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Design and fabrication of Passive Fluid Driven Microchamber for Fast Reaction Assays in Nano lab-on-chip Domain

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ABSTRACT

A simple design and fabrication of microfluidics using capillary effect to support fluid flow across reacting assays with limited sample availability is proposed and the analysis was done using COMSOL 3.5 Multiphysics simulation to create minimum possible gap between microchamber and Laboratory on chip sensing elements. The design is based on differential pressure drop flow using capillary effect concept which has facilitated a number of interesting flow phenomena in micro-domains. For an average pressure drop of about 100/m in the setup, flow rates of about 0.7 to 1 µl/s were obtained. The components consist of a microchannel and a microchamber and were designed with 10 microns in width to give a continuous open circuit flow. The proposed chamber could used for continuous flow across sensing element where there is a requirement for low residence time due to fast reaction/diffusion rates, a simple fabrication method was used to fabricate the microchamber which took us less than 48 hours to complete.

Key words: Passive, capillary effect, Lab on chip, microchamber, microfluidic

Introduction

The development of μ-TAS, Lab-on-a-Chip-systems and micro-reactors relies on the extensive use of computational fluid dynamics (CFD). These μ-fluidic systems, featured that at least one characteristic dimension is in the range between one and a few hundred microns, this device have found increasing use in a variety of applications fields such as chemical process and bio-technology, drug discovery and life-science to name a few (Fox et al., 2006; Dittrich et al., 2006; DeVoe et al., 2006; Situma et al., 2006) Capillary forces result from the interaction of liquid, gas(air) and solid surfaces, at the interface between them. In the liquid phase, molecules are held together by cohesive forces. In the bulk of the liquid, the cohesive forces between one molecule and the surrounding molecules are balanced (Delamarche et al., 2005; Henrik Bruus et al., 2005; Hai Jiang et al., 2011). However, for the same molecule at the edge of the liquid, the cohesive forces with other liquid molecules are larger than the interaction with air molecules and smaller than the interaction with solid interface molecules. As a result, the liquid molecules at the interface are pulled together towards the solid (Jungkyu Kim et al., 2009; J. Cooper Mcdonald et al., 2005; Q. Li et al., 2011). The overall effect of these forces is to minimize the free surface of the liquid that is exposed to air. The proportionality between the decrease in energy of the surface that results from decreasing the surface is described by the surface tension and of interest for capillary forces is the contact between three phases: liquid, solid and vapour (air).

In a Poiseuille flow the fluid is driven through a long, straight, and rigid channel by imposing a pressure difference between the two ends of the channel Originally, Hagen and Poiseuille studied channels with circular cross-sections (Hu et al., 2008; Guoqing Hu and Dongqin Li, 2006; Gad-el-Hak et al., 1999; Bird et al., 1978) as such channels are straight- Forward to produce. However, especially in microfluidics, one frequently encounters other Shapes, especially in this study; we explore a straight line channel which also fabricated using photolithography as shown in figure1:

Poiseuille flow: pressure driven flow between parallel plates

\[
\frac{\partial U}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial U}{\partial y} + \frac{\partial U}{\partial z} = \frac{\partial P}{\partial x} + \frac{\partial P}{\partial y} + \frac{\partial P}{\partial z}
\]
Fig. 1: A sketch in the $xz$ plane of an infinite, parallel-plate channel of height $h$. The system is translation invariant in the $y$ direction and fluid is flowing in the $x$ direction due to a pressure drop $\Delta p$ over the section of length $L$. The channel is parallel to the $x$ axis, and it is assumed to be translation invariant in that direction (S J Tan et al., 2006; F. Schonfeld et al., 2006; Bird et al., 2004)

**Methodology:**

Initial pressure field $\Delta p$: Solve for velocities from momentum equation; $u$, $V$. Since $u$, $V$ is not quantified values they will not satisfy the continuity equation. So using the COMSOL will automatically correct the pressure correction $\Delta p$ to get the velocity to agree with continuity figure 2;

$$P(0) = P_0 + \Delta P$$

Solve for velocities using new pressure to suitable constant velocity thus, satisfy the continuity equation

**Device software design:**

![Figure 2: Model design for 10µm gap between the substrate and microfluidics. We used incompressible viscous flow with following boundary conditions set for our problem.](image)

**Table 1: Parameters and their corresponding values.**

<table>
<thead>
<tr>
<th>no.</th>
<th>Channel length L(m)</th>
<th>Density Of $\rho$ kg/m$^3$</th>
<th>Viscosity $\mu$ (pa.s)</th>
<th>Pressure $\Delta p$(pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10µm</td>
<td>1000</td>
<td>0.001</td>
<td>atm</td>
</tr>
</tbody>
</table>

**Device hardware design:**

The design started with alignment marks figure 3 which are located in four corners of the wafer and within the wafer there lies 16 dies which are also alignment marks in four different places to ensure the accuracy and precision of the alignment. Below are the sketches of the design for alignment marks. The actual masks are all designed using AutoCAD software and were fabricated and transferred onto the chrome mask. Alignment Mark Design The alignment marks are designed with the following dimensions as shown in the figure below and it is of two parts: The wafer alignment marks and die alignment marks figure 3. All dimensions are scaled in micrometer, Wafer Alignment Mark Specification; The wafer alignment marks play the role of references for designing desired pattern on the wafer and easily for mask alignment during photolithography process.
Fig. 3: Wafer Alignment Mark (unit in µm).

Wafer Alignment Mark Design Layout: these marks were aligned on the wafer at four different places; this is to serve as references for the creating desired pattern on the wafer.

Fig. 4: Wafer alignment layout.

Die Alignment Mark Design Specification: The die consists of four alignment mark which is designed with the following specifications. All dimensions are in micrometer figure 4.

Fig. 5: Die alignment mark design specification.
Device fabrication:

Micro chamber fabrication begins by creating a reusable master mold. The mold substrate is silicon. The substrate slide is cleaned in a piranha solution (H2SO4:H2O2). A rinse in deionised water follows. The clean silicon substrate is dried using filtered-compressed nitrogen, and dehydrated at 100°C for thirty minutes. Cleaning and dehydrating will prolong the life of the master mold. Four mL of Epoxy-based SU-8 photo resist from (Newton, Massachusetts) is spin-coated at 300 rpm with an acceleration of 83 rpm/s for 10 seconds and then to 3,000 rpm at 415 rpm/s for 30 seconds, per the manufacturer’s instructions. The SU-8 coated glass is then set on a perfectly level surface for 20 minutes to allow the photo resist to smooth out. This will allow for even heating of the SU-8 in the steps that follow. The mold is ramp heated from 50°C to 95°C at 2°C/min for 23 minutes and then held at 95°C for six minutes. Ramp heating is implemented for all heating processes to prevent thermal stresses which may cause cracks in the mold and reduce its life. Photo mask is placed in contact with the SU-8 for the photolithography procedure. The photo mask was created by first modelling the channel geometry in CAD and then printing this geometry on transparent medical film using a high resolution printer. The photo mask must be in direct contact with the SU-8. If there is any gap between the mask and the SU-8, a widening of the pattern on the final mold will result due to diffraction of the UV light exposure which follows. The SU-8 is exposed for 45 seconds in an ELC-500 UV light exposure chamber. This yields the necessary 240 mJ/cm2 of exposure energy for a 50 μm thick SU-8 film on a glass substrate. Post exposure baking takes place immediately after UV light exposure in order to cross link the exposed film. The SU-8 slide is ramp heated from 50°C to 95°C at 2°C/min for 23 minutes and then held at 95°C for six minutes. MicroChem SU-8 developer (Newton, Massachusetts) is used to remove any unexposed SU-8 from the glass substrate. The mold is developed for six minutes while being agitated on a shaker at 150 rpm. After an isopropyl alcohol rinse the mold is complete.

Replica fabrication:

Dow Corning Slygard 184 silicone elastomers and curing agent is thoroughly mixed 10:1 by weight. The PDMS is poured on top of the mold to the desired thickness. The PDMS is degassed in a vacuum for five minutes and then the chamber is vented. The PDMS is allowed to cure at room temperature for 12 hours. After curing, the PDMS is peeled off of the mold and an inlet and outlet is created using a biopsy punch. The PDMS negative relief and a clean glass slide are placed face up in a Diener Femto plasma Asher. Vacuum conditions are created and held for five minutes. Oxygen at 25 psi is introduced and the plasma Asher is run for three minutes. This procedure oxidizes the surface of both the PDMS and the glass, and surface-oxidized PDMS and glass will form a bond. It is important that no mechanical stress is applied to the PDMS or glass; otherwise, the surface modification will diminish. After the two surfaces are placed in contact with one another the channel is heated to 70°C for ten minutes to allow for full bonding.
Results and Discussion

From figure, a two parallel plates illustrating two surfaces separated by distance within which fluid flow due to capillary action, this was possible due combination of surface tension (which is caused by cohesion within the liquid) and forces of adhesion between the liquid and container acting the liquid. In figure 2: A sketch in the $xz$ plane of an infinite, parallel-plate channel of height $h$. The system is translation invariant in the $y$ direction and fluid is flowing in the $x$ direction due to a pressure drop $\Delta p$ over the section of length $L$, the smooth fluid is maintained due constant pressure drop. We studied the pressure driven, steady-state flow of an incompressible fluid through a straight channel, the Poiseuille flow. We found that a constant pressure drop $\Delta p$ resulted in a constant flow rate $Q$. This result can be summarized in the Hagen Poiseuille law

$$\Delta p = \text{Rhyd} Q$$

Where we have introduced the proportionality factor $\text{Rhyd}$ known as the hydraulic resistance. The Hagen Poiseuille law Equation above is completely analogous to Ohm's law, $\Delta V = RI$, relating the electrical current $I$ through a wire with the electrical resistance $R$ of the wire and the electrical potential drop $\Delta V$ along the wire. The SI units used in the Hagen Poiseuille law are $[Q] = \text{m}^3/\text{s}$; $[\Delta p] = \text{Pa} = \text{N/m}^2 = \text{kg/m s}^2$; $\text{Rhyd} = \text{Pa s/m}^3 = \text{kg/m}^4 \text{s}$.

The concept of hydraulic resistance is central in characterizing and designing microfluidic Channels in lab-on-a-chip systems, in this research our concern was relative height to established a continue fluid which was successful as explained below.

Fig. 9: Finished micro chamber.

Fig. 10: $h=10\mu\text{m}$ models.
Fig. 11: Graph showing pressure drop across the $h=10\mu m$ model.

Fig. 12: Assembly of the fabricated microchamber (a) Fabricated microchamber surface cleaning (b) fabricated microchamber Aligning for bonding (d) plasma bonding.

Fig. 13: Shows the flow rate with change in concentration. The flow-rate in the three sets of data were generated by applying the same fluid drop at the inlet port of the microchannel.
We set the model using three minimum possible heights; the significant parameter of the interest is the height (h) between the two surfaces as capillary is largely determine by diameter of tube or distance between the two surfaces. From the table above, it can be seen that, the heights used for this study is 10µm. From figures 10 and 11 show the results we obtained when the channel height is 10µm during software design, this result is quite impressive because it can seen that the pressure drops constantly, which confirm our previous theoretical statement in the analytical solution (A constant pressure difference $\Delta p$ is maintained over a segment of length $L$ of the channel, i.e., $P(0) = P_0 + \Delta p$ and $P(L) = P_0$). In figure 12 and 13 show the results of the fabricated after the software design and The flow-rate was calculated by measuring the time required for a volume of 20 nL to flow through the channel and across the channel Several measurements sessions were performed with about a 4 hours delay between them.

**Conclusion:**

We have studied the capillary action phenomena in microfluidic channel, with focus on obtaining minimum possible gap between two surfaces within which a fluid could flow passively without any external force. We have studied numerical models of 10µm gap between substrate and microchamber using relevant underlying concepts and principles of dynamic fluid. The results show that 10µm is the suitable distance for the smooth flow of the fluid by the capillary action and second part is report on a not complicated but flexible method for fabrication of software designed micro-chamber, the method for the fabrication of micro chamber with input/outlet. Using soft photo- lithography methods, we fabricated a reusable mold. The mold is then used to create the replica device, which we successfully completed the whole fabrication process within 24 fours.

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