الجمهورية الجزائرية الديمقراطية الشعبية

Democratic People’s Republic of Algeria
وزارة التعليم العالي و البحث العلمي
Ministry of Higher Education and Scientific Research
جامعة سعد دحلب البليدة 1
Saad Dahleb Blida 1 University

Faculty of Science
Physics Department
Laboratory LPCMIA

For obtaining the master’s degree in physics

Option: material physics

Theme:

Development and elaboration of metallic thin-film mold and millimetric tortuous channel

Presented by:

DRAZZI MOHAMED AINE.

- Defensed on 09/07/2024 in front of the jury composed of:

Jury Member:

Dr. OuldArab Halima	MAA	UKM	President
Dr. M’Hammedi Kawther	MCB	UB1	Examiner
Dr. Nadir Belgroune	MCB	UB1	supervisor
Dr . Bouamra Faiza	MCA	UB1	co-supervisor

Blida 1 -2023/2024

Acknowledgements

First and foremost, I must acknowledge my limitless thanks to Allah, the Ever- Magnificent; the Ever-Thankful, for granting us the wisdom, health and strength to undertake this research task and enabling me to its completion. Totally sure that this work would have never become truth, without His guidance.

Second, sincerely thank the jury members, the president Dr. Ould Arab Halima and the examiner Dr. M’hammedi Kawther

I express my gratitude to my research supervisor Dr. Belgroune Nadir and Bouamra Faiza respectively, for the continuous support of our thesis, their patience, and motivation, and for their advice. I would like to thank many people who have helped me through the completion of this thesis.

I would also like to express my sincere thanks to all the teachers who taught me and who by their skills supported me in the pursuit of my studies.

I warmly thank the material physics Master students for their moral help throughout the preparation period.

Dedication

This thesis is dedicated to:

My parents, who raised me with a love of science and supported me in all my pursuits. Your Love, encouragement and pride are my greatest motivation. Thank you for everything.

My sisters, whom I am truly grateful for having in my life.

To my coach, nadir Belgroune, for his expertise, his constant support and his precious advice throughout this work. Your guidance has allowed me to go out and give the best of myself. I'am infinitely grateful to you.

To all the persons who helped me by assistance and collaboration for the development of this work

DRAZZI AMINE

Abstract

This work investigates the development and elaboration of metallic thin-film molds and millimetric tortuous channels for microfluidic applications. Microfluidics, which manipulates small fluid volumes at the micrometric scale, has transformative potential in fields ranging from biotechnology to analytical chemistry. The study explores key fabrication techniques, including electroplating, and soft lithography, to produce microchannels. Detailed design and elaboration processes of PDMS microchannels are also presented. The results demonstrate the effectiveness of these techniques in achieving desired microchannel geometries and fluid flow characteristics. This research provides critical insights into the fabrication and design of microfluidic systems, contributing to advancements in microfluidic technology and its applications in various scientific and engineering fields.

Keywords: Microfluidic , Microchannel , PDMS, Mold

Résume

Ce travail explore le développement et l'élaboration de moules métalliques en film mince et de canaux millimétriques tortueux pour des applications microfluidiques. La microfluidique, qui manipule de petits volumes de fluides à l'échelle micrométrique, a un potentiel transformateur dans des domaines allant de la biotechnologie à la chimie analytique. L'étude explore les principales techniques de fabrication, y compris l'électrodéposition et la lithographie douce, pour produire des microcanaux. Les processus de conception détaillée et d'élaboration de microcanaux en PDMS sont également présentés. Les résultats démontrent l'efficacité de ces techniques pour obtenir les géométries de microcanaux souhaitées et les caractéristiques d'écoulement des fluides. Cette recherche fournit des insights essentiels sur la fabrication et la conception de systèmes microfluidiques, contribuant aux avancées de la technologie microfluidique et à ses applications dans divers domaines scientifiques et techniques.

Mots clés; microfluidique , microcanal , PDMS , moule

ملخص

يبحث هذا العمل في تطوير وتوضيح قوالب معدنية ذات غشاء رقيق وقنوات معقدة ميليمترية للتطبيقات الميكروسيالة. تتمتع الميكروسيالات، التي تتحكم في أحجام صغيرة من السوائل على مقياس ميكرومتري، بإمكانات تحويلية في مجالات تتراوح من التكنولوجيا الحيوية إلى الكيمياء التحليلية. تستكشف الدراسة تقنيات التصنيع الرئيسية، بما في ذلك الطلاء الكهربائي والطباعة الحجرية اللينة، لإنتاج القنوات الميكروية. يتم أيضًا تقديم عمليات التصميم والتفصيل الدقيقة لقنوات PDMS الميكروية. تُظهر النتائج فعالية هذه التقنيات في تحقيق الأشكال الهندسية المطلوبة للقنوات الميكروية وخصائص تدفق السوائل. توفر هذه البحث رؤى حاسمة في تصنيع وتصميم أنظمة الميكروسيالات، مما يساهم في تقدم تكنولوجيا الميكروسيالات وتطبيقاتها في مختلف المجالات العلمية والهندسية.

Table of contents

Lists of figure and table

GENERAL INTRODUCTION

Microfluidics, the technology that manipulates small volumes of fluids at the micrometric scale, plays a pivotal role in numerous applications, from analytical chemistry and medical diagnostics to environmental monitoring and inkjet printing. Within this domain, microchannels have emerged as essential tools for microfluidics devices due to their ability to conduct chemical reactions in confined, controlled environments. These microfluidics devices are integral in fields such as pharmaceuticals, biotechnology, and chemical engineering, where precision and efficiency are paramount.

Metallic thin-film molds and millimetric tortuous channels are crucial components in the construction of micro reactors. The thin-film molds enable the creation of intricate microchannel designs, while the tortuous channels enhance fluid mixing and reaction efficiency. This research is motivated by the need to improve the fabrication processes and design of these components to optimize the performance of micro reactors.

Despite the advancements in microfluidic technologies, challenges remain in the fabrication of high-precision molds and microchannels. Current methods can be time-consuming, costly, and may not always achieve the desired accuracy or reproducibility. Addressing these issues is crucial for the development of efficient and reliable microfluidics devices. Therefore, this work aims to develop and refine fabrication techniques for metallic thin-film molds and millimetric tortuous channels, thereby improving the overall functionality and applicability of micro reactors. The primary objective of this work is to develop fabrication processes for metallic thin-film molds and millimetric tortuous channels used in micro reactors. This work is limited to laboratory-scale experiments and does not extend to large-scale industrial production. The secondary objectives include evaluating the effectiveness of various fabrication techniques, such as electroplating and soft lithography. Additionally, the study aims to design and elaborate PDMS microchannels to enhance their application in microfluidic systems. This study focuses on the development and optimization of fabrication techniques for microchannels and molds, striving to improve the precision and reliability of these critical components in micro reactors.

This thesis is structured as follows:

Chapter 1: is devoted to the state-of-the-art review of microfluidic technologies, focusing on micro channels, their applications, and the importance of thin-film molds and tortuous channels. Then next, present the knowledge necessary for the modeling of microflow in microchannels and their characteristics.

Chapter 2: Detailed examination of microchannel technology, including a brief generality on microchannels and the different methods of manufacturing microchannels. (PCB and electroplating technologies). Additionally, the chapter delves into our fabrication process of metallic thin-film molds, which are essential for producing our microchannels.

Chapter 3: present the design and elaboration of PDMS microchannels, including a detailed description of the geometric structure, fluid flow principles, and fabrication steps. This chapter shows the experimental results of the fabricated microchannels and molds.

Finally, we give a conclusion and future work, summarizing the findings and suggesting potential directions for further work.

This structure ensures a comprehensive exploration of the research topic, from theoretical foundations and fabrication techniques to practical applications and prospects.

CHAPTRE 1: GENERAL AND STATE OF THE ART ON MICROFLUIDIC

1.1 Introduction

Microfluidics devices, the technology or systems manipulating small volumes of fluids at the micrometric scale, covers a wide range of applications from analytical chemistry to inkjet printer heads. This technology is crucial for miniaturization, volume reduction, safety enhancement, and increased sampling speed in bio-analytical protocols. Over the last decade, advancements in micro-manufacturing techniques have led to the development of integrated fluidic microsystems, where liquid circulation plays a vital role [1].

This chapter aims to provide an overview of microfluidic technology, its applications in chemical and biological fields, and the fundamentals of fluid modeling in microchannels. The basic assumptions for micro flow will be discussed through the Navier-Stokes equations and hydrodynamic laws at very small scales.

1.2 Overview of microfluidic technology and its origin

Micro-fluidic is the science that processes and transports the fluids at the micrometric scale, with at least one specific dimension in the micrometer range. On a small scale, the surface-to-volume ratio is particularly high, and flows are generally laminar, which is particularly helpful for drop formation conditions. Droplet generation techniques depend on an equilibrium control of the forces exerted on the interface, essentially through geometry and flow characteristics [2].

Immediately imagined and realized, the fluidic microsystems targeted the consumer market with the first integrated inkjet printer heads developed by IBM in the 1970s [3]. If the first chromatograph appears in 1979 [4], it will be necessary to wait until the beginning 1990s for the potential applications to biology and chemistry to emerge with the notion of laboratory on a chip (lab-on-chip). From this concept comes the promise of being able to integrate different biological and chemical operations on the same micro and nanostructure chip [5]. To obtain such systems, it was necessary to adapt the lithography processes to produce micro channels on the surface of a solid substrate. Some discoveries have largely facilitated the development of such chips, such as the use of PDMS (poly dimethyl siloxane) to manufacture microfluidic channels in 1998 [6]. A few years later integrated valves specially dedicated for PDMS channels [7], [8]. Therefore, microfluidics is gradually essential for the implementation of most bioanalysis protocols [9-10]. Microfluidic systems are considered key components of integration.

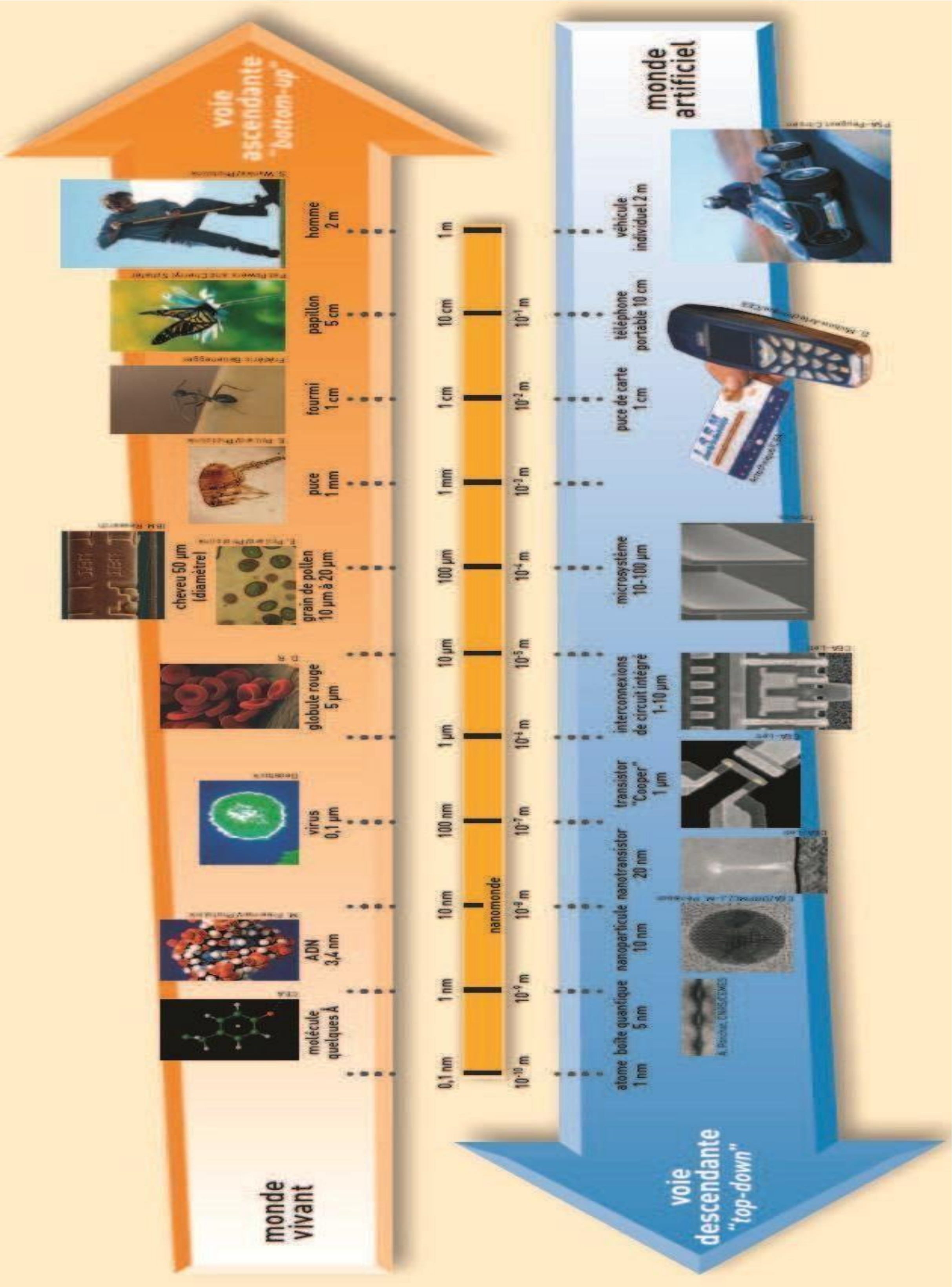

Figure I.1 *Mapping of different scales to objects handled or manufactured [11]*

Figure I.1 illustrates two main ways of developing objects or systems micro/nano metric: top-down and bottom-up. Two paths lead to the micro and Nano worlds: molecular manufacturing, which involves the manipulation of individual atoms and construction from the base, and ultra-miniaturization, which produces increasingly smaller systems.

- ✓ The descending path is that of the artificial world, which starts from macroscopic materials, chiseled by the hand of man and then by his instruments. It is it that borrows electronics for several decades mainly with silicon as a substrate, and its «slices» (wafers**)** as manipulated entities.
  - ✓ The upward path can overcome these physical limitations and also reduce manufacturing costs, notably by using self-assembly of components. This is the way followed by the living world.

Microfluidics offers the possibility of solving outstanding systems integration issues for the field of biology, chemistry, medicine, etc. For a decade the improvement of microfabrication techniques has led to the development of integrated flow microsystems [11-12], in which liquid circulation plays a central role.

1.3 Development of microfluidic components

The development of micro-fluidic was born from MEMS technology, which was defined as a microscopic system integrating into components electronic and mechanical. Its objective is to miniaturize the devices conventional macroscopic to measure physical quantities in microscopic devices. Due to strong capital promotions from government and industry, the development of MEMS technology has been rapid, making the detection components small and inexpressive. A typical example of MEMS is the accelerometer, which is currently integrated into every cell phone to detect gravity to identify the orientation of the cell phone.

Parallel to this concept, the conventional macroscopic wet laboratory processing equipment could be miniaturized into microscopic devices. These microscopic devices were designed to manipulate fluids and were therefore called micro-fluidic devices. Initially, most of the developments focused on the miniaturization of fluidic components such as pumps [13-14], mixers [15-16] and valves [17, 18]. These individual components constituted the fundamental elements of fluidic systems.

The objective of the development was to demonstrate fluid handling capability, but not for specific biomedical applications. For example, a two-way micro-pump based of silicon has been reported and its schematic drawing is shown in I.2 [19]

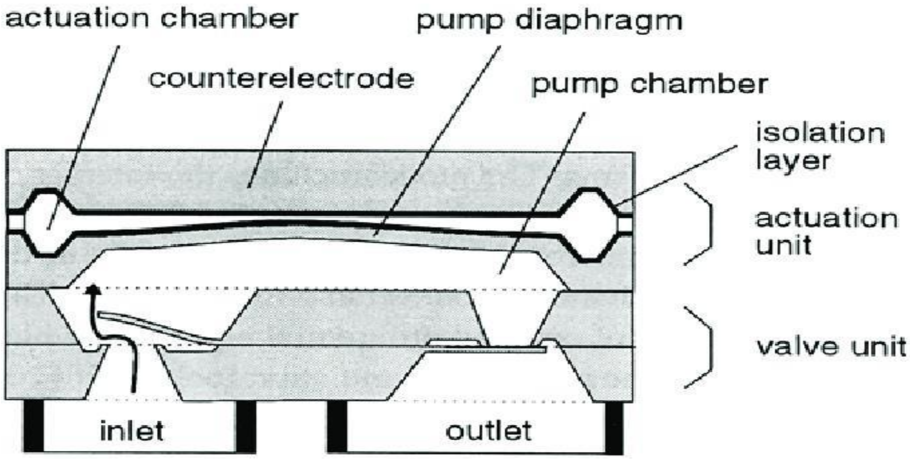

Figure I.2 *Electrically controlled silicon-based pump [19]*

At micrometer dimensions, the flow laws remain those of classical fluidics and can be studied with the Navier-Stokes equation in the case of incompressible liquids, whose inertial terms can be neglected here. Indeed, some phenomena, such as capillarity and viscosity forces, become predominant, while others, such as gravity, become negligible in the study of fluid flows.

The flow regime is predominantly laminar, characterized by a low Reynolds number (Re<1). Diffusion phenomena within these flows are well understood, enabling the development of associated applications such as micromixers or concentration gradient generators (figure I.3).

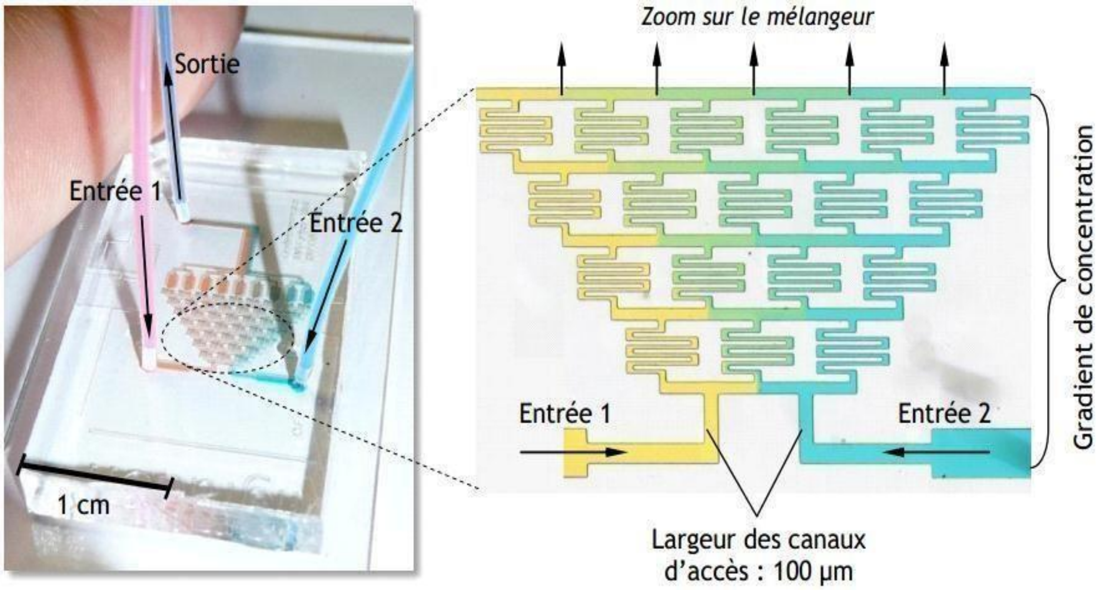

Figure I. 3 *Gradient generator developed in the SATIE laboratory at ENSCachan.[20]*

The microsystems developed in microfluidics are based on microtechnology processes specific to MEMS and must offer microscopic applications the same functionalities as macroscopic applications. Microfluidic technology, combined with the ability to control the behavior of fluid flows, has naturally led to its application in the life sciences. At the physiological dimensional scale of blood circulation (microns to tens of microns), it is possible to reproduce mimetic environments with controlled, evolving experimental conditions [20].

1.3.1 Reynolds number

The Reynolds Re number is defined by the ratio of inertial to viscous forces within a moving fluid. It makes it possible to characterize the nature of the flow regime: if Re is greater than 2300, we speak of turbulent flow, if Re is less than 2000, we speak of laminar flow. Thus, in turbulent flow regime, fluid particles describe irregular random motion and unstable vortices appear and interact with each other. In contrast, in the case of laminar flow, the current lines of the fluid particles are locally parallel. The Reynolds number is expressed as follows:

$$\mathrm{Re} = \frac{\rho \mathrm{VL}}{n} \tag{1.1}$$

Where ρ is the density of the fluid, V is the characteristic velocity of the flow, L is the characteristic length of the flow and n is a viscosity (dynamic) of the fluid. Flows in the microfluidic domain are predominantly laminar, viscous forces dominating inertial effects. Microchannels and Reynolds numbers generally remain low due to small dimensions and low flow rates. For example, water flowing at a speed of 1 mm/s in a circular microchannel with a radius of 100µm, the Reynolds number is 0.1 [20].

1.3.2 Laminar flows and velocity profile of micro flows

The flow of fluid in a microchannel is generally laminar. Thus, all the lines of the currents of the fluid particles (or layers) are moved in a well-defined direction in a microchannel (Figure I.4). So these current lines do not intermingle. Thus, along a microchannel the flow is axial and parallel to the walls. The flows are then laminar without turbulence [21-22]. The laminar nature of flows can be advantageous in several microfluidic applications. For example, in electrophoretic separation systems based on dispersion phenomena or in separation devices focused on diffusion or reaction phenomena [20-22].It can also be a major disadvantage as in processes where mixing is necessary. Indeed, chemical reactions are generated in micro reactor, and in order to increase reaction kinetics, turbulent flow is required to increase mixing between chemical species [23].

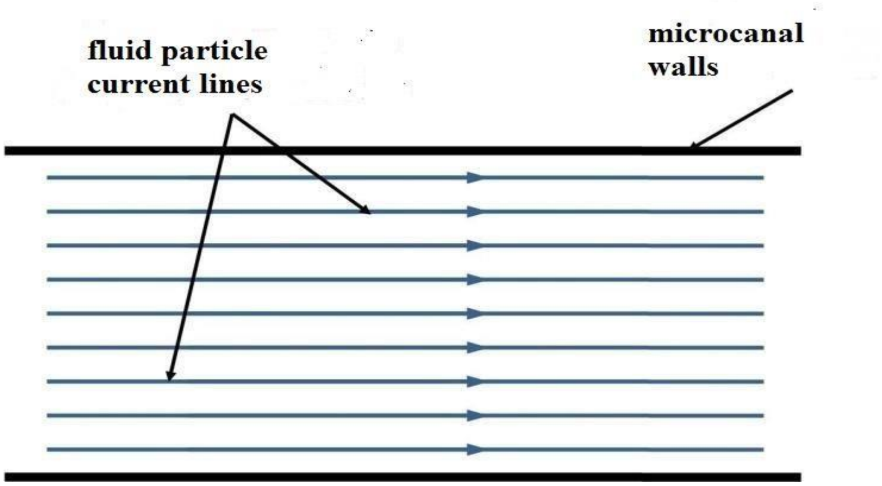

Figure I. 4 *Fluid particle current lines*

Rectangular and circular cross-sectional micro channels are commonly used in Microfluidic applications. Since the flow is laminar, the equations governing this flow (equation de Navier-stokes) can be simplified and applied to each geometry to determine the speed profile in the microchannel section [23-24].

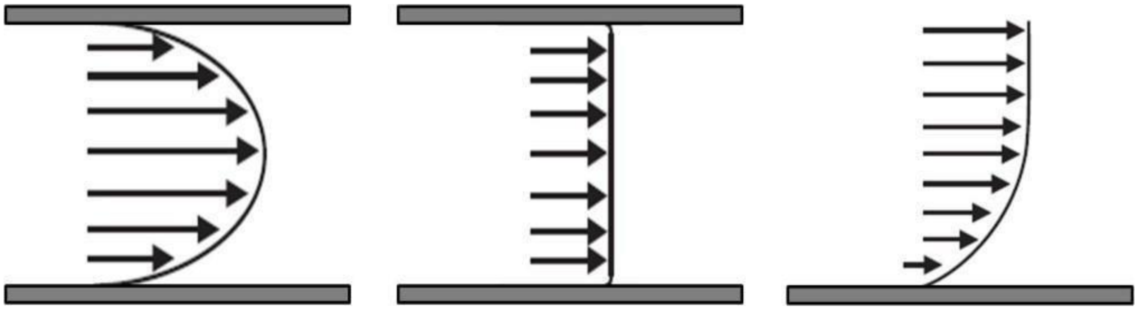

Figure I. 5 *Flow velocity profiles: (a) Parabolic shape profile, (b) uniform shape profile, (c) Velocity profile cancels near walls and then uniform.*

There are essentially three velocity profiles for laminar flows within the micro channels. The flows induced by a pressure gradient have a parabolic profile where the speed is maximum in the middle of the channel to cancel near the walls (Figure I.5.a). For flows controlled by electroosmotic pumps, the profile is almost uniform (Figure I.5.b). Finally, in the case of open micro channels with flow generated by pressure, the flow velocity gradients occur near the walls to cancel out (Figure I.5.c) [24].

1.3.3 The hydrodynamic flow: navier-stokes equation

The hydrodynamics of liquid flows remain fluid up to a few nanometers. Thus at the micron scale, one can apply the constitutive equation of an incompressible Newtonian fluid which is described by the navier-Stokes equation. In an established system, in the context of microfluidics where the terms inertia can be neglected, this equation is reduced to the following law:

$$\Delta P = \eta \Delta \vec{u} \qquad (1.2)$$

This is the poiseuille equation that can be solved according to the geometry of the channel. Here the resolution is given for a circular pipe of radius R, the flow profile is then parabolic in nature as shown in (figure I.6.) The velocity (vmax) of this profile depends directly on the applied pressure.

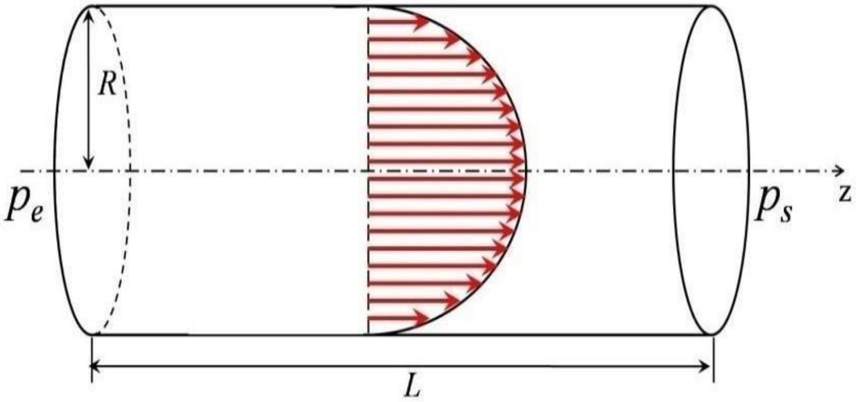

Figure I. 6 *the poiseuille flow velocity profile in a circular section microchannel.*

There is a linear behavior between the pressure difference P and the flow rate Q within the channel. In the case of a circular channel, we obtain classically Hagen-poiseuille law:

$$\Delta p = \left[\frac{8\eta L}{\pi R^4}\right] Q \qquad (1.3)$$

A very different physical situation is the transport of electrons in an electric conductor: the average speed of electrons is the same throughout the conductor section. The resistance of the conductor is inversely proportional to its section (πR^2) [20, 25]. By analogy with the Ohm law, a hydraulic resistance R_H is defined by:

$$R_H = \frac{8\eta L}{\pi R^4} \qquad (1.4)$$

1.4 Basic Devices in a Microfluidic System

One of the major issues in this field concerns micro flows: how and where to circulate fluid in microfluidic systems. There are a multitude of components of these systems. To answer these questions, we will go through some basic elements to illustrate this multitude [25].

1.4.1 Microfluidic interconnections:

It is necessary to solve the problems of fluid output of microvalves and at the output of micro channels. These interconnections realize a coupling between two microfluidic systems or between a microfluidic system and the outside world (Figure I.7). It is desirable that this connection is carried out in a simple, standardized, leak-free manner and similar to the connection of two circuits electronic [25].

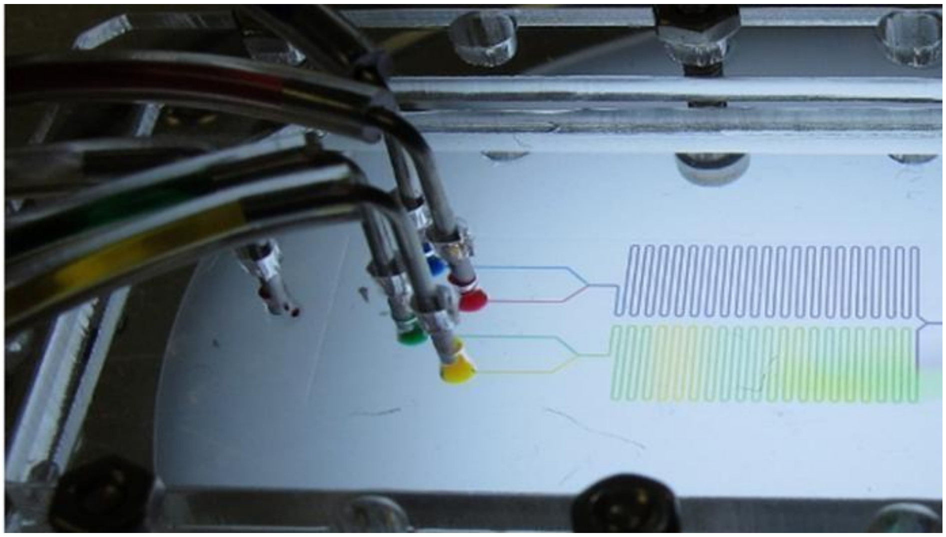

Figure I.7 *A microfluidic interconnection system with the outside world [26]*

We can find several microfluidic interconnection systems designed in the laboratories of research, but rarely used in industry due to unreliability. We can thus find needle connections as shown in Figure I.8.a, connections based on flexible polymer type "tygon" (Figure I.8.b), polymer-based connections, this time in rigid Teflon-PTFE (Figure I.8.c) and finally "nanoport" type quick-release connections (Figure I.8.d).

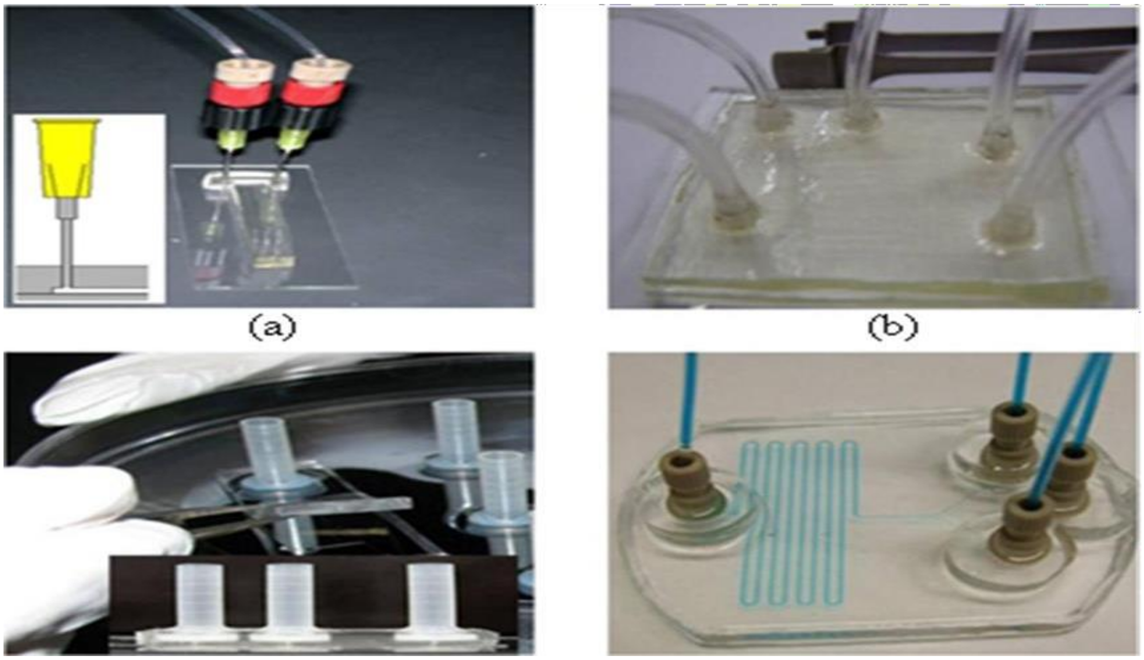

Figure I.8 *Different types of microfluidic connections: (a) Needle connections, (b) tygon-type flexible polymer connections, (c) Teflon-PTFE rigid polymer connections, (d) nanoport-type quick-mount-disassembly connections [27-28]*

1.4.2 Microchannels

The microchannel is a fundamental element for most microfluidic systems. It plays an important role in the realization of microfluidic devices (Figure I.9). These micro channels are generally used as a means of conveying fluids but they play the role of constitutive elements to realize micro reactors, micromixers, micro separators in BioMEMS [29]. The geometry of the microchannels and their technological design are essential for the proper movement of the liquid within the microfluidic system under the desired conditions for the applications to which they are dedicated [30].

Generally, a microchannel has lateral dimensions smaller than the millimeter and greater than the micron. Above 1 millimeter, the flow has the same behavior as conventional flows. Nowadays, micro channels have characteristic dimensions ranging from submicron scale to several hundred microns [30].

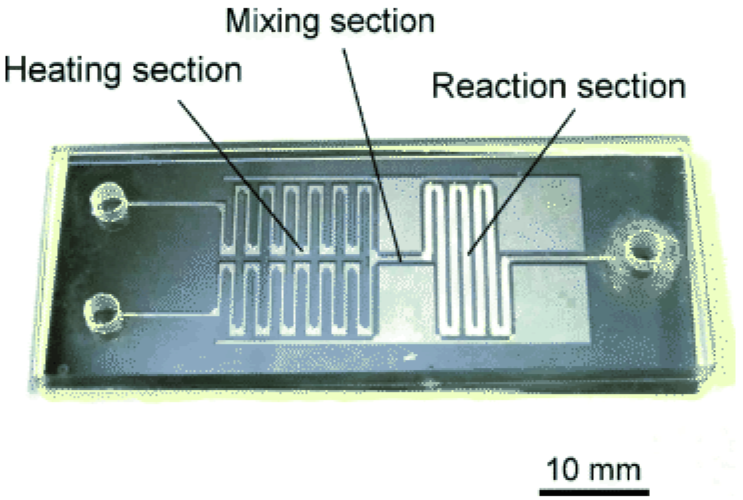

Figure I. 9 *a microchannel-based chemical microreactor [29]*

Microchannels can be manufactured by using different materials such as: polymers, glass, metals and silicon of microelectronic class (Figure I.10). The section of a microchannel can also have different shapes: circular, semi-circular, rectangular, triangular or even trapezoidal. Depending on the shape and material used, these micro channels can be manufactured using a variety of technological processes including surface micro-machining, volume micro-machining and molding [30].

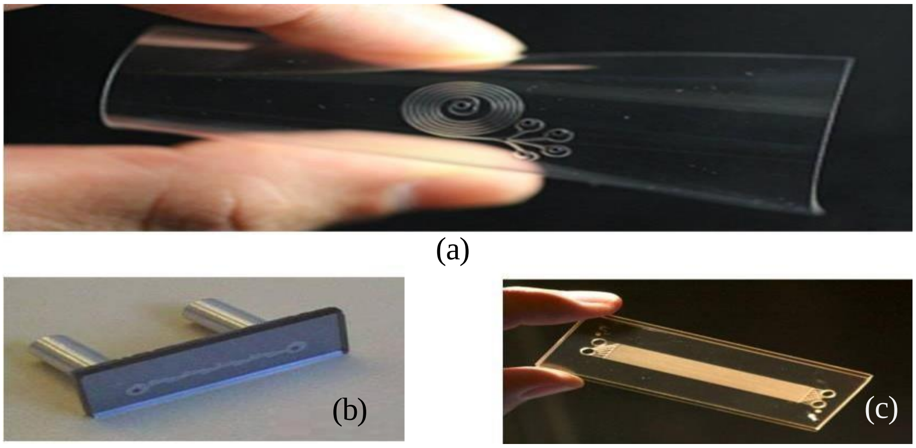
(a)

Figure I. 10 Microchannels made of different materials: (a) PDMS microchannels, b) Silicon microchannels, (c) glass microchannels [28].

1.4.3 Micro valves

Microvalves are designed as conventional valves used at the macroscopic scale. They allow the opening or closing of a micro channel, thus controlling the passage of the fluid. They can be passive or active, normally open (i.e. without control the valve is open) or closed [31]. Passive micro valves are controlled by the difference in pressure allowing the fluid to flow in one direction (check valve). For its operation, this type of micro valve requires no external energy [31]. Unlike active micro valves which can be controlled by actuators of type: piezoelectric [32], electrostatic [36], pneumatic [37], thermo-pneumatic [38] and thermoelectric [39]. But this type of micro valves is rather complex in their assembly and uses a high electrical voltage making them less attractive for several commercial applications.

1.4.4 Micropumps

The increasing number of applications involving the flow of micro quantities of liquid (a few milliliters per minute), required the development of various types of micro pumps. Most of the known applications are based on the miniaturization of existing pumps at Macroscopic [31]. Figure I.11 shows the micrograph and design scheme of the side-cavity acoustic transducer micro pump.

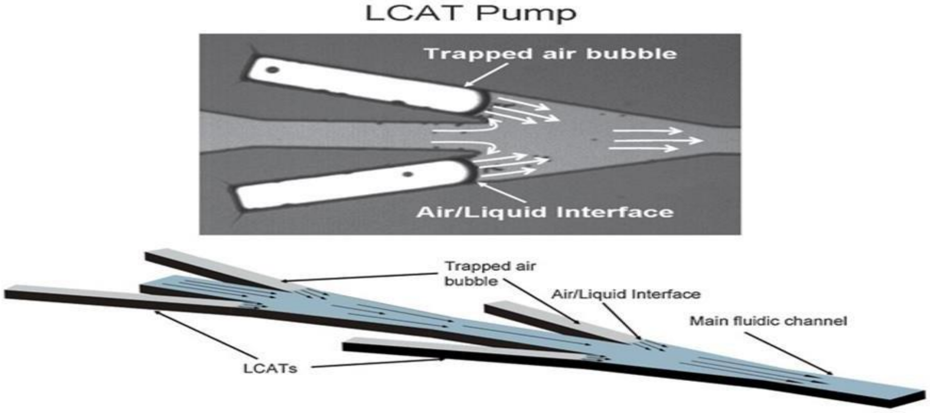

Figure I. 11 Design of the lateral cavity acoustic transducer micro pump.

However, the principle of most micropumps is based on the operation of a mechanical volumetric pump. In this case, an actuator creates a volume variation in a chamber connected to two valves. The differences between all these micropumps are essentially at the level of the type of actuation. We can thus find piezoelectric actuators [32-33], electrostatic [35], pneumatic [34] and thermo-pneumatic [37-40].

1.5 Application of Microfluidics

Among all microsystems are fluid microsystems which are devices using or conveying liquid or Gaseous fluids. Allowing the transport and manipulation of Nano liters of fluid in channels the

Size of a hair, microfluidics is a growing discipline with many applications in a wide range of fields.

1.5.1 The medical

µTAS (Micro Total Analyzing Systems) appeared in the 1990[41]. are microsystems with vocation biomedical that can be implanted in the human body. Eventually, these systems will allow the administration of the necessary dose of drug after an analysis made on the patient. Among these microsystems, insulin micro pumps are becoming increasingly common and compact to allow users to be autonomous.

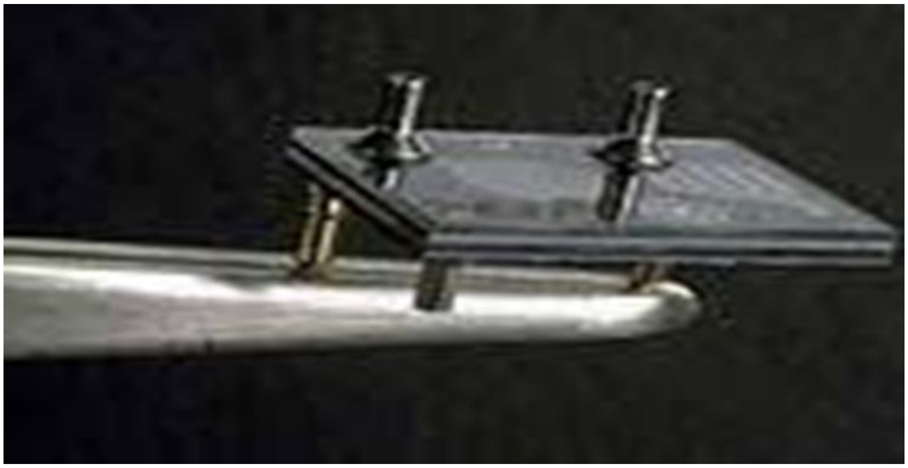

Figure I. 12 *Silicon pump for controlled drug delivery; DE biotech SA, (2004) [42]*

These micropumps involve micrometric elements such as catheters implanted in the body. Some are beginning to equip themselves with diagnostic tools to manage the insulin flow to be distributed according to the patient's need. Ultimately, the idea of diabetologists and more generally researchers is to make an insulin injector implantable on the human body and regulated automatically based on blood sugar levels. In other words, a real artificial pancreas.

1.5.2 Biotechnology

Thanks to miniaturization, we were able to realize systems allowing multiple operations, such as detecting biological molecules, transporting them, mixing them and characterizing them, from a raw sample. In traditional genomic analysis, the DNA fragment must be purified and amplified before being analyzed. This is a complex work and it would be interesting to integrate all the operations on the same chip, in order to be able to analyze directly and immediately a raw sample, such as a drop of blood for example. This involves miniaturizing systems such as cytometers, separators, bioreactors, and then associating them. We define the domain of integrated analysis microsystems, designated by µTAS, or that of lab-on-chip (lab-on-chip).

In 1994, a research group was able to manufacture a chip with three functions: reagent mixing, enzymatic reaction, and separation, [43]. Four years later, a device capable of titrating aqueous solutes, mixing, amplifying, enzymatic digestion, electrophoresis separation and detection was published in the journal Science by [44]. In recent years, all kinds of solutions have been devised to improve and simplify the control of fluid on chip.

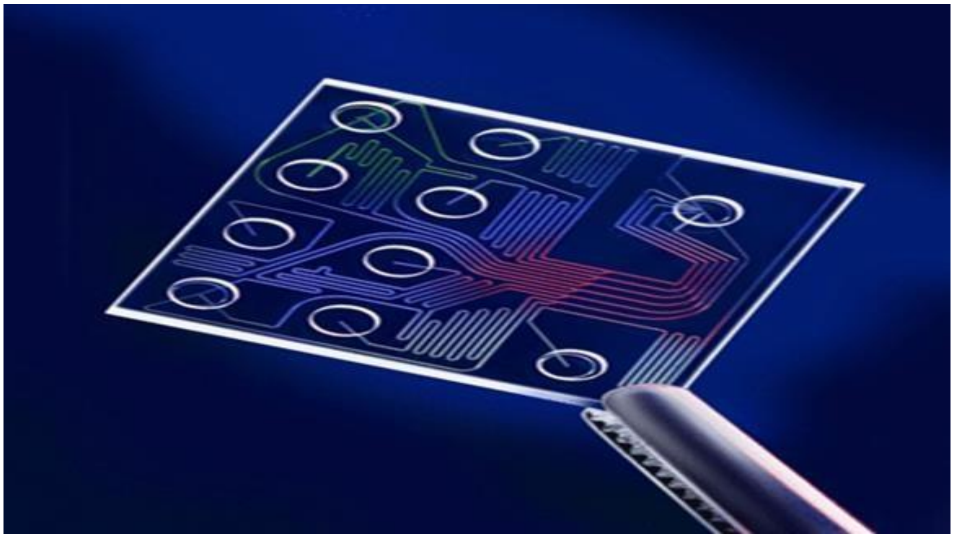

Figure I. 13 *Lab. on chip, Agilent Technologies, (2006) [45]*

Chips carrying out Polymerase Chain Reaction (PCR) Amplification (see Fig.I.13) are booming. This technique makes it possible to massively replicate a DNA sequence from a very small initial amount to detect, for example, genetic abnormalities.

1.5.3 Microfluidic chemistry

In the same way as biology and medicine, microfluidics has given a significant boost to chemistry. The development of fluidic microsystems affects almost all areas of chemistry, from analytical chemistry to process chemistry. In organic chemistry, microfluidics has removed a large number of barriers [46]. This is the case for reactions requiring complex mixtures of reagents. For these types of reactions, the use of a micro reactor allows not only to have a better mixture but to control it. The applications of microfluidics also concern the world of perfumery with the development of pico-drop [47]. It is a fragrance diffuser that delivers a constant micro-fragrance rate throughout the broadcast period and is able to diffuse about 100ml per month.

1.6 Conclusion

In this first chapter, we were able to introduce the state of the art on the field of microfluidic technology. We first presented the characteristics of this technology for knowledge necessary for the modeling of flows or more exactly micro flow in microchannels, as well as the basic assumptions for this kind of microflow through the Navier-stokes equations and the flow dynamics in the channels. Subsequently, we have given the basic devices constituting a microfluidic system and some application areas of microfluidics.

.

CHAPTRE 2 : MICROCHANNEL TECHNOLOGY

2.1 Introduction

The fabrication of microchannels is a crucial aspect of developing microfluidic devices. Several fabrication techniques have been developed over the years for different applications and materials. These processes include conventional, time-consuming technologies, depending on the applications of microchannel-based devices [48].

This chapter provides a comprehensive overview of microchannel technology. It begins by introducing the basic concepts and significance of microchannels, followed by a discussion of the various manufacturing processes used to create these intricate structures. Key techniques such as photolithography, electroplating, and soft lithography are examined, highlighting their methodologies and applications. Additionally, the chapter delves into our fabrication process of metallic thin-film molds, which are essential for producing our microchannels. These methods for faster and cheaper production must be explored for sustainable development in this area.

2.2 Overview of microchannel

The term "microchannel" refers to channels with a hydraulic diameter typically ranging from a few micrometers to few millimeters, enable precise control and manipulation of fluids at the microscale. This ability to manage fluids in such fine channels opens a plethora of innovative applications, from biomedical devices to chemical reactors and electronic cooling systems [49].

The concept of microchannels was introduced around 1980 by researchers Tuckerman and Pease. Microchannel/microstructure exchangers are innovative methods for transferring large thermal powers from small surfaces to a heat transfer fluid. Commonly made from materials with high thermal conductivity, such as aluminum, copper, or silicon, these channels are fabricated using micromachining and other complex microfabrication techniques like laser ablation, plasma, epitaxy, chemical etching, erosion, vapor deposition and electroplating.

These channels are created on polymeric, glass, silicon, and metallic substrates. While polymeric and glass substrates are typically used in biomedical and chemical devices, silicon-based and metallic substrates are used for electronics and mechanical engineering-related applications. However, fabricating these microchannels on such substrates in large quantities has always been a challenge due to the precision required. The lack of suitable fabrication technologies has hindered the further development of microchannel-based devices.

Microchannels combine an enormous exchange surface area relative to their overall dimensions (high surface/volume ratio), a very high convective exchange coefficient, a small footprint, low mass, and low flow requirements (typically from a few mL/min to 1L/min). These features make them highly suitable for the efficient cooling of processors, lasers, large electromagnets, etc [50]. Figure II.1 shows some examples of micro-channels/microstructures.

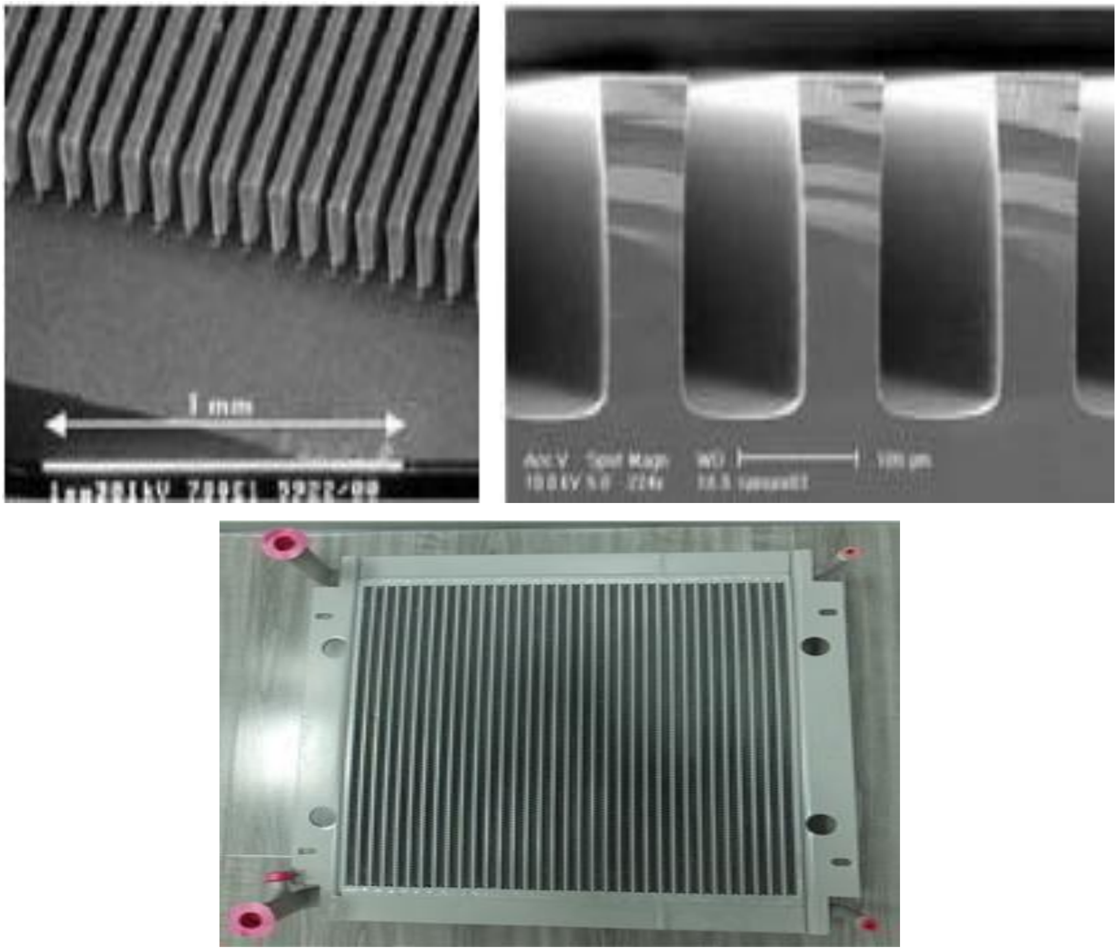

Figure II. 1 *Some examples of microstructures and Micro channels aluminium flat tube [50]*

Various microfabrication techniques are available to make the following geometries illustrated in figure II.2. The different forms existing for the study of a channel used for the design of a microfluidique devices, there are three shapes of geometries [51]:

- **Rectangular Channels:** Common in many applications, offering ease of fabrication and predictable flow characteristics.

- **Circular Channels:** Often used in applications requiring smooth flow with minimal resistance.
- **Triangular and Trapezoidal Channels:** Used in specialized applications for unique flow dynamics. Dimensions or hydraulic diameters of 247.2µm and 400µm and 229.2µm.

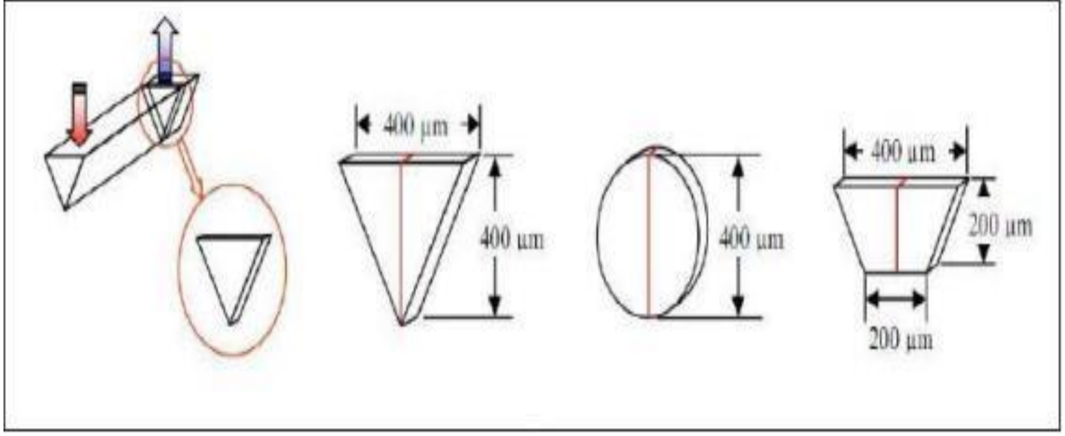

Figure II.2 *The different geometric shapes of micro-channels [51].*

2.3 Microchannel manufacturing processes

Microchannel manufacturing involves several advanced techniques to achieve the desired precision and functionality. The primary manufacturing processes include:

2.3.1 Photolithography

Photolithography is a precise method that uses light to transfer patterns onto a substrate coated with a photoresist. It is commonly used in the semiconductor industry and for creating microfluidic devices.

- **Coating:** Applying a photoresist layer on the substrate.
- **Exposure:** Exposing the photoresist to UV light through a mask with the desired pattern.
- **Development:** Developing the photoresist to reveal the pattern.
- **Etching:** Etching the exposed areas to create the microchannels.

This method allows for high precision and the creation of intricate microchannel designs. Photolithography is particularly effective for silicon and glass substrates, which are commonly used in microelectronics and biomedical applications.

2.3.2 Electroplating

Electroplating involves depositing a metal layer onto a substrate through an electrochemical process. This method is useful for creating durable and conductive microchannels.

- **Surface Preparation:** Cleaning and preparing the substrate to ensure proper adhesion of the metal layer.
- **Electroplating Setup:** Establishing the electroplating apparatus, including the electrolyte solution, electrodes, and power supply.
- **Deposition:** Applying the electrical current to deposit the metal layer onto the substrate.

Electroplating is essential for applications requiring metallic microchannels, such as in mechanical and electronic devices where conductivity and durability are critical.

2.3.3 Soft Lithography

Soft lithography uses elastomeric stamps to pattern materials at the microscale. This technique is versatile and widely used for fabricating PDMS (Polydimethylsiloxane) microchannels.

- **Master Mold Creation:** Creating a master mold with the desired microchannel pattern.
- **PDMS Casting:** Pouring liquid PDMS over the master mold and curing it to form the microchannels.
- **Peeling and Bonding:** Peeling the cured PDMS from the master mold and bonding it to a substrate.

Soft lithography is advantageous for its simplicity, cost-effectiveness, and compatibility with a wide range of materials.

2.4 Metallic Thin-Film Mold Fabrication Process

Mold technology is a critical aspect of manufacturing and production, particularly in industries that require mass production of identical parts. These molds, crafted with high precision and attention to detail, are used in various manufacturing processes to replicate products in materials ranging from metals and plastics to ceramics and composites. The process includes designing, creating, and using molds to shape materials into desired forms. At its core, mold making involves the creation of a negative space or cavity that perfectly mirrors the desired object’s shape. This cavity then serves as a template to produce multiple copies of the object, whether it be in plastic, metal, or any other material. The creation of metallic thin-film master molds is an essential step in the fabrication of microchannels. The fabrication process involves the following steps:

2.4.1 Maser mold preparation by Printed circuit board technology

We do this work at the laboratory of the University of Blida 1 faculty of science, electronic department. The basic steps to create a mold using printed circuit board technology are:

The first requirement is a semi-transparent paper document (a typon) (produced on a polyester tracing paper) representing the path of the copper tracks to be etched on the circuit board Using proteus software. Finally, you need a single- or double-sided PCB (fully copper-plated) coated with a UV light-sensitive resin. Only single- or double-sided plates can be produced in this way. The etching process is generally destructive, as layers are removed each time.

Figure II.3 *Superposition of typon and photo-sensitive plate for exposure*

Use a cutter and leave a few millimeters of margin around the edge of the card. The card must have a minimum length (approx. 10 cm) to avoid falling into the per chloride tank. Then remove the protective layer(s) (single or double-sided printed circuit board) and the plate is ready to be exposed.

Figure II.4 *The machine for cutting printed circuit boards*

- **Step 1: plate exposure.**

The typon is inserted between a UV light source and a copper plate coated with a layer of photoresist. UV light passes through it and strikes the photosensitive resin on the PCB. This resin then degrades under the effect of UV light.

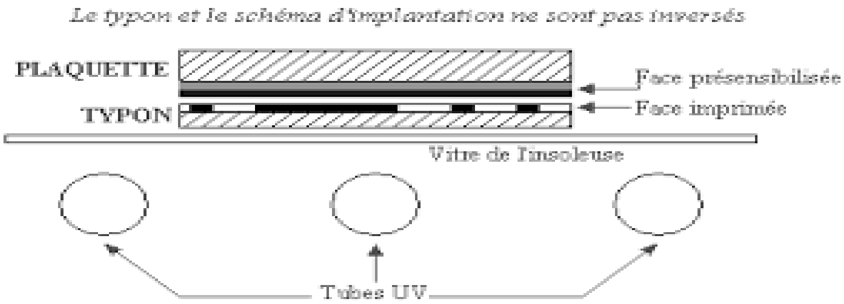

***Figure II.5** Cross-section of typon and printed circuit plate during exposure*

This phase only takes 2 to 3 minutes (at 70°C) with a professional insoleuse represent in figure II.6. It's important that the printed side of the typon is as flat as possible against the photosensitive resin, to limit the effects of light diffraction (to improve the definition of track contours). It is therefore generally carried out in an air vacuum to ensure optimal plating.

***Figure II.6** an artisanal and professional insoleuse*

- **Step 2: Revelation**

We now need to develop this “photo” and harden it so that it can withstand chemical etching. To do this, we dip the plate in a dilute sodium hydroxide solution. Within 5-10 minutes in this bath at room temperature (20-30 degrees), the parts exposed to UV radiation through the film will turn yellow and, by stirring the tray, will dissolve in the caustic soda solution, exposing the copper. These are the parts that will then be chemically attacked to remove them.

Rinse well with water. Once the card has been revealed, inspect it carefully:

- ✓ check that the reveal is complete
- ✓ check that no tracks have been cut (this can be corrected with a permanent marker)
- ✓ Check for short circuits (can be corrected with a cutter blade).

- **Step 3: Engraving**

This time, a corrosive acid (iron per chloride) is applied to the parts of the copper that are no longer protected by the photosensitive resin. The acid then destroys the unprotected copper, revealing the insulating support of the printed circuit. This operation is carried out in an acid bath heated to 50° and oxygenated by a foamer to activate the chemical reaction with the copper on the board.

Figure II.7 represent a handmade engraving machine with heater and foamer.

Figure II.7 *Handmade engraving machine... with heater and foamer*

- **Step 4: Cleaning**

After etching, the plate must be thoroughly cleaned with pressurized hot water to remove any acid residues that may remain in the corners of the tracks by capillary action (45° angles are often used to avoid this).

In the last fabrication process, any remaining photosensitive resin covering the acid-resistant tracks is removed with alcohol, resulting in the final PCB pattern of copper, as shown in figure II.8 this step ensures that the tracks are clean and ready for subsequent processes or for use in electronic applications. This printed circuit board (PCB) with two identical patterns consists of a series of parallel lines connected at alternating ends, forming a serpentine or meandering path. The copper tracks are clearly visible, with the background appearing as the substrate material.

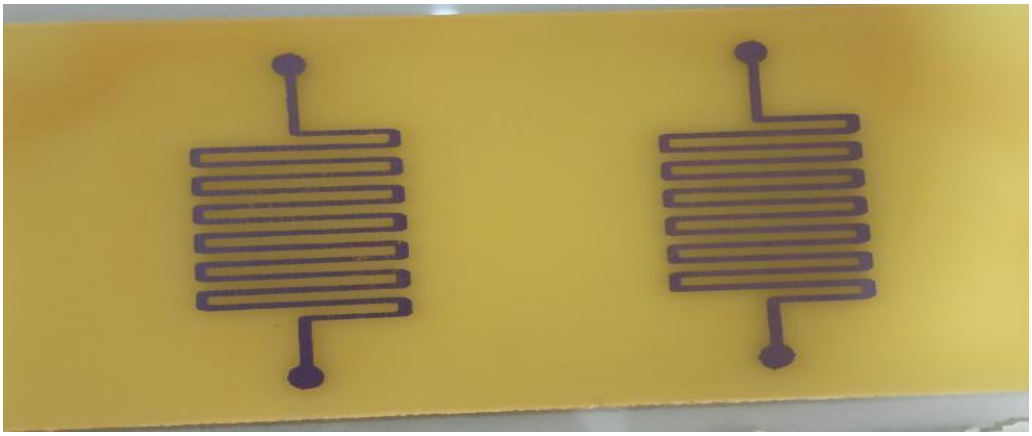

***Figure II.8** Final result after etching and cleaning the plate*

2.4.2 Thin film electroplating deposition process

Electroplating is a method that involves imposing an electric current between two or three electrodes immersed in a solution containing a metal salt of the metal to be deposited. Depending on the processing conditions (electrolysis bath, pH, conductivity, temperature, additives, current density, continuous or pulsed mode, etc.), it is possible to obtain Nano metric grain sizes. This production technique may have the disadvantage of incorporating into the coating impurities present in the electrolytic solution. These impurities have a strong influence on the physio-chemical behavior of the deposit. [52].

The aim of electroplating is to apply a surface layer to a metal to give it the desired properties: aesthetic, magnetic and/or electrical, this process can be used to give objects increased wear resistance, corrosion protection, as well as increased thickness.

a. Setup description

The principle of electroplating is very simple: it is electrolysis. It involves redox (oxidation-reduction) reactions, whichare triggered by a current source [53]. This electrochemical method is often based on traditional electroplating baths. The electrolysis bath is usually the critical component of the cell.

However, there are major factors that influence the last plating. These include:

- ✓ The voltage level of current.

- ✓ The temperature and chemical composition of the bath.
- ✓ The current length of time.
- ✓ The distance between the cathode and the anode.
- ✓ The electrodes' surface area.

In this process we will electroplate copper on copper (mold electroplating) at the LPCMIA laboratory of the University of Blida 1 faculty of science, physics department. The process works using four primary components:

- **Anode:** The anode, or positively charged electrode, in the circuit is the copper metal that will form the plating.

Figure II.9 *a piece of copper that will form the plating*

- **Cathode:** The cathode in the electroplating circuit is the part that needs to be plated. It is also called the substrate. This part acts as the negatively charged electrode in the circuit.

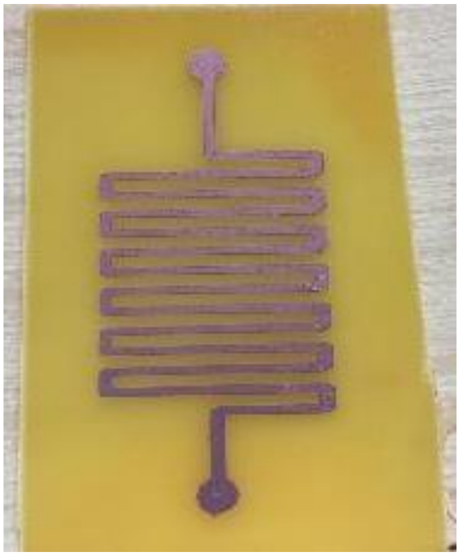

Figure II.10 *the mold that needs to be plated*

- **Power source:** Current is added to the circuit using a power source. This power source applies a current to the anode, introducing electricity to the system.

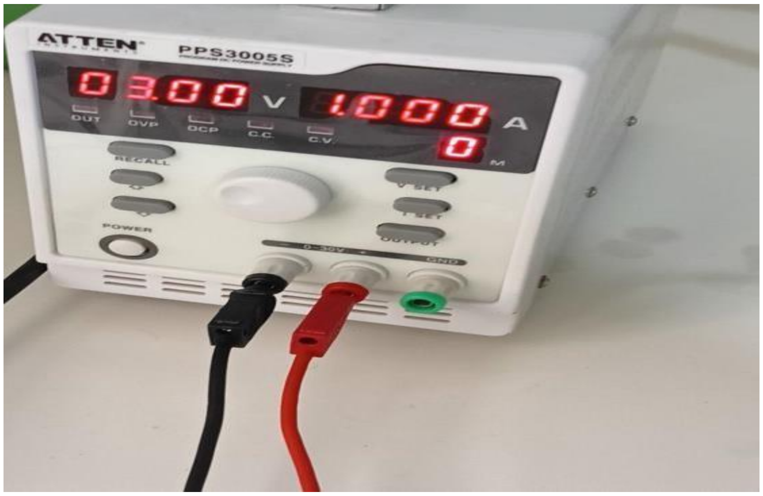

Figure II.11 *power source to do electroplating*

- **Solution:** The electrodepositing reaction takes place in an electrolytic solution. This solution contains one or more metal salts, use copper sulfate ($cuso_4$) to facilitate the flow of electricity.

b. Electroplating Procedure description:

- Step 1 Analyte Solution preparation

To prepare this solution, weight out 10 g of copper sulfate ($CuSo_4$) on a balance. Put the copper into beaker of 250 ml. Add distilled water into beaker up to 250 ml and mix the solution thoroughly with a spoon until completely dissolved. We obtain an electrolyte copper sulfate solution shown in figure II.12

Figure II.12 *(a) Copper sulfate (b) Copper sulfate solution*

- Step 2 assembling the system

When we prepare a solution, the two electrodes are cleaned using a paper and rinsed with distilled water and dry them, now they inserted in the electrolyte and are connected to the terminals of battery using insulated wire leads with alligator clips at both end, connect the piece of copper (cu) to positive battery terminal and the mold that need to be plated to negative terminal, They should not touch each other. Figure II.13 shows an electroplating setup where two electrodes are immersed in an electrolyte solution within a beaker a copper anode connected to the positive terminal and a mold cathode connected to the negative terminal.

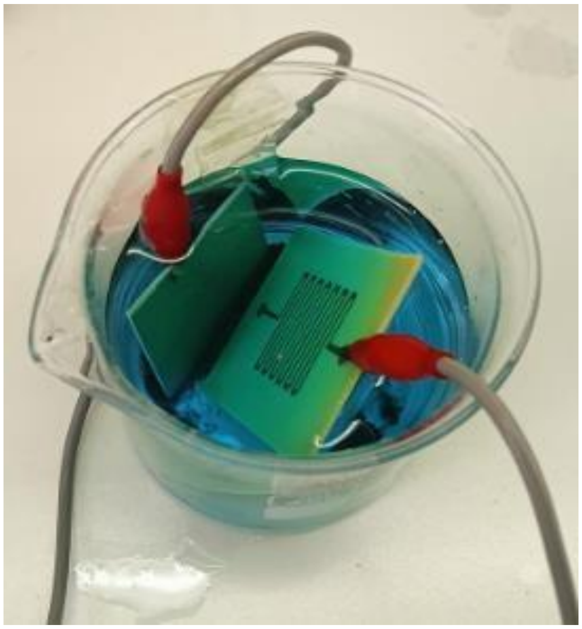

Figure II.13 *Showing anode cathode Electroplating Cell.*

- <u>Step 3 Running the Experiment</u>

Once the anode and cathode are placed in solution and connected, start by turning the power supply on. For electroplating you will need to form a circuit containing a 3 V battery. The power supply supplies a direct current (DC) to the anode. This current causes the metal to oxidize, allowing metal atoms to dissolve in the electrolyte solution as positive ions. The current then causes the metal ions to move to the negatively charged substrate and deposit onto the piece in a thin layer of metal.

Figure II.14 shows a laboratory electroplating setup with a digital power supply connected to two electrodes immersed in a copper sulfate solution. The power supply is set to 0.3 volts and 1.000 amperes. The copper anode is connected to the positive terminal (red wire), and the mold cathode is connected to the negative terminal (black wire). The setup ensures a controlled and precise electroplating process for coating the mold with a thin layer of copper.

- ✓ The digital power supply is set to a low voltage and a controlled current, ensuring a slow and steady deposition of copper onto the mold, which is essential for achieving a uniform and high-quality electroplated layer.
- ✓ The clear separation and secure connections of the electrodes help maintain the integrity and safety of the electroplating process.

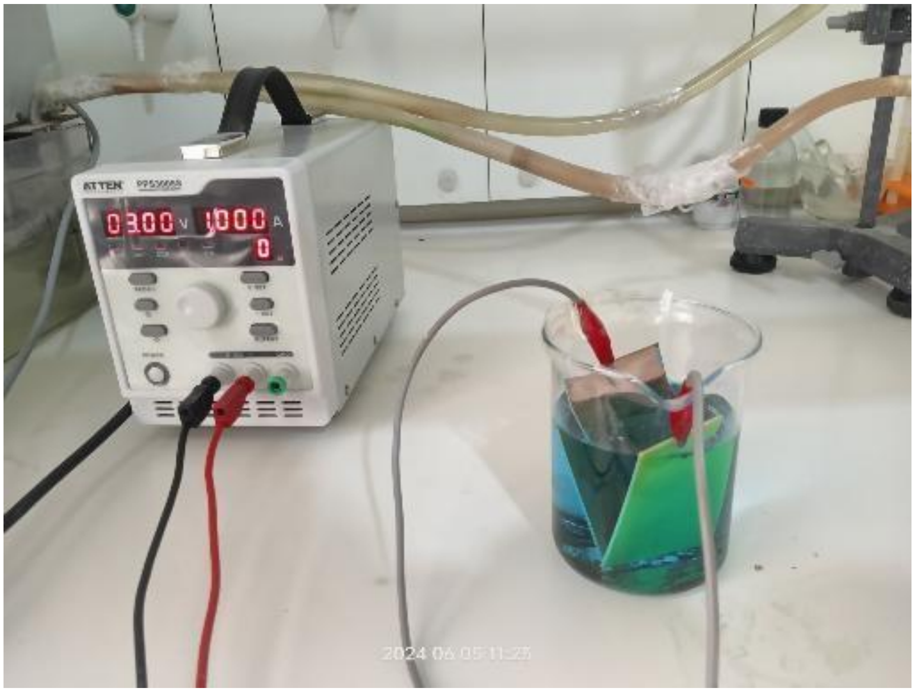

Figure II.14 *Shows an electroplating process for copper sulfate solution.*

2.4.3 Copper Thin film mold

After electroplating, the PCB should be rinsed with distilled water to remove any residual electrolyte solution and then dried. This step is essential to prevent corrosion and ensure the longevity of the copper tracks. Figure II.15 shows a PCB with a serpentine copper track pattern after undergoing electroplating. The tracks exhibit a reddish-brown copper deposition with some areas showing irregularities and clumpy buildup. The substrate is a yellowish-green material, commonly used for PCBs. An alligator clip is attached to one end of the track, indicating the point of electrical connection during the electroplating process. The image highlights the results of the electroplating, with notable uneven copper deposition that suggests potential issues with the process.

Figure II.15 *deposition of copper onto the piece*

Corrosion of copper piece: At the positive pole connected to the copper piece, the process of losing electrons occurs, the copper element transforms into positive copper ions and adds to the cuso4 solution to compensate for the persistent shortage of copper ions as they are deposited on the surface of the piece

Figure II.16 *Corrosion of copper piece*

After some hours of electroplating process, replace the copper piece with another copper piece and we repeat the experiment again. Finally the power supply is turned off, remove the piece that we plated, rinse with distilled water and dry well. The final remark that we will note is Increase in mold thickness: like many electroplating processes, copper plating increases the corrosion resistance of the material. Copper plating results in a high thickness build and the longer the workpiece is in the bath and the higher the current, the thicker the layer of metal applied. Figure II.7 Represent final mold after electroplating.

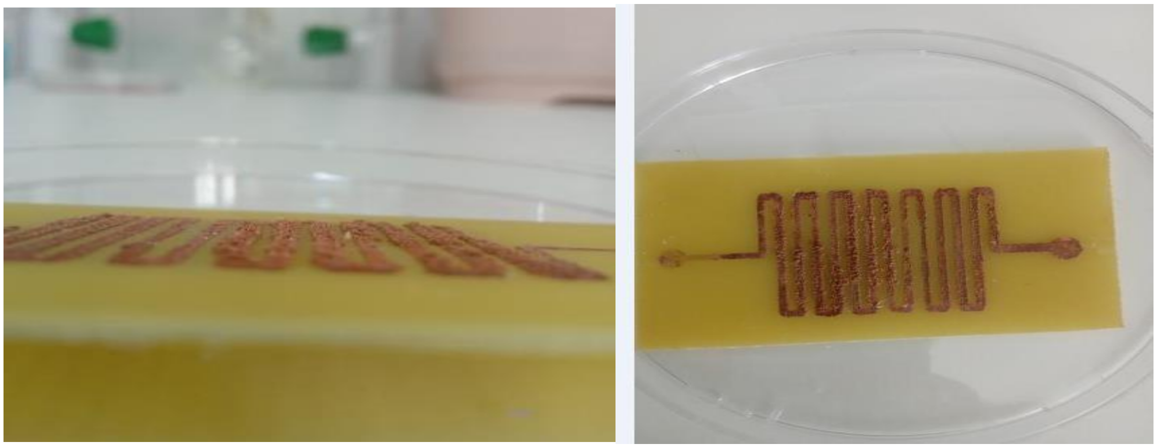

Figure II.17 *Final mold after electroplating*

2.5 Conclusion

During the past decade, microchannel technology has evolved into an established discipline with applications ranging from in-depth microanalysis and rapid catalyst selection to the synthesis of chemical, petroleum, fine chemical, pharmaceutical, energy generation, green chemistry, and environmental products.

In this chapter, we have presented an overview of microchannel technology, defined microchannels, and described various mold technologies and manufacturing processes such as photolithography, electroplating, and soft lithography. Additionally, we have detailed the fabrication process of metallic thin-film molds, highlighting their importance in high-precision applications. Understanding these processes is crucial for developing effective microfluidic systems that meet specific application requirements.

CHAPTRE 3: DESIGN AND ELABORATION OF PDMS MICROCHANNEL

3.1 Introduction

In this chapter, we present the design of the microchannels and detailed description of the geometric structure of the microchannels and we will make a 3D drawing, also we talk about the PDMS technology and the part of our result and main advantage and challenges of microchannel

3.2 Design and geometric structure

The proposed microchannel structure consists of two layers. The Glass bottom layer is taken as the support platform for the microchannel, and the top layer in PDMS. Figure III.1 depicts the 3D design and geometry of a microchannel, which is a crucial component in microfluidic systems. The microchannel is designed to facilitate fluid flow through a sinuous or tortuous path, enhancing interaction and reaction within the channel. Here is a detailed description of the various geometric features and design elements presented in the figure.

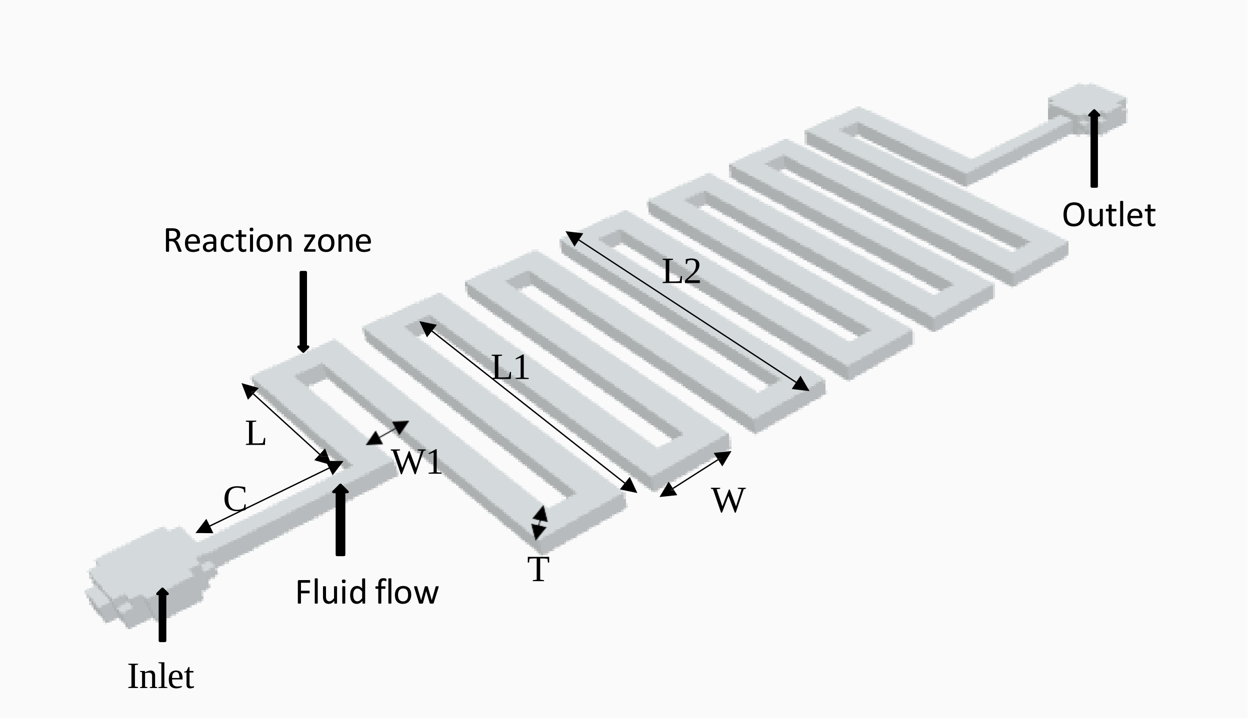

Figure III.1 *3D Design and microchannel geometry.*

3.2.1 Components of the Microchannel

The different parts of the microchannel will be detailed below:

a. **Inlet:** The inlet of microchannel is the entry point where fluids are introduced into a microfluidic device or channel system. Which allows a constant flow rate to be imposed through the entire channel network. The inlet of microchannel allowing for controlled and precise manipulation of fluid at the microscale

b. **Reaction Zone:** Reaction zone refers to the specific region within the channel where chemical reactions processes occur.in microfluidic device, these reaction zones are precisely controlled environments where reagents or samples are mixed and allowed to interact under controlled condition this controlled environment enables researchers to study reaction with high precision and efficiency.

c. **Fluid Flow:** The black arrow indicates the direction of fluid flow from the inlet through the reaction zone and towards the outlet. Then fluid flow is controlled to ensure it moves through the microchannel efficiently, optimizing the reaction conditions.

d. **Outlet:** The microchannel outlet is identical in shape to the inlet and allows the reaction products to be collected. It is designed identically to the inlet to ensure efficient fluid handling and proper collection of the processed fluids.

3.2.2 Geometric Dimensions and Parameters

The geometric dimensions and parameters of microchannels are fundamental to their design and performance. Accurate definition of these dimensions ensures optimal fluid dynamics, efficient mixing, and effective reaction conditions within the microfluidic system. The dimensions discussed include channel thickness, length, segment lengths, and widths, each playing a critical role in the overall performance and efficiency of the microchannel. Table 4.1 provides the characteristic dimensions of the microchannel, which are critical for understanding its design and functionality. These dimensions are measured in micrometers (µm) and are essential for ensuring precise fluid flow and efficient reactions within the microchannel system.

Table 3.1: The characteristic dimensions of the microchannel.

	C	T	L	L1	L2	W	W1
The dimension values (µm)	11000	200	14000	26000	28000	3000	2000

T is the thickness of the microchannel walls, which plays a crucial role in the structural integrity and fluid dynamics within the channel, L is lte length of a single segment of the microchannel, contributing to the total path length the fluid travels. L1 and L2 are these denote the lengths of different segments within the microchannel, W and W1 represent the width of the primary channel segments and the width of the narrower segments respectively, typically at the turns of the tortuous path, and finally C is the width of the connecting segments between the reaction zone and the rest of the microchannel.

These characteristic dimensions are critical for the design and functionality of the microchannel. They ensure that the fluid flows efficiently through the microchannel, optimizing reaction conditions and enhancing the overall performance of the microfluidic device. Properly dimensioned microchannels can achieve precise control over fluid dynamics, making them suitable for various applications in chemical reactions, biomedical analysis, and other microfluidic processes. By understanding and accurately defining these dimensions, researchers and engineers can design microchannels that meet specific requirements and perform reliably under different operating conditions.

3.3 Fluid flow principle in microchannels

Fluid flow in microchannels refers to the movement of fluid through narrow channels that are significantly smaller than typical macroscale channels. The behavior of fluid flow in microchannels differs from macroscale flows due to several unique effects such as increased surface area to volume ratio, the dominance of viscous forces over inertial forces (resulting in low Reynolds numbers), and significant interfacial interactions.

3.3.1 Working principle

The fluid enters the microchannel system through the inlet. The flow rate at the inlet is controlled to ensure a constant and precise flow through the channel network. As the fluid moves through the sinuous path of the microchannel, it passes through the reaction zone. In this zone, the walls of the microchannel may be coated with a catalyst (such as platinum) to facilitate chemical reactions as shown in figure III.2. Within the reaction zone, the controlled environment allows reagents in the fluid to react efficiently. The increased surface area to volume ratio in microchannels enhances the interaction between the reagents and the catalyst. After passing through the reaction zone, the fluid, now containing reaction products, exits the microchannel through the outlet.

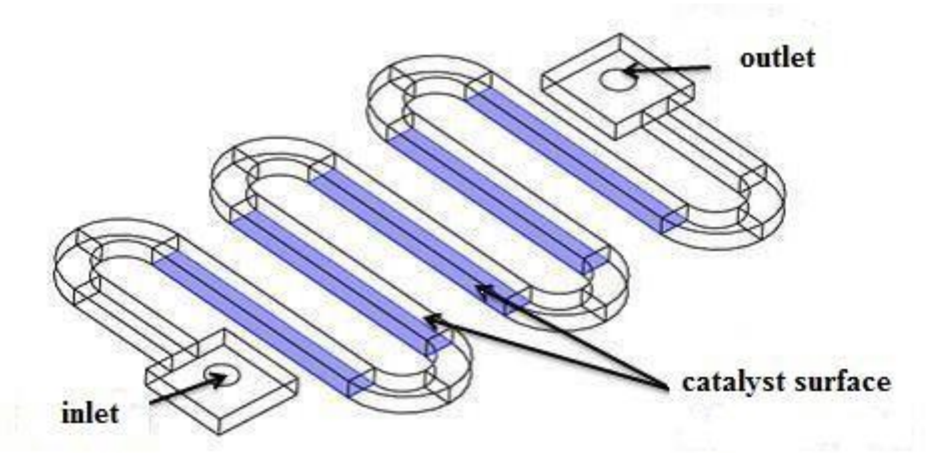

Figure III. 2 *Working principle*

3.3.2 Microchannel Principle of Operation

The principle of using these new devices is relatively simple. The role of this microchannels is relatively simple but highly effective for controlled chemical reactions and fluid handling at the microscale. The reagents are dissolved in a fluid and pumped at a controlled rate into the microchannels. These channels often join at a mixing zone where different fluid streams come into contact. In the mixing zone, the fluids mix, and reagents begin to react. This zone is carefully designed to ensure thorough mixing and efficient interaction between reactants. The mixed reagents flow through the reaction zone, a confined tubular space with a diameter less than 1 mm. The design ensures optimal conditions for the chemical reactions to occur. The reacted fluid flows towards the outlet, where the reaction products are collected for further analysis. The outlet flow is the sum of the inlet flow. The length of stay in the device is called residence time and is calculated as follows:

$$t_D = \frac{\mathrm{Lc2}}{D} \tag{3.1}$$

With Lc: characteristic distance of the pipe section, in the case of a cylindrical pipe this distance corresponds to the diameter of the tube d and D: The mixing zone and the chemical reaction zone are the key elements of the reactivity within microreactor depending on the constraints related to the chemical reaction itself (reaction time, temperature, pressure, ...).

The microchannel's design and operation principles enable precise control over fluid dynamics and chemical reactions at the microscale. The increased surface area to volume ratio, dominance of viscous forces, and controlled environment within the microchannels make them highly efficient for various applications in chemical analysis, biomedical devices, and other microfluidic systems [54].

3.4 Fabrication process of PDMS microchannel

3.4.1 Definition and Description of PDMS Polymer

Polydimethylsiloxane (PDMS), also known as dimethicone, is an organo-mineral polymer that belongs to the siloxane family. Siloxanes (R2SiO) are compounds derived from silicon, oxygen, and alkanes. Discovered in the early 20th century by F.S. Kipping, siloxanes have since become fundamental in the development of various silicone-based materials, with PDMS being one of the most prominent.

PDMS is characterized by its chemical formula (C2H6OSi) and consists of repeating units of the siloxane backbone, where two methyl groups are attached to each silicon atom. This structure results in a highly flexible and stable polymer chain. As an organometallic compound, PDMS combines organic methyl groups and inorganic silicon-oxygen bonds, giving it unique properties. PDMS exhibits isotropic and homogeneous properties, making it an ideal material for precise applications. Its elastomeric nature allows it to be flexible and return to its original shape after deformation. Additionally, PDMS is optically transparent, enabling easy visualization of processes within microfluidic devices. Its chemical inertness ensures that it does not react with most chemicals, making it suitable for a wide range of applications, including those involving biological materials.

The mechanical properties of PDMS include robustness to mechanical stress and fatigue, allowing it to withstand repeated mechanical stresses without significant degradation. Its flexibility makes it suitable for applications requiring bending or stretching, such as wearable devices. Thermally, PDMS is stable over a wide temperature range, maintaining its properties despite temperature variations.

Biocompatibility is another key feature of PDMS. It is chemically inert and non-toxic, making it safe for use in devices that come into contact with living tissues or fluids. PDMS can also be coated with highly biocompatible materials to enhance its compatibility with biological systems, making it suitable for implantable devices and microfluidic devices for biological analysis.

PDMS offers several advantages in the fabrication of microfluidic devices. It is easy to manufacture, can be molded and cured rapidly, and is relatively inexpensive compared to other polymers and materials used in microfabrication. Its straightforward handling during the fabrication process allows for easy integration into various device designs [55-56].

3.4.2 Fabrication steps of PDMS microchannel

PDMS soft-polymer microchannel is manufactured using a technique known as Soft-lithography. In a first step, this technique is based on the realization of a hard mold (in our case metallic mold) representing a Counter imprint of a tortuous microchannel pattern. This is followed using this mold to transpose the fluidic pattern into a matrix by casting the liquid PDMS polymer.

The manufacturing steps for PDMS microchannel from the resin mold is:

- **Step 1: The scaling and mixing of the PDMS and the curing agent**

First, a mixture of liquid PDMS pre-polymer with a concentration of 10:1 is prepared along with the curing agent to harden the PDMS. The components are mixed thoroughly (Figure III.3). Typically, the ratio between the curing agent and the PDMS is 10:1 by weight, although this ratio can be adjusted for specific applications to achieve different levels of hardness or softness. It is important to add the PDMS first and then the curing agent to ensure proper cross-linking of the polymer. An automatic PDMS mixer can be used for thorough mixing.

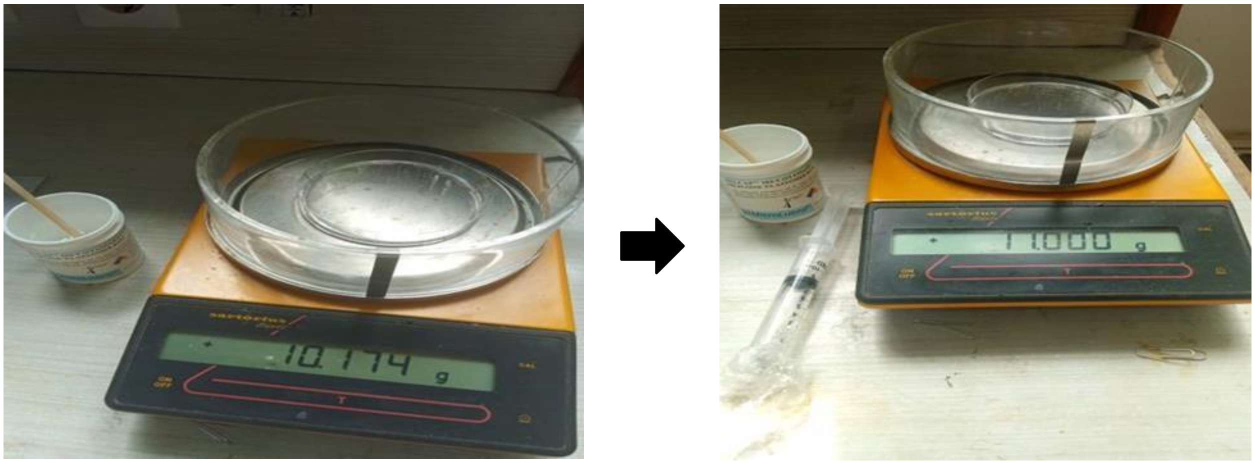

Figure III.3 *preparation of mixture of PDMS and curing agent*

- **Step 2: Mixture pouring on the mold**

Always clean the mold before using it to remove all dust and particles on our mold surface. We use a container to put the mold on it, Pour the mixture directly onto the mold. Some bubbles appear during the pouring, so we kept the mold in vacuum and Let it dry for 24 hours to remove air bubbles. (Figure III.4)

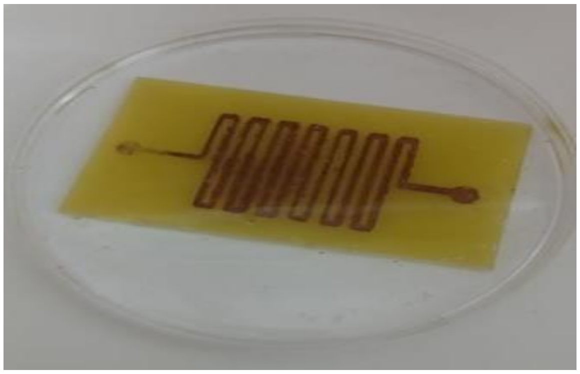

Figure III.4 *mixture pouring on the mold*

- **Step 3: PDMS baking**

Once the PDMS and the curing agent are mixed, the cross linkage has begun but alone it will take around 24 hours to get a solid enough device. That's why the mold and the PDMS have to be baked.so we put the mold onto the furnace, cooking (about 10 min at 80°C) allows the PDMS to cross-link and turn into an elastomer. (Figure III.5)

Be careful not to bake your PDMS too much, it will become "old", too hard and it will be really difficult to pierce it late. The temperature has to be chosen according to the mold container, and we able to manipulate your PDMS just after it cools down.

Figure III.5 *cooking the mold in furnace*

Step 4: The PDMS peeling off the mold

Then the PDMS layer can be cut and unmolded carefully from the mold. Wait for the mold and the PDMS to cool down, then we cut around your substrate and peel off the PDMS to release your devices. And During cutting be careful to keep the blade tangent to the mold to avoid breaking it.as in (figure III.6)

Figure III.6 *peeling of the mold*

Next, the micro-structured PDMS plate is then pierced at the ends of the microchannel to allow the insertion of connections for fluid inlet and outlet. The matrix thus obtained is sealed on a silicon support, a glass blade or even a cross-linked layer in PDMS.

3.4.3 Fabricated results and discussions

The manufacturing process was made to make flexible devices depending on the polymer, including microfluidic devices. A particularly important component is the strength of the bond between the PDMS layer. PDMS (Polydimethylsiloxane) technique is widely used in microfluidics, biomedical devices, and various other applications due to its unique properties such as flexibility, biocompatibility, and ease of fabrication. (Figure III.7) represent the final mold after doing pdms technique.

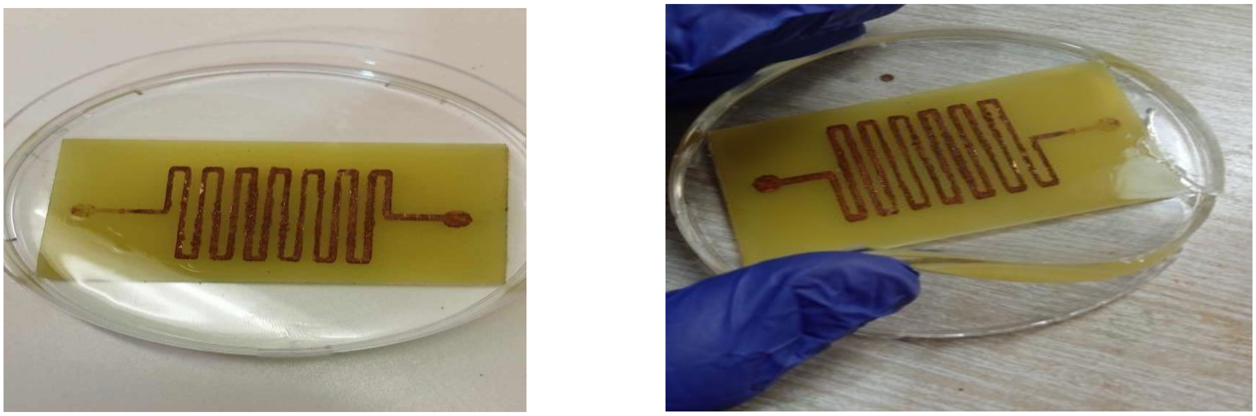

Figure III.7 *Final Mold after pdms technique*

3.5 The advantage and issues of micro channels

Micro-channel throughput has been widely studied over the past two decades in the search for efficiency, faster cooling of high-power density electronic devices. The advantage of micro channels lies in their high heat transfer coefficient and the ability to reduce the size of heat exchangers significantly. Other advantages are their reduced weight, low stock level, and reduced use of materials.

The decrease in micro-channel diameters results in several compact heat exchangers and higher heat transfer coefficients by a larger area per unit volume. Micro channels have practical applications in all highly specialized areas, such as bio-engineering and micro-manufactured fluid systems, micro pumps and Microheat pipes.

For example, the compact and low weight of micro channels have turned to the automotive industry micro heat exchangers, and micro channels today have almost completely replaced circular tubes in the automotive condensers and heat exchangers with hydraulic diameters of about 1 mm. More recently, microchannels have been successfully applied for automotive air conditioning systems, fuel cells, and microelectronics. The main micro channel issues are the difficulties of manufacturing and filtering high quality working fluid needed to flow through the channels. The high pressure drop and the pumping power required are also considered micro channel issues. [57].

3.6 Conclusion

At present, microchannel are manufactured with several methods and different materials, this will contribute to the diversity of the form and function of this device. This model shows the dehalogenation of hydrocarbons as it occurs in the microchannel.

In this chapter, we have defined the concept of the microchannel model. This curvy geometry model from the PDMS method consists of an inlet and outlet adapter section also microchannels representing the reaction area and a catalytic surface (platinum) that covers the channel walls. Then, we will present the very simple operating principle of the microreactor, able to provide a better control of the phenomena of fluid and reagent transport and also the kinetics of fast chemical reactions. Also, we talk about PDMS technology for microchannel realisation finally main advantage and challenges of microchannel.

GENERALE CONCLUSION

This work presented in this thesis has successfully demonstrated the development of fabrication processes for metallic thin-film molds and millimetric tortuous channels, which are critical components in microfluidic systems and micro reactors. Through detailed investigations into various fabrication techniques, including photolithography, electroplating, and soft lithography, we have established reliable methods for producing microchannels. Additionally, the design and fabrication of PDMS microchannels were elaborated, showcasing their potential in various microfluidic applications.

Based on the findings, several conclusions can be drawn. Firstly, the integration of multiple fabrication techniques can overcome the individual limitations of each method, resulting in reliable microchannels. Secondly, the design and material properties of microchannels significantly influence their performance in microfluidic systems. PDMS, due to its flexibility and biocompatibility, proves to be an excellent material for various applications. Lastly, the optimized fabrication processes developed in this work contributes to the broader field of microfluidics by offering innovative solutions for the development of microfluidic devices, paving the way for future research and practical implementations in biotechnology, medicine, and chemical engineering.

Future studies should explore the scalability of the developed fabrication techniques for industrial applications, ensuring that they can be applied in large-scale production without compromising precision or reliability. Research into alternative materials that offer improved properties, such as higher thermal stability or enhanced chemical resistance, could further enhance the performance of microfluidic devices. Additionally, investigating the integration of microfluidic systems with other emerging technologies, such as advanced sensors, could open new avenues for applications and improve the functionality of micro reactors. Finally, longitudinal studies to assess the durability and stability of the fabricated microchannels under various operating conditions would provide valuable insights for their practical deployment.

GLOSSARY OF TERME

MEMS : micro electromechanical System
BioMEMS : Biological Micro Electro Mechanical System
PDMS : Poly dimethylsiloxane
UV : ultraviolet
µTAS : micro Total Analysis System
PCR : Polymerase Chain Reaction
PCB : printed circuit board
CuSO4 : copper sulfate
P : pressure (pa)
ΔP : Pressure gradient over duct length L (Pa)
Re : Reynolds number
ρ : Density of fluid (kg/m3)
η : Water viscosity (m2/s)
V : volume of the microreactor (SI unit: m3)
R : Internal radius of pipe (m)
R_H : The hydraulic resistance (Ω)
L : The characteristic channel length (m)
Q : Volume flow rate (m3.s-1)
LC : characteristic distance of the pipe section
T_D : residence time
T : the thickness of the microchannel
W : the width of the microchannel
LPCMIA : laboratory of physics-chemistry of inorganic materials and their application

REFERENCES

1. R.Fulcrand (2009). Etude Et Développement D'une Plateforme Microfluidique Dédiée A Des Applications Biologiques, Intégration D'un Actionneur Magnétique Sur Substrat Souple. Thèse DeDoctorat. Université Paul Sabatier-Toulouse III.
2. A.Antoniotti**,** J.Koubi (2014). Calibration D'un Système Micro-fluidique Pour La Fabrication De Gouttes Mono Disperses. Laboratoire Physique de la Matière Condensée CNRS - UMR7336 - Université Nice Sophia-Antipolis Nice.
3. W. L. Buehner, J. D. Hill, T. H. Williams, et J. W. Woods, « Application of Ink Jet Technology to a Word Processing Output Printer », IBM Journal of Research and Development, vol. 21, no. 1, p. 2 -9, janv. 1977.
4. S. C. Terry, J. H. Jerman, et J. B. Angell, « A gas chromatographic air analyzer fabricated on a silicon wafer », Electron Devices, IEEE Transactions on, vol. 26, no. 12, p. 1880 - 1886, December . 1979.
5. A. Manz, N. Graber, et H. M. Widmer, « Miniaturized Total Chemical Analysis Systems: a Novel Concept for Chemical Sensing », Sensors and Actuators, B, vol. 1, no. 1-6, p. 244-248, 1990.
6. D. C. Duffy, J. C. McDonald, O. J. A. Schueller, et G. M. Whitesides, « Rapid Prototyping of Microfluidic Systems in Poly(dimethylsiloxane) », Analytical Chemistry, vol. 70, no. 23, p. 4974-4984, October. 1998.
7. M. A. Unger, H.-P. Chou, T. Thorsen, A. Scherer, et S. R. Quake, « Monolithic Microfabricated Valves and Pumps by Multilayer Soft Lithography », Science, vol. 288, p. 113-116, 2000.
8. T. Fujii, « PDMS-based microfluidic devices for biomedical applications », Microelectronic Engineering, vol. 61-62, p. 907-914, 2002.
9. D. J. Beebe, G. A. Mensing, et G. M. Walker, « PHYSICS AND APPLICATIONS

OF MICROFLUIDICS IN BIOLOGY », Annual Review of Biomedical Engineering, vol. 4, p. 261-286, 2002.

10. S. Haeberle et R. Zengerle, «Microfluidicplatforms for lab-on-a-chip applications », Lab on a Chip, 2007.
11. P. Puget et Y. Fouillet, « La microfluidique ou l"‴art de manipuler des petits volumes de liquides », Clefs C.E.A., no. 52, p. 107-110.
12. A. Doerr, « Microfluidics for the people », 2009.
13. A**.**Farid, Z.Yu**,** J.Tom (2009). Current Micro-pump Technologies and Their Biomedical Applications. Microsystems Technologies, Vol. 15, No 5, P. 647-666.
14. J.L.Sheng**,** K.W.Hong (2007). Peristaltic Piezoelectric Micro-pump System for Biomedical Applications. Biomedical Micro-devices, 2007, Vol. 9, No 4, P. 619-626.
15. J.G.Seok**,** C.S.Kim**,** C.Beom, (2010). Applications Of Micro-mixing Technology. Analyst, vol. 135, No 3, P. 460-473.
16. L.K.Fong**,** L.J.Wen (2008). A Novel In-Plane Micro-fluidic Mixer Using Vortex Pumps for Fluidic Discretization. JALA: Journal of the Association for Laboratory Automation, Vol. 13, No 4, P. 227-236.
17. K.W.OH**,** C.H AHN (2006). A Review of Micro-valves. Journal Of Micromechanics And Micro-engineering, Vol. 16, No 5, P. R13.
18. S.L.ZENG**,** B.J.QIN (2009). Micro-valve-Actuated Precise Control of Individual Droplets inMicro-fluidic Devices. Lab on a Chip, Vol. 9, No 10, P. 1340-1343.
19. R.Zengerle**,** J.Ulrich**,** S.Kluge (1995). A Bidirectional Silicon Micro-pump. Sensors and Actuators A: Physical, Vol. 50, No 1-2, P. 81-86.
20. O. Reynolds., «An Experiment alInvestigation of the Circumstances Which Determine Whether the Motion of Water Shall Be Direct or Sinuous and of the Law ofResistance in Parallel Channels»; Philosophical Transitions: Royal Society, vol.174,(1883),935-982.
21. Olivier FRANÇAIS – Hélène HORSIN MOLINARO «La microfluidique : principes physiques et mise en œuvre d'écoulements continus » Paris Saclay mars 2016
22. J. P Brody., Yager P., «Diffusion-based extraction in a microfabricated device » Sensors and Actuators A: Physical, vol. 58, n°.1, (1997), 13-18.

23. A .Hatch., Kamholz A. E., Hawkins K. R., Munson M. S., Schilling E. A., Weigl B. H., Yager P., A« rapid diffusion immunoassay in a t-sensor, »Nature Biotechnology, vol. 19, n°. 5, (2001), 461-465.

24. C.Garcia, «Biosensing for the analysis of raw milk", PhD Thesis, University of Bremen, Germany, (July 2014).

25. S. BeebyEnsell G., Kraft M., White N., »MEMS Mechanical Sensors, » ARTECH HOUSE, (2004).

26. Land K. J., Mbanjwa M. B., Govindasamy K., Korvink J. G., "Low cost fabrication and assembly process for re-usable 3D polydimethylsiloxane(PDMS) microfluidic networks", Biomicrofluidics, vol. 5, (2011), 036502.

27. Christensen A. M., Chang-Yen D. A, Gale B. K., "Characterization ofinterconnects used in PDMS microfluidic systems", Journal of Micromechanics and Microengineering, vol. 15, (2005), 928-934.

28. Greener J., Li W., Voicu D., Kumacheva E., **"**Reusable, robust NanoPort connections to PDMS chips", Chips and Tips, (2008). http://blogs.rsc.org/chipsandtips/2008/10/08/reusable-robust-nanoport- connections-to-pdms-chips/

29. Kumara Guruparan G., Sathish M., Sankara Subramaniam N., Sorna Kumar T., "Design and Fabrication of Micro Channels for MEMS Applications", Synthesis and Reactivity in Inorganic, Metal-Organic, and Nano-Metal Chemistry, vol. 36, n° 2, (2006), 185-191.

30. Gaudet M., "Conception, réalisation et caractérisation des microcanaux pour les applications microfluidiques", Thèse doctorat, Université des sciences et technologies de Lille 1, France, (Novembre 2006).

31. Anduze M., "Etude experimentale et numerique de microecoulements liquides dans les microsystemes fluidiques", Thèse doctorat, INSAT, Université de Toulouse, France, (Février 2000).

32. Esashi M., Shoij S., Nakano A., "Normally closed microvalve and micropump fabricated on a silicon wafer", Sensors and Actuators A, vol. 20, (1989), 163- 169.

33. Shoji S., Esashi M., Van Der Schoot B., De Rooij N., "A study of a highpressure micropump for integrated chemical analysis systems", Sensors and Actuators A, vol. 32, (1992), 335-339.

34. Rapp R., Schomburg W. K., Maas D., Schulz J., Stark W., "LIGA micropump for gases and liquids", Sensors and Actuators A, vol. 40, (1994), 57-61.

35. Zengerle R., Ulrich J., Kluge S., Richter M., Richter A., "A bidirectional silicon micropump", Sensors and Actuators A, vol.50, (1995), 81-86.

36. Ohnstein T., Fukiura T., Ridley J., Bonne U., "Micromachined silicon microvalve", IEEE, (1990), 95-98.

37. Schomburg W. K., Vollmer J., Bustgens B., Fahrenberg J. Hein H., Menz W., "Microfluidic components in LIGA technique", Journal of Micromechanics and Microengineering, vol. 4, (1994), 186-191.

38. Zdeblick M. J., Angell J. B., "A microminiature electric-to-fluidic valve", Technical Digest of Transducers, (1987), 827-829.

39. Jerman J. H., "Electrically-activated, micromachined diaphragm valves", Proceedings of Micro System Technologies, (1990), 806-811.

40. Van De Pol F. C. M., Van Lintel H. T. G., Elwenspoek M., Fluitman J. H. J., "A thermopneumatic micropump based on micro-engineering techniques", Sensors and Actuators A, vol. 21, (1990), 198-202.

41. Manz, A., Graber, N., et Widmer, H. M,. (1990) – “Miniaturized total chemical analysis systems: A novel concept for chemical sensing”, Sensors and actuators B: Chemical, 1(1- 6), 244–248.

42. DebiotechSA (2004) – "Implatable pump”, www.debiotech.com/debiotech.html.Lausane, Suisse.

43. Jacobson, S., Hergenroder, R., Moore, A. et Ramsey, (1994) - J.Anal. Chem, 66, 4127. 113

44. Burns, M., Johnson, B., Brahmasandra, S., Handique, K., Webster, J., Krishnan, M.,

Sammareo, T., Man, P., Jones, Helsdsinger, D., Mastrangelo, C., et Burke, D., (1998) – “An Integrated Nanoliter DNA Analysis Device”. science, Vol 282, 484-487.

45. Agilent Technologies (2006)- “Lab-on-a-chip”, http://www.chem.agilent.com/.
46. M. Kajjout, C. Rolando, et S. le Gac, « Microréacteurs microfluidiques et sélectivité en chimie organique », La Houille Blanche, no. 2, p. 83-88, mars 2006.
47. Y. Lecoffre, « Une application de la microfluidique à la parfumerie ». Le Picodrop
48. Shashi Prakash , Subrata Kumar, «Fabrication of microchannels». Proceedings of the Institution of Mechanical Engineers June 2014
49. KROUMA Saadia, Influence de la géométrie des nanoparticules dans un nano-fluide sur le transfert thermique, Mémoire de master de l’université de Biskra, 2014.
50. CHAREF KHOUDJA Nabila, Etude numérique des écoulements dans les microcanaux, Mémoire de magistère en physique dans l’université de Batna, 2010.
51. M Rahmat, P. Hubert. « Magistère en physique. Rapport finale Numerical simulation for the geometric design of micro heat pipes ». Décembre 2006.
52. STM International. In B374-96 (2003) Standard Terminology Relating to Electroplating ; ASTM International: West Conshohocken, PA, 2003.
53. Mosbah DAAMOUCHE, mise au point d’une technique d’élaboration des couches mince métallique par vois électrochimique, université El hadj Lakhdar Batna, 24 -01-2009
54. R. Marilyen . « micromicroréacteur pour la catalyse héérogéne Application : stockage d‟hydrogéne dans les hydrocarbures filtre pour capteur gaz » october 201588.
55. Emeline Feltrin, 2013, Surfaces PDMS structurées et/ou décorées par des nanoparticules : vers des propriétés optiques et de mouillage modulables. Autre. Université Sciences et Technologies - Bordeaux I, 2013. Français L’UNIVERSITÉ BORDEAUX 1 École doctorale des sciences chimiques ffNNT : 2013BOR15207ff.
56. hi Hong Nhung Dinh, 2015. Etudes technologiques de composants PDMS pour

applications biomédicales : développement de capteurs souples de pression par transfert de film. Micro et nanotechnologies/Microélectronique. Université Paris Saclay (COmUE),
Français. ffNNT : 2015SACLS127ff. fftel-01266753f

57. D.Benladghem, « Analyse numérique de la convection forcée développe dans micro- canaux : Etude comparative entre deux conduite à parois simples et à parois ondulées »,Mémoire de Master, Université Abou BekrBelkaid Tlemcen, 2013 -2014