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المؤلف الرئيسي:	عبدالهادي، سليمان محيي الدين
مؤلفين آخرين:	Kilani, Mohammed، Al Ata, Mohanad(Assist. Super.، Super.)
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البرمجه والمراقبة للمضخه الدقيقة الرقيقة للتطبيقات الطبية الحيوية

اعداد

سليمان محيي الدين عبدالهادي

الملخص

هذه الدراسه تقدم نمذجه ديناميكيه ومحاكاة لمضخه كهرومغناطيسيه دقيقه لطيفه حديثا، المضخه المقترحه تستخدم اثنان من DC motors لتحريك مكبسين مغناطسيين في انبوب حلزوني. حركة المكبسين تتولد بدون الحاجه الى استخدام محابس او بيل، الذي يجعل المضخه المقترحه مناسبه لتطبيقات السوائل ذات الجزئيه المحمله.
نمذجة المجال الكهرو مغناطيسيه المؤثره على المكبسين تم تجهيزه اولا من خلال اشتقاق قانون نيوتن الثاني على ذراع ال DC motor بعد ذلك يتم نمذجة القوة الكهرومغناطيسيه الناتجه من ال DC motor. هذا النموذج استخدم لتخمين القوة المطبقه على المكبس المغناطيسي المثبت في نهاية ذراع ال DC motor. ان مبدأ السوبر الموضعي يستعمل لتخمين القوة المؤثرة على المكبس المثبت في نهاية ذراع DC motor، نماذج ومعادلات القوة تسمح بتخمين معدل التدفق لمختلف قيم الضغط المؤثر على المكبس بناءً على قيم التيار الكهربائي.
نموذج محاكاة ديناميكي للمضخه ايضا تم تطويره باستخدام رزمة Simulink، يتضمن النموذج المكونات الميكانيكية والكهربائية للمضخة المقترحة وتسمح بتوقع نوع وكيفية التدفق لمختلف استراتيجيات التشغيل DC motor.

PROGRAMMING AND CONTROL OF A GENTLE MICROPUMP FOR BIOMEDICAL APPLICATION

By
Suleiman M. Abdelhadi

ABSTRACT

This study presents a dynamic modeling and simulation of a newly introduced gentle electromagnetic micropump. The proposed pump utilizes two DC motors to actuate two magnetic core pistons and move them in annular tube housing. The motion of the pistons generates a valveless and bearingless positive displacement pumping action, which is suitable for applications involving particle-laden fluids.

An analytical model for the electromagnetic field acting on the pistons is first derived by applying Newton's second law on the arm of the DC motor. An analytical expression of the electromagnetic force resulting at the DC motor is then developed. This model is used to estimate the force acting on a magnetic piston placed at the end of the DC motor's arm. The superposition principle is utilized to estimate the force acting on the piston which is placed at the end of the DC motor's arm. The predicted force allows for estimating the flow rate generated by the pump at various input of current.

A dynamic simulation model for the pump is also performed using the SIMULINK package; the model includes the mechanical and electrical components of the proposed pump and allows for predicting the flow pattern resulting from different actuation strategies and modulations for the DC motors.

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A	The Area
b	damping ratio of the mechanical system
c	damping value
e	The back emf
F	electric force
I_a	armature current
J	moment of inertia of the rotor
K	spring constant
K_d	derivative gain
K_i	integral gain
K_m	electromotive force constant
K_p	proportional gain
L	electric inductance
M	permanent mass
P	fluid pressure
Q	volume flow rate
r	radius of system
R	electric resistance
St	Stroke
T_L	load torque
T_m	motor torque
V_t	Source Voltage
ω	Angular velocity
θ_{PM1}	Inner permanent magnet theta
θ_{PM2}	Outer permanent magnet theta
ϕ	Flux of motor
μ	Fluid viscosity

PROGRAMMING AND CONTROL OF A GENTLE MICROPUMP FOR BIOMEDICAL APPLICATIONS

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By

Suleiman Muhyeddin Suleiman Abdelhadi
Dr. Mohanad Al-Ata (Chairman)
Dr. Mohammad Kilani (Co-Advisor)

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of M.Sc. in Mechanical Engineering

At
Faculty of Graduate Studies
Jordan University of Science and Technology

July, 2008

PROGRAMMING AND CONTROL OF A GENTLE MICROPUMP FOR BIOMEDICAL APPLICATIONS

By

SULEIMAN MUHYEDDIN SULEIMAN ABDELHADI

Signature of Author ……………………..

Committee Members	**Signature and Date**
Dr. Mohanad Al-Ata (Chairman)	……………………..
Dr. Mohammad Kilani (Co-Advisor)	…………………...
Dr. Mohammad Jaradat (Member)	……………………
Dr. Ashraf Saleem (External Examiner, Philadelphia University)	……………………

July, 2008

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Chapter One: Introduction

One of most growing areas in Micro Electrical Mechanical System "MEMS" is the development of microfluidic devices, where special applications require a precise fluid flow. The study of microfluidic devices fabrication began in the 1960s, but in 1970s a real microfluidic devices are produced such as ink-jet printer nozzles. Further developments of microfluids devices (e.g. micropumps, micromixers, and microactuators) have been achieved during the 1980s and 1990s, Micropumps are vital element in microfluidic chips that have been fabricated using different pumping principles and used in several applications including drug delivery systems [1], micro total analysis [2], and electronics cooling [3]. Note that all these applications require a precise control of a pure fluid flow, which can be implemented using microfluidics systems easily [4].

Recently, more complex microfluid applications have been introduced such as biomedical fluids which contain some organic molecules, proteins, biopolymers, living cells, or other biological elements, these particles are sensitive to abnormal stresses, and must be handled gently in order to preserve their fragile constituents [5]; moreover these fluids contain sometimes bubbles. Although a several different micropumping mechanisms have been realized, they have not generally met the demands imposed by biomedical systems, and until now, have not been a part of a commercial biomedical system [6].

1.1 Motivation

In this work, a new concept of micropump has been introduced. The pumping action depends mainly on two pistons movement in an annular groove. These pistons are made of permanent magnetic materials and alloys; the Gentle Electromagnetic Micropump (GEM) operates by rotating one core through annular groove, while the other core kept stationary at neutral position. The core moves under the electromagnetic force that is generated from permanent magnetic materials which put at the end of a DC motor's arm. The proposed system consists of two DC motors which have a permanent magnet connected to the end of their arms. The pump housing is a circular tube which has two permanent magnets inside it. The motion of the pistons generates a valveless and bearingless positive displacement pumping action, which is suitable for applications involving particle-laden fluids.

1.2 Aim and Objective

An analytical model and dynamic simulation for a newly introduced electromagnetic micropump concept will be develop in this work. The pump utilizes two motors to pull a couple of magnetic core pistons that move annularly in a circular tube housing. The motion of the piston generates a positive displacement pumping action. The aim of this study is to develop an analytical model for Gentle Electromagnetic Micropump (GEM) and to obtain the dynamic response and finite element simulation of proposed pump.

1.3 Scope

The proposed micropump has many advantages to overcome on the previous designs drawbacks. With respect to micro manipulating, since the proposed micropump consist of one moving core at any instance, and a highly flexibility to control it is displacement and velocity, then the proposed pump can be handle a very small volume with a higher accuracy, this of course instead of the working fluid properties and gas bubble if any found in fluid. In this work we can't build our system in microscale so this study will be dedicated to build an analytical model of the system.

1.4 Thesis Outline

This work presents an analytical model and dynamic simulation study for a newly introduced electromagnetic micropump concept. An analytical model has been developed for the proposed micropump, the dynamic simulation introduced to describe the GEM response in dynamic sense. Finally, a proposed microfabrication process described to fabricate the GEM as single unit.

Chapter one: the conceptual foundation of GEM and its operation and principle have been described in this chapter.

Chapter two: reviewed the development history of micropumps and their applications. The development history of micropump is described by presenting some designs and their operation; the drawbacks of these designs are also discussed. Furthermore, the most common application of micropump is described including drug delivery systems and others.

Chapter three: described the commonly available micromachining technologies, including their advantages and drawbacks in components and structures fabrication.

Chapter four: reviewed the basic system components and the relation between these components in dynamic sense, the mathematical model for each part has been built which described the sequence of these components actuation to obtain the optimum sequence.

Chapter 5 built PID controller by trial and error to obtain desired output and thee root locus has been used to verify stability our system.

Chapter6, built flow chart of our controller which presented programming of sequent moving for two DC motors to obtain desired flow rate.

Chapter Two: Micropump Development History

One of most growing areas in MEMS has been in the development of microfluidic devices, where special applications require a precise fluid flow. The study of microfluidic devices fabrication began in the 1960s, but in 1970s a real microfluidic devices are produced such as ink-jet printer nozzles. Moreover in the 1990s, many devices have been designed and fabricated.

This chapter reviews a brief description of development history of micropumps, including its design and main features. Moreover, the micropump types and application will be introduced.

2.1 Micropump History

In last two decades, most of the research of micropump focuses on the reciprocating diaphragm design, which originally introduced by Van Lintel [7] and Smits in the late 1980s [8]. In Van Lintel's design [7], the pump consists of three chambers etched in silicon and covered with flexible oscillating glass diaphragms that are actuated by a piezoelectric disk.

Moreover a phase-shifted diaphragm oscillation in the three chambers generates a peristaltic suction-compression cycle, which can move the fluid in the desired direction. However, Smits [8] design approximately is similar but with one pumping chamber connected to two passive valves, which act as fluid rectifiers and guide the flow in the desired direction, Figure 2.1 shows the diaphragm micropump with its main parts and flow direction.

In spite of both pumps worked successfully in pumping water, these designs of pump have a number of drawbacks when considered for biomedical applications. Because the pump chamber used in these pumps is normal to substrate plane, the volume flow rate restricted to lower value even though using a higher voltage as 100 V or more. Moreover, these types of pumps have a big problem in dealing with gas bubbles.

Since these bubbles have a higher compressibility compared to water, the created inside pump pressure reduced to minimum value or perhaps the flow will stop. Moreover, when the working fluid contain a particle or perhaps living cell, these type of pump will fail in there cases, because it uses a valve which prevents the particle flow (clogging the particles) or perhaps killed these living particles.

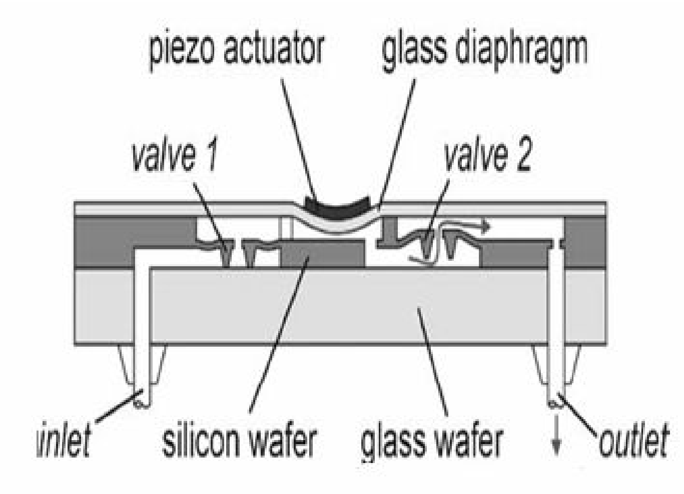

Figure 2.1. Diaphragm micropump that introduced by Lintel and Smits [7].

To solve valves problems, Stemme and Stemme [9] introduces a valveless micropump based on diffuser/nozzle ports principle, as shown in Figure 2.2. Since the cross-section increases in the diffuser and decreases in the nozzle, hence a pressure drops created through these elements during pump activity. This pump operates in two modes, first one is the suction mode, where the fluid flows through the diffuser rather than through the nozzle during chamber expansion, and second one is compression mode, where the fluid flows through the nozzle rather than through the diffuser during chamber compression mode. As result a net flow from the inlet to the outlet port.

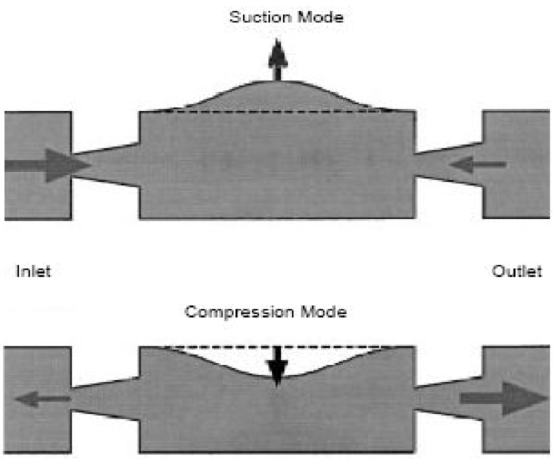

Figure 2.2. Diffuser/Nozzle pump ports and operation modes [9].

Another type of micropumps that has been fabricated and tested is the Electro hydrodynamic Pump (Ion Drag Pump). In this type of pumps the liquid is pumped under the effect of an electric filed, when the electric field is applied through the liquid the available charges move as response of electric field, these moving charges transfer momentum to the fluid and thus drag it, Figure 2.3 shows the ion drug pump mechanism. Unfortunately, this type of micropump can be applied on the unipolar space charges, which exist in insulating liquids like ethanol, methanol, propanol and deionized water [10]. As a result it could not be considered for water and other biological fluids pumping application.

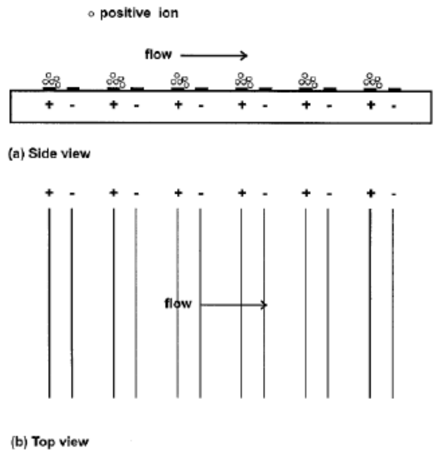

Figure 2.3. Ion drags pumping mechanism.

On the other hand, many other non-mechanical micropumps have been produced such as ultrasonic and RF (Radio Frequency), viscous micropump, electrochemical displacement, and magneto hydrodynamic, these pumps haven't any mechanical moving parts, but the performance is strongly influenced by the properties of the pumped fluid . In spite of a several different micropump design have been realized, but up to now they have not generally met the demands imposed by biomedical systems [11].

2.2 Previous Work (Integrated Electromagnetic Micropump (IEM))

The IEM pump works by the alternate motion of two permanent – magnet pistons inside annular tube housing. As seen in Figure 2.4, the motion of the pistons inside the housing is achieved by creating traveling magnetic fields which rotates along the annular tube, pulling the permanent magnet pistons inside the tube with it [12].

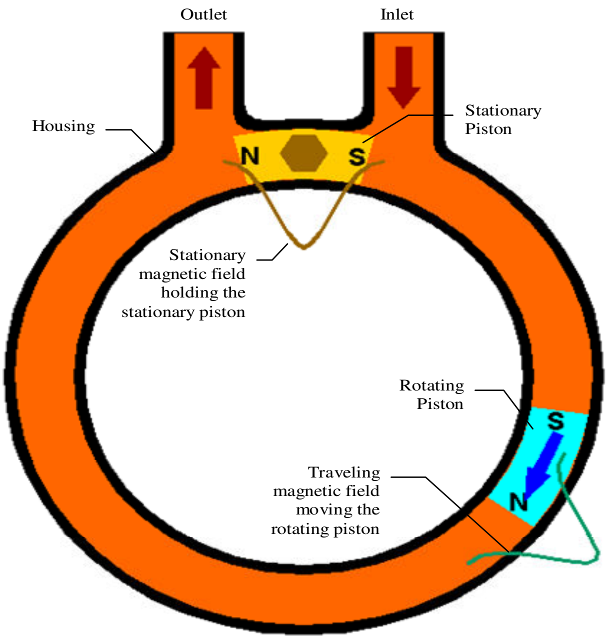

Figure 2.4: The operating principle of the IEM [12]

One way of achieving the IEM operation is through switching capabilities made available by modern solid state electronics, and by the recently available rare-earth Neodymium-

Iron-Boron permanent magnets. The coil-based pump utilizes the moving electromagnetic field generated by successive energization of a set of electronically switched solenoids. This moving field is used to control the movement of two permanent – magnet pistons inside annular tube housing. The pistons alternate moving and stationary states inside the housing, producing a gentle, and valve-less and bearing-less positive displacement pumping action.

Figure 2.5 illustrates the EIM pump concept, pumping occurs due to the synchronized rotation of two permanent magnet pistons placed in opposing polarities inside annular tube housing. The pistons are driven by a number of toroidal stator-pole windings wrapped around the housing. The magnetic field in each winding is electronically energized, attracting or repelling the magnetic pistons, depending on their polarity orientation. Pumping takes place in two phases; in the phase shown in the Figure, piston A is held stationary at 12 o'clock by energizing winding 1 with an attractive field, while piston B rotates clockwise by successive energization of windings 2 through 8 with an attractive field. As piston B rotates, it sucks fluid at its back face through the inlet line, while simultaneously pushes fluid at its front face through the outlet line. As piston B approaches the 12 o'clock position from the left, piston A starts rotating clockwise to clear a place for piston B, which stops at the 12 o'clock position, and exchanges roles with piston A, ending the first phase of the pumping cycle, and beginning the second phase where piston A rotates clockwise, pushing and sucking fluid as piston B did. When piston A completes the loop, it exchanges roles again with piston B and the pumping cycle is regenerated.

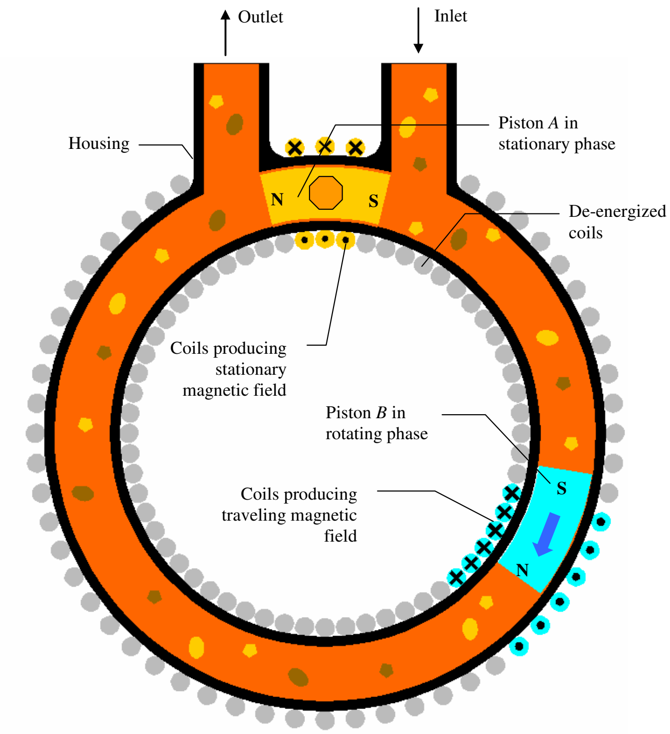

Figure 2.5: Operating principle [12]

The IEM solved drawbacks of previous designs, but it also has drawback especially at certain altitude, the maximum altitude of IEM reached to 40 cm.

2.3 Micropump types

Micropumps include many types such as: membrane pumps [13–14] both without check valves [13–15] and with check valves [14–16], electrohydrodynamic [EHD] pumps [17–18], electrokinetic [EK] pumps [19,20], rotary pumps [21–22], peristaltic pumps [23,24–25], ultrasonic pumps [26, 27], and several other types of pumps [28–29]. Other small-scale pumps have been developed for uses as blood pumps in ventricular assist devices [30 -31]. Nonmechanical pumps, such as the electrohydrodynamic and electrokinetic pumps do not have moving parts, which increases reliability. However, such devices are generally limited by low flow-rate and pressure-rise capabilities, the applications of the pump, the working fluids that can be pumped and high supply voltage requirements [32]. Mechanical pumps, such as rotary, peristaltic, and membrane pumps, have a wide variety of possible working fluids and applications. However, such mechanical micropumps such as rotary micropumps_ are believed to be feasible only when they are greater than a certain size [32].

2.4 Micropump Application

A wide variety of applications of micropump are found; in biomedical, Chemical, pharmaceutical,..etc. These applications can be summarized in two categories, first one is applications requiring precisely controlled fluid metering [33], and the second one is the applications requiring fluid handling in a confined space.

One of this applications is Drug Delivery Systems; many systems in our world use the pills and injections as drug delivery tools, however these tools have many limitations such as: gastrointestinal drug degradation and the inconvenience and pain related to intramuscularly and intravenous injections, which prevent uses in these cases [34]. So that micropumps introduced as an excellent alternative tool for drug delivery in above cases. It has the capability to deliver precise quantities of a drug at the right time and position. One application of these systems is insulin infusion in diabetic patients, this pump capable to pump a dosing in nanolitres level.

Micro Total Analysis Systems as second application of micropump, again many precise and accurate experiments always require a very small amount of liquid, this to assist the researcher to perform the required analysis. These experiments and analysis consider the central of some technologies, such as DNA analysis [35], drug discovery, pharmaceutical screening, medical diagnostics, and gas sensing and environmental analysis.

With respect to Total Analysis System (TAS), it performs many tasks and operations such as sampling, sample pretreatment, chemical reactions, analytical separations. However, all previous operations and tasks are performed using a macro scale tools, so that many drawbacks will be founded of this process such as: slow sample transport, high reagent consumption and poor separation efficiencies.

Because of that, the MEMS devices introduced as alternative approach to overcome on these drawbacks. The concept of a miniaturized TAS was first suggested by Manz and Widmer in the late 1980s [36]. The aim of miniaturizing the TAS is to produce a single chip contain all required device such as: sensor, pump, valves,..etc, to improve the response time and cost reduction of its.

A third application of micropump is Electronic Cooling, obviously, in last decades the IC's fabrication and products developed gradually, which allow us to produce a million of components on single chip. However these IC need an electric power to perform its function and operations. This power is dissipated later as heat energy. Unfortunately, this heat energy will damage the IC if it is kept on.

To improve the reliability of IC's and increase its life a cooling system require to this purpose. But in certain cases especially when IC dissipated a high amount of heat, e.g.: 1000W/cm, the existing system of cooling will be fail, so that a miniaturizing of this system will be required to improve it [37]. Moreover the MicroScale electronics cooling has many advantages over traditional macroscale cooling such as: low power consumption (can be negligible) and can be operate from the same dc source of IC, also both IC and cooling system can be manufacture together using the same manufacture process, which reduce the cost. Moreover, since the microsystem require a small amount of current, it will not generate a large electromagnetic field that affect on IC operation.

2.5 Summary

This chapter reviews the development history of micropumps, this including the diaphragm micropump, diffuser/nozzle micropump and ion drag micropump, the principle of operation of these micropump has been described, furthermore its advantages, disadvantages, and suitability with particle laden fluids also described.

This chapter ended with some types and applications of micropumps and the main benefits of miniaturize these devices also discussed. The applications that described are dug delivery systems, total analysis systems (TAS) and electronic cooling. However many other applications in different fields may be required micropumps and micro devices in general.

Chapter Three: Microfabrication Processes and Micropump Technology

This chapter reviews the basic microfabrication technologies that used to produce MEMS devices. Moreover, the microfluid mechanics and their characteristics are described including the size effects, surface to volume ratio, losses due to friction and surface roughness of microfluidics devices.

3.1 Microfabrication Processes

From its name, the machining science can be defined as: a sequence of steps, process and procedures performed to produce a designed shape, this shapes assembled together to get on the required devices and components. Like Macro scale, Micro scale has a group of micromachining processes used to produce microstructures and microdevices, these processes developed and modified specifically for MEMS.

In MEMS engineering, there are two main types of fabrication processes which are: silicon-based material processes and non-silicon based materials processes. For silicon based material processes also there are two main processes which are bulk and surface micromachining technologies, for each one of these technologies has a certain limitations, advantages and uses which is explained in next sections.

On the other hand, the LIGA (LIGA is a German acronym for Lithographie Galvanoformoung Abformung - in English, lithography, electroforming and molding) consider the main non silicon based material fabrication processes; i.e.; it's used to machine the plastic, ceramic, metals, ..etc of materials.

3.2 Bulk Micromachining

Bulk Micromachining process is a fabrication process used to realize micromechanical structures, within the bulk of a single-crystal silicon wafer by selectively removing wafer material to get on desired shape. In this process significant amounts of silicon are removed from a substrate, this to form membranes and a variety of trenches, holes, or other structures required. These structures cover a wide range of thickness from submicron to full wafer thickness (Up to 500 µm) with lateral size range from submicron to the lateral dimensions of a full wafer.

In bulk micro machining one of the etching techniques required to etching purpose, this etching technique may be wet or dry technique according to desired feature of final product. Moreover wafer-bonding is often necessary for the assembled the layers together since each layer fabricated alone, Figure 3.1 shows the micropump fabricated using bulk micro machining, each layer fabricated alone so the anodic and epoxy bonding required.

Since the Bulk Micromachining can control the depth of its structure and produced a membrane, it is used widely in sensors fabrications; Figure3.2 shows the vibration sensor fabricated using bulk micro machining.

On the other hand, the major limitation in bulk micromachining is the need for the manual assembly of its layers. Moreover, the anodic bonding required to complete assembling of the device, which consider costly relatively [10].

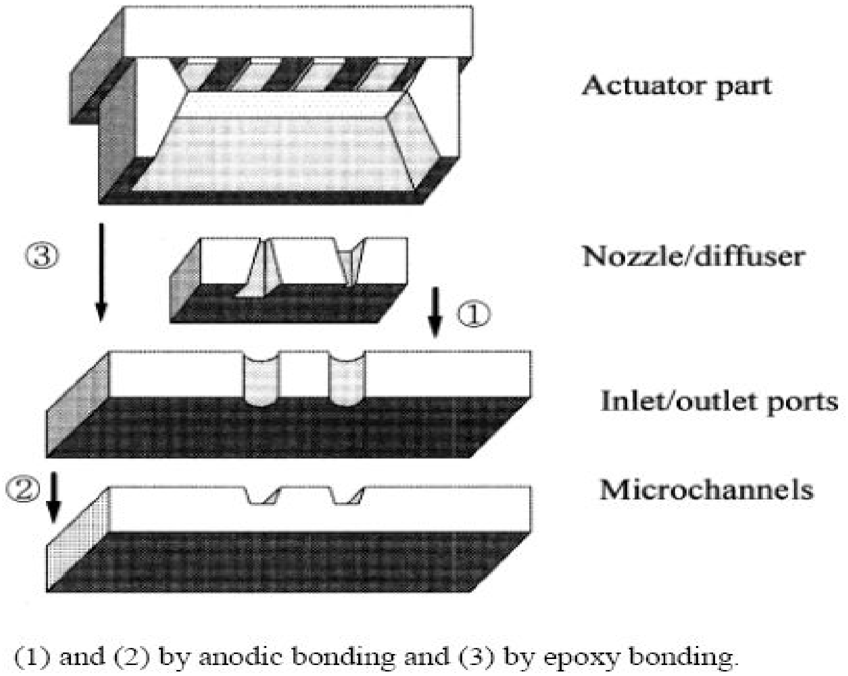

Figure 3.1. Micropump fabricated using bulk micromachining technology, later the anodic and epoxy bonding will be used for welding purpose [38].

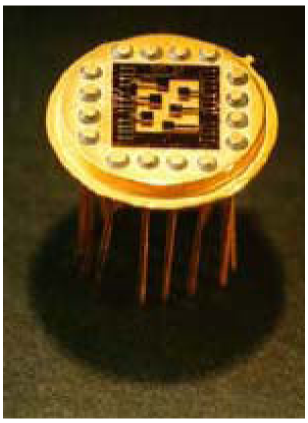

Figure 3.2. Vibration sensor, produced by bulk micromachining [39].

3.3 Surface Micromachining

In previous section the bulk micromachining technology is introduced, through this technology a large depth can be achieved. However, some drawbacks are introduced such as manual assembly and layers bonding. In this section the Surface micromachining technology will be introduce and the advantages of it like self assembly will be introduce. Surface Micro Machining techniques build up the structure in layers of thin films on the surface of the silicon wafer. This technology of fabrication consists of two different materials, a structural material (commonly polysilicon) and a sacrificial material (oxide) [40].

These materials are deposited and dry etched in sequence. Finally the sacrificial material is wet etched away to release the structure. The more layers; then more complex structure is produced, and more difficult it becomes to fabricate; such as microengineered tweezers, and gear trains. With respect to process sequence, first a sacrificial silicon dioxide is deposited on the wafer and patterned, and then a structural layer of polysilicon is deposited and patterned. This polysilicon layer will become structural elements such as gears. Other sacrificial layers have been removed leaving the desired structure using the etchant; e.g.; buffered hydrofluoric acid (HF). Figure 3.3 shows the surface micromachining steps sequences and Figure 3.4 shows some gears fabricated using this technology.

Since this technology integrates well with electronics, and self assembled process; then no assembly is needed. Adding to that the bonding steps are not required, this technology accepted in industrial, and many products including many sensors which are produced using this technology [10].

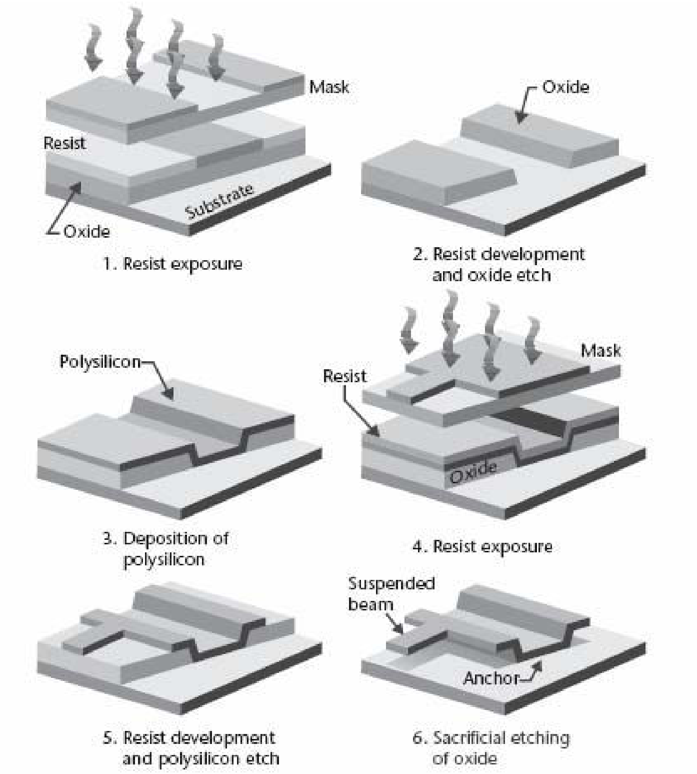

Figure 3.3. Surface micromachining technology steps and its sequence [41].

Figure 3.4. Micro gears are fabricated using surface micromachining technology [10].

3.4 Micromolding and LIGA

LIGA is a German acronym for Lithographie, Galvanoformung, Abformung (In English lithography, electroplating, and molding) [41], it has been developed in Germany in the early 1980s using X-ray lithography for mask exposure to produce parts and molding to produce micro parts with very high aspect ratio and height up to 1.0 mm or more from plastic, metal, ceramics, or their combinations. Moreover it's developed to produce the three-dimensional devices and structures [10].

In the LIGA process a resist layer several hundred microns thick is exposed through a mask to synchrotron X-ray radiation. By developing the exposed resist layer, a mold is formed that can be filled with metal by electroplating. After stripping the remaining resist, a metallic microstructure anchored to the substrate is obtained, Figure 3.5 shows the LIGA technology steps and sequence. Moreover to make devices with moving parts, the LIGA structure can be formed partly on a sacrificial layer, such as Ti, which can then be selectively removed to free part of the structure, with another part of the structure anchored to the substrate [39].

However, the LIGA technology is not compatible with CMOS processes. Moreover, the LIGA process requires a high cost, both of the masks and of access to the X-ray facilities. All this drawbacks limited the using LIGA technology in spite of its excellent resolution [39].

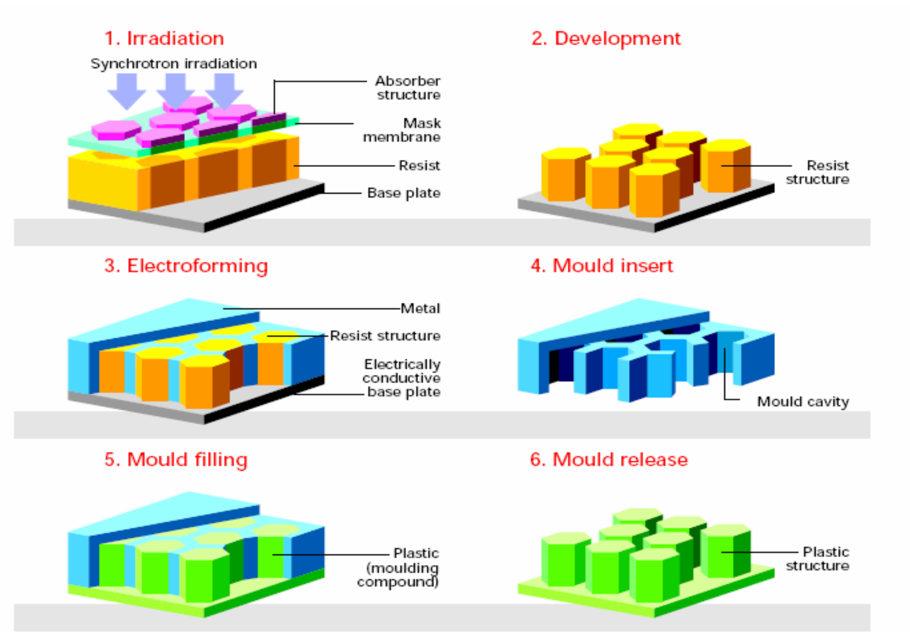

Figure 3.5. LIGA technology steps and sequence.

3.5 Microfluid Mechanics

To study the Microfluid Devices in all its aspects, then the Micro Fluidics must be study in full details to design and implement the micro fluid devices. However the laws and theorems that are applied to Microfluid are different from those used in Macrofluid mechanics as shown later in this section [42].

In MEMS device, the small length-scale and a large surface area relative to the volume, these reasons make the fluid flow in micro devices differ from those in macro devices, this in many aspects such as the transport of mass, momentum and energy through the surface

[42]. So the microfluidics branch of fluid mechanics has been established to achieve rational-design capability for useful microdevices, and to be able to characterize definitively and with a little experiment as much as possible [42].

To model a flow field, there are two ways basically used to modeling a flow field [43]. First one is based on dividing the flow field into deterministic methods and probabilistic ones, and second one is continuum model, where the matter is assumed continuous and indefinitely divisible, through this approach the velocity, density, pressure, etc., are defined at every point in space and time, and conservation of mass, energy and momentum lead to a set of nonlinear partial differential equations. However, since the continuum model is easier to handle mathematically than the alternative molecular models, therefore Continuum models should be used as long as they are applicable [44]. Moreover, many forces have been appear when the devices scale goes to micro scale such as Steric Forces, Electrostatic Forces and Van der Waals Forces, so all these forces and other forces must be take in consideration when a micro fluid modeling done [45].

Furthermore, in spite of the viscosity of liquid is a constant in either Macro/Micro flow, however in microtubes has a more significant role, this because the tube size appear as an important factor affecting on its [45], so the apparent viscosity of micro flow modeling must also be take in consideration.

With respect to micro flow friction, it has been modeled and tested by Blasius [46], it is consider as an important parameter even though micro tubes used, however the friction coefficient of fluid flow can be determined as

$$f_{Blasius} = 0.3164 \times Re^{-0.25} \qquad (3.1)$$

On the other hand, the microfluidics engineering like other engineering sciences, it has many challenges that complicate its development and research such as measuring flow properties, this because the sensors need to be much smaller than the size of the device under study. Moreover, the momentum and the energy of the flow is very small, which is difficult to design a sensor property without make any affects on this amount of momentum, and not alter the flow properties [45].

3.6 Summary

This chapter reviewed the available microfabrication techniques, and their benefits and limitations in machining the microstructures. The details of fabrication processes of both silicon and non silicon based materials are explained including its advantages.

PROGRAMMING AND CONTROL OF A GENTLE MICROPUMP FOR BIOMEDICAL APPLICATIONS

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By

Suleiman Muhyeddin Suleiman Abdelhadi
Dr. Mohanad Al-Ata (Chairman)
Dr. Mohammad Kilani (Co-Advisor)

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