A FLEXIBLE METHOD FOR RAPID-PROTOTYPING OF PDMS MICROFLUIDIC CHIPS USING DIRECT-WRITING FOR GENERATION OF POLYMER-MASTER-STRUCTURES

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ABSTRACT

We report a new, rapid and highly flexible method for the fabrication of master structures for casting of PDMS microfluidic chips. Conventional and time-consuming UV-lithographic fabrication of PDMS-molds is substituted by a direct-writing method to produce desired structures on planar, low-cost polyimide (PI) substrates by using a polymer dissolved in water. This technique facilitates the on-demand prototyping, requires no cleanroom and little training such that time-to-chip is reduced from typically ~24 h to less than 4 h. Structures exhibiting circular cross sections featuring dimensions from 110 to 340 µm in width and 6 to 100 µm in height have been fabricated to demonstrate the feasible range. The method was validated by fabrication of a PDMS microfluidic droplet generator.

KEYWORDS: Rapid-prototyping, PDMS microfluidic chips, master fabrication, open microfluidics, direct-writing

INTRODUCTION

During the last decades, rapid-prototyping of PDMS microfluidic chips for biological and chemical applications has attracted increasing interest in order to avoid the need of cleanroom facilities for the fabrication of silicon-based chips [1]. This way, costs per chip can be drastically reduced and large quantities could be produced in a more time-efficient manner. Nevertheless, conventional UV-lithographic master structuring (Figure 1-1A) [2] for PDMS molds is still the state-of-the-art and requires access to a cleanroom and corresponding equipment which inhibits the wide dissemination of this technology in biology- and chemistry-oriented laboratories. The rapid test of different chip designs is associated with time-consuming fabrication of new silicon masters and related costs. For these reasons, several rapid prototyping techniques or technologies for the facile master structuring have been developed like 3D direct ink writing [3], surface tension controlled water molding of PDMS [4] or maskless direct laser-structuring of PDMS [5].

As an additional alternative, the presented method can contribute to improve flexibility, reduce costs for master fabrication and thus, pave the way for broader dissemination of flexible PDMS-prototyping for microfluidic applications.

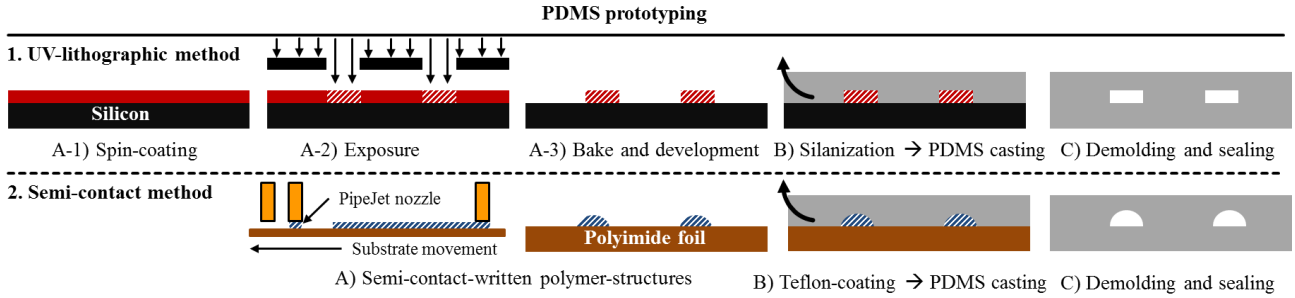

Figure 1: Schematic process flow of 1) the conventional UV-lithographic method and 2) the semi-contact method for PDMS chip fabrication.

FABRICATION OF POLYMER MASTER STRUCTURES

A direct-writing method [6] is used to create polymer structures on planar PI-substrates. The experimental setup comprises a non-contact liquid dispenser (PipeJet P9, BioFluidix GmbH) [7] mounted to a 3-axis robot and a substrate leveling unit. For the generation of polymer structures the tube (id: 200 µm) is primed with polyacrylic acid dissolved in DI water (PAA, 50 w-%, contact angle on PI: 59.3° ± 2°) and then moved while in close proximity to the substrate surface. A liquid bridge is established between the 200 µm-nozzle and the polyimide (PI) substrate (figure 1-2A and figure 2). Then, the controlled displacement of the foil surface below the dispenser allows for the creation of polymer lines *via* capillary flow. After drying, the structures are coated with a fluoropolymer solution (0.5 wt% Teflon AF1600, DuPont, USA) to avoid adhesion between PI-substrates and PDMS during casting and to prevent structure swelling caused by water diffusion from PDMS into PAA-based structures. Afterwards, PDMS (Sylgard 184, Dow Corning Inc., USA) is casted on the fabricated structures and demolded after curing.

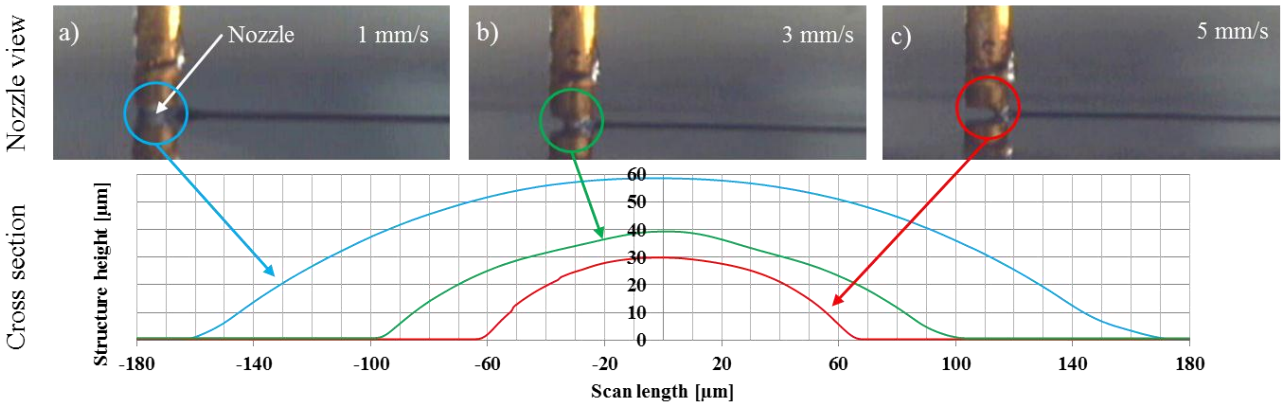

*Figure 2: View of nozzle during PAA-line generation on PI foils for different substrate displacement velocities of a) 1mm/s, b) 3 mm/s and c) 5 mm/s. d) Profiler-measurements demonstrate round cross sections of **5x** written structures for each displacement velocity. Obviously the liquid bridge shrinks with increasing displacement velocity resulting in smaller printed structures.*

The total area for structure generation (in the present case 50 mm x 80 mm) is basically only limited by the size of the substrate leveling unit. Due to surface tension, the generated structures exhibit round cross sections (figure 2) without the need of additional process steps to transform the structure shape [8]. Dimensions from 110 to 340 µm in width and 6 to 100 µm in height have been demonstrated by repeated printing. The width is mainly controlled by the displacement velocity of the substrate as demonstrated by the shrinkage of the bridging meniscus in figure 2 for a) 1 mm/s, b) 3 mm/s and c) 5 mm/s. As width decreases with increasing displacement velocity, so does the height of the printed line. Since achievable structure height for one single writing cycle is in the range of 6 to 12 µm, stacking of structures is realized by multiple writing cycles leading to a linear increase in height (figure 3) without significant structure broadening, except for 5 mm/s velocity (figure 4). This can be explained by the advancing contact angle of PAA on PI which was measured to be 71.2° (± 1.2°). By combination of up to 10 layers a maximum aspect ratio of 0.36 (h = 50 µm for w = 140 µm) could be achieved, by adjusting for each writing cycle the tube-substrate distance according to the previous layer's height.

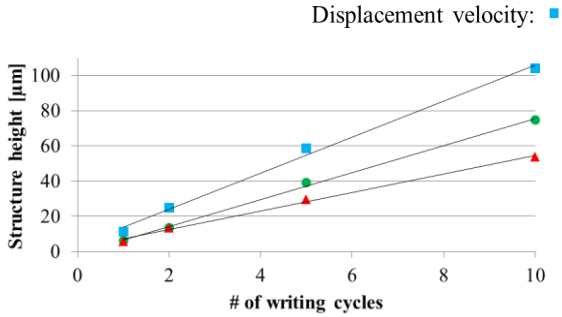

Figure 3: The height of the structures depends linearly on the number of writing cycles. Polymer-structures are written on top of each other.

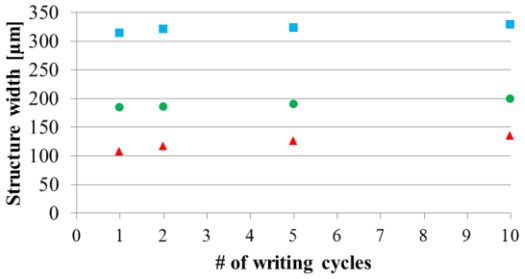

Figure 4: The width of the structures remains almost constant with increased number of writing cycles. Polymer structures are written on top of each other.

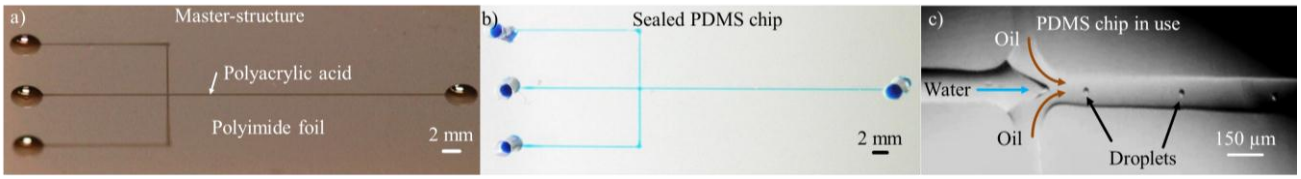

Figure 5: a) Semi-contact written PAA-droplet generator-master-structure. b) Sealed and ink-filled PDMS chip. c) Microfluidic droplet generator in use.

APPLICATION: MICROFLUIDIC DROPLET GENERATOR

A microfluidic droplet generator comprising three inlets, one outlet and a double T-structure has been fabricated in less than four hours to demonstrate the applicability of the reported method (figure 5). Structures were written five times with a displacement velocity of 5 mm/s. Channels exhibit dimensions of 150 µm width and 35 µm height. At flow rates of 30 µL/h for water and 200 µL/h for two perpendicularly crossing oil streams, periodic droplet generation could be observed (figure 5-c) at a frequency of 60 Hz with a single droplet volume of approximately 15 pL.

The entire process from fabricating the master structure to the sealed PDMS chip takes less than 4 hours (table 1). Prototyping the master structures takes 5-30 minutes and largely depends on the complexity of the desired chip design.

Table 1: Overview of process steps and required time for the generation of a PDMS chip beginning with the master fabrication using the presented method.

Step	Structure generation	Teflon coating	PDMS casting and sealing	**Total**
Required time	5-30 min (depends on complexity)	5 min	3 h	**< 4 h**

DISCUSSION

The reported method can be used for the rapid fabrication of master structures for PDMS molds. The technique enables the inexpensive test of a large range of fluidic designs within short turnaround times compared to the standard photolithographic structuring. Structure width is determined by the displacement velocity of the substrate and by the PAA-concentration. A linear dependency is found between structure height and the number of writing cycles (stacking of layers on top of each other).

For the reported first experiments the spatial resolution of the z-axis was only 10 µm. As the heights of the structures for 3 and 5 mm/s printing velocity is less than 10 µm, stacking of layers becomes more challenging. In further experiments resolution and quality of channels will be largely improved by a smaller axial resolution of the 3-axis-robot down to 1 µm allowing even more precise control of stacked layers. By the surveillance of the tube-substrate distance the z-coordinate for the optimum writing distance for the first writing cycle can be automatically determined and adjusted for subsequent cycles.

Some structures like crossing T-channels remain challenging as the structure is locally written twice at the joining point, leading therefore to a double height. Several possibilities are envisioned to solve this issue and thus to obtain equal channel height in a T-crossing. The temperature, for example, can be controlled in order to slow evaporation of the water part and therefore allow the line reaching its local geometrical equilibrium.

Besides 2D-master structuring, the presented method offers several additional opportunities. On the one hand, local structure stacking enables the creation of 3D-like structures [9], on the other hand, dimensions can be tuned in a finer way either by changing the polymer concentration or substituting the substrate. Thus, the contact angle varies and other aspect ratios can be achieved. In addition to channel fabrication it is possible to generate fluidic reaction chambers. This could be realized either by capillary flow at fixed positions (round shape) or by line merging in liquid state when writing lines in close proximity (rectangular shape).

CONCLUSION AND OUTLOOK

We have successfully demonstrated the rapid fabrication of a PDMS microfluidic chip utilizing a direct-writing technique in less than 4 hours using PAA and PI substrates as master. The simple and inexpensive equipment consisting of a 3-axis-robot, a non-contact liquid dispenser and a substrate leveling unit could become a standard tool for the rapid test of fluidic designs in biology and chemistry laboratories not having access to cleanroom facilities. Future work will focus on tackling novel applications based on this platform technology and realizing a broader range of dimensions. It is obvious that the spectrum of usable substrates and structuring materials can be widened in the future to enable the use of materials with different properties than PDMS as well.

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