Micromachining of Polymeric Bio-MEMS with Lasers

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ABSTRACT

The development of MEMS has been driven by the need for miniaturization and lowering the overall manufacturing cost. The field of MEMS is concerned with the development of integrated systems of sensors, actuators and associated electronics. Even though the electronics industry provides an economy of scale for the silicon industry, crystalline silicon is still a complex and relatively expensive material to produce. The development of polymer micromachining technologies that complement traditional silicon approaches has enabled the broadening of microelectromechanical systems (MEMS) applications. Polymeric Bio-MEMS (Biomedical Micro-Electro-Mechanical Systems) have great potential in their current and future applications which include genomics, proteomics, molecular diagnostics, point-of-care diagnostics, tissue engineering, single cell analysis and implantable micro-devices. The polymeric materials are very fragile and not rigid which restrict their manufacturing processes. To minimize many such problems, excimer lasers and femtosecond lasers have been used for the precise micromachining of Bio-MEMS, the details of which are discussed in this paper.

Keywords: excimer laser, femtosecond laser, micromachining, polymers, MEMS, Bio-MEMS

1. Introduction

Bio-MEMS (Biomedical Micro-Electro-Mechanical Systems) have great potential in their current and future applications which include genomics, proteomics, molecular diagnostics, point-of-care diagnostics, tissue engineering, single cell analysis and implantable micro-devices. Among the advantages of polymeric materials are: their chemical resistance, easy to workout, can be cheaply mass produced and some of them are non-toxic which is safe to be used on clinical materials. Polymeric Bio-MEMS a class of biosensors that consist of a biological recognition system, called the bioreceptor, and a transducer. The interaction of the analyte with the bioreceptor causes an effect that the transducer can convert into a measurement, such as an electrical signal.

1.1 What are Polymers?

"Poly" means "many" and "mer" means "parts." So "polymer" means "many parts." The parts are usually the same part used repeatedly in a chain-like manner. Polymers are also referred to as plastics because they are easily molded [1]. Polymer means many monomers. Sometimes polymers are also known as macromolecules or large-sized molecules. Usually, polymers are organic (but not necessarily). A monomer is a molecule that is able to bond in long chains. A polymer can be made up of thousands of monomers. This linking up of monomers is called ‘polymerization’. It is the long chains that give polymers their unique properties. Polymers usually have high melting and boiling points. Because the molecules consist of many monomers, polymers tend to have high molecular masses.

Consider ethane, CH3-CH3, which is a gas molecule at room temperature. Because of their small size, ethane molecules are very mobile and can run almost anywhere they want to, without interacting with other molecules. Now, if we double the chain length or the total number of carbons to four, we get butane, CH3-CH2-CH2-CH3, which is a liquid fuel. In liquids, atoms or molecules can no longer act as independent units. Because of their larger size, butane molecules are less mobile than ethane molecules. Their lowered mobility allows them to run into or interact with one another more frequently. When the chain length increases 6 fold, as in paraffin, CH3(CH2CH2)10CH3, we get a waxy substance. In this case, the solid-like property of paraffin is a reflection of the entanglement of its long molecules when they move. If we keep on increasing the number of repeating carbon units to, say, 2000, that is, CH3(CH2CH2)2000CH3, we have a polyethylene polymer, which is a very strong, brittle solid. The polymer molecules have become so long and so entangled that their movement becomes almost completely restricted. At this point, they appear to be attached to other molecules, which act as "permanent" neighbors.

1.2 Examples of Polymers:

Polymers may be divided into two categories: (i) Natural polymers, (ii) Synthetic polymers

(i) **Natural polymers** (also called biopolymers) include silk, rubber, cellulose, wool, amber, keratin, collagen, starch, DNA, and shellac. Biopolymers serve key functions in organisms, acting as structural proteins, functional proteins, nucleic acids, structural polysaccharides, and energy storage molecules.

(ii) **Synthetic polymers** are prepared by a chemical reaction, often in a lab. Examples of synthetic polymers include PVC (polyvinyl chloride), polystyrene, synthetic rubber, silicone, polyethylene, neoprene, and nylon. Synthetic polymers are used to make plastics, adhesives, paints, mechanical parts, and many common objects.

1.3 Applications of Polymer materials

From door panels, flooring and engine components, lightweight plastic materials help to realize better fuel efficiency that allows engineers to create innovative designs which are durable and strong, yet attractive. Polymeric materials are used in and on soil to improve aeration, and promote plant growth and health. Many biomaterials, especially heart valve replacements and blood vessels, are made of polymers like Dacron, Teflon and polyurethane. Plastic containers of all shapes and sizes are light weight and economically less expensive than the more traditional containers. Clothing, floor coverings, garbage disposal bags, and packaging are other polymer applications. Automotive polymer materials and plastics are essential in the design and manufacture of automotive components. Windshields for fighter planes, pipes, tanks, packing materials, insulation, wood substitutes, and adhesives are some of the polymer applications in the industry. Playground equipment, various balls, golf clubs, swimming pools, and protective helmets are often produced from polymers. Acrylic, polyamide, PVC etc are some of the polymeric materials widely used in many applications such as pharmaceutical. Among the advantages of polymeric materials are, they are chemical resistance, easy to workout, can be cheaply mass produced and some of them are non-toxic which is safe to be used on clinical materials.

1.4 What are MEMS?

MEMS is an acronym for the Micro-Electro-Mechanical Systems. MEMS is the technology of microscopic devices. MEMS are made up of components between 1 and 100 µm in size and MEMS devices generally range in size from 20 µm to one mm [2]. The development of MEMS has been driven by the need for miniaturization and lowering the overall manufacturing cost. The field of MEMS is concerned with the development of integrated systems of sensors, actuators and associated electronics. MEMS devices are manufactured using similar microfabrication techniques as those used to create integrated circuits. They often, however, have moving components that allow physical or analytical functions to be performed by the device. They usually consist of a central unit that processes data (the microprocessor) and several components that interact with the surroundings such as microsensors [3]. The fabrication of MEMS evolved from the process technology in semiconductor device fabrication, i.e. the basic techniques are deposition of material layers, patterning by photolithography and etching to produce the required shapes. Silicon is the material used to create most integrated circuits used in consumer electronics in the modern industry. Silicon is an attractive material because of its low cost and high quality, its useful electro-mechanical properties, and the possibility of monolithic integration with electronics. The economies of scale, ready availability of inexpensive high-quality materials, and ability to incorporate electronic functionality make silicon attractive for a wide variety of MEMS applications. The global market for MEMS, which includes products such as automobile airbag systems, display systems and inkjet cartridges totaled $40 billion in 2006 according to Global MEMS and Opportunities, a research report from SEMI and Yole Development and is forecasted to reach $72 billion by 2011 [3, 4]. A number of products have been commercialized in recent years, notably ink-jet printer heads, silicon pressure sensors, crash-bag accelerometers and micromachined gyroscopes. This list is expected to grow substantially over the coming years. MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its techniques and microsystem-based devices have the potential to dramatically affect of all of our lives and the way we live.

1.5 What are Polymeric MEMS ?

Even though the electronics industry provides an economy of scale for the silicon industry, crystalline silicon is still a complex and relatively expensive material to produce. The development of polymer micromachining technologies that complement traditional silicon approaches has enabled the broadening of microelectromechanical systems (MEMS) applications. Silicon micromachining processes, while clearly able to produce an enormous range of useful MEMS devices, do have their limitations. Firstly, they are based on a very limited range of materials (notably silicon, silicon dioxide, silicon nitride, and a few metals), whereas MEMS in general call for a much broader materials base including, for example, polymers and functional materials (e.g. magnetic materials, ferroelectrics and shape memory alloys). Silicon processes are also poorly suited to the realisation of 3D (three-dimensional) structures. Such structures are proving essential for an increasing range of MEMS devices, in particular actuators. Polymers can be produced in huge volumes, with a great variety of material characteristics [4]. Micromachined polymers may be employed as structural or functional elements as well as soft, flexible substrates that contain other devices. This versatility is afforded by the development of a wide range of processing techniques unique to polymer materials. For example, simple polymer structural elements can be photo-patterned or casted, eliminating the need for complicated etching steps and lithographic masking required in silicon processing. A major advantage of such processing approaches is the reduction in cost to manufacture micro- and nano-structures. MEMS devices can be made from polymers by processes such as injection molding, embossing or stereo-lithography and are especially well suited to microfluidic applications such as disposable blood testing cartridges.

The properties of polymers also play an important role in driving new applications as well as device performance. Low Young's modulus polymer films permit delicate, nondestructive interactions with pliable cells and tissues, creating a mechanically favorable environment within these biological systems; the bulk mechanical properties are often tunable over a wide range. Many polymers also exhibit chemical and biological inertness desired in in vitro (e.g. lab-on-a-chip (LOC)) or '*in vivo'* (e.g. implant) applications. (In vitro (Latin for within the glass) refers to the technique of performing a given procedure in a controlled environment outside of a living organism. ... In vivo (Latin for "within the living") refers to experimentation using a whole, living organism as opposed to a partial or dead organism).

1.6 What are Bio-MEMS ?

Bio-MEMS is an abbreviation for biomedical (or biological) micro-electro-mechanical systems [5, 6]. Interest in MEMS for biological applications (Bio-MEMS) is growing rapidly, with opportunities in areas such as biosensors, pacemakers, immuno-isolation capsules, and drug delivery. Bio-MEMS is typically more focused on mechanical parts and microfabrication technologies made suitable for biological applications. A broad definition for Bio-MEMS can be used to refer to the science and technology of operating at the microscale for biological and biomedical applications, which may or may not include any electronic or mechanical functions. The interdisciplinary nature of Bio-MEMS combines material sciences, clinical sciences, medicine, surgery, electrical engineering, mechanical engineering, optical engineering, chemical engineering, and biomedical engineering. Some of its major applications include genomics, proteomics, molecular diagnostics, point-of-care diagnostics, tissue engineering, single cell analysis and implantable micro-devices.

Over the past few years some highly innovative products have emerged from Bio-MEMS companies for revolutionary applications that support major societal issues including DNA sequencing, drug discovery, and water and environmental monitoring. The technology focuses on microfluidic systems as well as chemical testing and processing and has enabled devices and applications such as 'lab-on-a-chip', chemical sensors, flow controllers, micronozzles and microvalves to be produced. Although many devices are still under development, microfluidic systems typically contain silicon micromachined pumps, flow sensors and chemical sensors. They enable fast and relatively convenient manipulation and analysis of small volumes of liquids, an area of particular interest in home-based medical applications where patients can use devices to monitor their own conditions, such as blood and urine analysis [6].

1.7 What are Polymeric Bio-MEMS?

Polymer-based technologies introduced in the 1990s have played a large role in advancing MEMS into new applications, especially in the area of biomedical MEMS (or Bio-MEMS). Using polymers in Bio-MEMS is attractive because they can be easily fabricated, compatible with micromachining and rapid prototyping methods, as well as have low cost. Many polymers are also optically transparent and can be integrated into systems that use optical detection techniques such as fluorescence, UV/Visible absorbance, or Raman method. Moreover, many polymers are biologically compatible, chemically inert to solvents, and electrically insulating for applications where strong electrical fields are necessary such as electrophoretic separation. Surface chemistry of polymers can also be modified for specific applications. The most common polymers used in Bio-MEMS include Polymethyl methacrylate (PMMA), Polydimethylsiloxane (PDMS}, Off-stoichiometry thiol-ene polymer (OSTEmer) and SU-8 (a high contrast, epoxy-based photoresist).

1.8 What are Bio-sensors?

Biosensors are devices that consist of a biological recognition system, called the bioreceptor, and a transducer. The interaction of the analyte with the bioreceptor causes an effect that the transducer can convert into a measurement, such as an electrical signal. The most common bioreceptors used in biosensing are based on antibody–antigen interactions, nucleic acid interactions, enzymatic interactions, cellular interactions, and interactions using biomimetic materials. Common transducer techniques include mechanical detection, electrical detection, and optical detection. Polymeric Bio-MEMS are in this class of biosensors. One of the many areas of applications of Bio-MEMS is in stem-cell engineering. Differentiation in stem cells is dependent on many factors, including soluble and biochemical factors, fluid shear stress, cell-ECM interactions, cell-cell interactions, as well as embryoid body formation and organization. Bio-MEMS have been used to research how to optimize the culture and growth conditions of stem cells by controlling these factors [7].

2. Machining of Bio-MEMS

The polymeric materials are very fragile and not rigid which restrict their manufacturing processes. For example, conventional drilling may not be suitable to drill a hole on a soft non-rigid polyamide. Conventional photolithography-based micromachining techniques are limited to two-dimensional fabrication and only particular materials can be used. Laser micromachining enables to overcome those limitations and facilitates three-dimensional micromanufacturing with a variety of materials. In order to overcome this problem, the non-contact laser drilling process is the best solution. There are various benefits to be gained from using lasers as tools. These include no tool wear, ease of automation, small heat-affected zones, narrow kerf (cut) width and virtually no restrictions on the geometries that can be cut. (kerf is the width of material that the process removes as it cuts through the plate [8, 9].

3. Laser Machining of Polymeric Materials

Material removal by thermal shock or ablation can be achieved by laser-based processes. Laser patterning on polymeric materials is considered a green and rapid manufacturing process with low material selection barrier and high adjustability. Transferring photon energy of the laser light to polymer is challenging, however, as it is transparent to a wide range of wavelengths, which requires generation of high peak intensities to trigger a nonlinear absorption effect. Carbon dioxide (CO_2) lasers are among the most frequently used lasers for industrial applications over long periods, since its equipment is relatively simple and requires low capital investment.

Laser micromachining is a process of ablation which is used to remove the unwanted part of the material that based on the desired design. The ablation process depends on the materials and the ablation parameters. The laser micromachining does not require the mask to transfer the pattern to wider range of the materials and it also provides the high resolution of the images. In the Laser micromachining the direct etching of solids by pulsed laser radiation – relies on the process of ablation. Laser-solid interactions during ablation are complex, and depend both on the material and on the laser parameters (primarily the wavelength, pulse duration and intensity). However, in all cases absorption of laser energy at the surface of the solid results in ejection of material from a thin surface layer. Any solid can be laser machined under the correct conditions, and processes have been established for an extremely wide range of materials. [10].

The laser ablation technique can be applied to fabricate Bio-MEMS components such as reservoirs and complex connecting channels on polymers, which can be used in DNA sequencing and enzyme assays.

4. Excimer lasers for micromachining of Bio-MEMS

The gain medium of excimer laser is usually gas mixture of noble gas such as argon, krypton or xenon with reactive gas such as fluorine or chlorine. A pseudomolecule that is named excimer will be generated under high pressure and electrical stimulation. This excimer is formed by the inert gas molecule which temporary bound with themselves or with halogens only under the electrical stimulation. The electrical stimulation usually comes from electrical discharge or high-energy electron beams. This excimer can only exist in excited state and will emit photons to form laser light in UV range by undergoing spontaneous or stimulated emission. Excimer lasers are pulsed laser sources emitting in the ultra-violet (UV) region of the spectrum. They are relatively broadband sources and usually have a rectangular beam output of the order of ~25mm x ~10mm. The beam divergence is usually ~1-5mrad and it is different in the two orthogonal beam directions.

Excimer laser micromachining is used particularly for the micromachining of organic materials (plastics, polymers etc.) as material is not removed by burning or vaporization. Hence, material adjacent to the machined area is not melted or distorted by heating effects [11]. In most of the cases, ArF (193 nm) and KrF (248 nm) excimer lasers have been used for MEMS-related laser machining work to date. Because of their short wavelength, these lasers offer high imaging resolution, notwithstanding their relatively broad linewidth. Furthermore, strong absorption at UV wavelengths leads to low material removal rate in most materials, typically between 0.1 and 1 mm per pulse; this allows precise control of etch depth simply by counting pulses. These attributes make excimer lasers generally better suited than longer-wavelength lasers for MEMS applications. Excimer laser micromachining is normally done in projection mode, where a mask is imaged onto the workpiece by a reduction lens. A typical field size at the workpiece might be 5 x 5 mm^2, depending on the material and laser energy.

A key feature of laser micromachining as a MEMS fabrication tool is its ability to produce complex 3D surface profiles. Stepped multi-level structures can be produced by performing multiple exposures with different mask patterns, while scanning of the mask and/or workpiece during exposure can be used to generate continuous (or at least finely stepped) relief. Continuous relief can also be generated by straightforward projection ablation using half-tone masks. Typically both the mask and workpiece are mounted on precision motorized stages, so that the scanning operations can be performed automatically under computer numerical control. Other parameters can also be varied during the process, in particular the fluence and repetition rate of the laser.

In a study, ArF excimer laser (193 nm) was used for the development of polymer surface for the design and fabrication of a microfluidic system similar to that of natural vasculatures [10]. Besides from poly(dimethyl siloxane) (PDMS), laser ablation on biodegradable polymeric material, poly(glycerol sebacate) (PGS) and poly(1,3-diamino-2-hydroxypropane-co-polyol sebacate) (APS) were investigated. The results showed that nano/micro-sized fractures and cracks are generally observed across PDMS surface after laser ablation, but not on PGS and APS surfaces. The widths of channels were more precise on PGS and APS than those on PDMS. Repeated laser ablations on the same position of scaffolds revealed that the ablation efficiencies and edge quality on PGS and APS were higher than on PDMS, suggesting the high applicability of direct laser machining to PGS and APS. To ensure stable ablation efficiency, effects of defocus distance into polymer surfaces toward laser ablation stability were investigated. The depth of channel is related to the ratio of firing frequency and ablation progression speed.

In another study [11], a KrF excimer laser (l5248 nm) was used as a laser source to ablate polymers. An optical imaging system with a three-element processing lens (f588.4 mm) formed 5–103 demagnified images on the polymer surface. Laser fluences of 0.1–3.0 J/cm2 and repetition rates of 1–8 Hz are used. Various masks, including a slit of 220 mm wide and pin holes of diameters 200 and 600 mm were employed. Polyethyleneterephthalate (PET) and polyimide (Kapton) films with a thickness of 100 mm and acrylic with a thickness of 3 mm were used as base materials. The motion stages had a 0.1 mm resolution, and their moving speed was varied between 1 and 10 mm/s. A charge coupled device camera was installed to monitor the ablation process. Ablation depths of the target materials as a function of laser fluence were measured.

In yet another study [12] a KrF excimer laser (248 nm) was used for micromachining of poly(methyl methacrylate) (PMMA). To study the surface quality of PMMA, the microdrilling process was carried out to produce the holes. By using the KrF excimer laser, the relationship between the ablation parameter and the size of the holes was investigated. To further confirm the relationship between ablation parameters and the surface quality, several microchannels of the microfluidic structures were fabricated by varying the energy and frequency in order to obtain the optimized parameters. It was observed that the width of the microchannels increased when the laser energy increased. After the micromachining process, the microchannels were fabricated again by different beam size. The increment in beam size caused the width of the microchannel to be increased.

In a PhD dissertation work, Liu [13] presented a comprehensive characterization study on two UV lasers, that is, KrF (248 nm) and ArF (193 nm) excimer lasers micromachining of five representative MEMS materials, Si, sodalime glass, SU-8, PDMS and polyimide.

Vertical profile of etched channels and holes were found to be tapered in all materials. Etch rate change in vertical and lateral directions was investigated as three major laser parameters (fluence, frequency, and number of laser pulses) were varied.

For KrF excimer laser, In the vertical direction, Si had the highest etch rate followed by PDMS, glass, and SU-8. Etch rate increased almost linearly for all four materials as fluence increased but no significant variation in etch rate was observed as frequency of laser pulses was changed. Etch rate was also inversely proportional to the number of laser pulses. In the lateral direction, SU-8 showed the highest etch rate followed by glass, Si, and PDMS. This order was opposite to the vertical etch rate. Aspect ratio was found to increase as laser fluence and number of laser pulses increased but was not affected by laser frequency.

For ArF excimer laser, etch rate in both vertical and lateral directions was proportional to laser fluence. In the vertical direction, Si had the highest etch rate followed by three polymeric materials: SU-8, polyimide and PDMS. Etch rates of these three materials were close to each other. Glass had the lowest etch rate among the five materials used in this study. In the lateral direction, polyimide has the highest etch rate followed by SU-8, PDMS, glass and Si. No obvious effect of laser frequency on etch rate was observed. Number of laser pulses was found to be inversely proportional to etch rate per pulse.

It seems that specific heat and thermal conductivity are important factors that determines etch rate via photothermal process. However, since the laser ablation process is complicated, other materials properties such as phase transitions, optical penetration, ablation threshold and evaporation kinetics etc, also have their influence on etch rate variation. Through comparison to KrF characterization results, ArF was found to have similar etch rate order but smaller in magnitude. ArF was also proved to be better at creating finer structures at material surface. Materials absorbance spectrum is found to have important influence on etch rate, particularly for shorter wavelength. Aspect ratio is proportional to laser fluence and the number of laser pulses. It was not affected by laser frequency.

It was found that for all materials, kerf width increased as the laser fluence increased. For polyimide, it was found that higher fluence generated more materials debris around ablation site. Low fluence should be selected for better surface quality. Frequency does not affect surface quality significantly, so high frequency can be used to make up for slow etching time due to low fluence.

5. Femtosecond lasers for micromachining of Bio-MEMS

Femtosecond lasers are operated in pulsed form. Its pulse duration is of the order of a femtosecond (10^{-15} s). The peak power of the femtosecond laser is extraordinarily high. It can be focused into a very tiny dimension, much smaller than the diameter of human hair. All these characteristics of femtosecond laser make it promising in the applications related to medical surgery, nanofabrication and high density data storage and recording etc. Initially femtosecond lasers were generated by mode-locking techniques.

One of the requirements to fabricate micro/nano scale devices for biomedical applications by non-laser techniques is an expensive super-class clean-room In addition, they require masking and multiple steps as well as hazardous chemical reagents. One of the non-clean room techniques that achieves the microscale resolution is the laser ablation, specifically femtosecond laser ablation. Laser ablation by pulses with duration on the sub-picosecond or femtosecond time scales can remove materials with lower residual thermal effect, and the accuracy and quality of the device is often superior to conventional longer-pulse lasers. Also, it provides a convenient, economical and flexible way to fabricate programmable three-dimensional patterns by varying the beam scanning speed during ablation as well as laser pulse energy. Single pulse ablation threshold femtosecond laser fluence for PMMA and PDMS was found to be 2.6 J cm-2 and 4.6 J cm-2 , respectively [14].

Despite all extensive research and development, laser systems still suffer from HAZ (Heat Affected Zones), ranging from sub-micron dimensions to tens of microns, and bulges around the rims of the machined holes (typical height: 15 µm) caused by recast (debris). This causes difficulty to bond the substrate after machining. Hole diameters, machined with liquid-assisted femtosecond lasers down to 5 µm, with aspect ratios as high as 70, have been reported.

The short pulse width suppresses the formation of a heat-affected zone, which is vital for ultrahigh precision fabrication, whereas the high peak intensity allows nonlinear interactions such as multiphoton absorption and tunneling ionization to be induced in transparent materials, which provides versatility in terms of the materials that can be processed. More interestingly, irradiation with tightly focused femtosecond laser pulses inside transparent materials makes three-dimensional (3D) micro-fabrication available due to efficient confinement of the nonlinear interactions within the focal volume [15]. It has applications for biomedical and tissue engineering. Subtractive manufacturing based on internal modification and fabrication can realize the direct fabrication of 3D microfluidics, micromechanics, microelectronics, and photonic microcomponents in glass. These microcomponents can be easily integrated in a single glass microchip by a simple procedure using a femtosecond laser to realize more functional microdevices, such as optofluidics and integrated photonic microdevices. The highly localized multiphoton absorption of a tightly focused femtosecond laser in glass can also induce strong absorption only at the interface of two closely stacked glass substrates. Consequently, glass bonding can be performed based on fusion welding with femtosecond laser irradiation, which provides the potential for applications in electronics, optics, microelectromechanical systems, medical devices, microfluidic devices, and small satellites.

Polymers are cheaper and easier to manufacture than glass and crystals, which is advantageous for high-throughput production of low-cost photonic and microfluidic chips. Femtosecond lasers have thus been advantageously used for the micromachining of polymeric Bio-MEMS.

6. Conclusion

Polymeric Bio-MEMS have great potential in their current and future applications which include genomics, proteomics, molecular diagnostics, point-of-care diagnostics, tissue engineering, single cell analysis and implantable micro-devices. Among the advantages of polymeric materials are: their chemical resistance, easy to workout, can be cheaply mass produced and some of them are non-toxic which is safe to be used on clinical materials. The polymeric materials are very fragile and not rigid which restrict their manufacturing processes. Material removal by thermal shock or ablation can be achieved by laser-based processes. In this paper we have shown that (i) excimer lasers (KrF and ArF) and (ii) femtosecond lasers can be advantageously for minimizing many of the problems encountered in the micromachining of Bio-MEMS, like minimizing the heat effected zone, improvement in kerf width, higher aspect ratio and precision in microfabrication with minimum tolerances.

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