

Silicon-based Microfluidic Channels for Future Human Cell Manipulation by Dielectrophoresis and Electroporation

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This work presents the development and preliminary fluidic characterization of a silicon-based microfluidic platform for future electrically assisted contactless cell manipulation. Microfluidic channels were fabricated in (100) silicon by laser ablation, followed by wet etching, surface coating, and anodic bonding to BF33 glass. The devices were operated under pressure-driven conditions using an ELVEFLOW controller. Cell-stream focusing and water-in-oil droplet formation were investigated at two observation points by varying the relative and absolute inlet pressures of the cell-fluid, water, and oil phases. Preliminary experiments demonstrated stable device operation and controllable droplet generation. The cell-fluid-to-water pressure ratio $R_{c/w}$ determined the degree of cell-stream focusing, while the water-to-oil pressure ratio $R_{w/o}$ influenced droplet size. At constant $R_{w/o}=0.7$, increasing the absolute inlet pressures increased the droplet generation frequency from 3.5 to 8.2 Hz. These findings establish the fluidic operating basis for quantitative optimization and the integration of electrically assisted single-cell manipulation.

1. MOTIVATION & OBJECTIVE

Human cell manipulation in microfluidic systems has great potential for biomedical research, diagnostics, and therapy development. It enables precise handling and analysis of individual cells while minimizing contamination risks. Future lab-on-chip platforms therefore require accurate fluidic control and reproducible microenvironments for single-cell applications.

Reproducible microfluidic channel structures are essential to meet these requirements. Silicon-based devices are attractive due to their mechanical and chemical stability, fabrication precision, and compatibility with microsystem technologies. Compared to conventional PDMS-based systems, silicon chips offer improved reproducibility, long-term stability, and enhanced integration capabilities [1–3].

This work aims to develop a silicon-based microfluidic platform for electrically assisted contactless cell manipulation. A key objective is the generation and control of water-in-oil droplets as isolated microreactors for encapsulated single cells. The focus is on device design, fabrication, and experimental characterization of its fluidic performance, providing a scalable basis for the integration of electric-field-based manipulation techniques.

2. FABRICATION PROCESS

Sample structures shown in Fig. 1 were fabricated on blank silicon wafers. Structuring was done by laser ablation. Fabrication parameters were adjusted to achieve a channel depth of 100 μm .

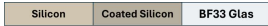
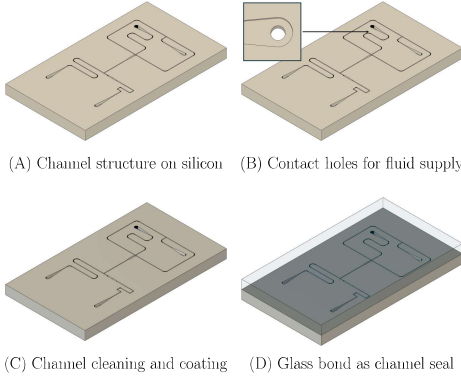


Figure 1: Schematic of the channel structure at different fabrication steps.

Additional Fabrication Steps

- Removal of laser debris by wet etching (HF and TMAH)
- Coating of channel surface by submerging in APTES/PDMS mixture
- Separating each sample from silicon wafer using dicing machine

Representative images of the fabricated microfluidic channel structures at two different stages of the fabrication process are shown in Fig. 2.

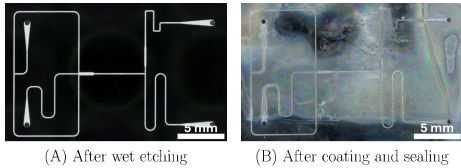


Figure 2: Channel structures at different fabrication stages. A: Laser-structured silicon after wet etching. B: Silicon and BF33 glass each coated with an APTES/PDMS mixture, after anodic bond.

Chip Specifications

- Substrate: (100) Silicon
- Top Seal: BF33 glass
- Layer thickness: Si and BF33 glass 500 μm
- Channel width: 100–300 μm
- Channel depth: 100 $\pm$ 4 μm
- Static contact angle after coating: > 100°

3. MEASUREMENT SETUP

The channel cutout Fig. 3 shows both observation points (marked red) where fluid characterization is performed using PIV (Particle Image Velocimetry).

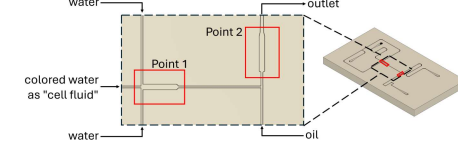


Figure 3: Left: Schematic overview of the experimental setup, showing how the individual inlets are connected and where the flow behavior is characterized. Right: Full-chip view, indicating the measurement location.

Fluid transport was pressure-driven using an ELVEFLOW pressure controller. The ratios used throughout this work refer to the applied gauge pressures:

$$R_{c/w} = \frac{p_{c/w, \text{set}}}{p_{w/o, \text{set}}}, \quad R_{w/o} = \frac{p_{w/o, \text{set}}}{p_{oil, \text{set}}}$$

where p_{set} denotes the applied inlet gauge pressure. The ratio is defined as payload fluid (inner fluid) divided by carrier fluid (outer fluid). Since both water and oil are transparent, the water was dyed to make the water droplets more visible. To increase the contrast, the sample was illuminated with a green laser. Images were taken through the sealing glass, perpendicular to the sample surface.

4. CHANNEL CHARACTERIZATION

To identify suitable operating conditions for stable droplet generation, the applied inlet pressures were systematically varied. The resulting changes in droplet formation, spacing, size, and frequency were evaluated at the two points introduced in Fig. 3.

At observation point 1 (Fig. 4 A+B), the influence of the cell-fluid-to-water pressure ratio ($R_{c/w}$) was investigated. At observation point 2 (Fig. 5 A+B), the water-to-oil pressure ratio ($R_{w/o}$) was varied to characterize its effect on the emerging droplet pattern. In addition, in Fig. 5 C+D measurements at constant $R_{w/o}$ and different overall inlet pressure levels were performed to assess the influence of the absolute pressure level independently of the pressure ratio.

Observation 1 - Influence of Cell-Fluid/Water Ratio

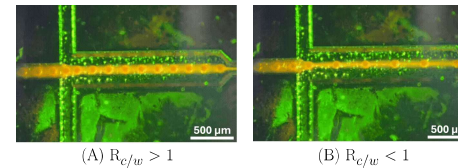


Figure 4: Influence of the cell-fluid-to-water ratio $R_{c/w}$. A: For $R_{c/w} > 1$, the cell-fluid pressure becomes dominant, resulting in a broader central stream. B: For $R_{c/w} < 1$, the lateral water streams dominate and strongly focus the cell fluid stream.

Observation 2 - Influence of Water/Oil Pressure

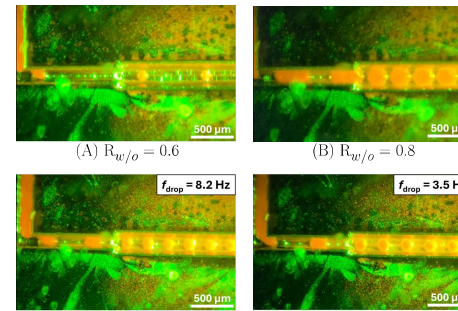


Figure 5: Influence of water-to-oil pressure conditions on droplet formation. A+B: Different pressure ratios $R_{w/o}$. C+D: Constant $R_{w/o}=0.7$ at different absolute inlet pressures.

5. PRELIMINARY FINDINGS

The fabricated silicon-based microfluidic channels enabled stable pressure-driven flow and reproducible water-in-oil droplet formation. The experiments demonstrate that both the relative inlet pressures and the absolute pressure level influence the resulting flow behavior.

At observation point 1, the cell-fluid-to-water pressure ratio $R_{c/w}$ controls the focusing of the cell suspension. For $R_{c/w} < 1$, the lateral water streams dominate and compress the cell-fluid stream, resulting in stronger focusing. For $R_{c/w} > 1$, the cell-fluid pressure becomes dominant, leading to a broader central stream.

At observation point 2, increasing the water-to-oil pressure ratio $R_{w/o}$ from 0.6 to 0.8 increases the volume of the aqueous phase entering the junction and results in larger droplets. In addition, experiments at a constant ratio of $R_{w/o} = 0.7$ show that the absolute inlet pressure strongly affects the droplet generation rate. Increasing the pressures from $p_w = 40$ mbar and $p_o = 57$ mbar to $p_w = 80$ mbar and $p_o = 114$ mbar increases the droplet frequency from $f_{\text{drop}} = 3.5$ Hz to 8.2 Hz.

The preliminary results indicate that pressure ratios determine the flow and droplet formation behavior, while the absolute pressure level strongly influences the droplet generation frequency.

6. CONCLUSION

A reproducible silicon-based microfluidic platform for pressure-driven flow and water-in-oil droplet generation was successfully fabricated and characterized. The experiments show that the relative inlet pressures control cell-stream focusing and droplet formation, while the absolute pressure level influences the droplet generation frequency. These results establish suitable fluidic operating parameters and provide the basis for the subsequent integration of electrically assisted single-cell manipulation techniques.

7. OUTLOOK

Future work will focus on the quantitative characterization of droplet size, spacing, frequency, and stability over a wider range of inlet pressure conditions. This will enable the identification of robust operating windows for reproducible droplet generation and controlled cell encapsulation.

Building on the established fluidic platform, the next development step will integrate electrically isolated electrode structures and an additional glass layer, as shown in Fig. 6. The resulting device will combine controlled droplet generation with electric-field-based manipulation, enabling the selective positioning and encapsulation of individual cells.

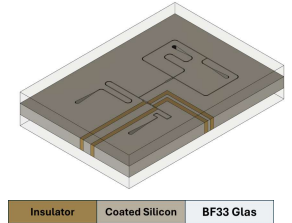


Figure 6: Schematic of future chip design featuring a second glass layer bonded to the bottom and insulating segments for electrode separation.

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