WONGWIWAT, PLAWUT. The Development of Biomedical Devices with Excimer Laser Micromachining, Modeling and Simulations. (Under the direction of Dr. Yuan-Shin Lee and Dr. Roger Narayan.)

This paper presents a new method of developing micro-scale medical devices by using excimer laser with analytical modeling and simulation of the processes. In recent years, the laser has attracted a significant interest of finding feasible techniques for developing new biomedical devices such as micro scaffolds for nerves, micro arrays for DNA, micro channels for drug delivery or bio-MEMS for bioelectronics devices. This paper focuses on exploring the applications of laser micromachining and advanced surface modification techniques for the development of the biomedical devices. Analytical modeling was conducted and constructed for laser micromachining processes such as pulse laser deposition, 3D material printing and spin coating to fabricate user-defined microstructures on a silicon wafer. Because laser micromachining with the excimer laser is a flexible and controllable process that has high resolution and contactless cutting, it is a good candidate to machine the silicon wafer that is hard, brittle and biocompatible as well as difficult to be machined by other traditional machining methods. The laser micromachining is complex and depends on the interaction of laser energy, material properties and the beam delivery system that has several parameters and need to be investigated before the actual operation so this research began with the study of laser process parameters relating to the laser ablation on a silicon wafer such as laser energy, spot size, working plane, feed rate of XYZ translation stage and number of pass. From the study, the shape of laser ablation was measured and used as the cutting profile of a laser machine tool.

To support the users at the design stage of biomedical devices, the 3D analytical model of laser ablation is essential to predict the microstructure virtually in CAD/CAM system. There are many researches developing their models to simulate the laser ablation for micromachining but there are errors in the simulation of laser phenomenon because it depends on their assumptions and methods used to formulate the model. Therefore, this
research proposed the better analytical model to calculate the laser cutting profile from the essential laser process parameters and material properties studied from the fundamental study. The analytical model starting from laser energy profile, modified beam propagation with Gaussian function and laser ablation modeling with cutting angle reduced the laser-machined surface errors compared to the previous work. Moreover, the model was further applied in the computer simulation of laser micromachining to get the optimal laser process parameters for minimal surface roughness. It demonstrated that this model is a great tool for engineer to design and develop the biomedical devices.

When the device meets the functional requirement, it does not mean that it can be used as a biomedical device because the quality and biocompatibility are other crucial factors in the biomedical device development. This research also proposes the surface modification techniques to improve the surface quality and biocompatibility of machined substrate. The improvement on quality of laser ablation by using the cyanoacrylate is proposed to protect the falling debris on the substrate while the diamond-like carbon coating with PLD and polyethylene glycol with UV lithography are introduced to reduce the protein adsorption on the laser-machined area. Moreover, the technique to detect the fluorescent protein adsorption by using the fluorescent spectrophotometer is proposed to quantitatively measure the amount of albumin on the substrate. All proposed methods make the micro devices fabricated from the laser micromachining become more feasible in the biomedical device applications. In conclusion, the techniques presented in this paper provide the essential tools of laser micromachining on a silicon substrate for developing and prototyping biomedical devices. In this paper, the presented new method can be used in modeling and applying excimer laser in design, planning and fabrication of micro-scale biomedical devices.
The Development of Biomedical Devices with Excimer Laser Micromachining, Modeling and Simulations

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

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DEDICATION

To my Mom and Dad, who have worked very hard to support me to achieve my goal!
To my Grandparents who passed away!
Plawut Wongwiwat was born in 1977, in Bangkok, Thailand. He received the bachelor’s degree in Mechanical Engineering from Chulalongkorn University, Thailand in 1998 and the master’s degree in Industrial Engineering in 2001 from the same university. For working experience, he worked as the assistant production chief at the transformer and power supply factory, Thai Tabuchi Electric co., ltd., for 3 years, as the part-time computer consultant at the fluid and oil analysis laboratory, Focus Laboratories ltd., for a year and as the part-time mathematics and physics tutor for high school students. After 3 years of working, he got the full scholarship from the Royal Thai Government to study abroad in the United State of America. Then, he has been studying his M.S. and Ph.D. in Industrial Engineering at North Carolina State University since 2004. His research interests include production, manufacturing, automation, rapid prototyping, computer graphics, CAD/CAM systems and advance micro/nano manufacturing.
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Figure 8-1  The PDCA of the development of biomedical devices (Recap)
CHAPTER 1

INTRODUCTION

1.1 Motivation

In recent years, it has attracted a significant interest of finding feasible techniques for developing new biomedical devices. It has been shown that the general public now considers more on their health and tries to find the way to live longer with healthy food, effective medicine, and reliable medical treatment. Therefore, the biomedical devices such as a biocompatible prosthesis, a micro scaffold for nerves or other organs, a micro array for DNA, a micro channel for drug delivery or a bio-MEMS for bioelectronics devices are currently challenging and have great potential for many medical applications.

Finding any suitable manufacturing processes to fabricate the biomedical devices is a part of industrial engineering. If we focus on the micro biomedical devices from silicon wafers, there are many micro-fabrication processes generally applied such as photolithography, soft lithography, atomic force microscopy, microfilm depositing, laser micromachining and etching, etc. Each process has advantages and disadvantages but if we consider on the application of micro pattern on silicon substrate, the photolithography and the laser micromachining seem to be the suitable processes for this job because they can fabricate such high details of user-defined micro patterns on the silicon wafer. But, the photolithography starting from mask fabrication, photoresist forming, photoresist removing to chemical etching requires many processes, much time and high cost so the laser micromachining is more preferable to construct the micro patterns on the substrate because it is fast and flexible so that users can define and control the micro patterns with CAD/CAM and it does not require any extra processes.

However, the major phenomenon in laser micromachining called the photo ablation, is not as simple as traditional machining because it is complex and depends on many
controlled processing parameters from both laser process parameters and material properties such as laser power, laser types, laser beam energy profiles, wavelengths of the laser, energy adsorption and reflection of materials, maximum fluence threshold of materials, focal distance of the beam, machining feed rates or machining path overlaps etc. Although many researches have studied on the laser ablation, modeled it and developed new techniques to improve quality of laser micromachining as well as increased the ablation rate, there are errors and limitations in the simulation of laser phenomenon because it depends on laser types, machining systems, assumptions and methods used to formulate the model. Therefore, there are a lot of opportunities to develop and improve such a better model that users can utilize and use in the design of the biomedical devices.

The new issues of quality and efficiency in the laser micromachining also come up to be considered such as ablation profiles, ablation rates, edge resolution, debris creation and residual substrate damage. Also, the surface quality affects the biocompatibility of the device and this is crucial factor in the biomedical application because the devices must not harm the living tissues inside the human being. So, it is very important to develop such a fabrication process or a combination of processes that meet all functional requirements in biomedical applications. The novelty on the laser micromachining and its applications are challenging, valuable and beneficial to study, model and further apply in the mechanical, industrial, manufacturing, biomedical engineering or material science fields.

1.2 Research objectives and scopes

This research has applied the Plan-Do-Check-Act (PDCA) circle in the development of biomedical MEMS devices as shown in Figure 1-1. The research focuses on novel development of laser micromachining in modeling, simulation and other applications along all phases in PDCA circle. In “Do” phase, the laser micromachining is selected as a tool to be used in this work to order to fabricate designed patterns on silicon substrates. With scientific approach, the work starts from the fundamental study on laser process parameters in the lab-built laser micromachining system in order to understand how these parameters correlated to
one another. Then, the analytical modeling is formulated, developed and simulated with Matlab software. The modeling is the part of “Plan” phase to support the design of the devices and its results of simulation are verified with the actual results from the fundamental study. The benefit of the proposed analytical model further demonstrates an application in the parameter optimization for surface quality improvement. Not only virtually method is applied to solve the problem, but the research also proposes many feasible techniques to improve the surface properties that are important in the biomedical devices i.e. surface roughness and biocompatibility as the part of “Check” and “Act” phase of the PDCA circle. These works provided useful techniques and the system of continuous development in the fabrication of biomedical devices.

![The process of biomedical device development](image)

**Figure 1-1:** The PDCA of the development of biomedical devices
There are many kinds of lasers such as CO2 laser, excimer laser, Nd:YAG laser or Ti:Sapphire laser but this research does not cover all kinds of laser technologies. Because the lab-built laser micromachining system is our major equipment used and studied for fabrication and verification, the laser specifically applied in all chapters is the UV excimer laser with ArF gas while the XYZ linear translation platform was installed to create 3-axis micromachining movement. However, many concepts in the research can be adapted to other types of laser micromachining. The material mainly focused in the research is a silicon wafer since it is generally used in a semiconductor field and can be applied to biomedical electronic devices such as biochips, biosensors or bio MEMS. Moreover, the interesting laser process parameters studied and experimented in this research are laser energy, laser repetition rate, laser spot size, focal working plane, feed rate of XYZ translation stage, number of machining passes and machining path overlap. These parameters affect the shape of laser ablation significantly and will be studied in this research.

After the laser process parameters are studied on the lab-built laser micromachining system, the research focuses on laser ablation modeling. The laser ablation is a core process in the micromachining because it reflects to the cutting profile. The model assumes that the photo ablation is the core process of laser micromachining and starts from considering laser energy profiles to the interaction between the light adsorption on materials by Beer’s law. The laser beam propagation function is changed to Gaussian beam function in order to give better beam energy distribution on the surface of materials rather than the linear function in previous research. Also, the incident angle of laser beam is added in the model to give more accurate results. All analytical formulations will be fully derived and verified with actual results from the experiment.

Continuing from the proposed model, the research simulates the laser ablation with Matlab software and constructs the user-friendly interface computer program. Because the excimer laser is a pulse UV laser, overlapping between laser pulses causes inevitable cusps of tool paths and these cusps increase the machined surface errors. Unlike traditional milling tools, the effective cutting length of laser is based on light energy and the beam goes all the way to the work piece. As far as the beam reaches the work piece and has enough energy, the
laser will cut materials. It is very complex when the laser overlaps itself by tool path planning or feed rate. With this simulation, 3D image of laser ablation is predicted by changing parameters and the optimal laser process parameters will be determined from the simulation.

The above parts of research focused on modeling and simulation in the virtual environment. However, from the fundamental study, the debris and recast are main quality problems in micromachining on the silicon wafer. The debris from material re-deposition probably clogs the micro channels or blocks the microcircuit. To improve quality of laser ablation on a silicon substrate, cyanoacrylate is used to protect the re-deposition of material and reduce the thermal diffusion. The depth and width of ablation on cyanoacrylate are studied. The effect of cyanoacrylate thickness on the quality and depth of cut on silicon wafer are investigated. This novel technique will show the improvement in quality of microstructure developing and prototyping biocompatible MEMS devices.

Not only the surface roughness, but also the biocompatibility is another important property for biomedical devices. The protein adsorption on the surface of material indicates the ability that living cells or tissues can attach to foreign materials. The coarse surfaces from cusps of laser ablation in the micromachining can change the surface property and also affect the biocompatibility of work pieces. In this work, two new high biocompatible materials i.e. polyethylene glycol (PEG) and diamond-like carbon (DLC), are introduced to improve the biocompatibility of laser micro-machined substrates. The pulse laser deposition (PLD) is applied to deposit the DLC while spin coating and UV photolithography are applied to deposit the PEG. The fluorescent-labeled albumin is also proposed to use in the protein adsorption testing while the protein absorption is imaged by fluorescent microscope and measured the UV luminosity by the fluorescent spectrophotometer. The research will show the effect of laser micromachining on the biocompatibility and how it can be improved by two proposed techniques. This work will benefit the development of the biomedical devices.

There are several research topics in this dissertation from the fundamental study in laser micromachining parameters to the application in biocompatibility testing on the laser
micro-machined surface. These issues are organized in many chapters and described in the following section.

1.3 Dissertation organization

This dissertation has been organized into 9 chapters and the remaining sections of this paper are presented as follows:

Chapter 2 will explore the literatures that are relevant to the current work of laser micromachining in modeling, materials, quality improvement and applications in micro/bio fabrication.

Chapter 3 will study on the fundamental system of laser micromachining. The laser process parameters of the lab-built laser micromachining system have been studied and the relationship between laser parameters and depth of laser ablation on a silicon wafer has been investigated. This study builds the foundation of the laser ablation modeling and states quality problems that can be solved in the chapter 5 and 6.

Chapter 4 will propose the laser ablation modeling technique. The conceptual idea starts from the analytical formulation of laser energy profile, beam propagation to the depth of laser ablation. The model has been improved from the previous work by applying the better beam propagation function and consideration of light incident angle in model in order to improve the accuracy of the laser ablation simulation. All analytical analysis and derivations are explained in this chapter.

Chapter 5 will demonstrate further application of the analytical model in the Chapter 4. The several actual experiments were also employed to verify the analytical model compared to the real laser ablation on the glass substrates. The ability to adjust many laser parameters virtually reduces cost and time of the actual set up of the laser micromachining system. Also,
the characteristics of the laser ablation from the simulation when the parameters have changed lead to the optimization of the laser process parameters for best surface finishing in the laser micromachining.

Chapter 6 will propose the novel technique to improve surface quality of laser micromachining. After fundamental study in the chapter 3, the surface quality issue has shown up because of the imperfect of photo ablation. In this chapter, the surface roughness has been improved by coating with the cyanoacrylate. The coated layer protected the debris re-deposition around laser-ablated areas.

Chapter 7 will propose the novel techniques to improve biocompatibility of laser-machined substrates. Unlike chapter 6, the biocompatibility issue has been focused because the unintentionally surface roughness from laser micromachining also induced the blood and protein adsorption. This may cause major problems in blood-related biomedical devices. The 2 advanced coating techniques, pulse laser deposition and UV photolithography, were applied to coat the target substrate with highly biocompatible materials, diamond-like carbon (DLC) and polyethylene glycol (PEG), to promote the biocompatibility on the laser micromachined substrates.

Chapter 8 will provide the conclusions of all the works presented in this paper and the possible future research opportunities in the laser micromachining and modeling areas.

Details of these discussions will be presented in the following chapters.
CHAPTER 2

LITERATURE REVIEW

This dissertation focuses on the laser micromachining in modeling and applications on the development of biomedical devices. Thus, the review begins with the literature reviews on laser technology, laser micromachining and laser ablation modeling. Then, the surface quality of machined substrate and biocompatibility of materials are mentioned in the last section of this chapter. These 2 factors are very important factors in medical device development because the failure of device may cause harm to surrounding tissues and might lead to the death of patients. This chapter will provide several important backgrounds relating to laser micromachining process, laser ablation and current researches related to biomedical device applications with the laser micromachining.

2.1 Laser micromachining in the micro/nano fabrication

Light Amplification by Stimulated Emission of Radiation or LASER is the device that emits the high-energy light by stimulating the laser medium. When the molecules of active laser medium stimulated by energy pumping of excitation source go up to the excited state, they try to go back to steady state by releasing their photon energy. The accumulation of photon energy for each excited molecule becomes the high-energy beam coming out of the laser system. The schematic diagram of laser system is presented in Figure 2-1. Basically, there are 2 types of laser operations, continuous and pulse laser, divided by the characteristics of laser amplitude output. Moreover, different laser systems emit lights with different spectrums such as UV, IR or any visible lights. The commonly used lasers in the industry are CO₂ laser, Nd:YAG laser and Excimer laser. In manufacturing, the lasers are used for cutting, welding, marking, machining and heat treatment.
Excimer laser is one of the pulse lasers that emit the ultraviolet light with high energy. The combination of inert gas and halogen gas in the excimer laser system determines the wavelength of UV laser beam such as 193 nm for ArF and 248 nm for KrF. These UV lasers are commonly used in eye surgery (LASIK) and semiconductor manufacturing. Because most of material absorbs UV light better than other lights, the excimer laser is useful for laser micromachining. In Figure 2-2, one of the regions that have high absorption is the area at the wavelength below 243nm (KrF) and metals, polymers and ceramics have high value of absorbance in that region.
Since the first laser was demonstrated in 1960, laser manufacturing has become a mega industry applying into science, industry, medicine, and consumer electronics. In general, the laser micromachining refers to laser-induced fabrication of surface pattern or 3D structure with typical feature size in order of µm rather than mm. The basically misconception assumes that the laser micromachining only covers erosive process but the techniques such as pulse laser deposition (PLD) have another additive process. Actually, the broad definition of laser micromachining includes application such as laser drilling, laser-assisted chemical etching, photo polymerization or UV lithography etc. The concept of laser processing can be presented in Figure 2-3.

Figure 2-2: Degree of absorption as a function of wavelength (Naessens, 2004)
The laser ablation by mask projection is the majority of laser micromachining techniques that uses a 2D mask to cut the substrate on the particular area (Rizvi, 2002; Ihlemann, Schmidt, & Wolff-Rottke, 1993; Harvey, Rumsby, Gower, & Remnant, 1995). The large pattern can be achieved by step and repeat process of machining within the mask area. The aperture placed above the mask is used to determine the shape of the beam. The coordination is controlled by a motion controller and the laser beam shape was shrunk and reversed by the projection lens.

The other technique uses the high intensity laser delivered and focused by the optics mirror and lenses into the smallest spot size. The substrate is moved by the motion-controlled platform to produce desired patterns (Rizvi, 2002; Böhlen, Fieret, Holmes, & Lee, 2003). The main advantage of this method over the mask projection technique is the flexibility of machining that can be designed and controlled with CAD/CAM program and not requiring the mask.
The application of UV laser in micromachining became the interesting research around 1990s when the study presented that many materials absorb the UV laser better than the other lasers. Then, when materials receive the laser energy above their limit, this phenomenon leads to the photo ablation that is noncontact and clean material removing process. In 1993, Ihlemann machined the microstructure from UV laser on polymers, glass and ceramics with 3 different laser ablation techniques i.e. contact mask ablation, mask imaging and spot writing (Ihlemann, Schmidt, & Wolff-Rottke, 1993). In his experiment, he investigated the parameters that are ablation rate, laser fluence and laser spot size on PET with 248nm UV laser. He produced micro patterns and concluded that the small structures less than 100 µm can be produced by excimer laser. A few years later, Harvey applied the mask projection, beam overlap and Half tone mask with UV laser and CNC system on different materials to create the microstructures (Harvey, Rumsby, Gower, & Remnant, 1995). The 2.5D and 3D structures were produced but the consideration in the laser fluence and laser motion synchronized with CNC movement was important in practical machining.

Table 2-1: Correlation of relative ablation efficiency with 248 nm (Brannon, 1997)

<table>
<thead>
<tr>
<th>Material</th>
<th>Absorption coefficient $\alpha$ (cm$^{-1}$)</th>
<th>Thermal Diffusivity $\kappa$ (cm$^2$/sec)</th>
<th>Rel. Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>$1.8\times10^6$</td>
<td>0.78</td>
<td>Poor</td>
</tr>
<tr>
<td>Copper</td>
<td>$9.0\times10^5$</td>
<td>1.11</td>
<td>Poor</td>
</tr>
<tr>
<td>CuCl</td>
<td>$1.6\times10^5$</td>
<td>0.003</td>
<td>Good</td>
</tr>
<tr>
<td>SiO2</td>
<td>$&lt;10$</td>
<td>0.01</td>
<td>Poor</td>
</tr>
<tr>
<td>Polyimide</td>
<td>$2.0\times10^5$</td>
<td>0.001</td>
<td>Good</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>$7.0\times10^4$</td>
<td>0.001</td>
<td>Good</td>
</tr>
<tr>
<td>Plexiglass</td>
<td>$5\times10^3$</td>
<td>0.001</td>
<td>Poor</td>
</tr>
<tr>
<td>Teflon</td>
<td>200</td>
<td>0.001</td>
<td>Poor</td>
</tr>
</tbody>
</table>
However, not all materials are suitable to be machined by laser. Even though the absorption on materials is relatively high, it is not only a factor that indicates how well material can be ablated by laser. The thermal diffusion is also one of the other factors. If the thermal diffusivity is too high, the ablation efficiency will not be good because the thermal energy is removed from the irradiated region quickly (Brannon, 1997). Since the silicon became the famous material in the semiconductor industry, many researchers were greatly interested in nanofabrication on silicon wafers and the excimer laser is one of interesting tools because a silicon substrate absorbs UV radiation very well.

In semiconductors, silicon is used in the fabrication of integrate circuit and other micro electronic devices. Silicon wafer has crystal structure of which the orientation is important on electronic and mechanical properties. As shown in Figure 2-4, orientation is defined by the miller index with [100] or [111] types being the most common for silicon. Each wafer is given either a notch or a flat edge that will be used in orienting the wafer into the exact position. Not only its orientation, but the impurity of silicon wafer in doping process also divides its types into n type and p type. The purpose of n type doping is to produce the carrier electron while the purpose of p type doping is to create a hole to reduce one of electron from crystal structure. The n and p type leads let silicon have different electronics properties for semiconductor. In Table 2-2, it provides some important properties that both [100] and [111] types are different.

![Figure 2-4: Silicon wafer crystal orientation (a) [100] and (b) [111]](image-url)
Table 2-2: The different properties on silicon in different crystal orientation

<table>
<thead>
<tr>
<th>Properties</th>
<th>Orientation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Modulus</td>
<td>[100]</td>
<td>129.5</td>
<td>GPa</td>
</tr>
<tr>
<td></td>
<td>[111]</td>
<td>186.5</td>
<td>GPa</td>
</tr>
<tr>
<td>Density of surface atom</td>
<td>[100]</td>
<td>6.78</td>
<td>$10^{14}$ /cm$^2$</td>
</tr>
<tr>
<td></td>
<td>[111]</td>
<td>7.83</td>
<td>$10^{14}$ /cm$^2$</td>
</tr>
</tbody>
</table>

*Data from EL-CAT, Inc.

The micro electronic and mechanical system (MEMS) based on micromachining and microelectronics technology has been developed rapidly since 1960. The MEMS devices consisting of microelectronics, microsensors and microactuators are applied for sensing, signal processing and micropositioning. The MEMS introduces a lot of very small devices in micro-scale benefits entire semiconductor industries. The future of MEMS is the development of non-contact signal communication such as electrical, magnetic and optical signals (Bao & Wang, 1996). The application of MEMS can be employed not only in the industrial or automotive area but also gets in the living body when people consider the application of biomedical electronics devices. The examples of MEMS applications were pressure sensors, inertial sensors, telecommunication components and microfluidic devices. In Figure 2-5, the tiny turbine was fabricated from the laser technology and this turbine may be used as the pump in micro mechanical system. The laser micromachining has been applied to create MEMS because of few processing steps, highly flexible CNC programming, capable for production processing, no major investment in clean room and many expensive process tools, applicable to many materials and capability with lithographic process and photo masking (Gower, 2001).
Before any implementation on laser micromachining begins, the study of laser processing parameters is necessary in every laser micromachining system. The next section will review on how researchers study on the laser process parameters and which parameters they studied.

### 2.2 Study on laser processing parameters

The laser ablation is not as simple and direct as the traditional material removal process such as milling, drilling or turning because it depends on many control parameters and the way of cutting does not directly relate to the geometry removal. So, the fundamental study on the laser ablation still becomes the basic need for any researchers before developing any micro devices. Because of the complexity of laser ablation, many researchers were interested and tried to investigate the laser ablation on different kinds of materials such as PMMA (Cheng, Wei, Hsu, & Young, 2004), Zirconia (Dear, Shephard, Wang, Jones, & Hand, 2008), Silicon (Li & Ananthasuresh, 2001; Bärsch, Körber, Ostendorf, & Tönshoff, 2003). Typically, the objective of the study on the ablation is to investigate the relationship between the control parameters in laser micromachining system such as laser fluence, laser overlapping and the focal length and the ablation output such as the depth of the cut, the

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Figure 2-5: Nickel rotor turbine mage by KrF laser LIGA. 470 µm diameter, 130 µm height.

(Gower, 2001)
cutting profile and the quality of the ablation. For example, in 2001 the feed rate of the XY stage, the laser pulse frequency, the discharge voltage and number of passes were used as control parameters while the roughness of the machined surface was used as primary indicator (Li & Ananthasuresh, 2001). Brannon studied the ablation and etching with excimer laser on the silicon substrate (Brannon, 1997). Chen (2005) also studied parameter study of near Nd:YAG laser on sapphire and silicon. The depth of ablation was studied on variation of fluence and scanning speed on both materials. Unlike other researches, he studied an additional different parameter called the laser ablation efficiency. It is obtained by the removed volume of material divided by the total energy on the substrate. Although more fluence would give more laser ablation rate, the ablation efficiency did not gain much but remained constant at higher laser fluence. He suggested that the plasma shield reduced the efficiency at higher fluence. (Chen & Darling, 2005).

Therefore, the laser process parameters need to be investigated as the fundamental study in every laser micromachining system before implementation in the actual micro fabrication. From these laser parameter studies, most researches found that the quality of the laser ablation on the silicon with nanosecond UV laser was still not good enough in high precision micromachining because of the thermal diffusion causing imperfect photo ablation. So, the surface quality occurring in the laser machining becomes a common issue in every long pulse laser such as excimer laser and this problem will be reviewed in the next section.

### 2.3 Surface quality of laser ablation

During laser ablation process, the schematic diagram of laser ablation is shown in Figure 2-6. The debris and recast produced from laser ablation creates the quality issue for micromachining. To solve this problem, the ultra-short pulse laser or femtosecond laser became the alternative. Liu (1997) also implemented the micromachining on silicon but he used the ultra-short pulse UV laser (Liu, Du, & Mourou, 1997). Lui (1997) presented that the ultra-short pulse laser is more applicable in high precision micromachining because the thermal diffusion in materials can be neglected.
The major disadvantages of the laser milling are the deposition of debris and the formation of recast around the milling area. Generally, the major causes come from the thermal material removal effect instead of perfect photo ablation when laser with long pulses such as micro or nanosecond laser is used. Using femtosecond laser is one solution to solve this problem. However, many researchers did not only focus on the laser system, but also studied on the other ways that can improve the quality of the laser ablation. The nanoparticles coming from 2 processes, phase explosion and thermal decomposition redeposit back on substrates and make the surface unsmooth from these debris. There are several methods to improve the surface quality of laser ablation. However, we can group the surface cleaning techniques into on-the-machine and post-processing techniques. The on-the-machine cleaning will perform the cleaning on the milling machine while post-processing technique will take a work piece out to clean in other secondary processes.

Because the laser ablation depends on many process parameters such as laser power, feed rate of XY stage, the laser pulse frequency, number of passes and material properties,
the first on-the-machine method is the adjustment of laser process parameters to achieve the optimal surface quality. Li (2001) proposed the orthogonal array method to perform the design of experiment to optimize the laser parameters by minimization of the surface roughness of the substrates (Li & Ananthasuresh, 2001). Li (2001) also suggested the way to improve the quality of the micromachining by processing in the water. In 2005, Ren used the nanosecond and femtosecond laser to machine the silicon in water (Ren, Kelly, & Hesselink, 2005). According to Ren’s work, the water improved ablation rate because it reduced the oxygen contact and re-deposition of debris that blocking the laser beam. There were a lot of following intentions on machining silicon wafer in different environments such as using water spray (Kang, Rizoiu, & Welch, 2007) or flowing water. Moreover, Huang (2010) studied the CO₂ laser parameters on PMMA cutting (Huang, Liu, Yang, & Yu, 2010). The parameters that he studied in his research were laser power, cutting speed and preheat temperature. Also, he laser-machined the PMMA in the water by holding the sample in the water container. The results showed that water promoted better the surface roughness while the preheat temperature and laser power at the proper level gave the optimal surface roughness condition.

Figure 2-7: The laser micromachining system for laser machining PMMA sheet in the water.
Another on-the machine method is to apply the laser itself to clean debris by adjusting the laser pulses at the machining system. For example, the double pulse laser machining technique can be used to improve surface quality of substrate (Noël & Hermann, 2009). This technique applies 2 laser pulses with short delay ranging from 1 to 10 ps. The second pulse is used to enhance the plasma and increase material removal rate. The amount of nanoparticle decreases with the laser pulse delay but the number of atoms and ions are increased. Dobrev (2008) cleaned the second machining path above the focal plane to remove the debris. Laser cleaning focuses the laser beam above the machining surface so that the laser energy is not enough to remove the material but it is enough to flatten debris and recast. From his experiment, the offset 1mm above was good for stainless steel, AISI 316 while the offset 2mm was good for copper (Dobrev, Pham, & Dimov, 2008).

The other type of surface quality improvement is the post-processing technique. Some techniques require the pre-processing such as masking film techniques to coat the substrate before removing the file in post-process cleaning. The masking techniques were also demonstrated with coating SiN films for anti-reflection of laser beam (Grohe, Harmel, Knorz, Glunz, Preu, & Willeke, 2006), using SiO₂ over-layer for damage resistance (Chong, Mitchell, Hayes, & Austin, 2002) or applying erasable marker ink for shield of re-deposition (Shin, Lee, Suh, & Kim, 2006).

However, to get better results, several cleaning processes should be combined to provide best removal of the loose and large debris on a substrate such as ultra sonic cleaning, de-oxidation and electrochemical polishing. Ultrasonic cleaning uses high frequency vibration to create ultrasonic wave to clean losing debris on the substrate. The cleaning efficiency depends on the magnitude of the acoustic pressure level. Chemical de-oxidation or pickling use the acid to clean the oxide layer of substrate and the debris will be removed se it attaches to the oxide layer. As shown in Figure 2-8, the electrochemical machining process is similar to electroplating but the substrate is used as anode instead of cathode. The debris will be removed and transfer to cathode side. The advantage of the electrochemical polishing process provides better results on not only the substrate surrounding but also the area inside the machined micro channels is improved.
Figure 2-8: The electro-polishing system to clean the silicon substrate (Dobrev, Pham, & Dimov, 2008).

The surface quality of laser ablation is not smooth because of imperfect laser ablation and unsuitable laser process parameters. Some researches took advantage of this imperfect phenomenon to increase the surface area of scaffold to promote cell adhesion while others tried to improve the surface quality to reduce blood adhesion. Therefore, this utilization of laser micromachining depends on its applications.

2.4 Laser ablation modeling

Many methods to model laser energy density are still complex and use fully optical science and mathematic modeling because it depends on the type of laser, light, lenses, homogenizer and shape of masks. The beam shaping can start from single mode Gaussian and apply Fourier transform relation between the input and output beam functions to create the more uniform laser energy distributions in Figure 2-9 (Dickey & Holswade, 1996). Beside the standard Gaussian beam, there are Super Gaussian, Flattened Gaussian, Fermi–
Dirac distributions or Super-Lorentzian developed for laser beam profile shaping (Shealy & Hoffnagle, 2006). The researchers can pick these beam energy distributions closed to laser light source and apply in their laser ablation model for many applications such as laser machining, lithography or laser-material interaction studies. However, in laser mask projection, the calculation of the radiation distribution occurring on the machined surface needs physics of light and beam propagation to transmit the illumination through masks and homogenizers. By applying Fourier transform on the coherent illumination and partially coherent illumination model, the energy flux vectors after mask and homogenizer were developed in (Paterson, Holmes, & Smith, 1999).

Figure 2-9: Profiles of square and circular spot geometries. (a) Square profile, $\beta=4$. (b) Square profile, $\beta=8$. (c) Square profile, $\beta=16$. (d) Round profile, $\beta=8$. (Dickey & Holswade, 1996)

In order to model the depth of laser ablation, the standard Beer’s law was used in many researches to calculate the ablation depth per pulse, (Böhlen, Fieret, Holmes, & Lee, 2003; Holmes, Pedder, & Boehlen, 2006; Pedder & Holmes, 2006; Ren, Narayan, & Lee, 2009). In Figure 2-10, by measuring the laser fluence and ablation depth per pulse from the experiment, the parameters from the Beer’s model such as threshold fluence, $F_{th}$, and
effective ablation length, $\alpha$, can be determined. So, when the incident fluence is known, the depth of ablation can be calculated from the Beer’s model and in (Böhlen, Fieret, Holmes, & Lee, 2003), CAD/CAM in laser micromachining started to use this concept and apply for 3D design and manufacturing.

Figure 2-10: Ablation rate measurements for polycarbonate at 248 nm wavelengths. Solid line is cubic polynomial fit to data; dashed line is best-fit “Beer’s law” ablation curve (Holmes, Pedder, & Boehlen, 2006).

Improving Beer’s model by considering the light reflection, angular dependence studied in (Paterson, Holmes, & Smith, 1999; Holmes, Onischenko, George, & Pedder, 2005; Pedder & Holmes, 2006; Pedder, Holmes, & Dyer, 2009) introduced a good technique to model and predict surface propagation in the laser ablation simulation. However, general numerical model for the surface propagation simulation and surface error analysis by considering the general form of laser energy distribution were not proposed much because mask imaging and half tone mask were more popular in micro/nano manufacturing and they required the complex laser energy density model for the specific designed mask. In direct-
write method, the laser system does not require the mask and try to reduce the laser beam down to the smallest spot size. The laser energy distribution is directly focused and used to ablate the substrate while XYZ translation platform moves and lets the laser beam to machine 3D pattern.

The models for laser ablation in micromachining process were proposed in many researches but the basic Beer’s absorption law always can apply to the beam fluence. If Beer’s Law is assumed and the material will be removed when the local fluence higher than the threshold fluence, the depth of removing material for \( F > F_{th} \)

\[
d = \frac{1}{\alpha} \ln \left( \frac{F}{F_{th}} \right)
\]

Where \( d \) is the etching depth, \( \alpha \) is the effective absorption length, \( F \) is the fluence incident on the solid and \( F_{th} \) is the threshold fluence.

If we consider the reflectivity at the surface \( R \), the model will be changed. However, the surface reflectivity is often ignored because it generally accounts for only 6-10% of total fluence.

\[
d = \frac{1}{\alpha} \ln \left( (1 - R) \frac{F}{F_{th}} \right)
\]

The parameter that we got from the above model is only the depth of cut from basic parameters of laser and material properties. But, Beer’s Law assumes a minimum fluence for ablation, i.e. cold ablation or photochemical ablation, and does not take some physical process such as photo thermal ablation that is obtained by the laser heating until the material vaporized. So, the ablation depth model will be changed.

However, the depth of cut is not enough for tool path planning. The shape of ablation as cutter must be known to calculate material removal rate. The easiest way is to assume the volume is cylindrical along the laser spot size. This method reduces the complication of the model but it needs to have the supporting equipment such as mask to make the laser fluence uniformly as much as possible or assume that the depth of etching is relatively small when it is compared with the laser spot size.
Bohlen developed the CAD/CAM software that generated tool path and simulated laser machining on materials (Böhlen, Fieret, Holmes, & Lee, 2003). His software was able to do cutting, hole drilling, slot cutting, 2D area clearing, pocketing and 2½D surface machining. In this research, the overlapping in laser tool path produced the extra depth of removal area as presented in Figure 2-11. The way to solve this problem was to simulate the shape of the ablation before machining operation.

![Figure 2-11: Schematic comparison of milling (Top sequence) and laser ablation (Bottom sequence)](image)

(Böhlen, Fieret, Holmes, & Lee, 2003)

Beside Beer’ law, Hurtony (2008) primarily used thermal conduction and molecular dynamic model to simulate the laser ablation. Sinko and Phipps (2009) developed the laser-surface interaction by using inverse-bremsstrahlung model for CO2 laser. However, the thermal diffusion is usually neglected in UV laser problem due to high efficiency of photon absorption. Because Beer’s model is not complex and was used by many researches, it is good to simulate the laser ablation with fast computational speed.

### 2.5 Biocompatibility of the micro-machined materials

Biocompatibility for material is the important factor for biomedical devices. When the blood contacts the surface of the foreign materials inside the human body, the thrombus
formation occurs and has been the problem in the development of cardiovascular equipment. However, at the implant point of view, the implant contacts with the human tissue, cells and proteins around the implant area. The process of protein adsorption and conformation is the great impact on the implants and tissue constructions. Compared with in-vivo study, the in-vitro testing is quick and relatively cheap way to estimate the biocompatibility of materials (Bumgardner, et al., 2004). Therefore, the in-vitro studying on the hemocompatibility and protein adsorption of materials was widely used in many researches in order to evaluate their materials and innovative processes in the biomedical applications. For example, Poly Ethylene Oxide surface (Gombotz, Guanghui, Horbett, & Hoffman, 1991), Silicone rubber surface (Zhou, Yuan, Zang, Shen, & Lin, 2005) and also the surface modifications of Silicon wafer (Zhang, Desai, & Ferrari, 1998; Sofia, Premnath, & Merrill, 1998), Stainless steel (Zhang, Kang, Neoh, Wang, & Tan, 2001), Polysulfone (Ishihara, Fukumoto, Iwasaki, & Nakabayashi, 1999) and Polyaniline film (Chen, Kang, Neoh, Wang, & Tan, 2000).

Understanding how the blood proteins interact with the biomaterial surface is important for biomedical devices. Serum Albumin, the most plasma protein in the blood, is the one of the typical proteins for biocompatibility test, such as immunoglobulin, fibrinogen and blood platelet. The blood proteins are the proteins found in blood plasma consisting of 3 major blood proteins, Albumin, Globulins and Fibrinogens. The most protein in serum proteins is Albumin containing 60% of blood proteins and creating the osmotic pressure in the blood cell and transporting lipids and steroid hormones. Globulins around 35% are used in transporting the ions, lipids and hormones in the immune system. Fibrinogen around 4% is essential for blood clotting. The other 1% of the plasma proteins are proteins such as enzymes, proenzymes and hormones. After the foreign materials are exposed to the blood, the hydrophobic and electrostatic interaction created the protein adsorption on the surface of materials. The related factors to the interaction are the physiochemical properties of interacted materials, blood and the material as well as the external condition such as pH, ionic strength or nature of buffer.

To measure how much protein adsorbs on the material surface, X-ray photo spectroscopy (XPS), Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron
Microscope (SEM) and Ellipsometer were the equipment that used to study the amount of the adsorption in the many researches (Gombotz, Guanghui, Horbett, & Hoffman, 1991; Ishihara, Fukumoto, Iwasaki, & Nakabayashi, 1999; Chen, Kang, Neoh, Wang, & Tan, 2000; Zhou, Yuan, Zang, Shen, & Lin, 2005). Both XPS and FTIR are spectroscopy that measures the element composition on the surface. However, XPS is well suited to provide quantitative analysis while FTIR can provide the data in qualitative way (Morent, De Geyter, Leys, Gengembre, & Payen, 2007). The significant element that the researchers are interested in is the nitrogen because the proteins are one of polymers that contain the amino acids, which have Nitrogen element. They are mainly focus on measuring how much amide compound, nitrogen element, adsorbs on the surface of the material. SEM is another method that used to image and measure the number of blood proteins or platelets adhering on the surface. By scanning, magnify and capture the image of the surface of sample, the cell can be counted and calculated the cell density to indicate the amount of protein adsorption. Moreover, Ellipsometer is the optical equipment that could be used to measure the protein thickness by investigation the refractive index of thin film. Using some method and mathematic model, the protein thickness can approximate the protein adsorption around the surface area (Zhang, Desai, & Ferrari, 1998).

In biomedical engineering, protein labeling plays important role in biology research because the method and techniques in protein analysis usually require labeled proteins. Proteins can be labeled with the radioactive or fluorescence depending on the applications. Fluorescent dyes like TAMRA or FITC have been used to label and image by the fluorescent microscope (Yam, Gu, Li, & Cai, 2005). Fluorescein isothiocyanate (FITC), Isomer I is widely used fluorescent labeling reagents because of the fluorophore’s high quantum efficiency and conjugate stability. FITC has maximum absorption at 495nm and maximum emission at 525nm. So, when FITC was detected by the Fluorescent spectrophotometer, it presented the graph as shown in Figure 2-12.
Figure 2-12: Normalized fluorescence of FITC-BSA on Polycaprolactone (PCL) (Benesch, Hungerford, Suhling, Tregidgo, Mano, & Reis, 2007)

By the concept of fluorescent spectrophotometer, light from the source passes through the monochromator and the excitation light wavelength is selected. The excited light is focused in the sample and the photometer measures the fluorescent emission from the sample. With holding the excitation light at constant wavelength, the emission spectrums of the fluorescent light from the sample are measured. In Figure 2-12, the graph showed the ability of the fluorescent spectrophotometer can observe the existence of FITC and that means it can tell about the protein adsorption.

2.6 Summary from the literature review on the micro biomedical device development

In this chapter, the laser micromachining process with direct-writing method shows its capability and flexibility to fabricate the micro patterns on materials. The microstructures on silicon wafers can be applied directly as the micro-electro-mechanical systems (MEMS) or the laser-machined polymer can be used as a scaffold in tissue engineering. This chapter started from reviews of laser micromachining technology, fundamental study of the laser
processing parameters, the modeling of laser ablation and the issues on the surface quality and biocompatibility of the machined substrates. The flow in this chapter shows a roadmap of the biomedical device development. The next following chapters will begin with the basic study on the laser process parameters of the lab-built laser micromachining system. Then, the analytical modeling will be introduced to further simulate the designed pattern of microstructures. After that, the novel methods to improve the surface quality and biocompatibility are introduced. Finally, the new concept to apply the laser micromachining in order to fabricate the biomedical devices is proposed the late chapter.
CHAPTER 3
PARAMETER STUDY OF THE LASER
MICROMACHINING ON
SILICON WAFERS

As explained on the literature review, because of the complexity of laser ablation, the parameter study of the laser micromachining system is required before developing any micro devices. In this chapter, the lab-built excimer laser system is introduced and it will be used to fabricate the micro patterns or micro channels on the substrates. The processing parameters related to laser and XYZ translation platform are discussed and investigated. The shape of laser ablation and the relationship between the depth of laser ablation and laser machining parameters are studied in order to be further applied in the laser micromachining in the other chapters.

3.1 Lab-built laser micromachining configurations

Basically, the main concept of this machine configuration is trying to reduce the size of laser beam to increase the laser intensity at the working spot. A commercial ArF gas excimer laser (COMPexPro 201, Coherent, Inc.) was used in our system to emit UV laser pulse with wavelength at 193 nm. The energy of the output laser pulse can be adjusted up to 400 mJ and the maximum repetition rate was 10 Hz. Fused silica biconvex lens were used in a telescopic set to reduce the primary spot size of the laser. Then, the laser beam was delivered by set of three high UV reflection mirrors while the aperture was used to reduce the spot size manually. Finally, the beam was focused by 10x objective to create minimum laser spot size on the material surface. The working distance of the work piece relates to this focal distance of the objective lens. A CCD camera was applied above the objective lens to
monitor the micromachining process. All laser system configurations are presented in Figure 3-1.

The 3 axis micropositioning module (A3200, Aerotech Inc.) was used to provide 3-axis synchronous translation motions with laser parameters. The numerical program, G-Code, was applied to move the workpiece on the stage along designed patterns while laser energy and pulse were controlled by a controller that users could manually input. The synchronization in the stage motion and the laser with small spot size with high fluence created the micromachining called the direct-writing method. It does not need any mask and is able to write the contoured path or complex patterns

![Figure 3-1: Laser micromachining scheme](image)

In our experiment, the substrate mainly focused in this chapter is a silicon wafer. Although there are different types of orientations as presented in Figure 2-4, we did not focus
on the type of silicon as a major parameter comparing to the laser processing parameters so we chose only one type of silicon wafer in our experiment. The silicon wafer type that we used throughout the experiment was N type [1 0 0].

3.2 Laser processing parameters

In this section, the processing parameters from our lab-built laser micromachining system have been carefully selected. All parameters come from the literature review and can be varied by a user during the machine setup process. The details and relationship of the laser parameters has been mathematically described in the following.

3.2.1 Laser fluence

In laser term, laser fluence or beam intensity are used to describe the strength of a radiation field. By definition, the fluence can be determined from energy divided by area as presented in Equation (3.1). To change the laser fluence in laser system, we can determine nominal laser energy, change the aperture size and select the working plane.

\[ F = \frac{E}{A} \]  

(3.1)

Where \( F \) = Laser fluence, \( E \) = Laser energy and \( A \) = Laser spot area

3.2.2 Beam profile and focal length

The typical UV laser beam profile is not circle or ellipse but rectangular of which the energy profile along X and Y direction are different as shown in Figure 3-2. Although beam delivery system such as biconvex lenses, aperture and objective lens in our laser micromachining configuration could reduce the beam size, they did not change the beam intensity profile. For our excimer laser, the aspect ratio 2:1 of UV beam came out at the laser gun. In Figure 3-3, the actual laser spot on different substrates show the laser energy profile of the UV laser system.
Figure 3-2: Typical excimer beam profile

Figure 3-3: Laser spot showing its energy profile on thermal paper and silicon wafer

When the laser beam was passed through the objective lens, it was focused into single spot at the focal point. This optic phenomenon can be presented in Figure 3-4. From the 10X objective specification, the focal length was 15 mm below the objective. However, the XYZ stage was moved relatively to focal plane in Z direction and did not initially start from the edge of objective lens. To find the focal plane, basically the focal point located where the laser beam has the smallest size so we did some preliminary experiment and measured the spot size at different Z value. After the test, the focal plane located at $Z = 12.00$ mm. It meant
that the gap between the bottommost and topmost was 27.00 mm and it was our working space.

Figure 3-4: The focusing beam passing through the focal point

3.2.3 Feed rate of XYZ linear translation platform, laser repetition rate and the laser spot overlap

Because UV laser is not continuous laser, the space between each pulse is important in laser ablation. Typically, there are 2 types of overlap, pulse overlap and path overlap. The pulse overlap is the cohesive area between 2 adjacent laser pulses along feeding direction. So, the factors directly relating to the pulse overlap are feed rate of the XYZ stage, pulse repetition rate of the UV laser and the laser spot size. The relationship among those parameters can be present in Equation (3.2).

\[ F = \frac{6(1 - P)DR}{100} \]  

(3.2)

Where \( F \) = Feed rate in mm/min, \( P \) = % Overlap, \( D \) = Beam diameter in \( \mu \text{m} \) and \( R \) = Repetition rate in Hz
3.2.4 Laser ablation of material

When the UV laser is shot on the surface of a material, the material will absorb radiation energy. For sufficient fluence of laser energy, the decomposition in material will start. The removal of material due to the interaction with strong laser irradiation is called laser ablation. Because laser ablation of material relates to the absorption of laser energy, it depends on both laser process parameters and properties of material that can be presented by Beer-Lambert’s model.

According to the Beer-Lambert law, the relation of beam fluence to depth in the material is

\[ F(x) = F_0 e^{-\alpha x} \]  

(3.3)

Where \( F_0 \) is the initial beam intensity, \( \alpha \) is the absorption coefficient of material and \( x \) is the depth below the material surface.

The models for laser ablation in micromachining process were proposed in many researches but the basic Beer’s absorption law always can apply to the beam fluence. If Beer’s Law is assumed and the material will be removed when the local fluence is higher than the threshold fluence, the depth of removing material for \( F > F_{th} \) is.
Where \( d \) is the etching depth, \( \alpha \) is the effective absorption length, \( F \) is the fluence incident on the solid and \( F_{th} \) is the threshold fluence.

However, the depth material from the above model is considered only spectral absorption. Actually material parameters include type and thickness, spectral absorption, substrate reflectivity and density. Therefore, for a given material, the process parameters on laser micromachining need to be studied and adjusted to achieve the optimum machining performance such as the material removal rate or surface roughness.

### 3.3 Experimental results

From the laser process parameters in the previous section, the depth and shape of ablation are the important factors in the laser micromachining because it is similar to the cutting tool in the traditional machining process. From equation (3.4), the depth of ablation is basically based on the laser energy so the laser beam energy and its profile need to be investigated. So, the experiments to investigate the relationship between the depth of laser ablation laser energy and other processing parameters were employed and their results are shown in the followings.

#### 3.3.1 Energy lost in the system

Actually, the energy of laser beam right at the top of the substrate was not equally to the nominal energy that user input on the controller. The energy lost happened starting from the first set of biconvex lens to the last objective lens above the material. However, the major lost occurred at the aperture because the aperture directly obstructed the beam and reduced the laser spot size. Since the aperture could be freely rotated, it was linearly discretized into 9 levels (\( A = 0, 1, 2, 3, 4, 5, 6, 7, 8 \)) in order to make it controllable. The nominal energy was

\[
d = \frac{1}{\alpha} \ln \left( \frac{F}{F_{th}} \right)
\]

(3.4)
changed from 100 to 225 mJ to see investigate the effect of the aperture size on the actual energy.

Figure 3-7: Relationship between actual energy and nominal energy

From Figure 3-7, when the laser nominal increased, the actual energy on the material increased linearly and also when the aperture size opened larger, the actual energy still changed linearly but more than the energy at the smaller aperture. It meant that the laser energy lost in the system was constant and depended on the laser aperture size. To estimate the efficiency in the laser system, the efficiency factor was calculated from the basic Equation 3.5 and presented in the relationship among the aperture size in Figure 3-8.

Actual Energy = Efficiency x Nominal Energy

(3.5)
From Figure 3-8, the efficiency of the system varies from 1.6% to 8.5% depending on the aperture size. From the graph, the laser energy lost in the system is quite high, >90%. But, the laser energy is not directly related to the laser ablation but the laser energy density or laser fluence is more important. The fluence coming from the laser energy and the laser spot size, indicates the capability of the laser to machine the substrate and this will show in the following section.

3.3.2 Measurement on laser spot size and calculation of laser fluence on the silicon wafer

Before we got the laser fluence, we had to know the spot size because the fluence is equal to laser energy divided by spot area. In our lab-built laser system, the size of the laser

Figure 3-8: The efficiency of the lab-build laser system
beam was reduced by biconvex lens, aperture and objective lenses. To measure the maximum laser spot size for each aperture size (from A=0 to A=8), thermal paper was used to put on the focal plane of the objective lens. The ablation areas from the thermal paper were measured and calculated in the Figure 3-9. Moreover, in order to compare with the spot size on silicon wafer, we used the same laser power, 150 mJ for different apertures. All comparing results were shown in Figure 3-9.

![Comparison of the spot area between Silicon and Thermal paper](image)

Figure 3-9: Spot size for different aperture

We can notice that in Figure 3-9 if the aperture opened larger, beam spot size was larger. On the same plane, the spot sizes on the thermal paper were larger than the spot sizes on the silicon. Also, the spot size on the plane lower than the focal plane had smaller area. However, if we noticed the shape of laser spot in Figure 3-10, the shape of the laser spot at the
A = 0 looked like small ellipse and when the aperture expanded, the spot changed and got closer to circle shape.

![Figure 3-10: Laser spot on the silicon wafer at nominal energy = 150mJ](image)

From the spot size that we got from the thermal paper, the maximum laser fluence could be calculated and presented in the Figure 3-11. In this time, the laser fluence still increased linearly when nominal laser energy increased. The fluence of the laser that easily ablated silicon started approximately around 0.1 J/cm² (Brannon, 1997). From the graph in Figure 3-11, all fluence in our laser system were greater than 5 J/cm² and also had capability to reach 22 J/cm² for A=8, the largest aperture at the nominal energy = 225 mJ. However, to change the aperture size, it did not mean that we knew the laser fluence immediately because both parameters, laser energy and spot area, were changed in the same time. So, the value of laser fluence related to the factor whether laser energy or spot size changed more. In summary, at this point the single drilling hole with laser micromachining could be determined roughly by changing the aperture opening. However, the depth of ablation still depended on the laser fluence that was subsequently investigated.
3.3.3 Depth of the ablation on a silicon wafer

To find the depth of the ablation, the microchannels were machined in different parameters. After machining, the samples were cut and captured the cross-sectional depth by SEM (Scanning Electron Microscope in AIF, NC State University). The depths of the ablation were measured and the statistical parameters such as the average and standard deviation were calculated.
3.3.3.1 Investigation on relationship between the depth of ablation and working plane

On the different working planes with the same nominal energy, the depths of ablation on silicon varied because the spot sizes of each plane were converted to focal plane and different in area on each level as presented in Figure 3-12. Changing in laser spot size let the laser intensity on the substrate changed along different working planes. From the graph, the laser working spot was further from the focal plane, the laser cutting ability reduced. The result showed that the smallest width was 31.46 µm and the highest depth was 21.71 µm.

Figure 3-12: The depth and the width of ablation on the different working planes for A=1, Nominal Energy = 150mJ and feed rate = 2.4 mm/min
From Figure 3-12, the depth of ablation increased to the point around focal plane and started decreasing nonlinearly. This is because changing of area of spot size along the working plane away did not linearly expand along the distance further from the focal plane. However, unlike aperture sizes, the advantage of adjusting the focal plane is that we can change the spot size without disturbing laser energy thereby conserving energy.

Figure 3-13: Cross sectional pictures of the laser ablation on silicon on the different working plane for the same nominal energy at 150mJ, A=1 and feed rate = 2.4mm/min

### 3.3.3.2 Investigation on relationship between the depth of ablation and the aperture size

The effect of changing aperture size on the laser ablation was investigated. From our experiment, the relationship between depth of ablation and aperture size was presented in Figure 3-14. When aperture size was extended, the actual energy of laser on the material increased. The increment of laser fluence depended on both factors and it did not mean that the fluence would increase linearly. However, specifically in Figure 3-11, when the aperture size was expanded, laser fluence in larger aperture number was still greater than in the lower aperture. Therefore, from Figure 3-14, the depth of ablation went deeper when aperture size opened wider.
3.3.3.3 Investigation on relationship between the depth of ablation and the nominal energy

At this time, the nominal energy of laser was varied while we kept the other parameters constant. The effect of changing nominal energy on laser ablation was shown in Figure 3-15. The trend of the laser ablation obviously presented linear relationship with the nominal energy. It proved that depth of ablation linearly depended on laser nominal energy when we fixed the beam spot size. However, the depth of ablation did not go double when the fluence increased twice.
3.3.3.4 Investigation on relationship between the depth of ablation and the feed rate of XYZ Stage

When we changed the feed rate of XYZ stage, the percentages of pulse overlapping were changed. The effect of feed rate on laser ablation was presented in Figure 3-16. In that graph, when the feed rate increased the depth of ablation reduced while the width did not change much. To calculate % of pulse overlap, the feed rates at 1.2, 2.4, 3.6, 4.8, 6.0 and 7.2 mm/min, were equal to 97.5%, 95%, 92.5%, 90%, 87.5% and 85% of pulse overlap.
Figure 3-16: The depth and width of ablation on feed rate of XYZ stage at $E = 150 \text{mJ}$, $A=1$ and $Z=-500 \mu\text{m}$ from the focal plane.

Figure 3-17: Cross sectional pictures of the laser ablation on silicon on the different feed rate of XYZ linear translation stage for the same nominal energy at 150 mJ for $A=1$. 

(1) 1.2 mm/min (2) 2.4 mm/min (3) 3.6 mm/min (4) 4.8 mm/min (5) 6.0 mm/min (6) 7.2 mm/min
3.3.3.5 Investigation on relationship between the depth of ablation and the number of pass

When we used laser to create channels on substrate with multiple passes, the depth on each channel showed the difference in depth as in the Figure 3-18. We determined laser nominal energy = 150 mJ with feed rate = 2.4 mm/min and Z = -500 μm from the focal plane. At the same aperture, A=1, depth of ablation increased linearly while the width of ablation did not increase as much as the depth. Considering the amount of cutting depth on single pass, 6.58 μm, if we compared with the double or triple passes, 13.31 μm and 17.57 μm, the value increased in multiple times of the number of passes with small errors.

![Depth and Width of Ablation on different number of pass](image)

Figure 3-18: The depth of ablation on different number of pass at E = 150mJ, A=1 and Z = -500 μm from the focal plane

46
To protect small errors occurring in the multiple passes, the working plane should be adjusted in every passes in order to keep the cutting depth of each pass constant. The limitation of the cutting was where the working plane went such a low distance that the fluence on working area went below the fluence threshold. From Figure 3-12, the minimum working plane, -750 $\mu$m below focal plan still had the ablation, 4.2 $\mu$m. Therefore, from the result in Figure 3.18, if the single pass ablation, 6.5 $\mu$m occurs at -500 $\mu$m, it required more than 38 passes to cut 250 $\mu$m deep and the cutting depth will reduce to 4.2 $\mu$m.

### 3.4 Discussion

#### 3.4.1 Spot size error from measurement with the optical microscope

From optical microscope, we could measure the spot size that was 73.73 $\mu$m wide and 123.50 $\mu$m high. To compare with measurement from cross sectional picture from SEM, the spot size was 49.57 $\mu$m wide and 91.24 $\mu$m high. This error happened because if we look at the top view from the optical microscope in Figure 3-20, the dark oval area contains unwanted area that has oxidation and debris on surface around the actual cutting area. However, the brighter area inside the laser ablation spot seemingly provides closer spot size to the one from SEM than measuring on the edge of dark area.
Figure 3-20: The picture of the single spot and slot that created from moving single spot at A=1 and Z = -500 µm from focal plane

Figure 3-21: The picture of cross-sectional view of the microchannel at A=1 and Z = -500 µm from focal plane
3.4.2 Depth of ablation and its cutting profile compared with laser spot shape

If we consider shape of laser ablation as the cutting tool, the symmetry on the cutting shape make the tool flexible in movement along XY direction. However, in Figure 3-10, the spot shape would become similar circle when the aperture opened larger or the working plane went further from the focal plane. The following effect from the larger spot size was the smaller in laser fluence. That meant the depth of the penetration in laser ablation would be lower and sometimes the smaller width of ablation for micro-channel applications was more preferable. Therefore, we have to trade off between width and depth of ablation.

3.4.3 Relationship among depth of ablation and other laser process parameters

From relationship among depth of ablation and laser process parameters, the trend of cutting depth on laser nominal energy and number of pass seemed to have linear relationship. However, for the working plane, linearly increasing the distance from the focal plane did not mean that the area would increase linearly. For instance, the increment of radius of the circle makes its area square increasing. So, if we can find the point that gives the area increasing linearly, the laser ablation probably changes linearly. Moreover, when feed rate of XYZ linear translation stage was adjusted, the percent of pulse overlaps was changed. This relationship did not relate to the laser ablation linearly, presented in Figure 3-16. But, if we recalculate to the average number of pulse in one area, the relationship between the cutting depth and the XYZ stage movement was improved as presented in Figure 3-22.
Therefore, we can estimate the depth systematically when we would like to adjust the laser process parameters in order to machine any desirable widths and depths of micro channels.

3.4.4 Quality of cutting surface

Unlike polymer, the silicon ablation quality was considered poor the term of surface roughness. From Figure 3-23, on the cutting surface, there were debris and recast from imperfect photo ablation remaining in the laser-cutting path. The debris created from the oxidation and re-deposition of vapor plume causes the inefficiency ablation because the debris blocks the laser beam not to ablate the material while the recast created from re-solidify of liquid from the channels causes a burr effect on the edge of ablation.
In order to solve this problem, there are many researches that proposed the ablation quality improvement. For example, using the femtosecond pulse laser to machine the material prevented thermal diffusion in the ablation process and let the material vaporize before the thermal transferring (Bärsch, Körber, Ostendorf, & Tönshoff, 2003), machining silicon in water used the water or other type of liquid to protect the oxidation and redeposition of debris (Ren, Kelly, & Hesselink, 2005) or selecting the optimal parameters in laser machining determined the optimal surface quality occurring in the laser ablation by design of experiment (Li & Ananthasuresh, 2001). In our research, the surface quality improvement will be discussed again in the Chapter 6.

3.5 Summary from the study of the laser processing parameters

The fundamental study on laser processing parameters demonstrates the capability of UV laser on laser micromachining and supports researchers to develop models and techniques that can improve laser machining performances. First, we started from investigating the laser system capability on the laser energy, laser spot size to maximum applicable fluence. After that, the laser ablation relating to material parameters and machining parameters were studied and presented in many graphs and figure in section 3.3. The results from the experiment can guide users on selecting the value of appropriate
parameters in machining on silicon substrates. That will be useful for future research in microelectronics and mechanics devices. However, the surface quality of laser ablation from the surface debris on the silicon wafer is not good enough so the Chapter 5 will present the method to improve the surface quality of the material after laser ablation. However, before we go through the surface modification techniques, the actual laser ablation profile from the experiment gave us the idea to model and simulate mathematically. This modeling technique will be useful in the CAD/CAM programing of the laser micromachining for fabrication of microstructures and is presented in the next chapter.
CHAPTER 4

ANALYTICAL MODELING OF EXCIMER LASER ABLATION FOR DIRECT-WRITE MICROMACHINING

From the Chapter 3, the laser parameters of the lab-build laser micromachining system were investigated and the critical parameter is the profile of laser ablation because it relates to the cutting ability of the laser micromachining. In this chapter, we propose the new technique to simulate the shape and depth of laser ablation. From literature review, there were several techniques to develop analytical models that could predict the actual laser ablation efficiently and we chose the Beer’s law model as the laser ablation model. However, to make the simulation better, our new approach is based on the previous work in Ren (2009). In his work, the quantitative modeling for machined surface error analysis for excimer laser micromachining was proposed by application of the variant of laser beam profile in Gaussian shape and classical Beer’s law. By his method, the direct-write laser machined surface shape could be simulated and predicted including the different laser energy profile, overlapping effect, irregular cutting shape and distance between adjacent machining paths. However, the assumption on the laser propagation on objective lens by using linear equation contrasted to the physics of optics and created errors in the calculation of beam width. Also, the depth of ablation was considered in the vertical direction that was difficult to apply in the complex situation like 5 axis micromachining. In this chapter, we modify the laser beam propagation equation and create the numerical algorithm for simulation the complex shape of laser ablation. All models and algorithms in this research can be used in CAD/CAM for surface micromachining on biomedical engineering devices.
4.1 Modeling of laser energy profile in laser micromachining

There are many ways to model the laser energy profile as shown in Figure 2-9 but in our research laser energy distribution can be approximately formulated as the Gaussian function in Equation (4.1) for 2D problem.

\[ F(x) = F_{\text{max}} e^{-\frac{x^2}{2\sigma^2}} \]  

(4.1)

Where \( F \) is the fluence at \( x \) position on the profile, \( F_{\text{max}} \) is the maximum laser fluence and \( \sigma \) is the range of beam spreading over the laser energy distribution.

The circular or elliptic shape laser beam can be formulated in the two dimensional Gaussian function in Equation (4.2) for 3D problem. Typically CO\(_2\), Copper vapor, Ti:Sapphire and Nd:YAG laser create this kind of laser beam.

\[ F(x,y) = F_{\text{max}} e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right)} \]  

(4.2)

Where \( \sigma_x \) and \( \sigma_y \) is the range of beam spread on \( x \) and \( y \) direction over the laser energy distribution.

For rectangular shape laser beam like TEA CO\(_2\) and excimer laser, the energy distributions along \( X \) and \( Y \) direction are different. In this research, we used the multi-mode laser energy profile similar to (Ren, Narayan, & Lee, 2009).
As shown in Figure 4-1, we modified Gaussian function for the beam length, the longer side, with a step function and put the constant beam profile in the middle as shown in Equation (4.3) while the other width, the shorter side, has the regular Gaussian energy profile in Equation (4.4).
Also, the modified 2D multi-mode Gaussian function is shown in Equation (4.5)

\[
F(x, y) = \begin{cases} 
F_{\text{max}} e^{-\frac{(x-x^{'})^2 + (y-y^{'})^2}{2\sigma_x^2 + 2\sigma_y^2}} & x \leq x^{'}, \\
F_{\text{max}} e^{-\frac{(x-x^{'})^2 + (y-y^{'})^2}{2\sigma_x^2 + 2\sigma_y^2}} & x^{'} \leq x \leq x^{'}, \\
F_{\text{max}} e^{-\frac{(x-x^{'})^2 + (y-y^{'})^2}{2\sigma_x^2 + 2\sigma_y^2}} & x^{'}, \leq x \leq x^{'}, \\
F_{\text{max}} e^{-\frac{(x-x^{'})^2 + (y-y^{'})^2}{2\sigma_x^2 + 2\sigma_y^2}} & x^{'}, \leq x \leq x^{'}, \\
\end{cases}
\]  

The examples of 3D laser beam profiles in rectangular shape and circle shape are shown in Figure 4-2. Both models in Figure 4-2(a) and Figure 4-2(b) were constructed from Equation (4.2) and Equation (4.5).
From all Gaussian equations, $\sigma$ is the range of beam spreading over the laser energy distribution and both tails of the graph end at the infinity, $\infty$. However, in the real laser system, the beam width has the defined size. Therefore, we define the limit of the beam shape within $X_{\text{max}}$, $X_{\text{min}}$, $Y_{\text{max}}$ and $Y_{\text{min}}$ as presented in Figure 4-1. We assume $3\sigma$ beam spread at the limit so we can calculate $\sigma$ from the Equation (4.6) or Equation (4.7).

For rectangular beam shape in Figure 4-1

$$
\sigma_x = \frac{x_{\text{max}} - x^+}{3} = \frac{x^- - x_{\text{min}}}{3}
$$

(4.6)

$$
\sigma_y = \frac{y_{\text{max}} - y_{\text{min}}}{6}
$$

(4.7)

In this section, we shape the laser energy profile with Gaussian function and multi-mode Gaussian function. From the direct write machining method, because the laser beam is focused into the tiny spot at the focal point we will consider the beam propagation by the objective lens. The proposed modeling technique is proposed in the following section.
4.2 Modeling of laser beam propagation

When the laser beam passes the objective lens, it is converged to a small single spot at the focal point behind the lens. This optic phenomenon can be presented in the Figure 4-3. In the previous research, the beam propagation was modeled with basic cone shape along the laser penetration direction, Figure 4-3(a) (Ren, Narayan, & Lee, 2009). However, in the optic science, it is more rational and accurate to use the Gaussian propagation of the beam after the objective lens as shown in Figure 4-3(b). Also, the technical specification of the objective lens such as magnification, focal length and numerical aperture, can be useful and be a part of parameters in laser micromachining.

With z is the distance between the focal plane and working plane, we can find the beam width, $R(z)$, at that plane by the Gaussian equation, shown in Equation (4.8). $R_0$ is beam waist at the focal plane and $Z_R$ is the Raleigh range.
The Rayleigh range \( (Z_R) \) determines the characteristic curvature and is related to the beam properties such as beam wavelength, \( \lambda \) or total angular spread of the far beam, \( \Theta \) and beam waist, \( R_0 \).

\[
Z_R = \frac{\pi R_0^2}{\lambda} = \frac{2 R_0}{\Theta} \tag{4.9}
\]

In Figure 4-4, when the width of the beam is varied along the distance away from the focal plane because of the objective lens, the shape of the laser energy profile is changed and becomes wider. However, the \( F_{\text{max}} \) at the other plane goes lower and the area under curve represents the energy of the laser beam going toward the substrate. Without energy lost in the beam propagation, the area under laser energy distribution should be constant for all energy profile beneath the lens.

![Diagram](image)

Figure 4-4: Change of the laser energy profile at the different penetration depth
Based on the energy conservation, the total laser energies at different working planes are constant as presented in Figure 4-4. The area under curve in Figure 4-4 (b) is equal to the area under curve in the Figure 4-4 (c). Assume that there are 2 planes; plane 1 is the focal plane and plane 2 is the working plane. \( F_{\text{max}} \) and \( \sigma \) for each plane are \( F_1, F_2, \sigma_1 \) and \( \sigma_2 \). Without energy lost, the relationship between fluence on both planes can be expressed in Equation (4.10).

\[
\int_{-\infty}^{\infty} F_1 e^{-\frac{x^2}{2\sigma_1^2}} dx = \int_{-\infty}^{\infty} F_2 e^{-\frac{x^2}{2\sigma_2^2}} dx
\]  

(4.10)

Using the Gaussian integral,

\[
\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}
\]  

(4.11)

We can obtain the relationship between the maximum fluence on focal plane, \( F_1 \) and working plane, \( F_2 \)

\[
F_2 = \frac{\sigma_1}{\sigma_2} F_1
\]  

(4.12)

From this point, we will start to use the Gaussian equation, Equation (4.8). The beam spreads on the laser profile on each plane have the Gaussian relationship.

\[
\sigma_2 = \sigma_1 \sqrt{1 + \left( \frac{z}{Z_R} \right)^2}
\]  

(4.13)

Substitute Equation (4.13) in Equation (4.12) and we can get

\[
F_2 = \left[ 1 + \left( \frac{z}{Z_R} \right)^2 \right]^{-\frac{1}{2}} F_1
\]  

(4.14)
We try to reduce complexity of equation by determining the Gaussian curvature constant as a function of $z$

$$K(z) = \left[ 1 + \left( \frac{z}{Z_R} \right)^2 \right]^{1/2}$$  \hspace{1cm} (4.15)

So, we can reduce the complex form into

$$F_2 = K(z) \cdot F_1 \quad \text{and} \quad \sigma_2 = \alpha_1 \cdot K^{-1}(z)$$  \hspace{1cm} (4.16)

The fluence on any working plane along $x$ direction at $z$ distance from focal plane can be finally described in Equation (4.17)

$$f_2(x,z) = K(z) \cdot F_1 \cdot e^{-\frac{x^2}{2\sigma_1^2} K^2(z)}$$  \hspace{1cm} (4.17)

The final equation can be used to determine the laser energy profile at different working planes on the substrate in 2D model. However, in 3D model, there are some modifications on the model because $Z_R$ depends on the beam waist and in 3D problem, beam waist in $X$ and $Y$ directions may not have the same value. Therefore, we denote $Z_{RX}$ and $Z_{RY}$ and then we will get $K_x(z)$ and $K_y(z)$ according to Equation (4.15).

From the integral 2D Gaussian from Equation (4.2) and conservation of energy, we can get the relationship between the maximum fluence of focal plane and working plane.

$$F_2 = \frac{\sigma_x \sigma_y}{\sigma_x \sigma_y} F_1 = K_x(z)K_y(z) F_1$$  \hspace{1cm} (4.18)

Therefore, the 3D energy distribution function for Gaussian beam model can be formulated in equation (4.19).
We can apply the Equation (4.19) is the energy distribution for circular and elliptical shape. With the same method, we can derive the 3D model for the multi-mode Gaussian function, Equation (4.5). However, because of the middle shape that is constant function, there is one more variable, that is the ratio between the middle part and total beam length, $L_m/L$, and it makes the equation more complex.

\[
F_2 = \frac{(5a_1 - 1)}{(5a_2 - 1)} K_x(z)K_y(z) F_1
\]  
(4.20)

\[
\sigma_{x2} = \frac{\left(1 - a_1\right)}{\left(1 - a_2\right)} K_x^{-1}(z) \sigma_{x1}
\]  
(4.21)

Where

\[
a_1 = \frac{L_m}{L_1} \text{ and } a_2 = \frac{L_m}{L_2}
\]  
(4.22)

To simplify the problem, we assume that the saddle part in the middle of the function on different planes has the same ratio, $a_1 = a_2$. So, we can get the 3D multi-mode energy distribution for rectangular beam shape.

\[
F(x,y,z) = \begin{cases} 
K_x(z)K_y(z)F_1e^{-\frac{(x-x^-)^2}{2\sigma_x^2}K_x^2(z) + \frac{y^2}{2\sigma_y^2}K_y^2(z)} & x < x^- \\
K_x(z)K_y(z)F_1e^{-\frac{y^2}{2\sigma_y^2}K_y^2(z)} & x^- \leq x \leq x^+ \\
K_x(z)K_y(z)F_1e^{-\frac{(x-x^+)^2}{2\sigma_x^2}K_x^2(z) + \frac{y^2}{2\sigma_y^2}K_y^2(z)} & x^+ < x 
\end{cases}
\]  
(4.23)

In this section, the final models for different laser energy profiles are modified by factor $K(y)$ that represents the beam propagation coefficient for X and Y direction. We will
use it to form the depth of ablation for analysis and simulation the surface of laser micromachining in the next section.

### 4.3 Laser ablation modeling

When the UV laser is shot on the material surface, the material will absorb the radiation energy. For sufficient fluence of laser energy, the decomposition in material starts. The removal of material due to the interaction with strong laser irradiation is called the laser ablation. The excimer laser is a pulse laser so the ablation on the surface of material will be formed pulse by pulse and we can describe the depth of ablation phenomenon in the mathematic model in equation (4.24). From the equation, the ablation, \( S \), is the product of the penetration function that considers the laser fluence and surface normal of material.

\[
S = \int \left( F \left( x, y, z \right) \cdot \mathbf{n}(x, y, z) \right) dt
\]

(4.24)

In this research, we apply Beer-Lambart model as the penetration function. From the Beer’s law, we can simply calculate the depth of ablation in a function of laser fluence over the threshold fluence as shown in equation (4.25) where \( F \) is laser fluence, \( F_{th} \) is threshold fluence, \( \alpha \) is absorption coefficient of particular material and \( d \) is the depth below the material surface.

\[
d = \begin{cases} 
\alpha^{-1} \ln \frac{F}{F_{th}} & F > F_{th} \\
0 & \text{otherwise}
\end{cases}
\]

(4.25)
Figure 4-5: Threshold Energy and laser ablation in micromachining

In Figure 4-5, the Gaussian beam profile is applied over the substrate and the ablation occurs where the local fluence is greater than threshold fluence and the maximum ablation locates in the middle of the laser energy distribution. First, considering 2D model, by substitute the F(x) from Equation (4.1) into Equation (4.25) and simplify

$$d(x) = \alpha^{-1} \left( \ln \frac{F_{\text{max}}}{F_{\text{th}}} - \frac{x^2}{2\sigma^2} \right)$$  \hspace{1cm} (4.26)

For any Z position, we know the beam propagation factor, $K(z)$ from the Gaussian equation (4.15). So, we can formulate the depth of ablation on the surface of material at any working plane in equation (4.27)

$$d(x,z) = \alpha^{-1} \left( \ln \frac{K_x(z) \cdot F_{\text{max}}}{F_{\text{th}}} - \frac{x^2}{2\sigma^2} K_x^2(z) \right)$$  \hspace{1cm} (4.27)
When the multiple pulses hit on the partial machined surface, the direction of the laser may not be perpendicular to that surface normal. In Figure 4-6, the laser vector, \( \hat{v} \), ablates the substrate at point P and the normal vector of the surface at P is \( \hat{n} \).

![Figure 4-6: The laser ablation on the partial machined surface](image)

Consider the direction of these 2 vectors, the factor, \( k \), is defined.

\[
k = \hat{v} \cdot \hat{n}
\]  

(4.28)

Therefore, the modified depth of ablation with local energy profile

\[
S = d(x,z) = \alpha^{-1} \left( \ln \frac{k \cdot K(z) \cdot F_{\text{max}}}{F_{\text{th}}} - \frac{x^2}{2\sigma^2} K^2(z) \right)
\]  

(4.29)

From equation (4.29), the magnitude of ablating displacement, \( S \), can be calculated. However, its direction of the laser ablation, \( \hat{s} \), comes to the question that where this depth should penetrate to, \( \hat{v} \) or \( -\hat{n} \) or \( -\hat{z} \). From the physics of material removal by laser, the laser
ablalation occurs from energy absorption inside the material not from the collision of the ion or electron so the direction of the S should follow the inversed direction of surface normal, \(-\hat{n}\).

We can apply this concept into 3D model such as the elliptical shape profile in equation (6.30)

\[
d(x,y,z) = \alpha^{-1} \left[ \ln \left( \frac{k \cdot K_x(z) \cdot K_y(z) \cdot F_{max}}{F_{th}} \right) - \frac{x^2}{2\sigma_x^2} K_x^2(z) - \frac{y^2}{2\sigma_y^2} K_y^2(z) \right] \quad (4.30)
\]

For multi mode laser energy distribution or rectangular shape beam,

\[
d(x,y,z) = \begin{cases} 
\alpha^{-1} \left[ \ln \left( \frac{k \cdot K_x(z) \cdot K_y(z) \cdot F_{max}}{F_{th}} \right) - \frac{(x-x^-)^2}{2\sigma_x^2} K_x^2(z) - \frac{y^2}{2\sigma_y^2} K_y^2(z) \right] & x < x^- \\
\alpha^{-1} \left[ \ln \left( \frac{k \cdot K_x(z) \cdot K_y(z) \cdot F_{max}}{F_{th}} \right) - \frac{y^2}{2\sigma_y^2} K_y^2(z) \right] & x^- \leq x \leq x^+ \\
\alpha^{-1} \left[ \ln \left( \frac{k \cdot K_x(z) \cdot K_y(z) \cdot F_{max}}{F_{th}} \right) - \frac{(x-x^+)^2}{2\sigma_x^2} K_x^2(z) - \frac{y^2}{2\sigma_y^2} K_y^2(z) \right] & x^+ < x 
\end{cases}
\]

From this point, we can get the single pulse ablation, S from equation (4.29), (4.30) or (4.31). Then, with multiple pulses, the total ablation can be calculated from the equation (4.24). In the next section, we will create the moving model of the laser beam to new position for micromachining process and simulation technique for programming.

### 4.4 Modeling procedure for machining process

Unlike the conventional machining process, the shape of cutting does not come from the geometry of the cutting tool but it depends on the energy absorption on the surface of the material. The absorption over the threshold energy creating the cutting profile is determined by the energy distribution and the beam propagation. Moreover, the distance from the center
of the beam, distance from the focal plane and the surface normal of the substrate affect the magnitude of the laser intensity. In this section, we consider machining parameter such as XYZ feed rate, laser reputation rate and the adjacent trajectory overlap in the laser micromachining. In Figure 4-7, the 2 types of typical overlap in laser trajectory of micromachining.

![Image of laser trajectories](image)

**Figure 4-7: The overlap of the laser-machining trajectory**

### 4.4.1 The laser ablation along single and multiple adjacent laser trajectories

When the laser moves for cutting the work piece, there are several overlaps within the single machining trajectory. From the previous section, the local laser fluence and ablation rate has been formulated. The feed rate, F in mm/min, and the reputation rate, R in Hz, control the position of the next pulse as presented in equation (4.32)

\[
\hat{P}_2 = \hat{P}_1 + \frac{F}{60R} \cdot \hat{f} \tag{4.32}
\]

Where \( \hat{P}_1 \) is the starting vector, \( \hat{P}_2 \) is the destination vector and \( \hat{f} \) is unit vector at the feed rate direction.
When the laser moves to new point, $P_2 = (u, v, w)$, the local penetration can be calculated by equation (4.33) while the function of ablation, $d$ is determined from equation (4.29), (4.30) or (4.31).

$$\delta s = d(x - u, y - v, z - w)$$

(4.33)

If the surface of material is partially machined, new depth of ablation can be found from equation (4.34). From equation (4.34), the new depth, $S'$, can be calculated from the previous depth, $S$, plus the incremental ablation, $\delta s$ from equation (4.33).

$$S'(x, y, z) = S(x, y, z) + \delta s(x - u, y - v, z - w)$$

(4.34)

For multiple adjacent laser trajectories problem, we can simply apply the overlapping distance to find new location, $P_2$ instead of calculating from the feed rate and the reputation rate. For example, if the overlapping distance is $\mu$ along +x direction, the equation (4.34) is just modified to be equation (4.35).
4.4.2 Boundary calculation, depth of ablation along z-direction estimation and direction of the laser beam

To model the system, it is not necessary to consider all surface of the work piece because the laser spot size is normally much smaller than the substrate. Considering the ablated area, it is the area where the fluence is greater that the threshold fluence so the boundary can be determined from where the fluence is equal to threshold fluence. According to equation (4.1), we can find the threshold fluence, \( F_{th} \) as presented in equation (4.36)

\[
F_{th} = F_{\text{max}} e^{-\frac{x_{th}^2}{2\sigma^2}}
\]  

Therefore, the boundary of the laser ablation, \([-x_{th}, x_{th}]\) can be found in equation (4.37)

\[
x_{th} = \sigma \sqrt{2\ln F_{\text{max}} F_{th}^{-1}}
\]  

With beam propagation,

\[
x_{th}(z) = \frac{\sigma}{K(z)} \sqrt{2\ln K(z) F_{\text{max}} F_{th}^{-1}}
\]  

In previous section, we discuss about the moving laser beam to new position, \( P_2 = (u, v, w) \). The general boundary condition for X and Y direction at \((u, v, w)\) is \([u-x_{th}, u+x_{th}]\) and \([v-y_{th}, v+y_{th}]\)
In Figure 4-6, the usual laser ablation moves following the inverted direction of surface normal, \(-\hat{n}\). In this case, the X and Y position of the ablated nodes on substrate after machining can be moved to new position. Therefore, the nodes in the calculation will be robust and need attention on the node collision, node deletion and node insertion. In order to avoid instability problem, in (Holmes, Onischenko, George, & Pedder, 2005), he suggested propagating the displacement to Z direction by equation (4.39).

\[
\delta z = \frac{\delta s}{(\hat{n} \cdot \hat{z})}
\]

(4.39)

With the propagation, all X-Y grids are maintained to make the calculation easier in programming but the shape of ablation will have errors from assumption because width of the ablation shape cannot be extended.

From equation (4.8), the constant, k, is the product of the local light direction, \(\hat{v}\) and surface normal, \(\hat{n}\). We may assume the light direction is going down opposite to \(\hat{z}\) or we can find it from the linear interpolation inside the beam propagation function. For example, at the \(-Z\) level in Figure 4-9, the direction of \(\hat{v}\), in the angle of \(\Phi\), can be calculated by differentiating the Gaussian beam propagation, equation (4.8).

![Figure 4-9: The local beam direction at Z position](image)

By differentiate the equation (4.8); the slope of the equation can be as the following.
At any position between point P and the center of the beam, we can use linear interpolation to calculate the slope for any light directions.

\[ \tan \phi = \frac{dR}{dz} = R_0 \frac{z}{(Z_R)^2 \left(1 + \left(\frac{z}{Z_R}\right)^2\right)} \]  

(4.40)

### 4.5 Summary from the analytical modeling of laser ablation

In this chapter, novel modeling techniques for direct-write laser micromachining simulation have been proposed. The improvement from the previous research in Ren (2009) by using different beam propagation modeling presented the significant error reduction. The further mathematic models were derived and can be applied for simulation of complex laser ablation in overlapping tool paths and inclined surfaces. This modeling concept can be beneficial for CAD/CAM programming and simulation in the laser micromachining that are currently applied in many research areas such as biomedical engineering, micro/nano manufacturing and rapid prototyping as well as the micro-electro-mechanical systems (MEMS). To validate our proposed model, we conducted the many experiments with our lab-built laser micromachining system and compared the actual laser ablation to the simulation results. The results of the experiment and simulation works are presented in the next chapter.
CHAPTER 5

PREDICTION OF LASER MACHINED SURFACE ERRORS

In this chapter, the analytical model derived from the Chapter 4 is used to simulate and apply in the actual laser micromachining. Because the overlapping in laser ablation of the next pulse interferes the shape of the previous pulse and it makes the laser-machining phenomenon more complex, the simulation from the model can predict the machined surface errors from the micromachining parameters such as the feed rate and adjacent machining-path overlapping in an easier way. This new model can also benefit tool path generation because it tracks back to the location of the center of the laser beam. In Figure 5-1, the diagram presents the effect of single trajectory overlapping on the total depth of ablation, D, and the surface error, h, by changing the machining feed rate, F. This figure clearly shows how the laser micromachining differs from the traditional machining because both the total depth of ablation and the surface error are varied and depend on how much feed rate is comparing to the original shape of the single laser ablation. It is different from the cutting shape of traditional tool that has fixed cutting profile. With the simulation, we can predict and generation CNC tool path easier and more efficiently by defining parameters such as laser energy, working distance from the focal plane and the tool path overlap.
5.1 Application of the modeling on Matlab software

Because the model in Chapter 4 is the analytical model and the solution relates to many equation systems, Matlab software is suitable to handle and solve numerous equations in the matrix forms. We developed the Matlab application that can simulate the complex 3D laser ablation as presented in Figure 5-2 so the model in the Chapter 4 can be further applied to optimize laser parameters in surface error analysis and study the surface quality of the laser micromachining in the following section. However, for simplicity in our conceptual explanation and comparison to the actual results, we used only 2D profile option, that is one of available features in our software to demonstrate the surface error phenomenon in the laser ablation although our software can simulate the 3D laser ablation shapes as shown in Figure 5-3.
The users can determine the laser processing parameters such as laser energy, type of energy profile, repetition rate, working distance, feed rate or overlapping distance in the Matlab application. The application will simulate the laser ablation in 2D and 3D depending on how users want it to be. However, the experiments need to be initially performed and the set data are used to fit and find the suitable parameters to use in the software. These preliminary experiments will help the simulation results more accurate and closed to the actual ablation.

In the next section, before the model will be used to simulate the laser ablation, the proposed technique in the modeling of which the laser beam propagation we modified by changing from linear to Gaussian function was validated by actual experiment with our lab-built laser micromachining system.
Figure 5-3: Our Matlab program can simulate the 3D complex micromachining (a) Single path overlap (b) Four machined path overlap
5.2 Comparison between linear and Gaussian modeling of laser beam propagation

To compare Gaussian beam propagation model that we proposed in this work with linear shape from (Ren, Narayan, & Lee, 2009), we used the excimer laser to construct the hole in different Z position and measured the variation of the spot size. By using laser energy 125 mJ, the laser with aperture, A = 2 and 4 machined the silicon wafer at changed Z position by XYZ linear translation platform. The results are presented in Figure 5-4(a) and Figure 5-4(b). From both figures, the actual spot size fits with Gaussian model better than linear one.

To statistically support the results, the parameter, mean square error (MSE), was used to compare the model. We measured more spot sizes on thermal paper, silicon wafer and glass with A = 2 and A = 4. The MSE was calculated and presented in Table 5-1. From the table, the Gaussian model showed significantly improve and provided less errors than the linear model at all substrates.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Aperture</th>
<th>Linear</th>
<th>Gaussian</th>
<th>Reduce (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal paper</td>
<td>A = 2</td>
<td>57.70</td>
<td>28.04</td>
<td>51.40</td>
</tr>
<tr>
<td></td>
<td>A = 4</td>
<td>77.59</td>
<td>51.05</td>
<td>34.21</td>
</tr>
<tr>
<td>Silicon wafer</td>
<td>A = 2</td>
<td>196.60</td>
<td>71.47</td>
<td>63.65</td>
</tr>
<tr>
<td></td>
<td>A = 4</td>
<td>509.32</td>
<td>53.12</td>
<td>89.57</td>
</tr>
<tr>
<td>Glass</td>
<td>A = 2</td>
<td>41.94</td>
<td>28.69</td>
<td>31.59</td>
</tr>
<tr>
<td></td>
<td>A = 4</td>
<td>33.18</td>
<td>26.68</td>
<td>19.59</td>
</tr>
</tbody>
</table>

Table 5-1: The MSE of the fitting models, linear and Gaussian.
Figure 5-4: The width of the spot size at different Z position from the laser micromachining at laser energy, 125mJ and the substrate is silicon wafer.
The major errors occur around the beam waist because the beam does not follow a linear relationship in the convex area at the focal point in Figure 5-5. The linear assumption will affect the laser micromachining around the focal plane because the laser ablation is not normally larger than the Rayleigh length so the spot widths around the beam waist area do not have much different. Also, it is not good to assume the constant laser widths because the laser micromachining sometimes applys somewhere further below the focal plane and at that area, the spot size is much larger comparing to the size at the focal plane. So, the Gaussian model for beam propagation seems to be a fit model for the objective lens.

![Diagram of Focal Plane, Error, Linear, and Gaussian](image)

**Figure 5-5: Comparing the Gaussian and linear modeling.**

In the next section, we will use the Matlab to simulate the laser ablation shape on the material and compare with the real experiment data.

### 5.3 Depth of ablation simulation with our analytical model

The experiments for comparison between the real laser ablation and Matlab simulation were employed. The excimer laser was used to machine glass. The laser machining parameters such as laser energy, feed rate and machining overlap were still
considered in the experiment. Aperture mainly used in this experiment was $A = 4$ and all samples were machined at that focal point.

5.3.1 Simulation on depth of ablation by variation of laser energy

The first experiment was the study to find the material property, absorption coefficient, in Beer equation, equation (4.25). By changing the laser nominal energy, the depth of ablation varied and the slope of the relationship represented the absorption coefficient as presented in Figure 5-6. After we got the coefficient by linear regression, the Matlab simulation using this parameter drew the 2D profile to compare the results. The machined profiles of glass samples were image and measured the depth of ablation by the light microscope (Meiji Techno, TC-5000).

![Ablation rate measurement for glass](image)

Figure 5-6: The ablation rate measurement of glass for the absorption coefficient calculation

The accuracy of maximum ablated depth depended on how well the linear regression fits the actual depth of ablation from experiments while the simulation propagated the depth along the spot area. In Figure 5-7(a)-(e), the simulation lines on the right were mapped to the
actual images on the left and the simulation results presented the shape of ablation closed to the actual one.

Figure 5-7: The comparison of experiment and simulation results for different laser nominal energy. The aperture, $A = 4$ and feed rate $= 2.5$ mm/min were used in the micromachining. All scale bars in the left images are 25 micron long.
5.3.2 Simulation on depth of ablation by variation of feed rate

When the feed rate changed, the number of pulse per area was changed. The Matlab simulation compared the results from the experiment by changing the laser feed rate.

![Image](image_url)

(a) 5 mm/min  (b) 2.5 mm/min  
(c) 1.25 mm/min  (d) 0.625 mm/min

Figure 5-8: The comparison of experiment and simulation results for different feed rate. The aperture, \( A = 4 \) and laser nominal energy = 175 mJ were used in the micromachining. All scale bars in the left images have 25 micron long.

From Figure 5-8, the result also showed the closed form of ablation similar to the actual one. However, at the low feed rate, Figure 5-8(d), the actual laser ablation presented the asymmetric shape. Because the actual laser beam might not be perfectly perpendicular to the surface of material, the error happened significantly at high depth of ablation. Moreover, the bottom-most of the ablation from simulation did not showed the sharp curve that is because of the cosine functions of the surface normal vectors around that area do not have much different.
5.3.3 Simulation on depth of ablation by overlapping

The more complexity in laser micromachining than the traditional machining is the overlapping effect between tool paths. With the simulation, the ablation profile can be determined easily with the same concept. In Figure 5-9, we used the same parameters simulating the profile of ablation when 2 adjacent path were overlapped each other. The results showed excellent estimation of laser ablation.

Figure 5-9: The comparison of experiment and simulation results for different overlapping between 2 adjacent paths. The aperture, A = 4, laser nominal energy = 175 mJ and feed rate = 2.5 mm/min were used in the micromachining. All scale bars in the left images are 25 micron long.
5.3.4 Simulation on depth of ablation by variation of surface angle

To study the possibility for 5 axis micromachining, the samples were inclined in different angles. From the simulation, when the surface is bent, the shape of ablation is changed as presented in Figure 5-10. To compare with the actual laser ablation, we made the inclined fixtures and put them on the linear translation platform. Then, the excimer laser was used to machine the glass sample with the same parameters. The results of this experiment are presented in Figure 5-11.

At this point, our results showed the quality of simulation that can predict the actual laser ablation efficiently. Also, the beam propagation model with the Gaussian model can improve the mean square error from the linear function estimation. The next section will discuss about the accuracy of the model, programming issue and further application in the modern industry and research.

![Diagram showing depth of ablation with different surface angles](image)

Figure 5-10: The shape of laser ablation in different surface angles from horizontal plane.
The surface error analysis from the Matlab simulation

The surface error from laser micromachining normally comes from the pulse overlap or tool path overlap. The repetition rate and feed rate of the stage determine the overlapping distance between 2 adjacent pulses while the gap between 2 laser-machined paths determines the tool path overlap. Also, in Figure 5-12, the depth of ablation is the depth of groove in cutting while the surface error is the height of ridge between adjacent paths. Unlike the traditional machining such as turning or milling, the lower feed rate or the smaller overlap does not mean that the size of crest will reduce because the effective cutting length of laser depending on the beam propagation, not depending on the geometry of the cutting tool. When the laser overlap gets close enough to the deepest point of the previous groove, the
reference bottom line can be ablated more and this phenomenon is hard to be investigated by geometry modeling because the depth of laser ablation depends on many factors.

![Graph](image)

Figure 5-12: The surface error from the two adjacent pulses

From the simulation of two-pulse overlap in Figure 5-13, we used the program to generate 2 laser pulses that have depth = 10 micron and width = 34 micron. These results were compared to the actual experiments before in Figure 5-9. From Figure 5-13 (a) to 13(f), the overlap distance is closer and this thing can be the result from increase of feed rate or repetition rate. The surface error ridge shows transformation from positive to negative value or reversal direction. At Figure 5-13(c), the ridge is almost perfectly ablated by laser and at Figure 5-13(d), the depth of laser ablation has increased. The depth of the laser ablation increases from single pulse, Figure 5-14(a), to double, Figure 5-14(f), while the surface error is difficult to tell when the ridge is reduced and moved to the opposite direction because of the machining overlap.
Figure 5-13: The surface error from two adjacent pulses in different overlap
When we employed multiple pulses, we can see in Figure 5-14 that the ridge size reduces from the feed rate at 22.5 mm/min to 15 mm/min and then surface error turns to the other side at feed rate = 12.5 mm/min. At feed rate = 10 mm/min, we can see the new ridge causing from the reversed surface error more clearly. Again, these new ridges are smaller when feed rate is reduced, while the depth of ablation also goes deeper at the same time.

Figure 5-14: The surface errors from multiple adjacent pulses

Therefore, we plot the result of depth of ablation and surface error versus the percent overlap area between pulses in Figure 5-15. The depth of ablation has a parabolic increase
when the laser pulse has greater percent overlap or shorter gap while the surface error shows the oscillating curve that has the minimum approximately at 30% and 65 % pulse overlap.

Figure 5-15: The depth of ablation and surface error in different % pulses overlap

To find lowest surface error, we manipulated the Matlab program to simulate and search for the optimal feed rate. Finally we found the percent pulse overlap with minimum surface error located at 34.013% and 64.313%. The surface errors at those points are 2.2836 micron and 2.6482 micron respectively. The conditions and the surface results of the laser ablation have shown in Figure 5-16.
In this section, we showed an example of 2D surface error analysis from the modeling that we had achieved from the modeling technique in the Chapter 4. With this method, we can also apply in 3D laser micromachining for real laser micromachining application.

### 5.5 Discussion

Using our model to simulate the beam propagation and laser ablation can predict the laser ablation shape with the improvement from the previous research (Ren, Narayan, & Lee,
The model provided the closed and acceptable shape for simulation the laser micromachining. However, the accuracy of the model depends on the fitting model that estimates the actual etch rate on the substrate. In our research, we used the Beer’s equation to fit the ablation as presented in equation (4.25) because the ablation rate from the experiment was closed to Figure 5-6. However, we found that some materials do not behave following the Beer’s equation. In (Paterson, Holmes, & Smith, 1999), the photo resist material, DuPont RISTON, showed the ablation rate as presented in Figure 5-17 and the fitted empirical function, equation (5.1), was used to fit depth of ablation. Therefore, we can simply adjust the model equation (4.25) to any better fitting model such as equation (5.1) or polynomial fitting that gives the least mean square error.

\[ d = b \tan^{-1} \left[ a \ln \left( \frac{F}{F_0} \right) \right] \]  

\[ (5.1) \]

Another difficulty that we found in computer modeling was the shape edge management for the CAD surface. From the mathematic modeling pointing of view, the cosine product of the surface normal vector and the laser beam direction vector seemingly
does not cause the troublesome in the system but actually it needs some carefully attention. Since the shape edge or corner create the suddenly change of the surface normal, the low resolution of grid X-Y in the modeling may not cover the details of that change and causes the abnormal depth of ablation and direction of ablation. To prevent this problem, the shape edge management algorithm can probably be put in the CAD/CAM software to make the better and smoother surface. In our research, we applied the moving average of local ablation to roughly solve some problems and this issue can be further improved in the future researches.

5.6 **Summary from the prediction of laser machined surface error with our analytical model**

From the proposed modeling techniques for direct write laser micromachining simulation, the improvement from the previous research by using different beam propagation modeling presented significant error reduction. The analytical models were derived and could be applied for simulation of complex laser ablation in overlapping tool paths. The reversion of surface error that is normally hard to predict can be easily found by simply changing the parameters in the mathematical model.

In Chapter 4 and Chapter 5, the modeling techniques and the applications of our new analytical model to predict the surface errors of laser micromachining were demonstrated. This can help the manufacturing engineer to find the optimal conditions for smooth surface in laser micromachining. In Chapter 6 and Chapter 7, we will focus on further improvement on the surface quality and biocompatibility of laser machined structures. The surface modification techniques in the next chapters will make the laser micromachining more feasible and suitable to apply in the fabrication of biomedical devices.
CHAPTER 6
CYANOACRYLATE COATING ON SILICON WAFER FOR QUALITY IMPROVEMENT IN LASER MICROMACHINING

This chapter presents the novel quality improvement in laser micromachining on silicon wafer that is one part of the main framework of the research. The debris re-depositing around the ablation area is not desirable because it may contaminate the optical devices, interfere with the function of a MEMS device or clog the channels of a microfluidic device. Application of film masking and machining in water leads to the proposal of hydrogel and cyanoacrylate coating technique on silicon substrate. The coating process was proposed by using the Dimatix materials printer and spin coating. The laser ablation on cyanoacrylate-coated silicon wafer was investigated and imaged by Scanning Electron Microscope and the surface roughness was measured by Atomic Force Microscope. This novel technique provides an alternative to improve the quality of the laser ablation on silicon wafer for developing and prototyping biocompatible MEMS devices.

6.1 Introduction
Laser micromachining on silicon wafer is the remarkable fabrication process to produce the microelectronics devices because it is able to produce in high speed, high precision and high resolution (Brannon, 1997). There are many applications that require detailed structures on a small scale such as MEMS, medical devices, inkjet printer nozzle, material cutting and drilling. Unlike a polymer, silicon is hard but brittle and not easy to be laser machined with high quality. The laser ablation on a silicon wafer presented in Figure 6-1(a) shows the surface roughness on a micro channel created by laser micromachining. Figure 6-1(b) shows a cloud of undesirable tiny debris around the laser machined micro
channels. From quality study on excimer laser in year 2001, the quality issues on the silicon substrate occurring during laser ablation were discussed and presented (Li & Ananthasuresh, 2001). The debris and recast layer of melted and vaporized materials on the surface of silicon wafer are created from imperfect photo ablation on material and have potential to reduce mechanical, chemical and electrical properties of MEMS devices. To solve this problem, there were several researches focusing on finding the parameters causing the re-deposition of debris. It has long been interested to develop the protecting techniques and the post-processing process to eliminate the debris out of the substrate or apply the ultra fast pulse laser in order to complete the photo ablation before beginning of the thermal diffusion. For instance, the effect of air pressure on debris re-deposition was studied (Singh, Argument, Tsui, & Fedosejevs, 2005) as well as machining in the vacuum, helium or oxygen environment were applied. Some researchers suggested the laser micromachining of silicon in flowing or water spray to obtain the better surface quality (Li & Ananthasuresh, 2001; Ren, Kelly, & Hesselink, 2005; Kang, Rizoiu, & Welch, 2007). There were also efforts in developing masking techniques to shield the re-deposition in laser micromachining by coating SiN films for anti-reflection of laser beam (Grohe, Harmel, Knorz, Glunz, Preu, & Willeke, 2006), using SiO$_2$ over-layer for damage resistance (Chong, Mitchell, Hayes, & Austin, 2002) or applying erasable marker ink (Shin, Lee, Suh, & Kim, 2006).

![Figure 6-1](image_url): A micro channel fabricated by laser micromachining on silicon wafer imaged by (a) SEM and (b) Optical microscope
Traditionally acetone and methanol are used as cleaning liquid. Although both solvents can remove some stain on the substrate in the regular cleaning process on a silicon wafer, the debris created from material cannot be eliminated easily because the falling back material has high adhesive strength. Therefore, we tried to integrate the film masking technique that can remove the debris of the material re-deposition after machining and heat reduction at the heat affected zone with cooling materials. The idea of laser micromachining on a silicon wafer in water was already purposed in order to protect debris re-deposition and reduce heat. The result showed that materials re-deposited less than machining in the air (Li & Ananthasuresh, 2001). However, the water in that technique caused deviations from the desired tool path while the thin film layer in the masking technique did not distract laser direction and provided the debris removal ability because the debris itself adhesively stuck on the substrate.

We take both advantages and propose a novel material coating technique and find the best coating material to improve surface quality of laser ablation of biocompatible silicon wafer. Hydrogel commonly used in cell culture is the semisolid material that we used for protection of the material re-deposition. Alternatively, the cyanoacrylate is well known as the fast acting glue widely used in household, industrial and medical application. It is more applicable and controllable for film coating the silicon wafer than hydrogel. Details of the proposed technique are presented in the following sections.

6.2 The mechanism of laser ablation

The basic mechanism of laser ablation is based on the absorption of UV energy on the materials. The schematic diagram of laser ablation is presented in Figure 2-6. When a substrate absorbs laser energy high enough, the laser material removal process begins. Basically there are 2 types of phenomenon occurring during UV absorption, photo ablation and thermal diffusion. The photo ablation is non-thermal process happening when photon energy overcomes the binding energy of material. The energy will break the bonds of solid causing ejection of material or vaporization. The other process is the thermal diffusion
process relied on the intense pulse energy heats the surface of the substrate. The laser heating melt the material and molten material tried to splatter out from cutting area. It causes pile-up or recast effect around edge of laser ablation.

In micromachining, debris and recast resulting from the laser ablation are important factors to determine the surface finish quality of laser micromachining. As shown in Figure 6-2, the laser ablation causes recast and debris around the micro channel. Even though a silicon wafer has high UV absorbent but it also has high thermal diffusion so the laser ablation on silicon wafer is not as good as on a polymer. From Table 2-1, although the material property of the silicon itself provides the poor laser ablation, the machining parameters such as feed rate and pulse rate also affect the pulse overlap and the surface roughness of the machined substrate as shown in Figure 6-2(b).

![Figure 6-2: SEM image on the laser micromachining on silicon wafer](image)

### 6.3 Materials and methods

#### 6.3.1 Materials

At the first stage, the proposed coating material is hydrogel because it is made from water and it has potential to reduce heat diffusion in the laser ablation while it can protect the
debris from re-deposition. The other material is cyanoacrylate that provides more adhesive strength than hydrogel, thinner for film height and also transparency for laser micromachining. In this work, both types of materials were tested.

1) Hydrogel

Gel is a semi-solid material formed from colloidal solution. Its weight and volume are similar to liquid while it behaves like solid. Hydrogels are water-based gels very similar to natural tissue because of their significant water content. Currently the hydrogels are used in many applications such as scaffold in tissue engineering, biosensor, medical electrodes or contact lenses. In this research, we applied the agarose gel, one of hydrogel mainly used in cell culture. Agar, a gelatinous substance derived from seaweed, is dissolved in water and coated on the silicon wafer. The basic parameter of the agarose gel is how concentration of agar in water contains should be. The semi-solid property will be different, more solid or more liquid, depended on different amount agar in water. Basically cell culture uses 1-2% of agar in growth medium.

2) Cyanoacrylate

Cyanoacrylate is the fast acting adhesive discovered by Harry Coover during WWII. There are many kinds of cyanoacrylate that are used in medical and industrial application. For example, 2-Octyl Cyanoacrylate is used for medical glue, Ethyl-2 Cyanoacrylate is used for super glue and n-Butyl Cyanoacrylate is used for veterinary glue. However, the fume from cyanoacrylate when it is vaporized irritates human eyes, nose and throat. Longer chain compound such as 2-Octyl Cyanoacrylate is preferred to use in medical application. In this research, the cyanoacrylate is not used to adhere to materials directly but it is used to coat the substrate. Generally, the cyanoacrylate rapidly polymerizes within a minute and fully cures within 2 or 3 hours.
### 6.3.2 Methods

1) **Film masking technique**

The main concept of this technique is to apply a thin transparent film on a silicon substrate. As shown in Figure 6-3, the cyanoacrylate layer is coated on a silicon wafer and ready for micromachining after it is fully cured. During laser ablation, the plume of debris occurs and re-deposits on the substrate. The film layer will protect the surface of the substrate from re-deposition. Because the acetone can dissolve the cyanoacrylate easily, it is used to clean the film on the silicon wafer. The standard cleaning procedure to clean the silicon substrate by acetone and methanol is applied.

![Diagram of film masking technique](image)

**Figure 6-3:** The masking technique to remove the surface debris by cyanoacrylate film

There are several ways to coat the material on a silicon wafer substrate. If we place a droplet of liquid on the silicon wafer, the surface tension of the liquid will create the puddle on the surface of the substrate. Using the puddle phenomenon, the film thickness, can be calculated as follows:
Where \( h \) = puddle thickness

\[
\gamma = \text{surface tension of liquid (dynes/cm)}
\]

\[
g = \text{gravitational acceleration (980 cm/s}^2\text{)}
\]

\[
\rho = \text{density of liquid (g/cm}^3\text{)}
\]

\[
\theta = \text{contact angle}
\]

In this research, two techniques of coating on a silicon wafer are presented for laser micromachining. In Figure 5.5, the first method is the utilization of the FUJIFILM Dimatix material printer to print the coating material on the substrate. By combining each droplet of material to form layer and accumulating layer by layer, the film of coating material is produced on the substrate. The coating was done by dropping the cyanoacrylate on a silicon wafer and waiting until it solidifies. The film layer is 10.42 ± 1.42 µm. Further studies on the film thickness and depositing parameters can be performed for the further improvement.

![Puddle](image)

Figure 6-4: The material deposition to form the coating layer on silicon wafer

The other method is using the spin coating as presented in Figure 5.6 to form the coating layer on a silicon wafer. The puddle is dispensed around the surface by the angular acceleration to coat the surface of material. The film thickness depends on the rotational speed of the spinner.
The coated silicon wafers with hydrogel prepared by spin coating gave the film thickness around 150-200 µm. The limitation on the high surface tension of water lets the thickness of hydrogel higher than the cyanoacrylate one. So, it needed higher power laser to penetrate to a silicon substrate.

2) Laser micromachining

After coating on the silicon wafer, the coated substrates were machined by ArF UV laser (193 nm) at 150 mJ Energy and 10Hz Repetition rate. The 50 µm wide micro channels were fabricated by moving linear micro-positioning platform with 1.2 mm/min feed rate at 100 µm below the focal plane. Three samples of each coated substrate were fabricated and studied. To measure quality of laser ablation, the AFM NSCRIPTOR™ DPN System by Nanoink inc., was to image and measure the surface roughness. The optical microscope and SEM are also applied to image the surface debris on the substrate.

6.4 Results and discussions

6.4.1 Vaporization of hydrogel on a substrate

Preliminary study of experiment on hydrogel coating shows the ability of the protection film for removing the surface debris on the substrate. Because of the surface tension of the water is quite high, the film thickness around hundreds of microns can takes more than single path of the laser micromachining to go through the film. We also found that the heat from the laser ablation is too high for hydrogel and it vaporizes water from the
silicon wafer quickly. Without any refilling system, hydrogel will run out and then there is no protection on the substrate anymore. After the laser machining finished there was no difference between hydrogel coated silicon wafers and the uncoated ones since there was no film of hydrogel to protect the debris re-deposition. As it is hard to control film thickness and the hydrogel vaporizes too fast because of heat during laser micromachining, we considered the alternative material, the cyanoacrylate, to coat the silicon wafer easily and not costly.

6.4.2 Comparison between cyanoacrylate-coated and uncoated silicon wafer

Coating with cyanoacrylate is another option because it sets quickly, transparent and strongly adheres on the substrate. In this research, the single cutting from the laser micromachining was able to penetrate the cyanoacrylate coating film. The thin film around 10 µm thick was cut through so a micro channel was created on the silicon substrate. In Figure 6-6, one can find the machined channel on cyanoacrylate film is wider than the one on the silicon substrate because of laser ablation and heat in that machining area.

Figure 6-6: A micro channel on the coated silicon substrate.
Figure 6-7(a) and Figure 6-7(b) show the laser micro-machined silicon wafers with and without the coating from an optical microscope. After we applied the basic cleaning process with acetone and methanol in an ultrasonic shaker, the surface debris on the surface of material was significantly reduced as shown in Figure 6-7(b). It is obvious that there was little surface debris on the silicon substrate (Figure 6-7(b)), comparing with the uncoated silicon wafer (Figure 6-7(a)) because most of tiny debris were removed together with the cyanoacrylate film.

![Image](image1.png)  ![Image](image2.png)

(a) Plain silicon wafer after laser ablation  (b) Silicon wafer after coating and cleaning process

Figure 6-7: Comparing the surface debris around micro channels between uncoated silicon wafer and cyanoacrylate coated silicon wafer. Imaged by optical microscope.
(a) Silicon wafer without coating  
(b) Silicon wafer with cyanoacrylate coating

Figure 6-8: Comparing the surface debris around micro channels between uncoated silicon wafer and cyanoacrylate coated silicon wafer. Imaged by SEM.

Figure 6-8 shows the SEM images of the two laser machined micro-channel samples. One can see from the Figure 6-8 (a) that the debris is very scattered around the micro-channel on the uncoated silicon wafer. Figure 6-8 (b) shows the SEM image of the micro-channel machined with the cyanoacrylate film coating.

To measure the surface finish of the laser micro-machined silicon wafer, we used the AFM to measure the surface roughness of a silicon substrate. By using the AFM, one can find the surface topology of the laser micro-machined silicon wafer. Figure 6-9 shows the comparison of the surface roughness measured by using AFM. Figure 6-10 shows the surface roughness of plain silicon wafer before machining to be within range of 0.023 µm. Figure 6-11 shows the surface roughness of the silicon wafer after machining to be 0.596 µm, relatively high comparing to the original surface finish shown in Figure 6-10. Figure 6-12 shows the AFM measured surface finish of the silicon coated with cyanoacrylate to be 0.027 µm, very close to the original silicon surface finish.

Comparing the surface roughness, there was little difference between the original plain silicon wafer and the coated silicon wafer after machining (0.023 µm and 0.027µm).
However, the uncoated silicon wafer after machining has the surface roughness, 0.596 µm, relatively high comparing to the previous two samples as shown in Figure 6-9. Therefore, the numerical measurement confirmed that the surface quality of the machined silicon substrate with cyanoacrylate coated was similar to the original silicon wafer before machining.

Figure 6-9: The surface roughness on different type of silicon wafers.

Values are expressed as mean ± standard deviation.
Figure 6-10: AFM Image from plain silicon wafer before micromachining (0.023 \( \mu \)m)

Figure 6-11: AFM Image from uncoated silicon wafer after laser ablation (0.596 \( \mu \)m)

The 150 mJ laser was used with feed rate, 1.2 mm/min at 100 \( \mu \)m below the focal plane.
Figure 6-12: AFM Image from cyanoacrylate coated silicon wafer after laser ablation (0.027 μm)

The 150 mJ laser was used with feed rate, 1.2 mm/min at 100 μm below the focal plane.

6.5 Summary

In this research, we have presented a new technique of coating with the cyanoacrylate on a silicon wafer for quality improvement of laser micromachining of microchannels. The presented coating film technique with cyanoacrylate coating creates the protective layer on the silicon substrate. The advantage of the cyanoacrylate is that its adhesive strength is high to coat on the silicon wafer, its transparent color gives the laser beam easy to pass through the thin film layer and it also can be dissolved in acetone so it can be cleaned by the traditional cleaning process that already uses the acetone and methanol. After coating the cyanoacrylate on the silicon substrate, the surface roughness was measured by AFM. The result showed that the presented technique generated very good surface finish of the micromachined silicon wafer with coating. However, the coating technique requires the extra step and cost of additional material to implement. So, there might be some concern about the trade off between the quality improvement and costs. As the results showed in this work, the presented technique provides a good remedy in quality improvement of laser ablation on
silicon substrate and it can be used for developing and prototyping biocompatible MEMS devices.
Biocompatibility is the very important term that refers to how materials interact with human body and one significant property in the biomedical devices. This chapter presents the effect of the micro-machined regions on the biocompatibility in the protein adsorption for medical devices applications. As presented in the literature review on how the FITC label can indicate the level of protein adsorption, the protein adsorption testing on the laser micro-machined area was applied by detecting the fluorescent probes with the fluorescent microscopy and the fluorescent spectrophotometer. Then, we applied two surface coating techniques to change the surface properties in biocompatibility and observed the protein adsorption again.

7.1 Materials and methods on the biocompatibility testing

7.1.1 Laser micromachining of the silicon wafer samples

In our experiment, the arrays of micro channels were machined on [100] silicon wafer. The laser pulse was maintained at 10Hz while the laser energy was 150mJ. The system was setup to keep the work piece located at 500 micron below the focal plane. The aperture was chosen at number 1 to give 90 microns widths of the micro channel. The XYZ linear micro-positioning platform was controlled with standard G-codes. The feed rate of the micromachining was 1.2 mm/min and the number of pass was 5. The array of micro channels in Figure 7-1(b) and the square machined area, Figure 7-1(a) were created for protein adsorption testing.
7.1.2 Methods for PEGDA coating by UV lithography

Poly (Ethylene glycol) Diacrylate (Mn = 258 from Sigma Aldrich) was spin-coated (Headway spinner) on the machined silicon substrate at speed = 3500 rpm for 50 seconds. The thickness of PEGDA film was measured by reflectometer (Nanometrics Nanospec/AFT) and the thickness was 1.0581±0.0462 microns. Then, the UV lamp (253.7nm) was used to cure the PEGDA film on the silicon substrate for 12 hours. As shown in Figure 7-2, the PEGDA film is coated on a silicon wafer and ready for biocompatibility testing.
7.1.3 Methods for DLC coating with PLD

The pulse laser deposition (PLD) is one of the physical vapor deposition (PVD) techniques. In our PLD system, a commercial excimer laser (LPX 200 Coherent, Inc) was employed in the system to emit UV laser pulse with wavelength at 249 nm for KrF gas. The laser beam was delivered and focused by optical systems to ablate the graphite target. With sufficient energy, laser pulse ablated and vaporized the target material to deposit on the desired substrate. In corporation of metal such as silver or titanium, portion of target was integrated with the desired metal in a circular pattern. The target was rotated to let the UV laser beam to ablate the graphite and metal for multi-component film matrix. All PLD process was in ultra high vacuum chamber. The PLD concept is presented in Figure 7-3.
In our experiment, the silicon substrates were cleaned with acetone and methanol in an ultrasonic bath for 10 minutes before placing in a high vacuum chamber for the pulsed laser deposition. To coat the DLC film on the substrate, the KrF excimer laser, Lambda Physik LPX200, was used to ablate the high purity graphite. The laser pulse repetition was maintained at 10 Hz while the energy density was estimated at 5 J/cm². The target to substrate distance was maintained at 4.5 cm. The hydrogen-free DLC thin film was deposited for total time 2 minutes.

![DLC film (a) and PEGDA film (b) on a silicon wafer](image)

Figure 7-4: DLC film (a) and PEGDA film (b) on a silicon wafer

### 7.1.4 Protein adsorption testing

The Fluorescein isothiocyanate-labeled bovine serum albumin (FITC-BSA from Sigma Aldrich) was chosen for our study because the FITC-labeled protein can easily be observed under the UV light. The FITC-BSA was prepared by dissolving in the phosphate buffered saline (PBS, pH = 7.4) at the concentration of 2 mg/mL. Then, the samples were immersed in the buffer solution and incubated in the incubator at 37 °C for 24 hours. After the protein adsorption, the samples were rinsed in the PBS solution and water. To dry a sample, the nitrogen air was used after cleaning and then directly imaged the protein adsorption with a fluorescent microscope (Meiji Techno, TC-5000) and measured the
fluorescent light intensity from a fluorescent spectro photometer (Hitachi F-2500). The UV filter #9863 is applied at excitation side while the UV-35 filter is applied at emission side. FL Solution is the software that used to collect data.

As shown in Figure 7-5, the intensity of green color indicates the amount of the FITC-BSA.

![Image showing fluorescence intensity](image)

**Figure 7-5**: The image of the FITC-BSA from the fluorescent microscope presents the gradient of green color caused by different amounts of the protein in PBS solution.

### 7.2 Results and discussions

#### 7.2.1 The effect of adsorption time on silicon wafer

From the fluorescent spectrophotometer, because the FITC has the maximum emission at 525nm, we can see the peak of the fluorescence spectra curve around that specific wavelength. However, from the graph in Figure 7-6, when we increase the testing time, the amount of the protein adsorption increases as presented in the amount of intensity of the fluorescent light that the fluorescent spectrophotometer detect. Therefore, the fluorescent spectrophotometer can detect the amount of the fluorescent probed protein adsorption on the surface of silicon sample.
Figure 7-6: The fluorescence spectra of FITC-BSA, 4mg/mL on the plain silicon wafer for different adsorption time.

7.2.2 The effect of laser micro-machined surface on biocompatibility

After laser micromachining, the surface roughness of the machined area inside and on rims of the micro channel were very high because of the laser machining parameters, such as feed rate, pulse overlap or number of pass, and the imperfect photo ablation, such as debris or recast. As shown in Figure 7-7, the debris of silicon around a micro channel created the rough surface on the silicon wafer.
In Figure 7-8, after 24 hours of adsorption, the protein showed the rich area especially inside the micro channel, edge and the debris around the channels. Comparing the color, the debris area and inside the micro channel in Figure 7-8(Left), the protein adsorbed more in the debris rich area than the channel. This means that the higher surface roughness may not have the larger protein adsorption but the more appropriate size of coarseness should probably promote the protein adsorption. This result is confirmed again when the samples were measured in the fluorescent spectrophotometer in Figure 7-9. Comparing the square machined area; the peak of the graph from laser micro-machined samples shows higher intensity than the other non-machined samples.
Figure 7-8: The FITC-BSA adsorption from the fluorescent microscope (Left) Array of 5x5 micro channels (Right) 2x2 square area
7.2.3 Effect of protein resistant materials coating on the laser micromachined surface on biocompatibility

As shown in Figure 7-10, both coating materials can reduce the protein adsorption on the laser micromachining process. However, the protein adsorption on the coated substrate should be rarely seen on the surface because of both PEG and DLC are excellent protein resistant materials. Considering the PLD process, the film thickness ranged in nano-scale can probably not fully cover the coarse area in micro-scale. Moreover, during spin coating of the PEGDA, the recast, edge and piled up area along the micro channels blocked and distracted the flow of coating liquid so the coating material can not coat evenly on the structure. We also tried to increase the film thickness but it also increase the UV curing time.
Comparing the graph in Figure 7-11, the peak of the graph from DLC coated surface shows lower intensity than the plain silicon samples.
Figure 7-11: The fluorescence spectra of FITC-BSA, 4mg/mL on the silicon wafer and coated ones

7.3 Summary

We present the laser micromachining on the silicon wafer and its effect on the biocompatibility of material. Silicon wafer by itself is biocompatibility material but the surface roughness of the substrates after the laser micromachining leads to more protein adsorption on the uneven area. By coating the PEGDA with UV lithography and coating the DLC with PLD process, the better biocompatible materials reduce the protein adsorption on the micro machined area. However, the DLC coating with PLD deposits the nano-scale thickness that cannot fully cover the high surface roughness in micro scale while the spinner in the PEG coating cannot evenly coat the surface that has the structure on it. The challenging problems bring a chance for future researches in finding the way to coat the laser micro-machined surface uniformly and effectively. This study provides a good opportunity for many significant laser techniques such as micro machining, deposition and lithography in developing and prototyping biocompatible MEMS devices.
CHAPTER 8

CONCLUSION AND FUTURE RESEARCH WORKS

8.1 Conclusion

In this dissertation, we have presented the details of techniques of analytical modeling and simulation of laser micromachining of microstructures, process control of laser micromachining, the surface modification techniques for bio-devices manufacturing and biomedical applications. The accomplishments of this research can be summarized as follows:

- Fundamental study of laser micromachining parameters provides the essential laser parameters for the lab-built laser micromachining system. The parameters i.e. laser energy, laser spot size, laser fluence, repetition rate, focal length, working distance, feed rate and machining overlap are considered in our excimer laser micromachining system. All necessary experiments were employed in this study. Laser ablation profile on the silicon substrate is the target output and the following results such as the absorption coefficient between UV laser and a silicon wafer, laser fluence and the efficiency of the system could be obtained from the experiments. This work makes the lab-built laser micro machining system ready to fabricate the microstructure.

- Analytical model of the laser ablation improves the prediction of laser cutting profiles. Because there are errors from the assumption of beam propagation model in the previous research from our research group and the modeling techniques from the literature are still too complex and not suitable for fast and accurate calculation of laser micromachining, the analytical model having the laser process parameters studied from the fundamental study of laser micromachining system has been
The 3D analytical model of laser ablation including laser energy profile with Gaussian beam propagation, the beam incident angle and laser ablation with Beer’s law were mathematically formulated and the analytical procedure in this work can be adapted to other laser energy profile, beam propagation and different laser ablation function. It is a great tool for users to design and develop the microstructure from laser micromachining.

- The simulation software by Matlab has been proposed to predict the laser ablation and find the optimal process parameters for minimal surface roughness in laser micromachining. The computer application using Matlab and the analytical model was constructed and the actual experiments on the glass substrate were employed. The results of laser profile were compared to show the accuracy of the analytical model. The experiment also proved that using the Gaussian function in modeling assumption provides less error than the linear function from the previous work. Moreover, the simulation shows how the analytical model can solve the complex phenomenon of the overlapping in laser micromachining and let us understand how we can find the optimal laser parameter for the minimal surface roughness in the easier and faster way than other researches.

- This work proposes a novel quality improvement method of laser micromachining of micro-channels by coating with the cyanoacrylate on a silicon wafer. The undesirable debris re-deposition around the laser ablation area has long been observed and this may contaminate the optical devices, interfere with the function of a MEMS device or clog the channels of a microfluidic device. The application of the film masking and the laser micromachining in water led to the possibility of applying hydrogel and cyanoacrylate coating techniques on a silicon substrate. In this study, we proposed a coating process by using the Dimatix materials printer and spin coating. A superb surface finish quality of the laser ablation on cyanoacrylate-coated silicon wafer was
observed by using the Scanning Electron Microscope (SEM) and the Atomic Force Microscope (AFM). This proposed technique provides a good remedy in quality improvement of laser ablation on a silicon substrate and it can be used for developing and prototyping biocompatible MEMS devices.

- The effect of the micro-machined regions on the biocompatibility in the protein adsorption for medical devices applications was studied. From the study, the surface roughness on the micro-machined area promoted the protein adsorption so it probably causes the thrombus formation for the application in the cardiovascular or blood related devices. In contrast, this incident can enhance the cell promotion that is helpful for the biomedical implant MEMS devices. To modify the surface property in biocompatibility, both Diamond-like carbon (DLC) coating and Poly ethylene glycol diacrylate (PEGDA), the protein resistant and biocompatible materials, were proposed in this research. The UV lithography for coating PEGDA and Pulse laser deposition for coating DLC on the laser micro-machined substrates were applied while the coated substrates were biocompatibility tested with the Bovine Serum Albumin (BSA) to observe the protein adsorption. To image the quantity of adsorption, the fluorescein labeled BSA was used for fluorescent microscope to clearly image the reflective light. This study proposed a good opportunity for major novel techniques such as laser micromachining, PLD and UV lithography in developing and prototyping biocompatible MEMS devices.

In conclusion, all works in this dissertation provide the road map of continuous development of biomedical devices as shown in Figure 8-1. The work started from “Plan” phase meaning the design and simulation of biomedical devices. The fabrication process; i.e. the laser micromachining used to machine the designed patterns, are part of “Do” phase. When the surface quality and biocompatibility were concern issues in the “Check” phase, the surface modification techniques in “Act” phase were applied to solve the problems. The
continuous improvement by re-designing the process to use indirectly method to form the microcircuits by microorganisms demonstrated the PDCA improvement in this work. Therefore, not only proposed many contributions in the laser micromachining, this paper also forms the foundation of the development of biomedical devices in its framework.

![The process of biomedical device development](image)

**Figure 8-1:** The PDCA of the development of biomedical devices (Recap)

### 8.2 Future researches

There are several possible research works that we can continue to do after this research because it has already broken through the new area of the fabrication of biomedical device applications with the laser micromachining. Following is the list of interesting future researches coming up during the experiment.
8.2.1 Study on different types of silicon wafers and different gas for different wavelength of UV laser

The laser parameters can be further studied on the types of materials and UV laser. The orientation of silicon wafer is still one of the important parameters to be investigated but we did not put as one of the parameter in the study because we primary focused on the modeling and surface modification. However, to make the model more useful, it is better to get more data from different materials or lasers to see whether the laser ablation phenomenon is still similar to the ones that we previously studied or not.

8.2.2 Homogenizer and the new way to model the laser fluence

The distribution of laser energy from the excimer laser is the rectangle Gaussian profile. By putting the laser beam homogenizer into the lab-built laser micromachining system, the laser energy distribution will change to the rectangular function that has more shape edge and closed to the traditional milling cutter. However, the laser energy density function will not be similar to the Figure 4-1 and need to derive the analytical model for depth of ablation again but the step of mathematical calculation can still follow the concept in the Chapter 4.

8.2.3 Tool path generation from the laser ablation modeling

From our model in the Chapter 3, the model can find the depth of ablation at any point on the substrate when the center of UV laser beam and the working plane is known. However, tool trajectory can be calculated from the offset between the surface of object and the working position of laser beam. That offset distance is equal to the depth of laser ablation and it can be pre-calculated by determining some of laser parameters such as laser energy, repetition rate and machining feed rate. So, we can generate the tool path from this algorithm. This concept can be proposed in the future research for tool path generation of laser micromachining.
8.2.4 Optimization of surface errors in laser micromachining

In Chapter 4, we demonstrated the optimization of the surface error from variation of feed rate only. However, there are many other laser process parameters in the model such as laser fluence, working plane, tool path overlap and repetition rate etc. If there are more parameters in the system, the problem will be more complex and the optimization technique such as linear programing may be applied to find the optimal laser processing parameters for the minimal surface errors for laser machined area.

8.2.5 Microcircuit fabrication with microorganisms

The connection of the magnetic nanoparticles from the magnetotactic bacteria may not completely link together to conduct the electricity because of inadequate amount of the nano-magnetite from the microorganism. Alternatively, using the nanoparticles as the biocatalysts in the other processes such as Chemical Vapor Deposition (CVD) or Ion Beam Assisted Deposition (IBAD) to form selectively high conductive patterns on the substrate may be more possible. The reason to use the magnetotactic bacteria instead of the regular magnetic nanoparticle is because the magnetosome inside these microorganisms can orient along the magnetic field. This orientation will affect the growth of conductive material on the substrate and may affect the electrical conductivity of microcircuits.

8.2.6 Nerve regenerative guidance with laser micro-machined scaffold

The main reason that we tried to smooth the surface of micro-machined substrate and make it biocompatibility is because the small smooth and biocompatible micro channel can be probably used as a scaffold for nerve regeneration. Neuroregeneration is the premising topic referring to the regrowth of nervous tissue to recover neurological injuries. The laser micromachining can support tissue engineering to create the pattern on the scaffold materials such as hydrogel, biocompatible polymers or silicon wafer to guide the neural stem cells or others to regenerate in the scaffold.
8.3 List of publications

From the contents in this research, we have published several conference and journal papers. Here is the list of papers that have already been published and accepted.


Proceedings of the 2012 Industrial and Systems Engineering Research Conference (ISERC2012), Accepted.

REFERENCES


