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METHODS FOR FABRICATION OF MICROFLUIDIC DEVICES
METODE IZRADE MIKROFLUIDNIH UREĐAJA

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ABSTRACT

This paper contains an overview of fabrication methods used for the construction of different microfluidic devices, along with some example applications. All the different procedures, methods, and their respective variants are collectively referred to as microfabrication methods. Microfabrication plays a crucial role in microfluidics, as the fabrication method directly influences the potential application of a device. The overview of fabrication methods can be categorized based on the mechanical properties of the materials used. In this context, the primary mechanical property considered is material rigidity, classifying materials into hard, plastic and soft categories. Other mechanical properties affect the possibility of use in extreme temperatures (hot or cold), reactive or neutral environments, and one of the most critical characteristics of microfluidic devices - biocompatibility. Some of the most widely used methods discussed in this paper include photolithography and its variants, etching technique for silicone and glass, PDMS molding, micro milling, and 3D printing. Additionally, paper-based microfluidics is highlighted as an excellent example of biocompatible microfluidic devices applied in medical applications.

***Keywords**: microfabrication, photolithography, etching, micromilling, 3D printing, paper microfluidics, PDMS, PMMA, COC*

REZIME

U ovom radu dat je pregled metoda izrade mikrofluidnih uređaja i sistema kao i mogućnosti njihove primene. Metode izrade mikrofluidnih uređaja (mikrofabrikacija) predstavljaju različite procedure, postupke i njihove varijacije. Metodologija izrade mikrofluidinih uređaja direktno utiče na mogućnost njihove primene, kao i primene različitih medijumima. Metode izrade mikrofluidnih uređaja mogu se podeliti na osnovu mehaničkih svojstava materijala. U ovom radu izvršena je podela metoda fabrikacije na osnovu krutosti materijala. Krutost materijala najviše utiče na veličinu i rezoluciju struktura koje se mogu izraditi. Na osnovu krutosti materijala koji se koriste za izradu mikrofluidnih uređaja vrši se klasifikacija na tvrde, plastične i meke materijale. Tvrdi materijali koji se najčešće primenjuju u procesu fabrikacije su staklo i silikon. Plastični materijali koji se koriste u procesu fabrikacije su poli(metil metakrilart), ciklični olefinski kopolimer, i dr., dok se primena mekih materijala u procesu fabrikacije bazira na polimetilsiloksanu. Primena metoda fabrikacije zavisi i od mogućnost primene u različitim temperaturnim uslovima (toplim ili hladnim), reaktivnim ili neutralnim sredinama, kao i od biokompaktibilnosti samog uređaja. U ovom radu su predstavljene neke od najrasprostranjenijih metoda izrade mikrofluidnih uređaja, kao što su: fotolitografija i njene varijacije, metode graviranja koje se koriste za staklo i silikon, livenje polimetilsiloksana, mikroglodanje i 3D štampanje. Konačno, pomenuta je i papirna mikrofluidika kao primer metode za izradu biokompaktibilinh mikrofluidnih uređaja sa primenom u medicini.

***Ključne reči**: mikrofabrikacija, fotolitografija, MEMS, PDMS*

INTRODUCTION

The first micro sized machines were developed in 1970’s and were named MEMS (micro-electromechanical systems). One of their earliest applications was in automotive industry, specifically in airbags, where they integrated detection, analysis and signal processing into a single device. This demonstrated the complex capabilities of MEMS technology, even leading to the creation of a "heart on a chip". The widespread use of MEMS is evident from the fact that today's market for this technology is worth over ten billion US dollars *(Kozomora,2024)*. Within MEMS-based systems, known as Microsystems for Total Analysis (µTAS), the need for fluid manipulation in various applications emerged. This necessity led to the miniaturization of fluid systems, opening a new chapter in fluid mechanics – microfluidics. Microfluidics enables the manipulation of fluids and flows on a microscale. The first microsystem was based on electrokinetic separation, demonstrating the advantages of microscale approach - not only achieving rapid separation with high efficiency, but also improving mobility and reducing costs. These advantages led to the development of a wide range of microfluidic systems, including electroosmotic pumps, diffusion-based separators, chemical microreactors, and mixers. The aim of this paper is to analyze different microfabrication methods for these systems and their applications, as well as to create an introductory handbook of methods for new researchers. Due to the sheer number of available methods for fabricating microfluidic devices—more than twenty, including their variations—we have chosen to focus on only a select few. The selection criteria were based on encompassing the most commonly used methods among researchers, along with some unique or specialized techniques that may be relevant for niche or highly specific applications.

Based on the material used for manufacturing microfluidic devices, a classification can be made according to their rigidity into *(Tabeling, 2023):*

- Hard materials – Silicon and glass. The manufacturing technologies are based on etching, lithography, and material deposition. The structure dimensions range from 200 nm to 500 µm.
- Plastic materials – A wide range of materials is used, with various surface characteristics (hydrophobic, hydrophilic, etc.). Some of these materials include PMMA (poly(methyl methacrylate)), COC (cyclic olefin copolymer), and photoresists such as SU-8. The manufacturing technologies include micromilling, laser ablation, and injection molding. The structure dimensions range from 20 µm to several millimeters.

- Soft materials – PDMS (polydimethylsiloxane) is the most commonly used material. The structure dimensions range from 0.5 to 500 µm.

To explain specific methods for microchip fabrication, it is important to emphasize that the manufacturing process must be carried out in an environment with an appropriate level of cleanliness for the given method. Fine particles such as dust and pollen (Fig. 1),ranging in size from several tens of nanometers to tens of micrometers, may be present in the laboratory *atmosphere (Tabeling, 2023)*. These particles can compromise the microchip manufacturing process, cause clogging of microchannels, or alter the surface properties of the material *(Tabeling, 2023).*

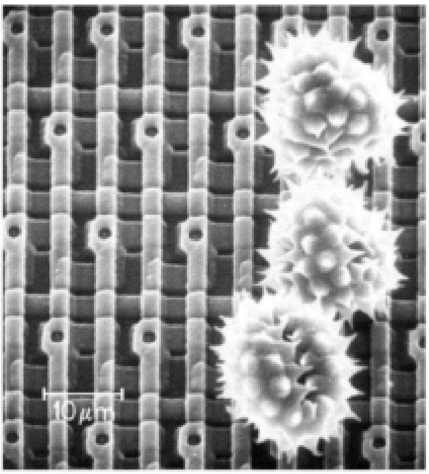

Fig. 1. Pollen in comparison with electrical chip (Tabeling, 2023)

Photolithography

Photolithography is a method that uses light to create relief structures in a polymer-based photoresist *(Handrea-Dragan et al.,2022)*. During the photolithography process, photolithographic masks are used to shield certain areas of the photoresist from a collimated light source *(Tabeling, 2023)*. A collimated light source refers to light waves that are parallel or nearly parallel. There are two types of photolithographic masks *(Tabeling, 2023):*

- High-resolution masks – Consist of a thin quartz plate with chrome layers forming the desired structure.
- Low-resolution masks – consist of plastic sheets on which the structure is printed with ink. These masks are the most commonly used due to their low cost and accessibility.

In addition to disposable photolithographic masks, digital mirrors and reusable PDMS masks are also used today *(Handrea-Dragan et al., 2022)*. The microchip fabrication process using photolithography begins with the deposition of the photoresist. A photosensitive polymer (photoresist) is applied as a very thin layer onto a solid substrate made of glass or silicon *(Tabeling,2023 & Handrea-Dragan et al., 2022)*. This is done using a device called a spin coater, shown in Fig. 2. The device consists of a rotating disk that holds the substrate in place using vacuum. The disk rotates at a speed of 1,000 to 10,000 min^{-1}. The photoresist is dispensed onto the disk, which then starts spinning. As a result, the photoresist spreads into a uniform thin layer while the solvent within it evaporates. Depending on the type of photoresist used, the film thickness varies from a few fractions of a millimeter to 200 µm. After application, the photoresist still contains about 15% solvent, which may lead to cracking. To fully evaporate the solvent, the coated substrate is subsequently heated to 70 °C for a few minutes *(Tabeling, 2023).*

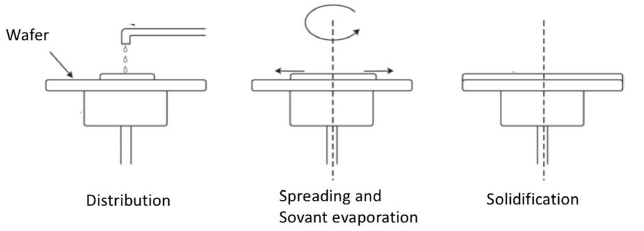

Fig. 2. Deposition of the resist on a spincoater (Tabeling, 2023)

After the application and drying of the photoresist, the photosensitive polymer, along with the substrate and mask, is placed in an alignment device and then exposed to the light flux of a collimated source (Fig. 3) *(Tabeling, 2023)*. The light flux induces a physicochemical reaction in the polymer, altering its solubility. Depending on the type of photoresist used, either the exposed or unexposed area is subsequently removed through chemical etching *(Tabeling,2023; Handrea-Dragan et al.,2022)*. There are two types of photoresists: positive and negative. In a positive photoresist, the areas protected by the mask become soluble, while the unprotected areas remain insoluble. In a negative photoresist, the opposite occurs. In positive photoresists, light breaks or weakens the internal bonds of the polymer, causing molecular reorganization toward a more soluble structure. Conversely, in negative photoresists, light induces the formation of covalent bonds between the primary and secondary polymer chains, making it less soluble *(Tabeling, 2023)*. For example, when using a positive photoresist, all areas protected by the photolithographic mask will become the desired cavities in the microfluidic chip after the entire process is completed. In addition to selecting the appropriate mask, achieving high-quality photolithography requires precise control of process parameters, with the most critical factor being the quality of the photoresist itself. The choice of photoresist determines the selection of the light source, specifically its wavelength *(Handrea-Dragan et al., 2022)*.

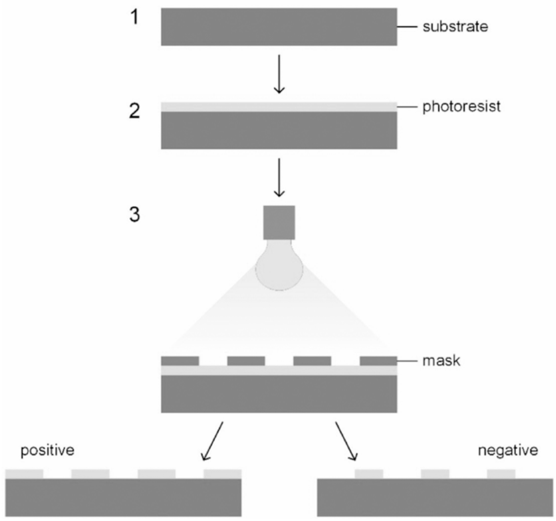

Fig. 3. Principle of photolithography (Tabeling, 2023)

Direct writing refers to any technique capable of altering the chemical composition, by inducing polymerization, removing, depositing or processing various materials on different surfaces to form predefined structures *(Handrea-Dragan et al., 2022)*. There are numerous methods for obtaining the desired structure, which can be categorized into additive and subtractive techniques.

- Additive techniques include inkjet printing, dip-pen nanolithography, and micro pens *(Tabeling, 2023)*.
- Subtractive techniques include focused ion beam (FIB) processing and laser machining *(Tabeling, 2023)*.

Silicon is widely used for microfluidic chip fabrication due to its abundance in nature, well-documented properties, and compatibility with various processing technologies...

Wet etching

Wet etching is a process in which an alkaline or acidic solution is used to chemically remove material from a surface *(Gosalvez et al., 2010)*. Concentrated acids are used for metal etching, while silicon etching requires alkaline solutions such as potassium hydroxide (KOH), tetramethylammonium hydroxide (TMAH), or ethylenediamine pyrocatechol (EDP) *(Gosalvez et al., 2010).* The masks used in this process must be chemically inert to the etchant, such as silicon oxide or silicon nitride *(Gosalvez et al., 2010).* There are two main types of wet etching, **isotropic** and **anisotropic**, which differ based on diffusion transport intensity and surface reaction kinetics *(Tabeling, 2023)*:

- Isotropic etching occurs uniformly in all directions forming structures such as spherical cavities (Fig. 4.a) *(Tabeling, 2023)*:
- Anisotropic etching proceeds along a single crystallographic plane, resulting in structures with flat surfaces resembling the facets of a diamond (Fig. 4.b) *(Tabeling, 2023)*.

It is important to note that anisotropic etching cannot be performed on glass, as glass is an amorphous solid.

Dry etching

Dry etching is the removal of a substrate that has been exposed to ion species contained in a gaseous phase or plasma. There are four types of dry etching *(Tabeling, 2023)*:

- Physical etching – Ions are accelerated in an electric field at low pressure and bombard the surface, removing material. These ions are referred to as ballistic ions.
- Chemical etching – Chemical species migrate to the surface due to the influence of an electric field, where a chemical reaction occurs, producing volatile species and cavities.
- Physicochemical etching – A combination of the two previous methods and the most commonly used technique.
- Physicochemical etching with an inhibitor – In this process, a protective layer is applied along the walls of the etched cavities, enabling the formation of structures with a higher aspect ratio (height-to-width ratio).

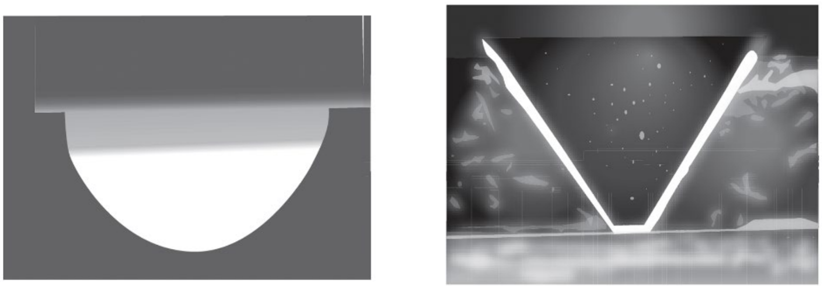

Fig. 4. a) Isotropic wet etching in glass; b) anisotropic wet etching in silicon (Tabeling, 2023)

Microchannel fabrication using PDMS

Polydimethylsiloxane (PDMS) is a polymer used in the fabrication of microfluidic chips. At lower molecular weights, it exists in a liquid state and can be used as a lubricant, hydraulic fluid or anti-foaming agent. At higher molecular weights, it transforms into a soft, rubber-like resin *(Tabeling, 2023)*. PDMS possesses numerous favorable properties that make it an ideal material for microfluidic chip fabrication. These properties include durability, transparency, biocompatibility, resistance to nonpolar gases, low cost, and commercial availability *(Lucas et al., 2008 & Au et al., 2016)*. The microchannel fabrication using PDMS begins with the creation of a mold from a rigid material, typically SU-8 or plastic. These molds are manufactured in cleanroom environments to prevent contamination. Once the mold is prepared, a mixture of PDMS and a cross-linker is poured into it and then heated to approximately 70°C, allowing the polymer to solidify *(Tabeling, 2023).* After the curing process, the PDMS is carefully removed from the mold and placed onto a substrate, usually glass *(Tabeling, 2023)*. Since PDMS has poor adhesion properties, its surface is often treated with oxygen plasma before bonding, which enhances adhesion to various materials *(Lucas et al., 2008).* Typically, PDMS microchannel dimensions range from 2 to 200 µm *(Tabeling, 2023)*.

The main drawback of conventional PDMS casting is the difficulty in controlling the top and bottom surfaces *(Lucas et al., 2008).* Achieving two coplanar surfaces is nearly impossible with standard technique. A solution to this issue is a process called double-sided casting, which enables the creation of coplanar surfaces and ensures a precisely defined PDMS layer thickness *(Lucas et al., 2008).* The procedure is largely the same, except that it involves two molds (top and bottom), with one of them needing to be highly flexible to allow for easy PDMS removal (Fig. 5) *(Lucas et al., 2008).*

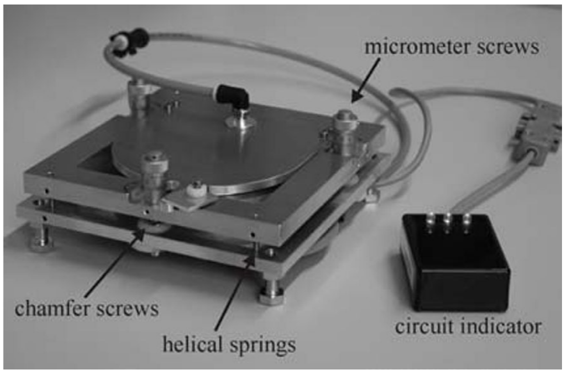

Fig. 5. Double-sided molding device (Lucas et al., 2008).

Micro-engraving

Micro-engraving is a manufacturing technology for microfluidic chips that includes CNC micro-milling and laser ablation. CNC (Computer Numerical Control) micro-milling is a subtractive technique that removes material using a high-precision cutting tool. The tool diameter can be as small as 25 µm *(Tabeling, 2023).* Due to the nature of the process, microchannels sizes are typically limited to 100 µm, and the resulting surface roughness is relatively high (Tabeling, 2023). One of the key advantages of micro-milling is its **versatility**. Unlike many other fabrication techniques, which are either restricted to two-dimensional (2D) structures or require complex and costly processes to achieve three-dimensional (3D) features, micro-milling enables direct fabrication of intricate 3D structures *(Krimpenis et al., 2013)*. Recent advancements have introduced genetic algorithms (GAs) to optimize key micro-milling parameters *(Krimpenis et al., 2013)*. Genetic algorithms are a search heuristic that mimics natural selection process to improve machining efficiency. They are used to optimize three critical micro-milling parameters:

- Feed rate - the speed at which the material platform moves.
- Cutting depth – the depth of material removal in each pass.
- Spindle speed – the rotational speed of the cutting tool *(Krimpenis et al., 2013)*.

On the other hand, laser ablation (Fig. 6) is a high-precision process in which laser light interacts with a material, breaking its chemical bonds. This interaction, driven by a sudden increase in temperature and pressure, causes material to eject from the surface *(Tabeling,2023; Waddell, 2006)*. Laser ablation can be applied to materials including ceramics, glass, and metals. However, in microfluidic chip fabrication, it is used almost exclusively for polymeric materials due to their favorable processing characteristics *(Waddell, 2006)*.

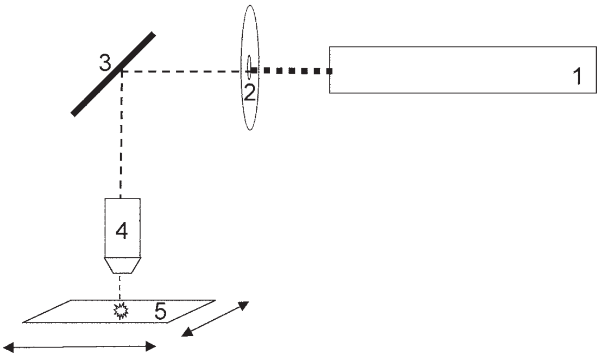

Fig. 6. Simplified schematic of a laser ablation micromachining system. The dashed line denotes the path of laser emission. Radiation is emitted by the laser (1), the beam passes through an aperture (2) and is steered by a turning mirror (3) through the focusing objective (4). The substrate (5) is mounted on a computer-controlled x-y stage. (Waddell, 2006)

3D Printing

In the last few decades, three-dimensional (3D) printing, also known as additive manufacturing, has experienced remarkable growth and diversification in terms of applications, materials, and the ability to produce various shapes, structures, and geometries. Some of the most commonly used techniques include DLP-SLA *(Tabeling, 2023; Au, 2016)*, PolyJet, Selective Laser Sintering (SLS) *(Tabeling, 2023; Au, 2016)* and FFF or FDM *(Tabeling, 2023; Au, 2016)*. DLP-SLA (Digital Light Processing Stereolithography) is a technique that uses 365 nm light to selectively polymerize a photo-reactive liquid resin, forming a three-dimensional structure layer by layer (Fig. 7) *(Tabeling, 2023)*. During printing, the material is selectively exposed to light, causing it to solidify. The platform in the reservoir containing the liquid material, on which the printing takes place, is lifted and then returned to the reservoir so that another specific area can be exposed to light and solidified. It is important to emphasize that different photopolymers have different light absorption properties, meaning that using the same parameters on two different photopolymers will not yield the same structure *(Au, 2016)*. PolyJet (Photopolymer Inkjet Printing) is a technique in which microdroplets of photopolymer are deposited onto the printing surface using precision nozzles and the material is polymerized using UV light *(Tabeling, 2023)*. While this technology is highly flexible and supports a wide range of printable materials, the formulations of the polymers used are mostly proprietary, requiring users to purchase expensive, manufacturer-specific resins *(Au, 2016)*,. Additionally, PolyJet printing has limited applications in microfluidics due to:

- Lack of comprehensive studies on fluid-polymer interactions.
- Uncertain cytocompatibility, which is critical for biological applications.

FFF (Fused Filament Fabrication) and FDM (Fused Deposition Modeling) are techniques that involve extruding thermoplastic material through a heated nozzle *(Tabeling, 2023)*. This technique allows the printing of biocompatible and inexpensive polymers from filament spools, such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate, polyamide, and polystyrene *(Tabeling, 2023)*. However, the FDM-printed structures tend to have lower density and are more prone to cracking under compression, as the adjacent layers do not always fuse properly. This issue can be mitigated by using high-end printers with heated chambers, but such systems significantly increase costs, limiting their feasibility for microfluidics applications. The future of 3D printing in microfluidics is highly promising, particularly because many original patents for additive manufacturing have expired. This has led to:

- Lower production costs.
- Increased accessibility.
- Greater freedom for material and process innovation.

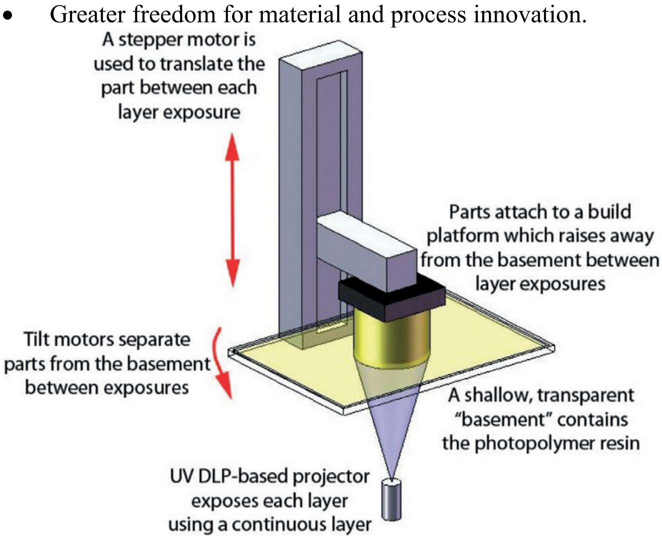

Fig. 7. DLP-SLA technique (Au, 2016)

Paper-based microfluidics

Paper-based microfluidics emerged as a concept after 2005 with the goal of replacing conventional microfluidic materials such as glass, silicon, plastic, PDMS *(Tabeling, 2023)*. This technology enables the fabrication of microfluidic devices from paper or other porous materials that operate with minimal liquid volumes (ranging from 10^{-6} to 10^{-9} L) based on capillary forces *(Tabeling, 2023; Nishat et al., 2021)*. The main reasons for using paper are its significantly lower cost, wide availability and the ability to be incinerated, which is a major advantage in terms of contamination risk. This technology allows for the simple production of microfluidic devices without the need for clean rooms and without requiring pumps for operation. By using a wax printer, channels can be created through which fluids flow in a manner very similar to traditional microfluidic devices. These printers create patterns on the substrate, forming hydrophobic barriers that clearly define hydrophilic channels and zones (Tabeling, 2023). One of the most promising applications of paper-based microfluidic devices is in the diagnosis of infectious diseases, especially in developing countries, where 75–80% of annual deaths are caused by diseases such as COVID-19, HIV/AIDS, tuberculosis, malaria, etc. *(Tabeling, 2023)*. These diseases can be diagnosed using microfluidic devices. These analytical tests are known as microPAD (Microfluidic Paper-Based Analytical Devices) tests and, besides infectious disease diagnostics, are used in many other applications today *(Nishat et al., 2021)*. MicroPAD tests are designed for the detection of small molecules such as uric acid, blood analysis for the presence of sodium, potassium, calcium, and chloride, liver enzyme activity analysis, antibody detection, and perhaps the most well-known paper-based microfluidic test—the pregnancy test *(Tabeling, 2023; Nishat et al., 2021)*.

DISCUSSION

In the following Table 1. are presented some of the most important advantages, lacks, applications of the different microfabrication.

Table 1. Fabrication methods and most important characteristics

Fabrication method		Material	Advantages	Disadvantages	Application
Photolito-graphy		Polystyrene, SU-8, Octade-cyltrchloro-silane, UV resin, TiO_2 (He at al., 2015)	High resolution Mass production Low cost (He at al., 2015)	Expensive equipment Complex procedure Expensive reagents (He at al., 2015)	μPAD (He at al., 2015)
Etching	wet	Metals, silicium oxide, silicium nitride, Trimethoxyocta-decylsilane (TMOS) (He at al., 2015)	Hight selectivity due to chemical reactions (MIT OpencourseWare, 2025) High precision Cheaper than dry etching (Semi cera., 2025) Anisotropic and isotropic etching Smooth etched surfaces (Choi at al., 2024)	The equipment used is expensive High expertise needed (Wayken Rapid Manufactoring, 2025) Poor feature size control (MIT OpencourseWare, 2025) Chemical contamination Orientation dependent Poor repeatability (Zhang at al., 2016) Mask needed (He at al., 2015) Undercutting (Semi cera., 2025)	MEMS NEMS Optoelectronics (Choi at al., 2024) Microfluidic devices Mechanical and ther-mal sensors Micro/nano calorime-ters (Pal et al., 2015)
	dry	Argon Chlorine (MIT Open-courseWare, 2025)	Widely used for small fea-tures (MIT OpencourseWare, 2025)	The equipment used is expensive High expertise needed (Wayken Rapid Manufactoring, 2025)	MEMS Semiconductor pat-terning (MIcronit, 2025)
PDMS casting		Silicone-based elastomers, Polyurethanes (Scott et al., 2021)	Simple procedure High fidelity, Nonplanar sur-faces can be replicated Low wear of stamp (Scott et al., 2021) Low cost (Zhang at al., 2016)	Time consuming (Scott et al., 2021) Needs other microfabrication for molding (Zhang at al., 2016)	bioMEMS (Ansari et al., 2021 & Lin et al., 2021) Fluidic microstruc-tures μTAS LoC (Lin et al., 2021)
Micro-en-graving	Micro-milling	Metals Polymers Composites Ceramics (Scott et al., 2021)	High removal rates Convenient and fast manufac-turing High aspect ratios Effective and low cost proto-type fabrication (Scott et al., 2021) Rapid large format produc-tion (Rodrigues et al., 2015)	High minimum feature size Difficult to obtain sharp angles Thermal deformation during manu-facturing Additional tool control systems (Scott et al., 2021) Limited materials Multiple treatment sessions (Ro-drigues et al., 2015)	Aerospace Orthopedic implants (Worty, 2025) Optics Electronics Sensored (Rawal et al., 2022)
	Laser abla-tion	Metals, Polymers, Composites, Ceramics, Graphite, Glass (Scott et al., 2021)	Low mechanical strength of workpiece required Non-contact machining (Scott et al., 2021)	Heating of workpiece Non-uniform depth of cavity Small features difficult to obtain Slow process Costly equipment (Scott et al., 2021) Limited for mass production (Ro-drigues et al., 2015)	Synthesis of mi-cro/nano materials (Zhao et al., 2021) Microneedle arrays Industrial microm-ach. Selective thin film re-moval (Gower, 2000) bioMEMS Fluidic microstruc-tures (Lin et al., 2021)
3D printing	DLP-SLA	UV hardening plastic, UV hardening resin (Protect 3D, 2025)	Transparent components Complex shapes Fine surface Mechanically resilient (Pro-tect 3D)	Limited materials High manufacturing cost Single color models Slow (Protect 3D, 2025)	Healthcare Prototype (Barone et al., 2019)

	PolyJet	Agilus 30, RGD 720, Ruber-like material (Patpatiya et al., 2022)	Large range of materials Large object printing (Au at al., 2016)	Durable at constant pressure (Gale at al., 2018)	Healthcare (Ansari et al., 2022) Surgical implants Surgical planning Custom implants (Shannon et al., 2020)
	SLS	Polyamide mixtures (Protect 3D, 2025)	High purity of sintered material Multi-material printing Metal pattern writing (Au at al., 2016)	Slow manufacturing process Slightly rough surface Single color models (Protect 3D, 2025)	Anatomical scaffolds Drug delivery Prosthetics Realistic industrial prototype design (Au at al., 2016)
	FFF FDM	ABS, PLA, Poly carbonate, Polyamide, Polystyrene (Gale at al., 2018)	Biocompatible and inexpensive material Large range of materials Liquid material extrusion (Au at al., 2016) Low cost High speed (Gale at al., 2018)	Low density and high porosity Compressive stress fractures Likely occurrence of leaks (Au at al., 2016) Leak prone, Limited to low melting thermoplastic, Limited resolution, No surface roughness control (Gale at al., 2018)	Surgical planning Prosthetics Industrial applications (Diy connect, 2025) Tissue engineering Prototypes (Cano-Vicent et al., 2021)
Paperbased microfluidics		Wax (He at al., 2015)	Simple and fast Mass production (He at al., 2015) Low cost (Li at al., 2012)	Low resolution Not resistant to high temperatures (He at al., 2015)	μPAD (He at al., 2015) Diagnostics (incl. health) Biochemical analysis Food quality control Enviro monitoring (Li at al., 2012)

CONCLUSION

This paper provides an overview of the most commonly used microfabrication methods for microfluidic devices, explaining their working principles and key characteristics. At the end of the paper, Table 1. summarizes essential aspects of each method, including available materials, advantages, disadvantages, and potential applications. By assesessing the strenghts and weaknesses of different methods we aim to improve future experimental and analytical aproaches ensuring that the desired results and insights would be deduced with a greater rate of succes. Selecting the most suitable microfabrication technique requires careful consideration. Researchers should analyze several key factors, such as:

- Material-process interaction – The influence of the material on the process occurring within the device, as well as the process's impact on the material (e.g., pressure effects, particle clogging).
- Channel size and resolution – The precision and dimensions that can be achieved with a given technique.
- Structural complexity and manufacturability – The feasibility of fabricating intricate microchannel geometries.

A well-informed choice requires a thorough understanding of each method's advantages, limitations, and relevance to specific research applications. As microfabrication technologies continue to evolve, they enable the creation of smaller, more complex, and higher-resolution structures, along with more flexible and efficient fabrication techniques. In this vast sea of rapidly emerging methods, we believe this paper will be especially valuable for those new to the field.

Finally, we would like to emphasize the biggest goal of this paper: to foster interdisciplinary research by making the sections on material sciences and fabrication more accessible to researchers unfamiliar with this field. To date, interdisciplinary collaboration has proven to be the most significant driver of innovation—not only in microfluidics but in microsystems as a whole.

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REFERENCES

Kozomora, V. (2024). Računarsko modeliranje mikromešača softverom „Comsol“. Fakultet tehničkih nauka, 3-11. Computer modeling of a micromixer using „Comsol“ software. Faculty of Thechnical Sciences, 3-11.

Kozomora, V. (2024). Značaj mikromešača u oblasti mikrofluidike. Zbornik radova Fakulteta tehničkih nauka. The Importance of Micro-Mixers in the Field of Microfluidics. Proceedings of the Faculty of Technical Sciences.

Tabeling, P. (2023). Introduction to Microfluidics, Oxford University Press.

Handrea-Dragan, I., Botiz, I., Tatar, A., & Boca, S. (2022). Patterning at the micro/nano-scale: Polymeric scaffolds for medical diagnostic and cell-surface interaction applications, Elsiver B.V.

Wikipedia, (accessed on 30.01.2025.), https://en.wikipedia.org/wiki/Collimated_beam

Gosalvez, A., Zubel, M., & Viinikka, E. (2010). Wet etching of silicon, Elsiver Inc.

Lucas, N., Demming, S., Jordan, A., Sichler, P. & Buttgenbach, S. (2008). An improved method for double-sided moulding of PDMS, J. Micromech. Microeng 18.

Au, A., Huynh, W., Horowitz, L., & Folch, A. (2016). 3D-Printed Microfluidics, Angew. Chem. Int. Ed. 55

Krimpenis, A., Fountas, N., Ntalianis, I., & Vaxevandis, N. (2013). CNC micromilling properties and optimization using genetic algorithms, Springer-Verlag London.

Waddell, E. (2006). Laser Ablation as a Fabrication Technique for Microfluidic Devices, Methods in Molecular Biology vol. 321: Microfluidic Tehniques: Reviews and Protocols

Nishat, S., Jafry, A., Martinez, A., & Awan, F. (2021). Paper-based microfluidics: Simplified fabrication and assay methods, Elsiver B.V.

Nguyen, N., Wu Z. (2005). Micromixers—a review, J. Micromech. Microeng. 15

Barone, S., Neri, P., Paoli, A., Razionale, A., & Tamburrino, F. (2019). Development of a DLP 3D printer for orthodontic applications, Procedia Manufacturing, volume 38

[14] *Wayken Rapid Manucaturing (accessed on 19.02.2025),* https://waykenrm.com/blogs/dry-etching-vs-wet-etching/#:~:text=Advantages%20and%20Disadvantages%20of%20Dry%20Etching&text=Doesn't%20use%20a%20large,used%20for%20this%20is%20expensive

Gale, B., Jafek, A., Lambert, C., Goenner, B. Brady L., Moghimifam, H., Nze, U., & Kumar, S. (2018). A Review of Current Methods in Microfluidic Device Fabrication and Future Commercialization Prospect, MDPI

Scott, S., & Ali, Z. (2021). Fabrication Methods for Microfluidic Devices: An Overview, MDPI

Rodrigues, R., Lima, R., Gomes, H., & Silva, A., (2015). Polymer microfluidic devices: an overview of fabrication methods, U. Porto Journal of Engineering

MIT OpencourseWare, (accessed on 19.02.2025.), https://ocw.mit.edu/courses/6-152j-micro-nano-processing-technology-fall-2005/59b9f31d836355a3380aa156925508bc_lecture17.pdf

Semi cera, *(accessed on 19.02.2025.),* https://www.semi-cera.com/news/detailed-explanation-of-the-advantages-and-disadvantages-of-dry-etching-and-wet-etching/.

He, Y., Wu, Y., Fu, J., & Wu W., (2015). Fabrication of Paper-Based Microfluidic Analysis Devices: a Review, RSC Advances

Zhang, S., Zeng, X., Matthews, D. T. A., Igartua, A., Rodriguez-Vidal, E., Contreras Fortes, J., ... & van der Heide, E. (2016). Selection of micro-fabrication techniques on stainless steel sheet for skin friction. Friction, 4, 89-104.

Choi, K., Kim, S. W., Lee, J. H., Chu, B., & Jeong, D. Y. (2024). Eco-friendly glass wet etching for MEMS application: A review. Journal of the American Ceramic Society, 107(10), 6497-6515.

Pal, P., & Sato, K. (2015). A comprehensive review on convex and concave corners in silicon bulk micromachining based on anisotropic wet chemical etching. Micro and Nano Systems Letters, 3, 1-42.

Li, X., Ballerini, D. R., & Shen, W. (2012). A perspective on paper-based microfluidics: Current status and future trends. Biomicrofluidics, 6(1).

Worty, (accessed on 19.02.2025.), https://www.worthyhardware.com/news/what-is-micro-milling-everything-you-need-to-know/#:~:text=The%20process%20allows%20for%20producing,spindles%20and%20advanced%20control%20systems..

Rawal, S., Sidpara, A. M., & Paul, J. (2022). A review on micro machining of polymer composites. Journal of Manufacturing Processes, 77, 87-113.

Ansari, A., Trehan, R., Watson, C., & Senyo, S. (2021). Increasing silicone mold longevity: A review of surface modification techniques for PDMS-PDMS double casting. Soft materials, 19(4), 388-399.

Shannon, A., O'Connell, A., O'Sullivan, A., Byrne, M., Clifford, S., O'Sullivan, K. J., & O'Sullivan, L. (2020). A radiopaque nanoparticle-based ink using PolyJet 3D printing for medical applications. 3D Printing and Additive Manufacturing, 7(6), 259-268.

Diy connect, (accessed on 19.02.2025.), https://diyconnect.net/popular-applications-of-fdm-3d-printing-technology/

Zhao, L., Liu, Z., Chen, D., Liu, F., Yang, Z., Li, X., ... & Zhou, W. (2021). Laser synthesis and microfabrication of micro/nanostructured materials toward energy conversion and storage. Nano-Micro Letters, 13, 1-48.

Gower, M., (2000). Industrial applications of laser micromachining. Optics express, 7(2), 56-67.

Micronit, (accessed on 19.02.2025.), https://micronit.com/expertise/manufacturing-expertise/dry-etching

Lin, L., & Chung, C. K. (2021). PDMS microfabrication and design for microfluidics and sustainable energy application. Micromachines, 12(11), 1350.

Cano-Vicent, A., Tambuwala, M. M., Hassan, S. S., Barh, D., Aljabali, A. A., Birkett, M., ... & Serrano-Aroca, Á. (2021). Fused deposition modelling: Current status, methodology, applications and future prospects. Additive manufacturing, 47, 102378.

Protec 3D, (accessed on 19.02.2025.), https://protec3d.de/pros-and-cons-of-3d-printing/#:~:text=Selective%20Laser%20Sintering%20(SLS)&text=Disadvantages%3A%20slightly%20rough%20surface%2C%20slow,PA2200%2C%20PA12MD%2C%20etc.)

Patpatiya, P., Chaudhary, K., Shastri, A., & Sharma, S. (2022). A review on polyjet 3D printing of polymers and multi-material structures. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 236(14), 7899-7926.

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