\(^2\) with the steel mask of 1.5 mm circular aperture at 20 Hz repetition rate and 100 \( \mu m/sec \) stage speed.
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The depth profiles were generated using Talymap software that calculated maximum and mean depth values of different areas across the width. The number of areas at which depth values were measured was increased with the increase in irregularity of the depth profile. Fig 7.5a shows a very irregular depth profile and the ablation depth was measured at 6 different points that gave an average maximum depth value around 1.31 μm. With increase in fluence from 2.7 J/cm² to 4.2 J/cm² the depth profile improved, due to uniform ablation across the width. However, uniformity along the length of the track depended on the accuracy of focus control.

As mentioned in the previous chapter, at low fluence, heating and melting effects dominate and it is likely that microcracks will occur. High fluence produced tracks with clean ablation, defined edges, low remelted areas and no microcracks. Machining with very low fluence led to tracks with unablated areas which reduced in size with increase in fluence. Fig 7.6 shows SEM micrographs of 100 μm wide tracks machined with a circular mask at 2.7 J/cm² and 3.4 J/cm² fluence. The track ablated at lower fluence showed unablated areas along the length of the track. However, non-uniform ablation also occurred when the laser produced a poor beam profile, particularly when the optics were not very clean.
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Fig 7.5 Depth profile of 100 μm wide tracks ablated at 20 Hz repetition rate, 100 μm/sec stage speed (a) 2.8 J/cm² (b) 3.4 J/cm² (c) 4.2 J/cm².
7.3.2.2 Number of pulses per spot size during machining of tracks

With increase in the number of pulses delivered in a given area at fixed fluence, the ablation depth increased. Therefore, the machining process can also be characterised in terms of fluence and the number of pulses delivered to a length of track equal to the spot size in the direction of motion. The number of pulses for a particular spot size can be expressed using equation 7.1:

$$P_n = \frac{D \times R}{S}$$  \hspace{1cm} (7.1)

where $P_n$ is number of pulses received per beam spot area, $D$ is the beam spot size in the direction of the beam movement, $R$ is the repetition rate and $S$ is the stage speed [2].

7.3.2.3 Effect of repetition rate

With increase in the repetition rate, the ablation rate increased proportionately. Fig 7.7 shows the plot of ablation depth of a 480 μm wide track machined using the square brass mask as a function of the repetition rate for fluences of 2.3 J/cm² and 3.2 J/cm² and the stage speed of 50 μm/sec.
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Fig 7.7 Plot of ablation depth as a function of repetition rate for 480 μm wide tracks.

However, increase in repetition rate also increased the subsurface damage in the tracks and so the surface roughness of the tracks. Fig 7.8 shows SEM images of two 480 μm wide tracks machined with a square mask at the same fluence of 1.7 J/cm² and stage speeds of 50 μm/sec, but different repetition rates. Fig 7.8a shows the area near the edge of the track machined at 5 Hz with an ablated depth of ~8 μm and fig 7.8b shows the edge area of the track machined at 10 Hz with the ablated depth of ~18 μm and more surface damage compared to the previous case.

Tracks machined with the same number of pulses per area with different repetition rate and fixed fluence showed the same depth, but different surface roughness values. This effect was investigated in 100 μm wide tracks machined with a circular mask at 4 J/cm². Table 7.1 shows the depth and the roughness values of the tracks measured using the Talysurf CLI 2000 and it was found that the depth was similar, but the roughness values were different. Tracks drilled at low repetition rates showed low roughness compared to tracks drilled at higher repetition rates.
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Fig 7.8 SEM images of side edges of the 480 μm tracks machined with brass mask at 1.7 J/cm², 50 μm/sec stage speed and different repetition rates (a) 5 Hz (b) 10 Hz.

Table-7.1 Ablation depths of 100 μm wide tracks in 100 μm thick glass at different repetition rates, stage speeds and fixed fluence of 4 J/cm².

<table>
<thead>
<tr>
<th>Energy (J/cm²)</th>
<th>Repetition rate (Hz)</th>
<th>Stage translation speed (μm/sec)</th>
<th>Pulses per area</th>
<th>Max Average Depth (μm)</th>
<th>Roughness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>10</td>
<td>50</td>
<td>20</td>
<td>3.05</td>
<td>0.109</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>100</td>
<td>20</td>
<td>3.7</td>
<td>0.1604</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>200</td>
<td>20</td>
<td>3.65</td>
<td>0.1820</td>
</tr>
</tbody>
</table>

Fig 7.9 (a) (b) (c) show the depth profiles of these tracks machined at 40 Hz, 20 Hz, 10 Hz repetition rates and stage speeds 200 μm/sec, 100 μm/sec and
50 μm/sec respectively, produced by the Talymap software while using Talyssurf CLI 2000. Fig 7.9c shows a good depth profile of the track across the width, which was machined at low repetition rate compared to the other two cases.

Fig 7.9c shows a good depth profile of the track across the width, which was machined at low repetition rate compared to the other two cases.

(a)

(b)

(c)

Fig 7.9 Depth profile for 100 μm wide track in 100 μm thick glass machined at 4 J/cm² (a) 40 Hz, 200 μm/sec stage speed (b) 20 Hz, 100 μm/sec stage speed (c) 10 Hz, 50 μm/sec stage speed.
During laser machining of tracks, using a pulsed laser like the one used here, with subsequent movement of the X-Y table, consecutive pulses overlap with each other. Fig 7.10a and b shows a schematic diagram of the overlap of the pulses during machining of the tracks using the circular and the square mask respectively. The overlap distance for consecutive pulses was determined using equation 7.2:

\[
\Delta d = D - \left[ \frac{S}{R} \right]
\]

(7.2)

where \(\Delta d\) = overlap distance for consecutive pulses, \(S\) = stage speed, \(D\) = beam spot size in the direction of the beam movement, \(R\) is the repetition rate.

However, the overlapping area for the tracks depends on the geometry. For example, tracks machined with a circular mask aperture have less overlapping area compared to those of a square aperture of the same size.

Fig 7.10 Overlapping of pulses along the X axis of the X-Y stage during machining of the tracks using (a) Circular mask aperture (b) Square mask aperture.

At low repetition rates of around 5 Hz, since the overlap distance between the pulses was small and as the nanosecond pulse caused heating and melting of the glass, this caused the formation of ripples after each pulse [3, 4]. This effect can be seen in fig 7.11 (a) & (b) showing SEM images of 666 \(\mu\)m (with
rectangular steel mask) and 100 μm (circular mask) wide tracks machined at 5 Hz and 10 Hz repetition rates respectively and 50 μm/sec and 100 μm/sec stage speeds respectively. Fig 7.11a shows ripples with melting along vertical lines after each pulse and fig 7.11b shows circular ripples at the edges of the track which makes the ablated surface uneven. With increase in the repetition rate, overlapping of the pulses increased further, reducing this effect and so no more ripples were observed.

Fig 7.11 Tracks ablated at low repetition rates in CMZ glass (a) 480 μm wide track ablated at 2.3 J/cm², 5 Hz and 50 μm/sec stage speed (b) 100 μm wide track ablated at 4 J/cm², 10 Hz and 100 μm/sec.

With a low number of pulses per spot size, the laser beam energy was not enough to enable uniform ablation of the tracks and this effect was clearly
identified near the start and finish of the tracks. Fig 7.12 a & b show optical images of 480 µm wide tracks machined with a square mask at fixed fluence of 3.4 J/cm² and fixed stage speed of 150 µm/sec and different repetition rates of 15 Hz and 20 Hz respectively. In both the tracks, a small unablated region near the end was identified, but the area of unablated region in the track machined at 15 Hz was larger compared to the 20 Hz one.

![Unablated area](image)

Fig 7.12 Optical images of 480 µm wide tracks drilled with a square mask at 3.4 J/cm², 150 µm/sec stage speed and (a) 15 Hz (b) 20 Hz.

### 7.3.2.4 Effect of stage speed

Since the resolution of the X-Y table in the x and y direction was 0.5 µm and 1 µm respectively, tracks could be machined at speeds as low as 50 µm/sec in the x direction and 100 µm/sec in the y direction. A low stage speed gave better quality and subsurface morphology, but using extremely low speeds would not meet the requirements of low cost high volume production. However, it was found that moderate stage speeds of the order of 400 µm/sec in combination with high
fluence ∼4.5 J/cm² and repetition rates around 20-30 Hz could produce tracks with low subsurface damage and minimum microcracks. With increase in stage speed with all other parameters constant, ablation depth/ablation rate decreased. This can be explained by the fact that with increase in stage speed at fixed fluence and repetition rate, the overlap distance between the consecutive pulses decreased. Fig 7.13 presents the plot of ablation depth as a function of stage speed and number of pulses for a 480 μm wide track, which shows that with increase in stage speed up to 150 μm/sec, the ablation depth decreased almost linearly but with further increase in stage speed, there was a much lower decrease in the rate of ablation depth, which was mainly due to a slower decrease in the number of pulses per area. It was also observed that at fixed fluence and repetition rate, increasing the stage speed increased the unablated areas especially around the ends of the tracks. Fig 7.14 shows optical images of the ends of the 480 μm wide tracks machined with the square mask ablated at different stage speeds ranging from 100 μm/sec to 400 μm/sec. An unablated region near the ends was identified in all the tracks but it was observed that, with an increase in speed, the area of the unablated region increased, starting from 7.14a to 7.14f.
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Fig 7.14 480 μm tracks ablated at 2.3 J/cm² fluence and repetition rate of 10 Hz at different stage speeds (a) 100 μm/sec (b) 150 μm/sec (c) 200 μm/sec (d) 250 μm/sec (e) 300 μm/sec (f) 400 μm/sec.

From analysis of the individual effect of each the above parameters, best parameters were identified for machining of tracks down to 5-20 μm depth. For machining of a 480 μm wide track with a square mask aperture, the best quality of the machined tracks with uniform material removal, no unablated edges and minimum defects like microcracks and recast formation and a depth of 10-12 μm was identified at a minimum of 3 J/cm² fluence, 15 Hz repetition rate, 50 μm/sec. For machining of 100 μm wide tracks at a depth of 5-8 μm with a circular mask.
aperture, the best machining quality was produced with 3.4 J/cm² fluence, 15 Hz and 50 μm/sec. Since low stage speeds gave low machining rates, high stage speeds in combination with high fluence and repetition rates were used, which still enabled uniform metallisation. These parameters were further used for machining track patterns described in chapter 10. Machining quality not only depended on the laser process parameters, but also on laser beam quality, which was affected by various factors such as laser production efficiency, condition and alignment of the optics.

7.3.2.5 Machining through different mask aperture sizes

Tracks using different size square mask apertures were machined with the same operating parameters. Ablation depth was investigated using the Talysurf CLI 2000. It was observed that with a decrease in mask aperture size, the ablation depth also decreased. Fig 7.15 shows the plot of the ablation depth as a function of mask aperture size, which varies linearly. This is because, with increase in spot size, the number of pulses delivered per area increased.

![Plot of ablation depth as a function of beam spot size with a square shape at a fixed fluence of 3.2 J/cm² and 15 Hz repetition rate.](image)

Since the beam intensity distribution was uniform with a small beam spot size, uniform ablation occurred across the width and the length of the tracks.
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machined with smaller size mask apertures. With increase in the beam spot size, the uniformity of the beam intensity decreased, resulting in non-uniform ablation across the width, depending on the energy fluence. Fig 7.16a,b,c,d shows optical images of the tracks machined with different sized square shaped mask apertures delivering the spot size of 133 μm, 333 μm, 480 μm, 666 μm at 2.8 J/cm², 15 Hz, 50 μm/sec.

![Optical images of the tracks machined with different sized square masks at 2.8 J/cm², 15 Hz, 50 μm/sec (a) 133 μm (b) 333 μm (c) 480 μm (d) 666 μm.]

It was difficult to identify accurately, the smallest possible track size that could be machined with the available excimer laser, since there were frequent problems with the laser unit in the later stages of this research, due to which, the machining quality of the features on CMZ glass were affected. However it was possible to machine tracks as narrow as 25 μm wide in CMZ glass. Fig 7.17 shows the optical image of a 25 μm wide track machined with a circular mask at a fluence of 4 J/cm², 30 Hz repetition rate and 50 μm/sec stage speed. Ablation was very non-uniform and mainly occurred in the central portion across the width of the track. Ablation depth was difficult to measure with any of the methods mentioned previously due to the very small area and highly non-uniform ablation.
7.3.3 Characterisation of the machined tracks

To obtain good reliability of the final glass substrate, the track subsurface should be free of voids and stress raising flaws with appropriate surface roughness of the tracks. For this reason, the machined tracks were characterised using various techniques such as SEM and optical microscopy to investigate debris, remelt and microcracks. Furthermore, various techniques used previously for ablation depth measurement were used for surface roughness and sidewall roughness measurements.

7.3.3.1 Formation of debris and recast layer

Loose debris was found adhered in the areas near the edges of the tracks as shown in fig 7.18, which presents the optical image of an uncleaned 480 μm track machined with a square mask. As mentioned in the previous chapter, loose debris was removed by ultrasonic cleaning of the machined glass in isopropanol. Since the tracks were ablated to a small depth, the amount of debris formed was much less compared to that from the microvia drilling process.

As described before, glass was laminated with a photoresist layer before laser machining to minimise the adhesion of debris directly onto the glass surface. Fig 7.19 a and b show SEM images of 480 μm wide tracks machined with and without lamination of the photoresist layer. Fig 7.19a shows uneven edges with a thin recast layer deposited, while fig 7.19b shows a clean edge without any recast layer deposited near the edge.
Fig 7.18 Optical image of uncleaned (ink marking still on glass surface) laser machined 480 μm wide track machined with a square mask.

Fig 7.19 SEM images of the 480 μm tracks machined with a square mask (a) without photoresist layer (b) with photoresist layer.

However, the ablated depth in the photoresist laminated glass was lower compared to that of the unlaminated glass. Fig 7.20 shows a plot of the ablation
depth and fluence for 666 μm wide tracks machined using a rectangular steel mask (fig 7.1c) at fixed repetition rate of 10 Hz and stage speed of 50 μm/sec for laminated and un laminated glass. A variation of almost 10 μm in ablation depth at all fluences was observed. This is because, low fluences of the order of ≤ 3.8 J/cm² in combination with the low repetition rates of the order of ≤ 15 Hz were used in most cases for machining of the tracks. At such low fluences and repetition rates, the photoresist film was not instantaneously machined as in the case of the microvia drilling process and required a few shots to be ablated, before machining through the actual glass surface commenced. However, the influence of other parameters such as stage speed and repetition rates still need to be investigated before it is possible to predict the overall effect of introducing a photoresist layer on the ablation rate of the glass.

![Graph](image)

Fig 7.20 Plot for depth of tracks vs fluence for 660 μm wide tracks machined with the square mask at 10 Hz repetition rate and 50 μm/sec.

In some tracks machined at low fluence of 2.3 J/cm² and low repetition rate of 10 Hz, even the photoresist layer was not removed in some areas, and was found attached to the glass layer resulting in unablated areas. Not only laser parameters, but the photoresist lamination process was also found responsible for this problem. This was usually the case when long UV exposure times of the order of 50-60 s were used for curing the laminate which made it harder (More details in chapter 5). To overcome the machining problems occurring due to the photoresist
film on the glass, further optimisation of the lamination and the machining processes of the photoresist film is required.

7.3.3.2 **Surface morphology of the tracks**

As already mentioned in the previous chapters, the ablation in glass occurs by both thermal and photothermal mechanisms, hence heating and melting occurs during ablation depending on the laser parameters and beam characteristics.

![SEM image of 666 μm wide track ablated with steel mask at 2.6 J/cm² fluence, 50 μm/sec stage speed (a) 5 Hz repetition rate (b) 15 Hz repetition rate.](image)

Since the laser beam at 248 nm is not enough to break bonds in glass, it causes lattice vibration resulting in heating and subsequent melting during ablation [5-7].

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This caused localised heating and melt ejection, resulting in the formation of debris and resolidified material. For the machining of tracks, the volume of ablated material was less compared to that for drilling microvias or holes and melt ejection was less compared to microvias. However, lumps of resolidified material were observed during surface investigation at high magnification, such as in the SEM. This was the case generally at very low fluence (2-3 J/cm²) in combination with low repetition rates (5-10 Hz). With increase in fluence or repetition rate or in other words, with increase in number of pulses per area, the amount of resolidified lumps formed decreased, however cracking of the surface was observed producing a highly rough surface. Fig 7.21 (a) and (b) compares SEM images of 666 µm wide tracks machined at different repetition rates, 5 Hz and 15 Hz and fixed fluence of 2.6 J/cm² and fixed stage speed of 50 µm/sec. In most tracks, surface cracks forming a branched interconnected network were observed, however the severity of surface cracking was low at low repetition rates and fluences. Fig 7.22 shows the magnified image of such a cracked surface examined by SEM in a 480 µm wide track.

**Fig 7.22 SEM image of 480 µm wide track ablated at 2.6 J/cm² fluence, 50 µm/sec stage speed and 10 Hz repetition rate.**

**Microcracking behaviour**

Microcracks were the major issue during machining of tracks which reduced the strength of the glass. Microcracks were generated due to thermally
induced stresses during machining. Microcracks were largely identified near the edges of the tracks in unablated or partly ablated areas as shown in fig 7.23. This was due to the fluence and number of pulses per area being insufficient to ablate or melt the glass; only localised heating occurred near the edges causing thermal cracking. Microcrack formation is discussed in more detail in chapter 8.

![Microcracks](image)

Fig 7.23 Microcracks formed during machining around the edges of a 480 μm track machined at 3.4 J/cm$^2$, 150 μm stage speed and 20 Hz repetition rates.

### 7.3.3.3 Surface roughness

Surface roughness is a key factor to be taken into consideration for the subsequent metallisation process. Increase in roughness favoured good adhesion of the metallised layer. Roughness values for the machined tracks varied between 3 μm to 0.1 μm depending on the laser parameters used and the size of the tracks. Roughness values in 100 μm wide and 480 μm wide tracks were measured to investigate the effect of laser parameters on surface roughness. Fig 7.24 a, b & c show the roughness profiles of 100 μm wide tracks measured with Talysurf CLI 2000 machined at different fluence. With increase in fluence, surface roughness of the tracks increased. Table 7.3 describes the variation of surface roughness values with respect to the fluence with fixed values of other laser parameters.

Surface roughness of the tracks also increased with increase in laser beam spot size because, as mentioned previously in section 7.3.1.4, with increase in spot
size, the number of pulses per area also increased. Surface roughness of tracks with different width ranging from 133 μm to 666 μm were measured using the Talysurf CLI 2000. Fig 7.25 shows the plot of surface roughness as a function of beam spot size which varies almost linearly. Increase in repetition rate also favoured an increase in surface roughness value as mentioned in the previous section, while with increase in stage speed the roughness value decreased as shown in fig 7.26. This was mainly due to number of pulses per area that decreased with increase in stage speed.

![Graph 1](image1)

![Graph 2](image2)

![Graph 3](image3)

Fig 7.24 Roughness profile of the 100 μm wide tracks ablated at 20 Hz repetition rate 50 μm/sec stage speed and (a) at 2.8 J/cm² (b) 3.24 J/cm² (c) 4 J/cm².

Sidewall roughness was also measured in two tracks ablated at 4.5 J/cm², 15 Hz, 50 μm/sec with the same technique as used for microvia sidewalls. An average sidewall roughness value of around ±0.19 μm was achieved, which was lower than the flat surface roughness of the track (±0.5 μm). Due to limited time
available for the study, the effect of the range of parameters on the sidewall roughness was not identified.

Table 7.3 Variation in surface roughness values with fluence in 100 μm wide tracks.

<table>
<thead>
<tr>
<th>Energy (J/cm²)</th>
<th>Repetition rate (Hz)</th>
<th>Stage translation speed (μm/sec)</th>
<th>Surface Roughness Ra value (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>20</td>
<td>100</td>
<td>0.11</td>
</tr>
<tr>
<td>3.42</td>
<td>20</td>
<td>100</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>100</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Fig 7.25 Plot for surface roughness profile as a function of beam spot size of the tracks ablated at 3.2 J/cm² fluence and 15 Hz repetition rate.

Fig 7.26 Variation of roughness with stage speed in 480 μm wide tracks machined at 2.3 J/cm² fluence and 10 Hz repetition rate.
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It was possible to achieve good adhesion of electroless copper and nickel on the tracks with uniform ablation with higher roughness of the tracks. Figs 7.27 & 7.28 show the SEM and optical images of electroless copper deposited on the laser machined track.

![SEM image of an electroless copper plated track.](image1)

Fig 7.27 SEM image of an electroless copper plated 480μm wide track.

![Optical image of an electroless copper plated track.](image2)

Fig 7.28 Optical image of an electroless copper plated 480 μm wide track.

7.4 Conclusion

- Since laser machining of CMZ glass produced a taper profile, tracks with trapezium like trenches were produced with a square mask, while with a
circular mask, V or U shape grooves were produced depending on the fluence of the laser beam.

- The effect of all the parameters on machining of the tracks was investigated individually and it was found that an increase in fluence and repetition rate increased both ablation depth and the surface roughness of the tracks. Increasing the stage speed to 200 μm/sec significantly decreased the ablation depth, above which a reduced variation in the ablation depth was observed.

- Low fluences of around 2.7 J/cm² in combination with low repetition rates of around 5-10 Hz or high stage speed of around 200 μm/sec produced tracks with non-uniform ablation across the width and the length and unablated regions especially near the start and finish of the tracks. Increase in repetition rate led to an increase in overlapping of the pulses which increased the ablation depth of the tracks and uniform material removal across the width and the length of the tracks.

- Tracks of around 480 μm width (square mask) machined with a fluence of 1.7 J/cm² in combination with repetition rates of the order of 10-20 Hz and low stage speed of 50 μm/sec produced good quality tracks with no microcracking and unablated edges. While for narrow tracks of around 100 μm width machined with a circular mask, good quality was achieved using a high fluence of 3.4 J/cm², but with nearly the same repetition rates of 15-20 Hz and 50-100 μm/sec stage speed. However, beam quality and laser performance also affected the machining process.

- Increase in beam spot size increased the ablation depth and roughness of the track. With the excimer laser used here, it was possible to machine 25 μm wide tracks.

- Lumps of resolidified material were identified as evidence of photothermal ablation. A network of interconnected surface cracks was observed in tracks at high magnification, the severity of which increased with increase in repetition rate. Microcracks were observed in the laser machined tracks due to thermal stresses induced during photothermal ablation. Microcracks were found in general in unablated regions of the machined tracks.
• Surface roughness increased with increase in number of pulses. Increase in surface roughness favoured uniform metal deposition during metallisation.

References


8 MICROCRACK FORMATION DURING LASER MACHINING OF GLASS AND EFFECT OF POST TREATMENTS

8.1 Introduction

Since glass is a hard and brittle material, laser machining leads to significant challenges such as microcracking, recast formation and high subsurface damage. However, as described in the previous chapters, using an appropriate laser tool with careful selection of operating parameters can minimise the above defects, but it is still difficult to completely prevent their formation. Such defects further reduce the strength of the glass and when subjected to repeated cyclic loading conditions or severe environments, it can cause failure. Post-heat treatments of glass including annealing and tempering can minimise the internal stresses and improve the strength of the glass. This chapter deals with an investigation of microcrack formation during laser machining of the CMZ glass and the effects of post treatments on its performance.

8.2 Microcracking during Laser Machining

Microcracking is a major issue during laser machining of microvias and tracks in CMZ glass. As discussed in chapters 3 and 4, laser ablation in glass is a complex process since, at high powers, non-linear optical effects play a significant role in laser-material interaction. Depending on the glass composition, chemical bond energies and the laser parameters used, ablation occurs by both thermal and athermal mechanisms, which is likely to induce stresses and subsequently microcracks in the machined area.

Microcracks were identified during microstructural investigation of the machined structures in the glass under both optical and SEM microscopes. Microcracks in the laser machined glass were believed to be formed at various stages including during laser machining, during glass handling for cleaning and sample preparation after the laser machining process, especially during ultrasonic...
agitation. In the initial stages it was difficult to identify whether microcracks were formed during laser machining or during glass handling. To avoid this confusion, critical stages of the glass handling were avoided by directly mounting the glass on a SEM stub before laser machining of the glass. From this it was identified that no new microcracks were generated in most cases in the machined area during careful glass handling after machining.

Since the operating window for machining microvias and tracks was very different, the mechanism of microcrack formation was also different in both cases. In microvias, microcracks were not identified at low magnification such as in optical microscopes, so SEM was used for this investigation. For tracks, both optical and SEM microscopes were used. Using FIB to machine into samples, the depth of microcracks could be measured. The following sections discuss microcracking behaviour in laser machined microvias and tracks.

### 8.2.1 Microcracking behaviour in microvias

In most microvias, microcracks were confined to the sidewalls as demonstrated in fig 8.1, however, the severity of cracking depended on the laser process parameters.

![Microcrack](image_url)

**Fig 8.1 Schematic diagram of the microvias with microcracks.**

Microcracking behaviour was investigated in 100 μm diameter microvias in 100 μm thick glass drilled with different laser parameters. Fig 8.2 shows SEM images of a cross-sectioned microvia drilled at 4.5 J/cm² fluence and 30 Hz repetition rate and 30 s of drilling time. A few hairline cracks were identified near the central region through the thickness along the sidewalls. At high repetition rates of the order of 50 Hz or above, microcracks were also observed through the
whole range of thickness. Fig 8.3 shows the SEM images of 100 μm diameter microvias drilled at high repetition rates such as 100 Hz and 50 Hz, highlighting the region of microcracks. As can be seen in the figure, each microvia was identified with microcracks along the side walls, in most cases travelling along the thickness of the glass.

Fig 8.2 SEM image of the cross section of 100 μm microvia drilled at 4.5 J/cm², 30 Hz, 30 s showing microcracks.
In the overall investigation it was observed that, in the microvias drilled at the low repetition rates of the order of 20-30 Hz, microcracks were confined to only a small area along the side walls. However, at the higher repetition rates of the order of 50-100 Hz, microcracks were found along the whole range of thickness, and in some cases microcracks were extended onto the glass top and bottom surface through entry and exit holes. Fig 8.3 (c) shows the microcracks extended near the surface of the glass in the microvia drilled at 100 Hz and 20 s drilling time.

It is still difficult to predict the exact root cause of these cracks. Many theories have been mentioned in the literature by several authors regarding the
behaviour of microcracking in glass microvias. B. Lan [1] has described microcracks induced during excimer laser machining as thermal in nature and has explained the mechanism of crack formation during machining. According to him, the irradiated laser pulses caused excitation of electrons in the glass, which further dissipated excess energy into the lattice by generating phonons. If the laser pulse duration is in the nanosecond range as here (34 ns) then heat transfer from the hot electron to the lattice plays a significant role to increase the temperature of the lattice and subsequently generate thermally induced stresses, which further cause microcracks in or near the ablated region. However, with increase in fluence even with a nanosecond pulse, the amount of excess heat dissipated in the surrounding area should reduce. This could be the case here since the amount of thermal damage around the entry and exit holes of microvias was found to reduce with increase in fluence. However, microcracks were still found in the sidewalls along the thickness of the glass in most microvias drilled with different combinations of fluence and repetition rate (high and low ranges of both parameters), which means that it is not possible to avoid thermal stresses entirely or that some other mechanism also may be involved in formation of microcracks in microvias. Keiper [2] has also attributed the formation of microcracks during drilling of holes in glass as due to pressure at the base of the hole which causes explosion of the strong plasma, but further suggested that they may be due to thermally induced mechanical stresses in the glass.

8.2.2 Microcracking behaviour in tracks

While machining tracks, microcracks were largely identified near the start and the finish areas of the tracks, which were either unablated or partly ablated and also in the unablated areas inside the machined tracks. This was due to the number of pulses per unit length received by the glass and the energy per pulse not being enough to ablate or to melt the glass, so that only localised heating occurred near the edges causing a thermal gradient which ultimately caused formation of the microcracks [3-5]. With the progression of the beam with stage translation, overlapping of pulses occurred as described in Chapter 7 resulting in more power
for ablation and led to the microcracks being confined to a small area near the start and the finish of the track where fewer pulses were delivered. Fig 8.4 shows the microcracking behaviour in one such 480 μm wide track ablated at a fluence of 3.2 J/cm² and 15 Hz repetition rate with the stage speed of 50 μm/sec. However in some cases, microcracks were also observed in regions other than these ends even though uniform ablation occurred. Fig 8.5 shows the optical image of one such 480 μm wide track ablated at 3.8 J/cm², 40 Hz, 200 μm/sec, where a long microcrack across the width of the track was observed in the central region of the track despite uniform material removal. This kind of microcracking behaviour was rarely observed in the machined tracks and so this mechanism is not clearly understood. As discussed in the previous sections, unablated areas were largely observed at low fluence and low number of pulses. Fig 8.6 demonstrates microcracks formed in 100 μm wide tracks at low fluence of 3 J/cm² 100 μm/sec and 20 Hz repetition rate.

Very high translation speed also induced microcracks in the laser machined tracks. While increasing the stage speed, the dwell time for the laser beam to stay at each location decreased which caused surface heating rather than ablation. Thermal stresses were therefore induced as a result of the thermal gradient with the progression of each pulse and formed microcracks. Fig 8.7 shows images of
480 μm wide tracks (near the start of the track) ablated at different stage speeds with a fixed fluence of 2.3 J/cm² and fixed repetition rate of 10 Hz. Microcracks were seen in unablated areas and were generated in the direction parallel to the movement of the stage. The crack length and number of microcracks near the start and the finish increased as the amount of unablated area increased. The track ablated at 100 μm/sec shows 6 cracks generated near the start end of the track and penetrating inside the track, while the track ablated at 200 μm/sec shows 8 cracks generated near the edge. However, it is difficult to quantify the microcracks with further increase in speed after 400 μm/sec.

Fig 8.5 Optical image of a 480 μm wide track ablated at 3.8 J/cm², 40 Hz and 200 μm/sec.

Fig 8.6 SEM image of a 100 μm wide track with microcracks, ablated at 100 μm/sec speed, 3 J/cm² fluence and 20 Hz repetition rate.
Energy fluence had a significant effect on microcrack formation in the tracks. Increase in energy fluence decreased the severity of microcracking. As mentioned in chapter 7, with increase in fluence, the amount of non ablated areas which promoted microcracking reduced. Fig 8.8 compares the morphology of 666 µm wide tracks ablated with a 5 x 10 mm rectangular mask aperture (fig 7.1b) at different fluences. Fig 8.8a shows large cracks in the central region with small cracks branching towards the edges. This track was ablated at low fluence of 2.5 J/cm² and 10 Hz repetition rate at 50 µm/sec. While hardly any cracks were observed under optical microscope examination in the track ablated with fluence of 3 J/cm² and 10 Hz repetition rate at 50 µm/sec (fig 8.8b).

![Image of microcracks at different speeds](image)

Fig 8.7 Optical images of the start of 480 µm wide tracks ablated at 50 µm/sec speed, 2.3 J/cm² fluence, 10 Hz repetition rate.

Low repetition rates also favoured the formation of microcracks due to larger unablated regions compared to that at higher repetition rate. Fig 8.8b and 8.8c compares the microcracking behaviour in the tracks ablated at different
repetition rates. Fig 8.8c shows a large amount of unablated area and some microcracks in the track ablated at a repetition rate of 5 Hz compared to tracks ablated at 10 Hz in fig 8.8b.

Microcracks formed during laser ablation were believed to be confined to small depths. To investigate the depth of microcracks formed during machining of the tracks, Focused Ion Beam (FIB) microscopy was used, which etched stress free, small cross-sectioned areas to reveal the interior features. First platinum was
deposited on the gold coated surface to be cross-sectioned and then a focused beam of gallium ions was used to remove material. The depth of the microcracks was measured in a 100 μm wide track ablated at 3 J/cm², 20 Hz. Fig 8.9 shows the images of the cross sectioned area produced by FIB, in which a microcrack is seen penetrating through the thickness. In addition to this, underlayer surface damage due to non-uniform ablation was also observed. The depth of the microcrack was measured and found to be around 3 μm. It was not possible to study more samples hence measured values cannot be assumed to be the same for all the microcracks found in tracks that are ablated at different laser parameters and different mask apertures. Still more investigation is required in this area.

Fig 8.9 Microcracks in 100 μm wide tracks ablated at 100 μm/sec speed, 3 J/cm² fluence, 20 Hz repetition rate.
So far it was observed that in 100-500 μm wide and 10 mm long tracks machined at laser parameters such as high fluence of 4.5 J/cm² with repetition rates of ~15-20 Hz and stage speed of 50 μm/sec along with superior beam quality no microcracks were found. However, microcracks may be generated while machining longer tracks or very large patterns, because there may be variation in beam focus which depends on the stability of the auto focus control system, variation along the glass thickness and the variation of laser beam quality over the time.

8.3 Annealing and Tempering treatments of the CMZ glass

Due to the presence of defects such as microcracks, the re-solidified layer around the machined features, void structures and other stress concentration areas compared to that in plain glass, the laser machined glass had low mechanical strength compared to the plain glass. This would be expected to reduce the reliability of the glass substrates. To improve the strength and reliability of the glass as a substrate material, laser machined CMZ glass was subjected to post treatments such as annealing and tempering.

8.4 Experimental details

The thermal annealing and tempering treatments of the 100 μm thick laser machined glass samples with microvias and tracks at different laser parameters were carried out in a Carbolite Oven. CMZ glass used for this study was edge treated by Qioptiq to remove any damage caused by cutting to size. Initial trial runs for annealing and tempering treatments were conducted in the 620 °C to 635 °C temperature range which was defined on the basis of suggestions given by the glass supplier. For the tempering treatment, initial trial runs were performed on plain glass sheets at different temperatures to optimise the tempering process and further processes were performed on machined samples.

In addition to this data, the thermal properties of the CMZ glass were also determined using two techniques; Differential Scanning Calorimetry (DSC) and
Thermo mechanical Analysis (TMA), which are generally used to determine the anneal point, strain point and glass transition temperature.

The Differential Scanning Calorimetry method measured the difference in the amount of heat required to increase the temperature of the sample and a reference material as a function of temperature [6]. However, the glass transition range for CMZ glass was not accurately identified with DSC and so the TMA method was also used. In this method a small probe indenter was pressed with a small force against the surface of the sample. The displacement of the probe with variation in temperature was measured [7]. An abrupt change in the dimension of the glass across the thickness was observed at the glass transition temperature. Fig 8.10 shows the change in dimension of the CMZ glass as a function of temperature. A double layer diffusion bonded glass sample was used for this analysis. A sudden change in dimension was observed within the 500-600 °C range which was considered to be the glass transition range. Based on this experimental data, the glass transition temperature was taken to be around 566 °C.

Laser machined 100 μm thick CMZ glass (most samples with 30 x 10 mm or 40 x 10 mm dimensions) were subjected to annealing treatments using different temperatures in the glass transition range 600-500 °C obtained from TMA analysis. Since the glass sheets were very thin, a soaking time of 30 mins to 1 hr was used for this stress relieving treatment. However, a longer soaking of 10 hrs or more was used to examine microcrack healing behaviour in the glass machined with tracks. Microstructures of annealed and unannealed glasses were compared and EDX analysis in the machined area of unannealed and annealed glass was done to observe any compositional changes.

8.5 Results and Discussion

8.5.1 Annealing of laser machined CMZ glass

Annealing is the treatment for glass materials in which they are heated to the annealing point and then slowly cooled to room temperature to relieve internal stresses. For glass, the annealing range is between $10^{11}$ to $10^{13.5}$ Ns/m$^2$ of the glass.
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viscosity. The annealing point and strain point are the temperatures at which the viscosity is $10^{12.4}$ Ns/m$^2$ and $10^{13.6}$ Ns/m$^2$ respectively [8, 9].

![TMA plot](image)

Fig 8.10 TMA plot for two diffusion bonded sheets of 100 μm thick CMZ glass.

Here the annealing treatment was used to relieve the internal stresses induced in the glass during laser machining. For this investigation, a typical annealing cycle for glass (fig 8.11) as described by Mace [10] was used in which the glass was heated 10-20 °C above the annealing point and soaked for about 30-60 minutes depending on the dimension of the glass. In general, for glass with thickness below 25 mm a typical soaking time is likely to be 1-0.5 hrs. After soaking at the annealing temperature, the glass was cooled at a slow rate ($\leq 10^\circ$C/min) to 10°C below the strain point.

In an annealing treatment, during heating and cooling cycles, the top and the bottom surfaces heat up and cool faster than the interior part, which induces tensile stress in the inner area and compressive stress on the surfaces during heating due to the thermal expansion and vice-a-versa during cooling due to the
shrinkage. However, stresses induced during heating are temporary which are removed during the soaking period of the cycle, hence heating rates are not so critical during annealing. In general, slow heating rates are preferred for glasses with high thermal expansion coefficient, which is not the case here since CMZ has a comparatively low CTE (around 3.6 x 10^{-6} /K). During the cooling cycle, non-uniform cooling across the cross section of the glass causes shrinkage near the upper and lower surface first, hence inducing compressive stresses in the inner area and tensile stresses at the glass surface that are likely to create more stresses and microcracks in the glass leading to a fragile structure.

![Diagram of annealing cycle](image)

**Fig 8.11** Typical annealing cycle for the glass.

The severity of the stresses developed depends on the cooling rate: the faster the cooling rate, the more is the shrinkage that can cause permanent stresses in the glass. Hence, the cooling rate is an important parameter during annealing treatments. Practically, permanent stresses are developed in the temperature range between the anneal point and the strain point (fig 8.11). Careful control of the cooling rate in the range from the soaking temperature to 10 °C below the strain point can avoid the development of these permanent stresses. Mace [10] has given
an expression for the critical cooling rate as described in equation 8.1, which was used for fused quartz having residual stresses in the range of 0.17 MPa to 2 MPa.

\[ R_c = \frac{24K\sigma_t(1-\nu)}{E\alpha t^2} \]  

(8.1)

where \( R_c \) is the critical cooling rate, \( E \) is the Young's Modulus, \( K \) is thermal diffusivity, \( \nu \) is the Poisson's ratio, \( \sigma_t \) is the acceptable stress at the mid plane of the glass, \( t \) is the thickness of glass and \( \alpha \) is the coefficient of thermal expansion.

In this work, the annealing cycle was used with two different annealing temperature ranges for the soak: 500-600 °C obtained from the TMA analysis and 620-635 °C as suggested by the glass supplier. Initially, CMZ glass was heated at 80 °C/min to the temperature of 630 °C and soaked for 30 mins and cooled at 5-10 °C/min. In later experiments after conducting DSC and TMA analysis to identify the glass transition temperature range, the CMZ glass was heated at 80 °C/min to the temperature of 580 °C or 10-20 °C above this and soaked for 30 minutes and slowly cooled down to 500 °C at the rate of 5-10 °C/min. Machined CMZ glass consisted of arrays of microvias and tracks machined at different parameters. Cooling rate values were not defined on the basis of equation 8.1 since the level of residual stresses was not identified in this case. The cooling rate used here was defined on the basis of rates described by several authors and several patents used in industry [11-14]. For this investigation, cooling rates of 5 °C/min and below were found to be appropriate in most samples. CMZ glass consisting of microvia arrays did not show any significant extra microcracking after annealing, but in the glass with tracks, more cracks were induced in the machined areas if the cooling rates were above 5 °C/min. Only a limited number of samples were available for testing which were subjected to different annealing conditions as shown in table 8.1.

Soaking of glass for longer periods at annealing temperatures is likely to heal the microcracks in the glass according to Boccaccini [15]. Based on this, a few samples were subjected to the annealing cycles for long soaking time of 10-24 hrs and a very slow cooling rate of 2.5 °C/min for healing of the microcracks. However, no crack healing was observed in this range.
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To identify any improvement in the strength of the machined glass after annealing treatment, fatigue test under three point bending was carried out, which showed increase in fatigue resistance after annealing treatment. Results of the test are discussed in detail in the next chapter.

Table 8.1 Annealing condition for different samples and their effects in 100 \( \mu \)m thick CMZ glass.

<table>
<thead>
<tr>
<th>Machining Details</th>
<th>Annealing Temperature (°C)</th>
<th>Soaking Period (mins)</th>
<th>Cooling Rate (°C/min)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracks machined at 3.6 J/cm(^2), 10 Hz, 50 ( \mu )m/sec</td>
<td>630</td>
<td>60</td>
<td>10</td>
<td>More microcracks induced in tracks</td>
</tr>
<tr>
<td>Array of 100 ( \mu )m microvias at 60 Hz, 20 s and 4.5 J/cm(^2)</td>
<td>630</td>
<td>15</td>
<td>10</td>
<td>Unable to see any microcracks on the glass surface or around the microvias</td>
</tr>
<tr>
<td>Tracks machined at 3.6 J/cm(^2), 20 Hz and 50 ( \mu )m/sec</td>
<td>625</td>
<td>30</td>
<td>2</td>
<td>No new microcracks formed.</td>
</tr>
</tbody>
</table>

8.5.1.1 Microstructure Examination

Since annealing treatments should relieve internal stresses, there may also be microstructural changes. To investigate such changes in laser machined glass, microstructures of heat treated samples were examined using SEM. Fig 8.12a and b shows the microstructures of 480 \( \mu \)m wide tracks machined in 100 \( \mu \)m thick glass, before and after annealing treatment. The surface of the machined track in the glass before annealing was highly rough, while the heat-treated glass showed a second phase in the form of dispersed particles (fig 8.12b). EDX analysis of the heat-treated samples was carried out to identify any variation in the glass composition. Some of the light elements like boron could not be detected by this method but for the other elements no significant variation in glass composition was observed. More study and investigation is still required to understand the changes taking place at the atomic scale in the glass structure, which are suggested for the future work.
**8.5.2 Thermal tempering treatment**

Thermal tempering is the process in which the glass is heated to slightly below the anneal point and instantaneously cooled using air, water or oil as a medium. Instantaneous cooling of glass from the anneal point results in the development of compressive stress on the surface of the glass such that it suppresses the tensile stresses in the central region of the glass [16, 17]. The effect of tempering in a glass sheet is demonstrated in fig 8.13, which shows the stress distribution in the glass across the thickness after tempering. Tensile stress decreases dramatically towards the surface.

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Fig 8.12 480 μm wide tracks machined at 3.8 J/cm², 15 Hz and 50 μm/sec
(a) before annealing (b) after annealing.
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8.5.2.1 Tempering cycle for 100 μm thick CMZ glass

Tempering of the 100 μm thick CMZ glass was performed using two tempering media: compressed air and quenching oil used for metals. CMZ glass was heated to two different temperatures (625 °C and 560 °C) and soaked for about 15-30 minutes depending on the size of sample and immediately cooled with compressed air using a spray nozzle or with quenching oil by directly dipping the hot glass sample in an oil medium at room temperature. Fig 8.14 shows a schematic diagram of the tempering cycle.

Initially, to optimise the process, tempering was conducted on plain CMZ glass sheets of 100 μm thickness, with compressed air cooling. Since the glass sheets were very thin and small, glass handling from the hot furnace was critical and direct cooling of the glass with compressed air using a spray nozzle did not cool the glass surface uniformly; this resulted in distortion of the glass due to non-uniform stress distribution and in some cases, failure occurred while cooling. Using oil as a tempering medium also did not work successfully on the glass surface, since glass became fragile after oil cooling.

To analyse the effect of temperature on the tempering process, a deflection test was conducted under 3 point bending load (fig 8.15) for the plain CMZ glass samples tempered and cooled with compressed air. The maximum deflection at the centre and the load at the fracture point were recorded under three point bending using an Instron 3366 instrument.
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[Diagram: Thermal tempering cycle of the glass.]

From the load-deflection curve it was possible to calculate the flexural strength of the glass under three point bending, which is expressed in terms of stress as shown in equation 8.2:

\[
\sigma = \frac{3P_{\text{max}} L}{2bd^2}
\]

(8.2)

where \(\sigma\) is the flexural stress, \(P_{\text{max}}\) is the load at fracture where maximum deflection occurs, \(b\) is the width of the glass sample, \(d\) is the thickness of the sample and \(L\) is the gauge length (distance between supports).

[Diagram: Three point bending setup.]

Table 8.2 describes the results of deflection at different tempering temperature. Overall, it was observed that the strength of the untempered glass
was higher compared to the tempered glass indicating that the tempering process was not accomplished properly and also the results appeared inconsistent and inconclusive. Due to the limited number of samples available, further investigation in this area was not carried out, but the scope for this has been suggested as future work in chapter 11.

<table>
<thead>
<tr>
<th>Tempering conditions</th>
<th>Deflection (mm)</th>
<th>Load at fracture point (N)</th>
<th>Flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untempered</td>
<td>2.7</td>
<td>1.4</td>
<td>157.5</td>
</tr>
<tr>
<td>Tempering at 625°C for 15 minutes</td>
<td>2.08</td>
<td>0.8</td>
<td>90</td>
</tr>
<tr>
<td>Tempering at 630°C for 15 minutes</td>
<td>2.2</td>
<td>0.945</td>
<td>106.3</td>
</tr>
<tr>
<td>Tempering at 640°C for 15 minutes</td>
<td>1.4</td>
<td>1.075</td>
<td>120.93</td>
</tr>
<tr>
<td>Tempering at 650°C for 15 minutes</td>
<td>1.25</td>
<td>0.43</td>
<td>48.35</td>
</tr>
</tbody>
</table>

8.6 Conclusions

- Microcracks were observed along the sidewalls in almost all microvias machined at different laser parameters and in tracks, microcracks were found to be generated in unablated areas.

- Due to the limited number of samples, it was difficult to identify any difference between annealing and tempering treatments in CMZ glass carried out using different temperature ranges 500-600°C and 620-635°C.

- For thermal annealing treatment of CMZ glass samples, cooling rates of 5°C/min or less were found to be appropriate; cooling rates above this induced more microcracks in the machined area.

- Long soaking time at high temperature did not successfully heal the microcracks.

- Changes in microstructure were observed in the annealed glass; a second phase in dispersed formed was identified with SEM. Still more investigation
and study is required to understand the changes taking place at the atomic level.

- Results of tempering processes were inconclusive and required further work.

References


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9 RELIABILITY TESTING OF THE GLASS SUBSTRATES

9.1 Introduction

Looking towards the market demand of miniaturised electronics, the development of IC packages is mainly focussed on high density thinner interconnects, which reduces pitch size and pad size and also the solder ball size. As a result of this, second level reliability becomes a major concern for the chip scale packages. In most of the hand held devices such as mobile phones, calculators and remote controls, repeated key pad strokes can cause fatigue damage. Mechanical stresses so produced lead to electrical failure of components as a result of failure of solder joints, solder pads and cracking of the board. For this reason, for chip scale packages, the three point cyclic bending test is widely used in the electronic industry to evaluate fatigue reliability [1].

This chapter focuses on reliability testing of the machined glass. By the rules of mechanics, machined glass is likely to possess less strength compared to plain glass. As discussed in the previous chapters, machining of glass leads to problems such as debris and microcracking. To investigate the impact of such undesirable effects on the reliability of substrate and flip chip interconnect, three point bend testing for fatigue analysis of machined CMZ glass of 100 μm thickness was carried out. The effect of laser machining parameters on the fatigue strength was also analysed for further process optimisation. The machined glass was subjected to post treatments like annealing and tempering to identify their effect on the fatigue strength, and thermal cycling was also performed.

9.2 Background

Since the glass is brittle in nature, plastic deformation does not occur: once the crack length exceeds the permissible limits, failure occurs instantaneously. During laser machining of glass, defects like cracks, recast layer and voids are formed in the vicinity of machined areas. These defects act as stress concentration areas and reduce the mechanical life of the substrates. However, the amount of
cracks and recast layer can be controlled by laser processing parameter selection. To investigate the effect of these parameters, fatigue testing under three point loading condition was conducted.

9.2.1 Three point bend testing

Bending fatigue is commonly used to test reliability for PCBs, flip-chips and various other electronic packages. In most cases, such devices are subjected to repeated cyclic loading under three point or four point bending depending on the dimension and substrate material.

Fig 9.1 illustrates the load distribution and bending moment in the three point loading condition. A compressive load is applied at the centre point with two supports bearing equally half of the applied load. For plain sheets, Fig 9.1b and 9.1c show the shear force distribution and bending moment distribution across the length of the sheet, where the central point along the neutral axis is subjected to maximum bending moment.

Assuming the three point beam loading condition, the applied stress (nominal stress or flexural stress) in the plain glass single sheet can be expressed using equation 9.1 [2, 3]:

\[ \sigma_{\text{nominal}} = \frac{M * Y}{I} \]  \hspace{1cm} (9.1)

where \( \sigma_{\text{nominal}} \) is the nominal stress across the thickness of the material, \( M \) is the bending moment, \( Y \) is the distance from the neutral axis towards the outer surface across the thickness, which is given as \( \frac{d}{2} \) for the maximum stress, and \( I \) is the moment of inertia. Since the glass sheets used were of rectangular shape, \( I \) can be expressed by equation 9.2.

\[ I = \frac{bd^3}{12} \]  \hspace{1cm} (9.2)

It can be seen from fig 9.1c that the bending moment varies along the length of the sample. Considering the maximum bending moment, the expression for the nominal stress can be given as:

\[ \sigma = \frac{3PL}{2bd^2} \]  \hspace{1cm} (9.3)
The above expressions apply to a plain sample without notches, grooves or holes. In this work, glass sheets were machined with microvias and grooves, which act as stress concentration areas causing inhomogeneous stress distribution in the glass. Fig 9.2 illustrates the stress distribution in the rectangular sample with a central hole and shows high stress at the root of the hole, compared to other sections, which is known as the peak stress ($\sigma_{\text{peak}}$). The stress distribution of the nominal bending stress across the cross section remains the same as for the plain glass. The relation for peak stress and nominal stress can be expressed as:
where $\sigma_{\text{peak}}$ is the peak stress near the edge of the hole and $\sigma_{\text{nominal}}$ is the nominal stress or applied stress. $K_t$ is defined as a stress concentration factor.

The value of $K_t$ varies with the size, geometry and location of the stress concentration area. In this work, the stress concentration areas were mainly grooves and holes, so the following section discusses the stress concentration factors for a single or array of holes and a groove in a plate with finite width.

Fig 9.2 Stress distribution in the glass sheet with a central hole in the bending condition.

### 9.2.1.1 Stress concentration factors for the holes

Considering a condition in which a plate with a transverse central hole as shown in fig 9.2 is subjected to a bending moment, the expression for the nominal stress in such a case is given by equation (9.5) [4-6]:

$$\sigma_{\text{nominal}} = \frac{6M}{d^2 (b - a)}$$ (9.5)

where, $\sigma_{\text{nominal}}$ is the nominal stress, $a$ is the diameter of the hole, $b$ is the width of the plate and $d$ is the thickness of the plate.

Peterson [5] has presented various plots for stress concentration factor as a function of the ratio of stress concentration area to the width of the part under different loading conditions and different geometry of the sample. Fig 9.3 illustrates the plot for stress concentration factor as a function of $a/b$ which is the ratio of hole diameter to width of the plate under simple bending, (where $M_y$ is 0) for a plate with finite width and a central hole. The same condition can be applied in this case for a glass sample with a single microvia drilled at the centre.
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Fig 9.3 Stress concentration factor for the plate with a central hole and finite width [5].

However, the glass substrate used here consists of an array of microvias, so it is more appropriate to consider the condition of a plate with more than one hole undergoing three point bending as shown in fig 9.4. In this case, the distance between two holes is also taken into consideration. Peterson [5] has presented results for stress concentration factor for a plate of finite width with two holes and multiple holes. Fig 9.5 describes the profile for stress concentration as a function of $a/b$, the ratio of hole diameter to distance between two holes. With increase in distance between two holes, the stress concentration factor decreases.

Fig 9.4 Stress distribution in the glass sheet with an array of holes in the bending condition.
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Fig 9.5 Stress concentration factor for a plate with more than one hole and finite width [5].

9.2.1.2 Stress concentration factors for the grooves

Since a single groove with tapered sidewalls was machined in the glass, the condition of a rectangular or triangular groove in bending as shown in fig 9.6 is applicable. Fig 9.7 shows the plot of stress concentration factor $K_t$ vs $r/t$, for grooves with rectangular or triangular profile compared to semicircular profile as reported by Peterson [5]. In this case, $r/t$ is the ratio of the radius of the arc, $r$ (fig 9.6) to the thickness $t$, according to which the stress concentration factors generally decrease with decrease in thickness of the material and increase in taper angle of the groove.

Fig 9.6 Groove subjected to a bending moment.
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Stress Concentration curve for rectangular or triangular curve

Stress Concentration curve for semicircular curve

Fig 9.7 Stress concentration factor for a plate with a groove [5].

9.3 Experimental Details

Three point bend testing of the laser machined CMZ glass was performed using an Instron 3366 tensile testing machine fitted with a 50 N load cell (fig 9.8). For this particular study, thin glass sheets of 100 μm thickness with width dimensions (b) of 10 or 20 mm and length dimensions of 30 mm or 60 mm were used for repeated cyclic loading under three point bending. Glass with microvias and tracks machined with different parameters were subjected to a fatigue bending test. The gauge length, L was kept at 15 mm during the whole investigation.

Microvia arrays were machined in the patterns shown in fig 9.9a and b. 100 μm microvias were drilled in single or double array with pitch size, d, of 0.5 mm or 0.25 mm. CMZ glass was also machined with a 480 μm wide and 10 mm long single track as shown in fig 9.9c.

Some of the samples were post treated with the annealing and tempering processes as discussed in the previous chapter and the results compared before and after to investigate any change in the fatigue life of the glass. In addition to this, machined glass was also subjected to thermal cycling in a chamber capable of a maximum ramp rate of 2 °C/min. Samples were subjected to three different thermal cycling conditions: 0 °C to 125 °C with 15 mins hold time for 20 cycles,
-20 °C to 125 °C with 15 mins hold time for 500 cycles, -40 °C to 180 °C with 15 mins hold time for 100 cycles. Unfortunately, only a limited number of samples were available for this investigation and this should be borne in mind when considering the significance of the results presented here.

Fig 9.8 Experimental set-up for fatigue testing of the glass under three point bending.

(a) (b)

![Diagram](image)

Fig 9.9 Schematic diagrams of CMZ glass machined with an array of 100 μm diameter microvias (a) with microvias in one line with pitch size of d, (b) with microvias in x and y direction with pitch size of d and (c) a 480 μm wide track.
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9.4 Results and discussion

9.4.2 Fatigue testing under three-point bending of CMZ glass samples.

For the initial trial, machined glass was subjected to a three point bending test under different loading conditions, using a triangular loading waveform. To identify the effect of stress concentration on the fatigue life of CMZ glass, a plain glass sheet of 30 mm x 20 mm size and 100 μm thickness was subjected to cyclic three point bending with a maximum applied stress, $\sigma_{\text{max}}$ of 112.5 MPa ($P = 1$ N) and minimum applied stress, $\sigma_{\text{min}}$ of 22.5 MPa ($P = 0.2$ N) based on equation 9.3 with an extension rate of 1 mm/min. Fig 9.10 shows the three point fatigue test profile with triangular waveform for the plain glass which was run through 127 cycles without failure.

![Fig 9.10 Plain 100μm thick CMZ glass sheet with 20 mm width, fatigue cycled under three point loading.](image)

Microcracks were observed in most of the laser machined samples in the operating range, however the severity of cracking was lower with high fluence, low repetition rate and short drilling time. The following sections discuss the fatigue testing results of the glass machined with these features.

9.4.2.1 Fatigue testing of the microvia drilled CMZ glass samples

Since in this case the glass sample contained multiple holes with a defined width, the stress concentration factor depends on the ratio of the hole diameter to the distance between two holes, $a/h$. The condition for the stress concentration
factor, $K_t$, illustrated in fig 9.5 is therefore applicable for this case, depending on the pitch size for the array. As shown above, plain glass could resist more than 100 cycles with maximum applied stress of 112.5 MPa. However, samples machined with 100 μm microvias irrespective of the pitch size and the patterns shown in fig 9.9, were unable to resist this stress and instantaneously failed before the maximum applied stress. Table 9.1 lists the number of cycles resisted at different applied stress for the plain glass and the glass machined at 30 Hz, 20 s and 4.5 J/cm², with microvias in a pattern shown in fig 9.9a at a pitch size of 0.5 mm. This shows that the CMZ glass resisted zero cycles until the applied stress was reduced below $\sigma_{\text{max}} = 78$ MPa. However, the number of cycles to failure varied widely depending on several conditions such as drilling parameters pitch of the microvias, amount of debris and recast layer deposition.

As shown in table 9.1 microvias machined at 30 Hz repetition rate and 20s subjected to the same loading condition failed within 20 cycles. This may be predicted due to formation of defects during machining or induced stresses during glass handling and ultrasonic cleaning. Fig 9.11 shows the instantaneous failure of a sample machined at 60 Hz repetition rate for 20 s under similar loading condition. In most cases, failure occurred across the central microvia.

<table>
<thead>
<tr>
<th>Machining parameters for microvia drilling</th>
<th>Applied stress $(\sigma_{\text{max}})$ MPa</th>
<th>Applied stress $(\sigma_{\text{min}})$ MPa</th>
<th>No. of cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain glass</td>
<td>112.5</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>4.5 J/cm², 30 Hz, 20 s</td>
<td>78.5</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>4.5 J/cm², 30 Hz, 20 s</td>
<td>67</td>
<td>22.5</td>
<td>20</td>
</tr>
<tr>
<td>4.5 J/cm², 30 Hz, 20 s</td>
<td>56</td>
<td>22.5</td>
<td>55</td>
</tr>
</tbody>
</table>

Increasing the stress ratio $\frac{\sigma_{\text{max}}}{\sigma_{\text{min}}}$, where $\sigma_{\text{max}}$ is the maximum applied stress and $\sigma_{\text{min}}$ is the minimum applied stress, from 2.5 to 10, keeping $\sigma_{\text{max}}$ constant, significantly increased the fatigue resistance of the samples. With a stress ratio of
2.5, samples with an array of microvias irrespective of the given pitches, resisted an average cycle count of 125, while with the samples machined at similar parameters, no failure or crack propagation was observed until 500 cycles for a stress ratio of 10.

![Graph](image)

Fig 9.11 Instant abnormal failure of a sample with an array of microvias drilled at 60 Hz, 20 s and 4.5 J/cm².

9.4.2.2 Fatigue cyclic loading of CMZ glass with laser machined tracks

Tracks (480 μm wide and 10 mm long) machined in CMZ glass with different laser parameters were subjected to three point bending under similar loading conditions to those used for the microvia samples. Since the tracks were ablated to just 5 to 10 microns in depth, the stress concentration factor was less compared to that for holes and the sample resisted more cycles compared to those with microvias. Table 9.2 describes the number of cycles resisted by the glass samples machined with tracks at fixed fluence and repetition rate, but different stage speeds. As discussed earlier, for tracks or grooves, the stress concentration factor reduces with an increase in the depth to width or depth to radius ratio. This is consistent with the data here, for which an increase in stage speed decreased the depth of the tracks and so reduced the stress concentration.
Table 9.2 Fatigue testing parameters and results for tracks machined in CMZ glass.

<table>
<thead>
<tr>
<th>Machining parameters for tracks machining</th>
<th>Applied stress MPa</th>
<th>Number of cycles to failure</th>
<th>Number of cycles without failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 J/cm², 20 Hz, 50 μm/sec</td>
<td>67.5</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>4.5 J/cm², 20 Hz, 100 μm/sec</td>
<td>67.5</td>
<td>-</td>
<td>300</td>
</tr>
</tbody>
</table>

9.4.2.3 Influence of debris deposition on fatigue life of CMZ glass

Debris and resolidified glass form a 1-2 μm thick layer around the microvias, that can act as a stress concentration area and promote crack formation or propagation of existing cracks near the edges of microvias. To study the effect of debris and resolidified layer on the fatigue life, CMZ glass was machined with and without the photoresist layer which had been shown earlier to strongly affect the amount of debris adhered to the surface. Fatigue tests were then run with similar dimensions and loading conditions after cleaning the glass samples.

The debris deposition had a significant effect on the fatigue life of the glass. CMZ glass laminated with photoresist prior to microvia drilling resisted up to 125 to 130 cycles on average compared to only 55 cycles with the glass directly machined. Two such laminated samples machined with microvia arrays as shown in fig 9.1a with a pitch of 0.5 mm at a fluence of 4.5 J/cm² and 20 s but different repetition rates of 30 Hz and 60 Hz were subjected to similar fatigue testing conditions and were found to resist 120 and 135 cycles respectively. Fig 9.12 shows the fatigue test profile for photoresist laminated CMZ glass machined with microvias at 30 Hz and 20 s with maximum applied stress of 56.5 MPa and minimum of 22.5 MPa stress (stress ratio of 2.5) which resisted 135 cycles before failure.
Glass was subjected to post treatments like annealing and tempering to improve the overall strength as discussed in the previous chapter. Since fatigue life is very important for substrate manufacture, heat treated samples were also subject to three-point bend test to compare the fatigue damage before and after the treatment of glass.

The annealing treatment had a significant effect on the fatigue life of the CMZ glass. It was observed that the annealed samples resisted a higher number of cycles. Four CMZ glass samples, each machined with microvias or tracks were subjected to the three-point bend test after annealing post treatments as listed in table 9.3. As can be seen, glass with a 100 μm diameter microvia array machined with a photoresist layer on it at 4.5 J/cm², 30 Hz and 20 s, annealed at 625 °C survived 723 cycles at applied stress of 56.5 MPa (σₘₐₓ) and 5.65 MPa (σₘᵢₙ) with no failure or growth of the cracks observed. Even the glass sample machined with 480 μm wide tracks resisted 300 cycles without failure or any crack initiation.

Tempering of the glass using the procedure described in the previous chapter did not lead to any improvement in fatigue life – in fact tempered samples broke instantly indicating that the procedure had a detrimental effect on reliability.
Table 9.3 Effect of annealing treatment on the fatigue life of the machined glass samples.

<table>
<thead>
<tr>
<th>Laser machined features</th>
<th>Annealing treatment</th>
<th>Fatigue testing details</th>
<th>No. of cycles applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array of 5 microvias</td>
<td>Annealing at 620°C for 30 mins and cooling at 5°C/min</td>
<td>$\sigma_{\text{max}} = 56.5$ MPa, $\sigma_{\text{min}} = 5.65$ MPa, extension = 1 mm/min</td>
<td>723 (no failure or damage in sample)</td>
</tr>
<tr>
<td>machined at 30 Hz, 4.5 J/cm$^2$ and 20 s, with a pitch of 0.5 mm in x and y direction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(fig 9.1b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array of 5 microvias</td>
<td>Annealing at 625°C for 30 mins and cooling at 2°C/min</td>
<td>$\sigma_{\text{max}} = 56.5$ MPa, $\sigma_{\text{min}} = 5.65$ MPa, extension = 1 mm/min</td>
<td>300 (no failure or damage in sample)</td>
</tr>
<tr>
<td>machined at 30 Hz, 4.5 J/cm$^2$ and 20 s, with a pitch of 0.5 mm in x and y direction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(fig 9.1b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 µm track machined at 3.8 J/cm$^2$, 20 Hz, 50 µm/sec</td>
<td>Annealing at 625°C for 30 mins and cooling at 2°C/min</td>
<td>$\sigma_{\text{max}} = 56.5$ MPa, $\sigma_{\text{min}} = 5.65$ MPa, extension = 1 mm/min</td>
<td>500 (no failure or damage in sample)</td>
</tr>
</tbody>
</table>

9.4.3 Thermal cycling of machined glass

Thermal cycling is another important and commonly used reliability test for flip-chip interconnects and PCB substrates. In this case CMZ glass, laser machined with microvias, tracks and circuit patterns was subjected to thermal cycling. Initially machined glass samples were subjected to thermal cycles between 0°C and 125°C with a hold time of 15 mins at each temperature and ramp rate of 2°C/min. No failure or further cracking was observed up to 30 cycles. Further machined samples were subjected to another 500 test cycles between -20°C and 125°C with 15 mins hold time and ramp rate of 2°C/min. Again, failure or damage was not observed in any of the samples. In some of the tracks, cracks were developed during machining, however no further extension of the crack length of existing cracks was observed and no additional cracks or defects were induced due to thermal cycling.
9.5 Discussion

From the test results it was found that the debris and recast layer around the microvias affected the fatigue life of the glass machined with microvias. However, due to the limited number of available machined samples, it was difficult to analyse or model the exact role of such defects on the fatigue life of the glass. In addition, there were insufficient samples of microvias machined with different laser parameters to show any significant change in the fatigue resistance. This was also affected by the laser equipment which by this stage of the project did not give efficient output energy for each operation and resulted in variation in the machining rates of the features on different occasions.

All the annealed samples showed high fatigue resistance compared to the unannealed samples, but still, due to time constraints, further cycles were not run to identify the fatigue limits. So far, tempered samples subjected to the fatigue test were found to break instantly, which may be due to non-uniform stress distribution in the tempered glass.

Further investigation is required in this area, which has been suggested in the future work.

9.6 Conclusions

- Machined CMZ glass samples with through hole microvias instantaneously failed under a load of 1 N and applied stress of 112.5 MPa at 1 mm/min of extension.

- Debris deposition affects the fatigue life of the glass sample. Glass machined with a laminated photoresist layer showed a significant increase in the number of cycles to failure compared to samples machined without the photoresist.

- Annealing made a significant improvement in the fatigue resistance of the machined glass with no failure observed in the samples used here with 500 cycles or more.

- No further cracks or failure was observed when machined glass was subjected to 500 thermal cycles between -20 °C and 125 °C.
References


10 MACHINING OF THE DEMONSTRATOR PATTERNS

10.1 Introduction

As described earlier, the overall aim of this research was to prepare glass substrates for electrical interconnect. This chapter focuses on the work carried out to produce circuit patterns based on simple devices using the process windows identified for microvias and tracks as discussed in previous chapters. Various factors such as machining rates, quality of the machined patterns and their influence on the subsequent processes, such as metallisation and lamination were investigated.

10.2 Experimental Details

Based on the process window identified for machining of the individual features such as microvias and tracks, different machining patterns were produced on the 100μm thick CMZ glass to develop single layer and double layer circuits. Process flow diagrams for each of these circuits are described in fig 10.1 and 10.2. Machining patterns were programmed in Q-Basic and automatically machined along with automatic focus control. Different programs used for different machining patterns are listed in the Appendix.

Glass was routinely cleaned in Decon 90 (2.67% by vol in deionised water) for 8 hrs to remove any organic residue on the glass surface and subsequently laminated with the photoresist layer before laser machining. Photoresist lamination not only improved the quality of the machined features, but also helped in selective deposition of the metallised layer on the glass surface. For the single layer circuit as shown in the process flow diagram (fig 10.1), a pattern was created using the excimer laser, which was subsequently metallised. 100μm thick CMZ glass was used for this purpose. Since the machining pattern for the single layer circuit was about 46 mm x 18 mm dimension, 100μm thick CMZ glass sheets of 60 x 30 mm size were chosen for this.
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Fig 10.1 Process flow diagram for developing single layer circuit.

Applying photo resist film on glass → Glass

Laser machining of circuit pattern

SAM monolayer formation

Removing photo-resist & deposition of electroless Ni or Cu

Glass lamination

Applying photoresist to the laminated glass

Laser machining of microvias on double layer glass

Metallisation of microvias

Fig 10.2 Process flow diagram for developing double layer circuit.
For the double layer circuit (Fig 10.2), a pattern was laser machined on CMZ glass, metallised and laminated with another CMZ glass sheet of the same dimension. Further processing was then required for machining blind holes on the laminated glass (work underway). This work was undertaken in collaboration with two other PhD students who metallised and laminated the glass layers.

10.3 Results and discussion

Best process parameters from the process windows identified for individual features were chosen to produce defect-free features with uniform surface profile and roughness along with good machining rates to achieve good adhesion of the metallised layer during subsequent processes. However, while machining a large number of big and small patterns, several issues in process repeatability occurred which depended on the software program used, performance of the X-Y tables, degradation of beam power and beam quality with time. With time, the control of the focus also weakened which affected the machining process.

10.3.1 Machining patterns developed for the single layer circuits.

For developing single layer circuits, tracks and pad patterns as shown in fig 10.3 were machined using a square brass mask of 7.3 x 7.3 mm (fig 5.2) which produced around 480 μm wide tracks. Two different programs, one each for machining tracks and pads were used, which are listed in the Appendix.

Fig 10.3 Circuit pattern machined on ink coated glass.

Initial machining trials were undertaken on the single sheets of a range of glass materials such as microscope slides of borosilicate and soda-lime glasses, CMZ glass and other material like Perspex. Close agreement between actual
dimensions of the machined tracks and pads with that in the program were observed while machining the first 3-4 patterns, after which repeatedly machining the above pattern caused backlash of the tables and reduced the dimensional accuracy of the pattern. For the actual process to develop a single layer circuit, glass laminated with the photoresist layer was used which is demonstrated in fig 10.4.

![Single layer circuit pattern machined in CMZ glass laminated with the photoresist layer.](image)

**10.3.1.1 Process parameters for single layer circuit**

Since photoresist-laminated glass was used for the patterns, it required a higher fluence or repetition rate to machine tracks with the same depth as that of unlaminated glass (more details in chapter 7). Initially, high speeds of 1200 μm/sec in combination with high fluence of 4.5 J/cm² and repetition rates of 30 Hz were used, but a large number of microcracks were observed which ultimately reduced the strength of the glass. Hence, a compromise was made with the machining rates by reducing the stage speed stage to 400 μm/sec. This required 45 minutes to machine one whole pattern shown in fig 10.3 and 10.4.

While this was a slow process, it should be noted that the excimer laser used here was an old model of laboratory equipment and not a commercial set-up. For high volume production, excimer lasers with high power of around 200-300 W, high repetition rates of the order of 300-500 Hz, with low beam divergence (1-2 milliradians or less), high laser beam stability, with high speed and high resolution tables are used. High pulse energy in combination with high repetition rates enable the machining of defect-free features with high ablation rates. In commercially
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available systems a variable mask technique is employed, which uses X-Y tables for replacing mask apertures, which reduces the time required for interchanging masks and thus reduces the machining time.

10.3.1.2 Defects in the machining patterns

Using inappropriate machining parameters, and especially stage speeds, caused formation of unablated areas, especially near the corners as shown in fig 10.5. Not only the laser process parameters affected this process; with time, as discussed above, the beam also became exhausted which caused non-uniformity during machining. It was also observed that some parts in the circuit patterns were ablated non-uniformly, so in some cases tracks and pads were ablated to half of their required width as shown in fig 10.5.

Fig 10.5 Optical image of the unablated areas in the track in the single layer circuit pattern on 100 μm thick CMZ glass.

10.3.1.3 Metallisation of circuit patterns

Machined patterns were successfully metallised using electroless copper or nickel plating. Fig 10.6 shows an optical image of one such pattern machined on a 1 mm thick microscope slide, with only the tracks metallised with electroless copper for which selective and uniform deposition of the metal is observed.
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As mentioned in chapter 7, non-uniform ablation of the tracks caused poor adhesion of the metallised layer. Along with appropriate laser parameters, good focus control and beam stability is required to achieve uniform metallisation all across the pattern. Fig 10.7 shows the optical image of the pattern machined and metallised on a CMZ glass sheet with discontinuity in the copper deposition in the upper line. This problem may have occurred due to poor focus control of the beam in that region or alternatively, during machining, the photoresist layer was not removed efficiently in that area.

Discontinuous metal deposition

Fig 10.7 Optical image of the single layer pattern coated with electroless copper.

10.3.2 Patterns produced for the double layer circuits.

Daisy chain patterns consisting of tracks and microvias were machined in 100 μm thick CMZ glass using a 1.5 mm diameter circular mask that delivered a 100 μm spot size on the work piece. For developing the double layer circuit, a daisy chain track pattern as shown in fig 10.8a was machined on the photoresist laminated single glass sheet for subsequent metallisation and lamination. Patterns of microvias were also drilled.
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10.3.2.1 *Process parameters double layer circuit*

Process parameters identified from the process windows gave similar results compared to the larger single layer pattern provided the software program was appropriately designed such as ensuring there was enough time interval for the laser shutter opening and closing operation to avoid overlapping of the features.

*Machining of the daisy chain track pattern*

The daisy chain track pattern was machined on the bottom sheet of the glass as demonstrated in the process flow diagram. 300 μm long tracks were machined at 4.5 J/cm² and 30 Hz repetition rate and 50 μm/sec stage speed as shown in fig 10.9. Tracks were machined without any unablated areas in any of the regions of the track.

![Machining of the daisy chain track pattern](image)

Fig 10.8 Daisy chain patterns machined using 1.5 mm diameter circular steel mask consisting (a) of 100 μm wide track (b) 100 μm diameter microvias.
Chapter 10: Machining of the Demonstrator Patterns

*Machining of daisy chain microvia pattern*

According to the process flow chart for double layer circuit development, a daisy chain pattern of blind microvias is required in the laminated glass layer. However, initial trials were undertaken on single glass sheets to check the dimensional tolerances of the pattern to match it with the geometry of the flip-chip to be used. The 100 µm diameter microvias were drilled in the 100 µm thick glass with a pitch size of 204 µm. Fig 10.10 shows an optical image of part of the microvia pattern drilled at 4.5 J/cm², 30 Hz and 20 s drilling time which required 15 minutes to machine the whole pattern of microvias. This could be reduced to 7 mins by limiting the microvia drilling time to 5 s along with using high repetition rates of 50 Hz. For an actual industrial application, the machining time for drilling the microvia pattern could be further reduced to around 3 mins by using an interchangeable mask with multiple holes (around 3 holes for 1 mm² beam spot size) along with a more advanced excimer laser set-up capable of giving more fluence along with low divergence.

Fig 10.9 Optical image of the daisy chain track pattern machined at 4.5 J/cm², 30 Hz and 50 µm/sec stage speed.

Fig 10.10 Optical image of the microvias of the daisy chain pattern in 100 µm thick glass.
Chapter 10: Machining of the Demonstrator Patterns

Since the microvia pattern was drilled on the top surface of the double layer to directly connect with a flip-chip, end terminals were required for the external connections for which 100 μm wide tracks and 750 μm wide pad patterns were machined. This is demonstrated in fig 10.11, which shows tracks and pads connecting to microvias on the corner. Two different programmes and laser parameters were used for microvia drilling and machining of the tracks and pads.

![Figure 10.11 Optical image of the tracks and pads machined in the microvia pattern.](image)

Since with the available set up of the excimer laser it was difficult to achieve alignment of the beam with the underlying track pattern, it was not possible in the time scale of this work to demonstrate a complete double layer device. However, some parts of the metallisation and lamination were carried out. Fig 10.12 shows the daisy chain microvia pattern metallised with electroless nickel. After metallisation of the machined pattern, glass lamination was also successfully performed as shown in fig 10.13, which shows a daisy chain track pattern metallised (10.13a) and laminated (10.13b). However further work is still underway to develop a complete double layer circuit along with attachment of a flip chip.
Fig 10.12 Microvia pattern metallised with nickel and copper.

Fig 10.13 Daisy chain patterns (a) Nickel plated tracks (b) double layer laminated glass with under layer track pattern.
10.4 Conclusion

- Machining of patterns was successfully performed with the optimised parameters used for individual parameters.
- The machining time for single layer patterns varied between 20 mins to 45 mins depending on the stage speeds used for machining tracks and pads.
- Machining time of daisy chain microvias varied from 15 mins to 7 mins with the drilling times in the range of 20 secs to 5 secs.
- Machining patterns were successfully metallised and laminated. However further processes are still underway to complete a full substrate design.
- Since glass is used as the substrate, reliability testing is also important. In the previous chapter, reliability of only machined single layers of glass has been discussed which identified the low strength of the machined glass due to thermal damage, stresses induced during machining and microcracks. To consider single layer circuits with components mounted and a double layer circuit with laminated glass sheets with flip-chip interconnections, several other factors such as fatigue strength of the laminated glass, reliability of the solder joints and other issues need to be investigated for their effects on reliability.
11 CONCLUSIONS AND FURTHER WORK

Based on the literature findings and the methodology defined, the current research was carried out in a systematic manner and grouped into five major areas:

Process optimisation - Identification of the process windows for microvia and track machining in CMZ glass and studying the effect of laser parameters on the machining process.

Characterisation of machined microvias and tracks - Investigation of debris, recast layer formation and microcracks.

Post treatments of the machined glass - Investigation of the effect of thermal treatments such as annealing and tempering on the machined glass.

Reliability testing of machined single glass sheets - Three point fatigue bend testing and thermal cycling.

Machining of demonstrator patterns - Work towards the preparation of single layer and double layer circuits.

This chapter presents a summary of the conclusions drawn from each area and the scope of future work.

11.1.1 Process optimisation of microvias and tracks

Process windows for drilling through-hole microvias and tracks in the CMZ glass using the KrF excimer laser operating at 248 nm were successfully identified. Modifying the beam delivery system, the energy at the work piece was increased from 3 J/cm\(^2\) to 4.5 J/cm\(^2\). This resulted in significant improvement in the microvia drilling process as the maximum microvia taper angle reduced from 19° to 14° for 100 \(\mu\)m entry holes, which enabled exit hole diameters up to 50 \(\mu\)m with the drilling time as little as 5 s at maximum fluence and moderate repetition rates of the order of 60 Hz.

The effect of all the parameters on the machining of tracks was investigated and found that an increase in fluence and repetition rate at a fixed stage speed increased both ablation depth and the surface roughness of the tracks. As the stage speed increased up to 200 \(\mu\)m/sec, with a fixed fluence and repetition
rate, the ablation depth decreased significantly, but with further increase in speed, less variation in the ablation depth was observed. Low fluences of around 2.7 J/cm² in combination with low repetition rates of around 5-10 Hz or high stage speed of around 200 μm/sec produced tracks with non-uniform ablation across the width and the length and unablated regions especially near the start and the finish ends. Increase in repetition rate led to an increase in overlapping of the pulses which increased the ablation depth of the tracks and uniform material removal across the width and the length of the tracks with reduced unablated areas.

Tracks of around 480 μm width (square mask) machined with a fluence of 1.7 J/cm² in combination with repetition rates of the order of 10-20 Hz and low stage speed of 50 μm/sec produced good quality tracks with no microcracks and unablated edges. While smaller size tracks, such as 100 μm wide, machined with a circular mask produced good quality tracks at slightly higher fluence of 3.4 J/cm², but with nearly the same repetition rates of 15-20 Hz and 50-100 μm/sec stage speed.

Other than laser process parameters, laser beam quality at the work piece and laser performance also affected the machining process. In the case of microvia drilling, poor beam quality or misalignment in the optical cavity or beam delivery optics caused non-uniform intensity distribution which resulted in eccentricity in the entry and exit holes. In the case of tracks, large unablated areas near the edges as well as in the central region of the tracks were observed. Due to the poor performance of the laser in the later stages of the research, very poor track quality was achieved.

Process limits to drill the smallest microvias and narrowest tracks were explored. It was possible to drill through-hole microvias down to 40 μm diameter in 50 μm thick glass provided the maximum energy at the work piece was 4.5 J/cm². Process limits for the narrowest track that could be drilled with this laser were not identified due to frequent problems with the laser unit in the later stages of the research, which affected its performance, however the machining of tracks as narrow as 25 μm was demonstrated.
11.1.2 Characterisation of the machined features

Machined features were successfully characterised using the experimental techniques described in chapter 5. Conclusions drawn from the various characterisation processes are listed below.

11.1.2.1 Debris and recast layer formation

Debris and recast layer formation around the laser machined holes and tracks was identified. Loose debris was easily removed by ultrasonically cleaning machined glass samples in IPA, but not the recast layer. To reduce the amount of debris and recast layer adhering to the glass, it was laminated with a photoresist layer before machining, which successfully reduced the level of debris and recast layer adhering the glass. However, even with photoresist, particularly for the microvia drilling process, drilling with longer irradiation times or high number of pulses did not show significant reduction in debris and recast layer formed around the entry and exit holes.

11.1.2.2 Surface morphology and surface roughness of the machined features

Chipping and irregular geometry of the entry and exit holes was observed in some microvias drilled at low repetition rates of around 40 Hz. During machining of tracks, lumps of resolidified material were identified as evidence of photothermal ablation. A network of interconnected surface cracks was observed in tracks at high magnification, the severity of which increased with increase in repetition rates.

Surface roughness along the microvia sidewall varied with the laser machining parameters and measured Ra values were between 0.8 μm – 0.3 μm. From the side wall roughness investigation in two microvias machined at different repetition rates, it was found that the roughness near the exit hole edge was less compared to other parts of the microvia interior.

In tracks, the surface roughness increased with increase in fluence and repetition rate with fixed number of pulses per area and significantly decreased with increase in stage speed up to 200 μm/sec at fixed fluence and repetition rate,
after which, reduced variation was observed. Increase in surface roughness favoured uniform metal deposition during metallisation.

11.1.2.3 Microcrack formation in the machined features

Microcracks were identified in both microvias and in tracks. In microvias, microcracks were found along the sidewalls, while in the tracks they were found to be generated in unablated areas, especially near the start and finish ends of the tracks. Severity of microcracking depended on the laser parameters and the beam quality.

11.1.2.4 Post treatments of the machined glass

Due to limited number of machined samples available for investigating the effect of post treatments on the machined glass, only a few results were produced, based on which the following conclusions were drawn.

It was difficult to identify any difference between annealing and tempering treatments in CMZ glass carried out using different temperature ranges of 500-600°C and 620-635°C.

Glass samples annealed using cooling rates of 5 °C/min or less were better compared to those annealed at cooling rates higher than this for which more microcracks were found. Long soaking time at high temperature did not successfully heal the microcracks. Changes in microstructure were observed in the annealed glass and a second dispersed phase was identified with SEM. Still more investigation and study is required to understand the changes taking place at the atomic level.

Results of tempering processes were inconclusive and required further work.

11.1.2.5 Reliability testing of the single sheet machined glass

Plain single sheets of glass could withstand applied stress to 112.5 MPa at a deflection of around 2.5 mm, however, machined CMZ glass samples instantaneously failed under a load of 1 N and applied stress of 112.5 MPa at 1 mm/min of extension. To investigate the effect of debris and recast layer formed around the glass, fatigue testing results of un laminated glass and glass laminated
with the photoresist layer before machining microvias were compared and it was found that laminated glass resisted around 125 cycles while the un laminated glass with microvia array resisted only around 55 cycles.

An annealing treatment had a significant effect on the fatigue resistance of the machined glass. One such glass sample machined with microvias with a pitch size of 0.25 mm, subjected to fatigue bending test showed no failure after 725 cycles with an applied stress of 56.5 MPa at 1 mm/min extension.

Thermal cycling of the machined glass within different temperature ranges and different cycles, showed no significant effect or changes in the samples. Machined glass subjected to thermal cycling between -20 °C to 125 °C resisted 500 cycles without any failure, dimensional change or cracks in the samples.

11.1.2.6 Development of circuit patterns

Machining of patterns was successfully performed with the optimised parameters used. The machining time for single layer patterns of around 46 x 18 mm varied between 20 mins to 45 mins depending on the stage speeds used for machining tracks and pads. The machining time for the daisy chain pattern of microvias varied from 15 mins to 7 mins with the drilling times in the range of 20s to 5 s. Machining patterns were successfully metallised and laminated, however further processes are still underway.

11.1 Further Work

The research investigation in each of the areas mentioned above was carried out successfully. However, due to unexpected problems and ultimate failure of the laser equipment, a few tasks according to the proposed plan remained un-investigated which are suggested in the future work plan. Other scope for future work is based on the conclusions drawn from the results of this research.
Chapter 11: Conclusion and Further Work

Scope of further work with regard to work left due to equipment failure

Development of double layer demonstrator patterns and reliability studies of the structure

A complete double layer demonstrator pattern was not developed since the final steps of the process could not proceed further due to unexpected failure of the excimer laser system and exceptional delay in commissioning of a new system. Further work aims to use the new system to build functional multilayer structures.

Reliability of the single layer machined glass sheets has already been investigated in this research work. However, while developing double layer flip-chip substrates, stresses may be induced from several sources, such as during laser machining of glass, during lamination processes, during ultrasonic cleaning and several other steps. To investigate the cumulative effect of these stresses, reliability testing such as three point bend test, thermal cycling and thermal shock resistance is required.

Fabrication of waveguides with 45° mirrors and 3D structures

Initial trials to produce waveguides with 45° mirrors were carried out using the standard optics head of the excimer laser used in this work and also an alternate head consisting of the image projection lens at 45° angle to the plane of the work piece. With the standard head, very shallow angles were achieved, while with the alternate head difficulty was experienced in machining glass and further characterisation was not carried out. Further work to produce waveguides with 45° mirrors will need to be conducted and the efficiency of the optical transmission characterised to determine if the glass can be used for both optical and electrical interconnect.

Post treatments of the machined glass

More investigation in the area of post treatments of the machined glass is required. To achieve uniform thermal tempering of the machined glass, an appropriate set-up is required for heating the thin sheets in the furnace followed by cooling with a multiple spray nozzle jig to achieve uniform air flow. Micro structural investigation using FIB and TEM analysis to observe the changes and
identify the phases evolved during heat treatments is then necessary to determine clearly any changes in performance.

**Reliability testing of the machined glass**

Very limited results were achieved and presented in this work, from which it was difficult to identify the effect of defects produced during machining of the glass on the fatigue life. To analyse this effect, a large number of samples machined at different laser parameters and having different surface morphology and amount of defects like microcracks, recast layer and debris are further required to undergo fatigue test.

**Scope of future work based on conclusions drawn from this research**

**Pre-heating or in-situ heating of glass samples while machining**

The main aim for this work is to avoid or minimise the unablated areas, especially while machining tracks in the glass, which further reduces the amount of microcracking. Some initial trials of glass preheating on a hot plate prior to machining of 500 μm wide tracks were already carried out. However, the effect of preheating was confined to only a small area near the end of a track from where the machining was started, mainly because glass samples cooled very quickly after transferring from the hot plate. To avoid instant cooling of the samples it is required to simultaneously heat the sample externally while machining below $T_g$ without any adverse effect on the laser beam delivery optics.

Overall, the research has been successful in demonstrating the machining of thin glass for the fabrication of high density substrates. The work has identified process windows for microvia and track formation and analysed the presence of defects. With further work it is hoped that glass substrates will be realised in the future for electrical and optical interconnect.
APPENDIX

Programmes used for different machining patterns

All the programmes were written in Q-basic language and executed in link.
Programme for machining single channel of 5 to 10 mm length. Generally, this programme was used for machining single tracks for process optimisation and characterisation.

*Horizontal channel of 10mm length (width of the channel depends on mask aperture size)*

```
FL00
RM
CM1;SB5;WS100;1PR20000;WS100;CB5;WS100
EP
BI1,2,3,4
BO5,6,7,8
CB5,6,7,8
1 VA100
EM1
1PR4000;WS100
%
CP
EX
END
```

*Vertical channel of 10mm length (width of the channel depends on mask aperture size)*

```
FL00
RM
CM1;SB5;WS500;2PR10000;WS100;CB5;WS100
EP
BI1,2,3,4
BO5,6,7,8
CB5,6,7,8
2 VA200
EM1
%
CP
EX
END
```

*Machining Pattern 1 for single layer circuit - I (Machining of tracks)*

1 VA400
2 VA200
SB5;WS100
1PR4000;WS100
CB5;WS100
1PR3200;WS100
SB5;WS100
1PR50950;WS100;2PR-1000;WS100
1PR32500;WS100;2PR17000;WS100
1PR-55000;WS100;2PR-8000;WS100
CB5;WS100
2PR-1750;WS100;1PR-2000;WS100
SB5;WS100
1PR-3500;WS100;2PR4000;WS100
1PR-2000;WS100
CB5;WS100
1PR-6500;WS100
SB5;WS100
1PR-4400;WS100;2PR-4700;WS100
CB5;WS100
2PR-800;WS100;1PR9400;WS100
SB5;WS100
1PR6800;WS100
CB5;WS100
1PR3400;WS100
SB5;WS100
1PR3500;WS100;2PR10000;WS100
1PR48000;WS100;2PR-13500;WS100
1PR-22000;WS100;2PR10000;WS100
1PR-13000;WS100;2PR-5000;WS100
1PR-5600;WS100
CB5;WS100
1PR-1200;WS100;2PR1750;WS100
SB5;WS100
2PR2250;WS100
CB5;WS100
2PR600;WS100;1PR12000;WS100
SB5;WS100
2PR-2100;WS100
CB5;WS100
2PR-2400;WS100
SB5;WS100
2PR-1600;WS100;1PR-10500;WS100
CB5;WS100
1PR10500;WS100
SB5;WS100
2PR-1000;WS100
CB5;WS100
2PR-2000;WS100
SB5;WS100
2PR-1500;WS100
CB5;WS100
1PR-12000;WS100
SB5;WS100
2PR3000;WS100
CB5;WS100

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Machining Pattern II for single layer circuit 2 (Machining of Pads)

F100
RM
CM1;SB5;1PR3000;WS100;2PR1000;WS100;1PR-3000;WS100;2PR-1000;WS100;CBS;WS100
CM2;2PR500;WS100;SB5;1PR2000;WS100;CBS;WS100;2PR-500;1PR7000;WS100
CM3;2PR500;WS100;SB5;1PR2500;WS100;CBS;WS100;1PR-2500;WS100;2PR-2750;WS100
CM4;SB5;WS100;1PR3000;WS100;2PR250;WS100;1PR-3000;WS100;2PR-250;WS100;CBS;WS100
CM5;SB5;WS100;1PR2000;WS100;2PR500;WS100;1PR-2000;1WS100;2PR-500;WS100;CBS;WS100
CM6;SB5;WS100;1PR2000;WS100;2PR500;WS100;1PR-2000;1WS100;2PR-500;WS100;CBS;WS100
CM7;SB5;WS100;1PR1500;WS100;2PR1000;WS100;1PR-1500;WS100;2PR-1000;WS100;CBS;WS100
CM8;2PR500;WS100;SB5;1PR2500;WS100;CBS;WS100;1PR-2500;WS100;2PR-3250;WS100
EP
BI1,2,3,4
BO5,6,7,8
CBS,6,7,8
1 VA400
2 VA400
1PR-11000;WS100;2PR-500
DLA;EM1;EM2;JLA2
2PR10500;WS100;1PR-43500;WS100
DLB;EM1;EM3;JLB2
2PR1000;WS100;1PR-1500;WS2000
DLC
2PR-1500;WS500
EM4
JLC4
1PR-11000;WS100;2PR5750;WS2000
DLD
2PR-1500;WS500
EM4
JLD4
1PR-16000;WS100;2PR7000;WS500
DLE
1PR4000;WS100
EM6
JLE2
1PR-10000;WS100;2PR-8250;WS100
DLF
2PR1500;WS100
EM5
JLF2
2PR-500;WS100;1PR-4000;WS100
EM6
2PR-2750;WS100;1PR-8000;WS100
DLG
2PR1500;WS100
EM5
JLG2
2PR-5000;WS500;1PR-3000;WS100
DLH
1PR3000;WS100
EM7
JLH2
1PR16250;WS100;2PR4500;WS100
DLI;EM1;EM8;JLI2
2PR3750;WS100;1PR1500;WS100
SB5;WS100
2PR600;WS500
CB5;WS500
2PR-2600;WS100;1PR32500;WS100
DLJ
2PR1500;WS100
EM5
JLJ2
2PR2000;WS100
DLK
2PR1500;WS100
EM5
Program for daisy chain track
FI00
RM
CM1:SB5;WS500;1PR408;WS100;CB5;WS100
CM2:SB5;WS500;2PR204;WS100;CB5;WS100
CM3:SB5;WS500;1PR-408;WS100;CB5;WS100
CM4:SB5;WS500;2PR-204;WS100;CB5;WS100
EP
B11,2,3,4
B05,6,7,8
CB5,6,7,8
1 VA100
2 VA50
1PR100;WS100
DLA
1PR408;WS100
EM1:JLA11
1PR408;WS100
DLB
2PR204;WS100
EM2:JLB11
2PR204;WS100
DLC
1PR-408;WS100
EM3:JLC11
1PR-408;WS100
DLD
2PR-204;WS100
EM4:JLD11
2PR-204;WS100
%
CP
EX
END

Program for daisy chain microvia pattern
FI00
RM
CM1:SB5;WS20000;CB5;WS100;1PR408;WS100
CM2:SB5;WS20000;CB5;WS100;2PR204;WS100
CM3:SB5;WS20000;CB5;WS100;1PR-408;WS100
%
CP
EX
END
Program for daisy chain end terminals

1 VA400
2 VA200
2PR100;WS500;2PR-100;WS500
SB5;WS100
1PR-5000;WS100;2PR-500;WS500
1PR-5000;WS100
CB5;WS100
1PR-1100;WS500;2PR100;WS500
SB5;WS100
1PR1200;WS100;2PR-600;WS500
1PR-1200;WS100;2PR600;WS500
CB5;WS100
2PR-100;WS500
SB5;WS100
1PR1200;WS100
CB5;WS100
2PR-100;WS500
SB5;WS100
1PR-1200;WS100
CB5;WS100
1PR-1200;WS100
CB5;WS100