# Supporting Information for Valved Microfluidics with Ostemers

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**equal contributions.*

## S1. Details of fabrication process

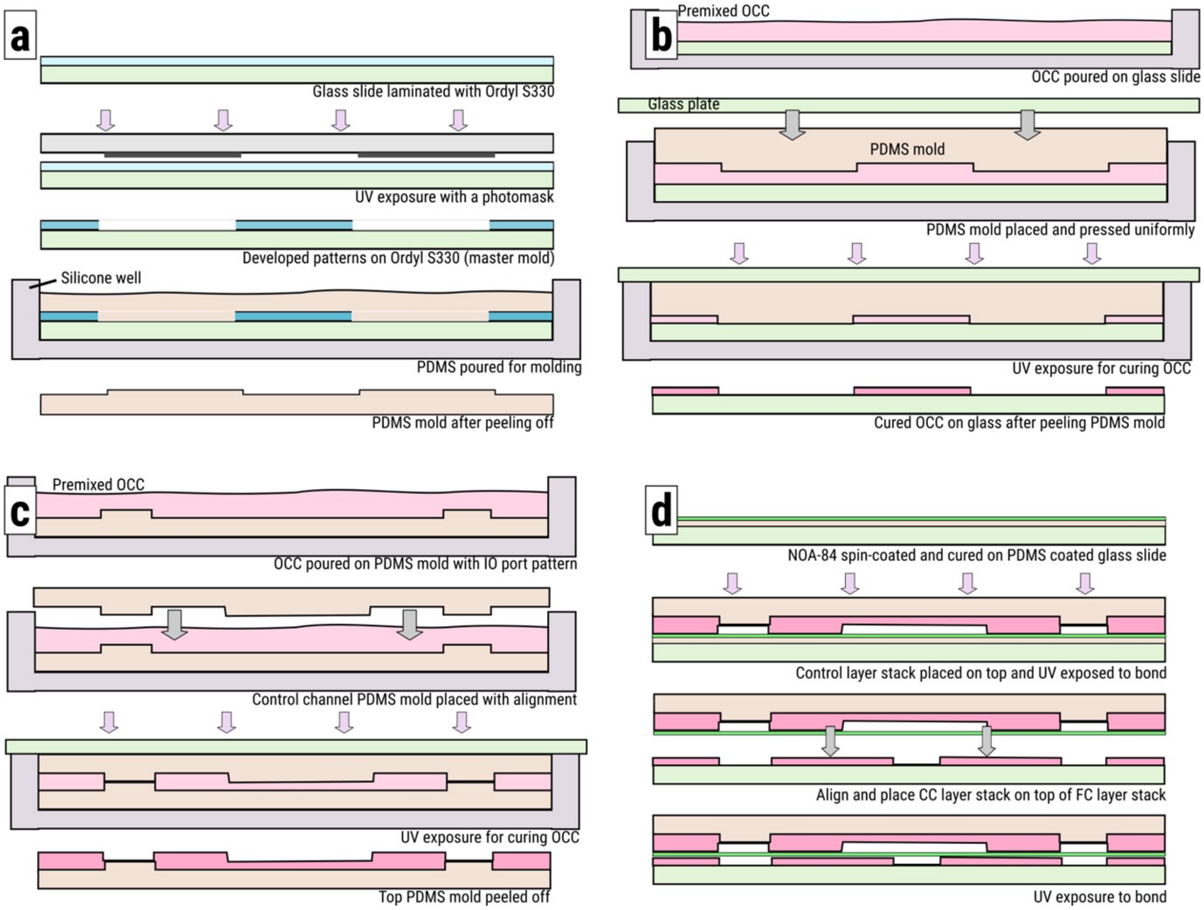


**Figure S1**. Schematic for the fabrication process of the chips. (a) Generation of PDMS molds (b) Flow channel made from OCC (c) Molding of control channel (d) Bonding of flow and control layer with NOA-84 membrane in between.

The detailed fabrication workflow is given below.

Primary master molds (DFR on glass)

1. Clean glass slides (e.g. rinse with IPA/DI water and dry with $N_2$ or air) to remove dust and organic residues.
2. Laminate the DFR film (ordyl SY355) onto the cleaned glass slides using a laminator at 120℃. After lamination, allow the slides to cool down to room temperature.
3. Align the prepared glass photomask on the laminated DFR slide in a mask aligner (MJB6, Karl Suss).
4. Expose to UV light at 365 nm at the respective dose for the DFR film.
5. Bake it at 100℃ for 10 mins and cool it down to room temperature for 10 mins.
6. Develop the DFR in ORdyl XFB developer for 10 mins or until features are cleanly resolved.
7. Rinse/stop development as per the development protocol, then dry the developed DFR structures.

Secondary molds (PDMS from DFR on glass)

8. Prepare PDMS (Sylgard 184) by mixing base:curing agent = 10:1 (w/w).
9. Place the mixture in a desicator and degas until air bubbles are removed.
10. Place the DFR primary mold on the silicon well and pour the degassed PDMS over it.
11. Cure at 85℃ for 1.5h.
12. Carefully peel the cured PDMS off the DFR masters.
13. These PDMS molds will act as a secondary molds for casting Ostemers layers.

Ostemers-322 Layers

The layers for flow channel (FC-55/30 μm ), control channel (CC-55 μm ) and a cover layer (CL-120 μm ) are made with following steps.

14. Prepare Ostemer-322 (Mercene labs) by mixing Component A : Component B = 1.09:1.
15. Place the mixture in a desiccator and degas until air bubbles are removed.

For flow channel Layer (FC) casting using PDMS mold (steps 16-21):

16. Place a glass slide at the bottom of a fitting silicone well.
17. Pour the degassed Ostemer-322 on to the glass slide inside the silicone well.
18. Place the PDMS flow layer mold onto the ostemer wit the patetrned side facing down (i.e features contacting the liquid ostemer-322).
19. Place a glass slab on the top of the PDMS mold to apply uniform pressure and ensure even feature definition.
20. UV cure at 365nm for 3mins. Here we have used a home-built flood exposure unit.
21. Remove the top glass slab and peel the cured Ostemer FC layer away from the PDMS mold carefully.

Control channel layer (CC) was casted using molds for control layer and for cover layer.

22. Place the PDMS CC mold on a glass slide with the pattern side up inside the silicone well.
23. Pour degassed Ostemer-322 over the lower mold (ensure complete filing of features).
24. Place a cover layer mold (CL) which contains the pillars of 120 µm high at the I/O pillar locations.
25. Ensure that the cover layer mold (CL) touches the lower mold the I/O port pillar locations and additional support points ( to define thickness and alignment).
26. Expose the full stack to 365nm UV using the same curing condition as above.
27. After curing, peel off the lower PDMS mold carefully and the Cured Ostemer-322 CC layer will be attached to the top cover layer PDMS mold.

Fabrication of the membrane layer (NOA 84)

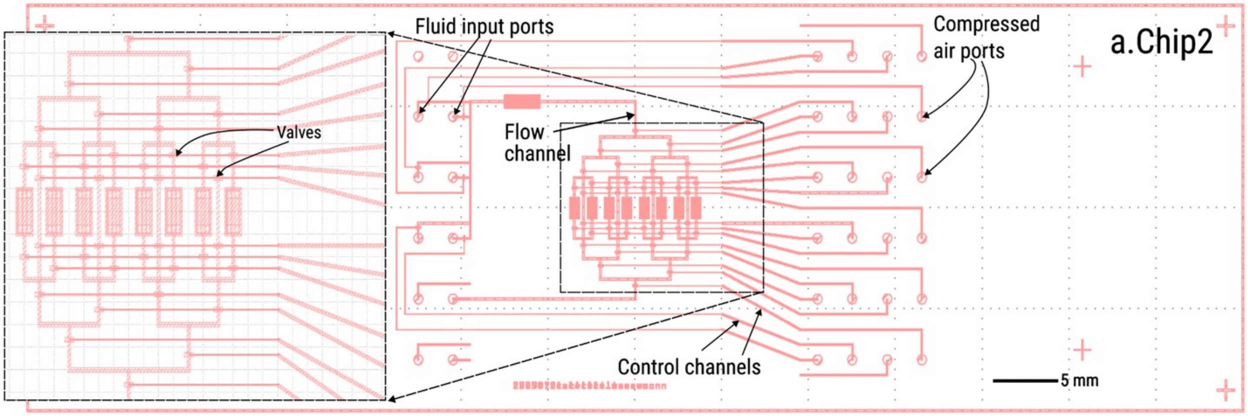
28. Clean the glass slides and spin coat the PDMS (10:1) as base: curing agent at 4000 rpm, cure it at 85℃ for 1.5h.
29. Dry the surface of the PDMS with $N_2$ or compressed air.
30. Treat the surface of the PDMS with oxygen plasma (KAS technologies), set RF power at 15 W and treat the surface for 12 S with the oxygen flow of 100 sccm.
31. Use the plasma-treated PDMS immediately for coating the NOA-84, spin coat it at desired RPM.

32. Transfer the spin-coated sample into a home-built airtight chamber and purge the chamber with nitrogen gas to reduce oxygen inhibition during curing process.
33. Irradiate using UV light for 3 mins to cure the NOA-84 membrane.

Bonding all layers

34. Place the cured CC layer (support with the cover layer mold) on top of the prepared NOA-84 membrane.
35. Expose to UV light for 120s to achieve permanent bonding between CC and membrane.
36. Carefully peel the bonded CC + NOA-84 membrane assembly of the supporting PDMS substrate.
37. Align the released CC + membrane stack on top of the previously cured FC (flow channel) layer.
38. UV cure the assembly for 600s to complete bonding between the FC layer and the upper stack.
39. We can vary the substrate like instead of using glass, we can use PET sheets using the same process without any modification.

## S2. Layout and photographs of designs for Chip2 and Chip4



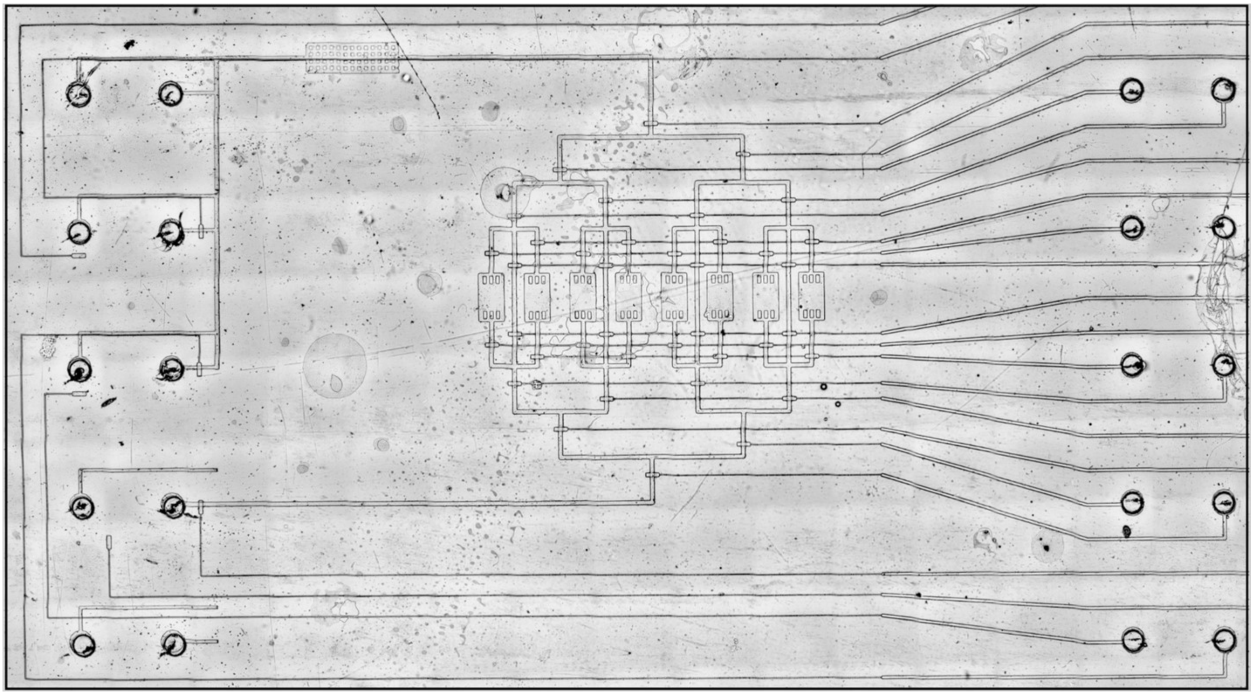
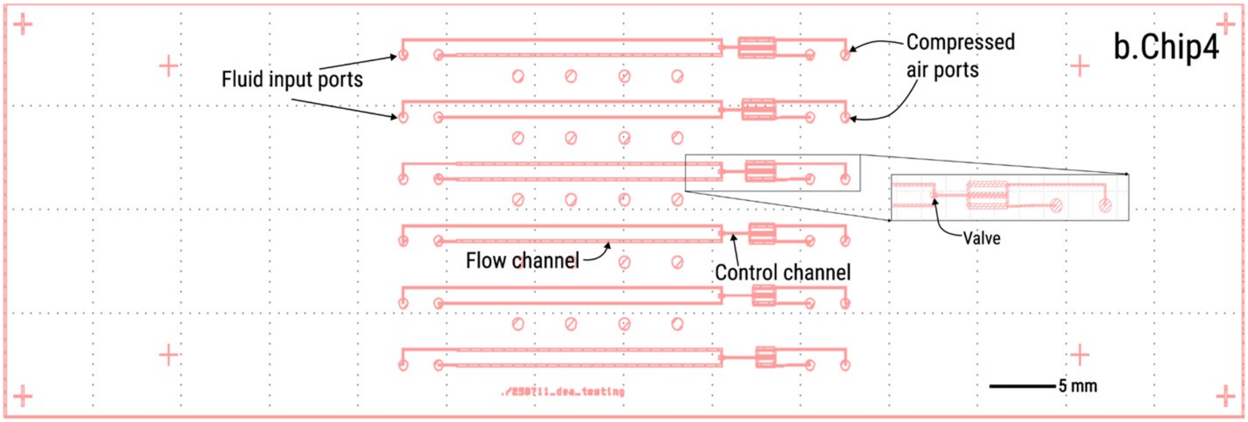


**Figure S2**. Schematic layout of Chip2 (above) and its photograph (below) generated by joining several high resolution images captured by a microscope.



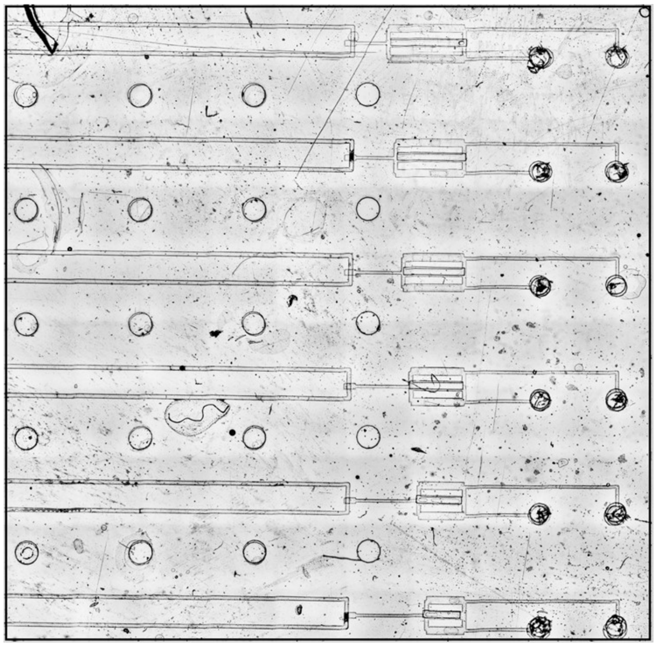


**Figure S3**. Schematic layout of Chip4 (above) and its photograph (below) generated by joining several high resolution images captured by a microscope.

## S3. Calculation for blocked area by valve using channel conductance measurements

To calculate the blocked area percentage, 1M KCl was filled in the microfluidic channel of length 3.5cm. The control channel was then actuated at different pressures to progressively constrict the flow channel. For each pressure, the current was measured for a fixed applied bias voltage. For time response studies, the current was measured for long duration, sampled at a fixed rate.

The resistance of the valve in the flow channel is given by $R = \rho l/(w * d)$, where $\rho$ is the resistivity of 1M KCl filling the flow channel ($\rho$=8.96 ohm-cm, equivalent to a conductivity of 111.6 mS/cm), *l* is the length of valve (145 µm ), w is its width (100 µm ) and d is the depth or height (55 µm ).

Equivalently $R = \rho l/A$, where A is the cross sectional area. Assume that the resistance of the rest of the channel is $R_0$ then initial resistance of the whole channel is $R_0 + R_{open}$ and final resistance is $R_0 + R_{close}$, where $R_{open}$ and $R_{close}$ are the resistance of the valve in open and closed states respectively.

We have, then the change in the resistance of

$dR = R_{close} - R_{open} = \rho l * (1/A' - 1/A)$, where A' is the valve cross section when it is actuated (closed).

Solving for A'/A we have:

$1/A' = 1/A + dR/\rho l$

$A' = A/(1 + AdR/\rho l)$

$A/A' = 1 + AdR/\rho l$

$A'/A = 1/(1 + AdR/\rho l)$

substituting the values in this equation we can find the area A'/A for various points on the graph. These values are presented in the tables below.

Blocked Percentage can be determined by

Blocked% = 100x (1 - A'/A)

| **Pressure (bar)** | **R_open (Ω) ×10⁵** | **R_closed (Ω) ×10⁵** | **ΔR (Ω) ×10⁵** | **A'/A exp** | **Blocked area (%) exp** |
|---|---|---|---|---|---|
| 0.2 | 5.46 | 5.52 | 0.06 | 0.28 | 71.87 |
| 0.4 | 11.42 | 12.22 | 0.79 | 0.02 | 97.11 |
| 0.6 | 6.94 | 7.63 | 0.68 | 0.03 | 96.68 |
| 0.8 | 5.29 | 7.14 | 1.85 | 0.01 | 98.74 |
| 1 | 6.02 | 6.13 | 0.11 | 0.17 | 82.43 |
| 1.2 | 10.68 | 12.98 | 2.30 | 0.01 | 98.98 |

| | | | | | |
|---|---|---|---|---|---|
| 1.4 | 5.71 | 5.95 | 0.23 | 0.09 | 90.97 |
| 1.6 | 5.40 | 6.17 | 0.76 | 0.02 | 97.01 |
| 1.8 | 6.84 | 8.26 | 1.41 | 0.01 | 98.35 |
| 2 | 6.66 | 8.13 | 1.46 | 0.01 | 98.41 |
| 2.4 | 5.58 | 8.40 | 2.81 | 0.008 | 99.16 |
| 2.8 | 7.81 | 10.57 | 2.75 | 0.0084 | 99.15 |

**Table.S1 Experimental Blocked area calculation for 55 μm height flow channel** with the membrane thickness of 1.5 μm . Conductance and resistance based parameters used to estimate experimental blocked area (A’/A) as a function of applied pressure for a 55 μm high flow channel with the membrane thickness of 1.5 μm

| **Pressure (bar)** | **R_open (Ω) $\times 10^5$** | **R_closed (Ω) $\times 10^5$** | **ΔR (Ω) $\times 10^5$** | **A′/A exp** | **Blocked area (%) exp** |
|---|---|---|---|---|---|
| 0.2 | 10.74 | 10.85 | 0.11 | 0.27 | 72.92 |
| 0.4 | 7.75 | 9.80 | 2.05 | 0.02 | 97.93 |
| 0.6 | 10.82 | 11.01 | 0.19 | 0.18 | 81.49 |
| 0.8 | 3.78 | 3.93 | 0.14 | 0.22 | 77.49 |
| 1 | 11.93 | 12.72 | 0.78 | 0.05 | 94.79 |
| 1.2 | 6.71 | 7.24 | 0.53 | 0.07 | 92.51 |
| 1.4 | 6.84 | 7.40 | 0.55 | 0.07 | 92.79 |
| 1.6 | 6.84 | 7.24 | 0.39 | 0.09 | 90.16 |
| 1.8 | 8.33 | 10.85 | 2.52 | 0.01 | 98.31 |
| 2 | 10.12 | 13.58 | 3.46 | 0.01 | 98.76 |
| 2.4 | 8.33 | 11.62 | 3.29 | 0.01 | 98.70 |
| 2.8 | 7.81 | 10.64 | 2.83 | 0.01 | 98.49 |
| 3.2 | 4.65 | 7.63 | 2.98 | 0.01 | 98.56 |

**Table.S2 Experimental Blocked area calculation for 30** μm **height flow channel** with the membrane thickness of 1.5 μm .Conductance and resistance based parameters used to estimate experimental blocked area (A’/A)as a function of applied pressure for a 30 μm high flow channel with the membrane thickness of 1.5 μm .

A small deviation is observed in the conductance-based blocked area estimate at intermediate pressure. This behaviour is expected because the blocked area calculation is derived from the difference between the open and closed conductance levels, when the valve is only partially constricted, the conductance change is relatively small and the inferred area becomes highly sensitive to baseline drift, electrode/solution impedance etc. At high pressure, the valve induced resistance change dominates these secondary contributions and the experimental blocked area converges to a complete closure of theoretical blocked area calculations. So the deviation at intermediate pressure reflects the measurement sensitivity rather than a change in the valve mechanics.
For the 30 μm -high flow channel, the theoretical model predicts blocked area values exceeding more than 100% at higher pressure. This can be observed in a condition where the deflection of the membrane is more than the height of the channel, in which case the arc overlap calculation continues to increase despite the channel already being fully closed. Physically, the blocked area is capped at 100% once the membrane contacts the channel floor.

## S4. Calculation for theoretical blockage of valve under a given pressure

The maximum deflection of a membrane ($w_0$) and applied differential pressure ($P$) across a circular membrane are related by

$w_0 = a\left(\frac{aP}{C_2 f(v) E't}\right)^{1/3}$, where $E' = \frac{E}{(1-v)^2}$, note that "a" is the radius of the circular membrane. In our case, "a" should be at least 100/2 μm .

From the figure below, we want to know the area of the arc above the horizontal line. This is equal to the area of the whole sector minus twice the area of the right angled triangle formed by "a" and "r". The base of this triangle is "r-w".

So that

$a^2 + (r - w)^2 = r^2$. When w and a are known, r can be found by solving this quadratic equation. Then we know the area of the triangle (½*a*(r-w)). We also have $\theta = \sin^{-1}(a/r)$, so that the area of the sector is $1/2 * r^2 * 2\theta$. The desired area then is A' $= r^2\theta - a * (r - w)$.

The percentage blocked area of the valve will be A'/A.

Plugging in the respective values, we get the following table, which is used for graph in Fig.4a.

Membrane radius (a) = 37.50 μm = 0.00375 cm

Membrane thickness (t) = 1.50 μm = 0.00015 cm

Young's modulus (E) = 7.00e+06 Pa, Poisson's ratio (v) = 0.3, Constant ($C_f$) = 2.67

| **Pressure (bar)** | **Membrane Deflection w (μm)** | **Radius r (cm)** | **Theta (rad)** | **Triangle Area (cm²)** | **Sector Area (cm²)** | **Arc (Blocked) Area (cm²)** | **Blocked Area (%) theory (raw)** |
|---|---|---|---|---|---|---|---|
| 0.2 | 28.12 | 0.005 | 2.04 | 1.52E-05 | 3.51E-05 | 1.99E-05 | 36.16 |
| 0.4 | 35.43 | 0.005 | 2.46 | 8.78E-06 | 3.46E-05 | 2.59E-05 | 47 |
| 0.6 | 40.56 | 0.005 | 2.72 | 5.27E-06 | 3.56E-05 | 3.03E-05 | 55.13 |
| 0.8 | 44.64 | 0.005 | 2.91 | 2.84E-06 | 3.69E-05 | 3.41E-05 | 61.95 |
| 1 | 48.09 | 0.005 | 3.06 | 9.71E-07 | 3.84E-05 | 3.74E-05 | 67.97 |
| 1.2 | 51.10 | 0.005 | 3.09 | -5.48E-07 | 3.87E-05 | 3.93E-05 | 71.43 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1.4 | 53.80 | 0.005 | 2.99 | -1.83E-06 | 3.76E-05 | 3.95E-05 | 71.77 |
| 1.6 | 56.25 | 0.005 | 2.90 | -2.95E-06 | 3.68E-05 | 3.98E-05 | 72.34 |
| 1.8 | 58.50 | 0.005 | 2.82 | -3.94E-06 | 3.62E-05 | 4.02E-05 | 73.05 |
| 2 | 60.59 | 0.005 | 2.75 | -4.83E-06 | 3.58E-05 | 4.06E-05 | 73.85 |
| 2.4 | 64.39 | 0.005 | 2.64 | -6.39E-06 | 3.52E-05 | 4.16E-05 | 75.56 |
| 2.8 | 67.78 | 0.005 | 2.54 | -7.73E-06 | 3.48E-05 | 4.25E-05 | 77.34 |

**Table.S3 Theoritical Blocked area calculation for 55** µm **high flow channel** with the membrane thickness of 1.5 µm .

| Pressure (bar) | Membrane Deflection w (µm) | Radius r (cm) | Theta (rad) | Triangle Area (cm²) | Sector Area (cm²) | Arc (Blocked) Area (cm²) | Blocked Area (%) theory (raw) | Blocked Area (%) theory (capped) |
|---|---|---|---|---|---|---|---|---|
| 0.2 | 28.12 | 0.005 | 2.04 | 1.52E-05 | 3.51E-05 | 1.99E-05 | 66.29 | 66.29 |
| 0.4 | 35.43 | 0.005 | 2.46 | 8.78E-06 | 3.46E-05 | 2.59E-05 | 86.16 | 86.16 |
| 0.6 | 40.56 | 0.005 | 2.72 | 5.27E-06 | 3.56E-05 | 3.03E-05 | 101.08 | 100 |
| 0.8 | 44.64 | 0.005 | 2.91 | 2.84E-06 | 3.69E-05 | 3.41E-05 | 113.59 | 100 |
| 1 | 48.09 | 0.005 | 3.06 | 9.71E-07 | 3.84E-05 | 3.74E-05 | 124.61 | 100 |
| 1.2 | 51.10 | 0.005 | 3.09 | -5.48E-07 | 3.87E-05 | 3.93E-05 | 130.96 | 100 |
| 1.4 | 53.80 | 0.005 | 2.99 | -1.83E-06 | 3.76E-05 | 3.95E-05 | 131.58 | 100 |
| 1.6 | 56.25 | 0.005 | 2.90 | -2.95E-06 | 3.68E-05 | 3.98E-05 | 132.63 | 100 |
| 1.8 | 58.50 | 0.005 | 2.82 | -3.94E-06 | 3.62E-05 | 4.02E-05 | 133.93 | 100 |
| 2 | 60.59 | 0.005 | 2.75 | -4.83E-06 | 3.58E-05 | 4.06E-05 | 135.39 | 100 |
| 2.4 | 64.39 | 0.005 | 2.64 | -6.39E-06 | 3.52E-05 | 4.16E-05 | 138.5 | 100 |
| 2.8 | 67.78 | 0.005 | 2.54 | -7.73E-06 | 3.48E-05 | 4.25E-05 | 141.79 | 100 |
| 3.2 | 70.87 | 0.005 | 2.45 | -8.90E-06 | 3.46E-05 | 4.35E-05 | 145.04 | 100 |

**Table.S4 Theoritical Blocked area calculation for 30** µm **height flow channel** with the membrane thickness of 1.5 µm

## S5. Theoretical and Experimentally observed blockages for 30 µm deep channel, as the pressure is varied.

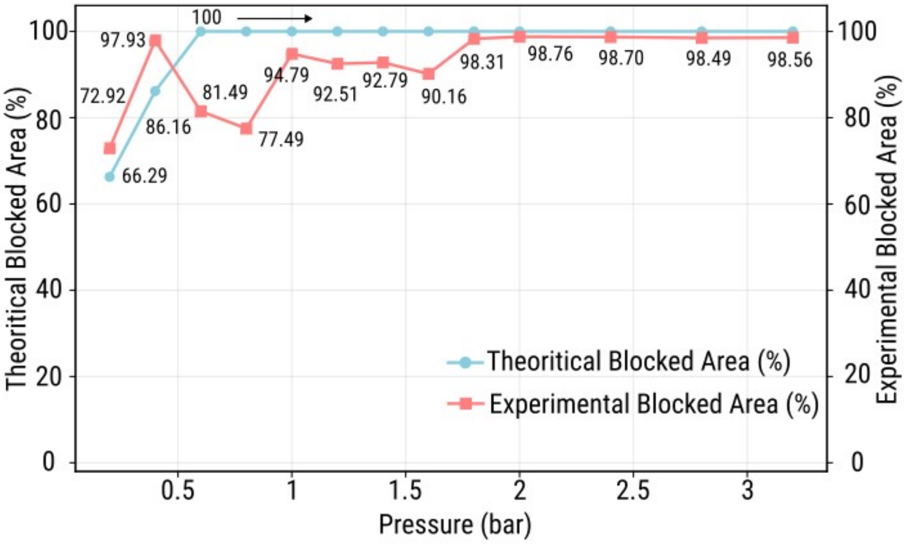


**Figure S4.** Effect of applied pressure on conductance and cross-sectional area reduction of the flow channel at the location of the valve. The membrane thickness is 1.5 µm and the height of the flow channel 30 µm.Blocked area rises sharply at low pressure and approaches a plateau close to 100% at higher pressure, showing that the valve achieves near complete closure beyond ~1-2 bar.

## S6. Switching dynamics of the valves

At a constant actuation frequency of 0.5Hz, we quantified the valve dynamics by extracting both the transition time and the corresponding time constant from the electrical current transient. The opening transient was defined as the time required for the signal to move from its baseline to 90% of the steady state open level **(start→90%)** adn the closing transition as the tme required to reach 10% of the open level **(start→10%)**. Assuming a first order response, the time constant was first obtained front he 10-90% definition using □= t/ln(10).

Time Constant (□) Calculation

- $t_{open}$ **(ms) (start→90%) -** Opening (rise): from the start of rise to the first time the current reaches ≥ 90% of the top value.
- $t_{close}$ **(ms) (start→10%) -** Closing (fall): from the start of fall to the first time the current reaches ≤ 10% above the bottom value (i.e., 90% of the drop completed).

Example:

**Note**:the numerical values provided here are illustrative examples for explaining the analysis workflow;the corresponding experimentally measured values are reported in **Table S5.**

**Step 1**

| | |
|---|---|
| Bottom level (closed), $I_{low}$ | $3.154 \times 10^{-6}$ A |
| Top level (open), $I_{high}$ | $3.580 \times 10^{-6}$ A |
| Amplitude, $\Delta I = I_{high} - I_{low}$ | $0.426 \times 10^{-6}$ A |

**Step 2:**

**Rise (90% of top):**
$I_{90,up} = I_{low} + 0.9 \cdot \Delta I = 3.154\times10^{-6} + 0.9 \cdot (0.426\times10^{-6}) = 3.5374\times10^{-6}$ A
**Fall (within 10% of bottom, i.e. 90% of drop):**
$I_{10,down} = I_{low} + 0.1 \cdot \Delta I = 3.154\times10^{-6} + 0.1 \cdot (0.426\times10^{-6}) = 3.1966\times10^{-6}$ A

**Step 3:**

| | **Raise (start→90%)** | **Fall (start→10%)** |
|---|---|---|
| **Start time, t_s** | $t_s$ up = 345.724 ms | $t_s$ down = 1007.280 ms |
| **Threshold-crossing time** | $t_{90}$ up = 511.111 ms ($I \geq I_{90,up}$) | $t_{10}$ down = 1503.459 ms ($I \leq I_{10,down}$) |

**Step 4:**

Opening time (start→90%):
$t_{open} = t_{90}$ up $- t_s$ up $= 511.111 - 345.724 = 165.387$ ms
Closing time (start→10%):
$t_{close} = t_{10}$ down $- t_s$ down $= 1503.459 - 1007.280 = 496.179$ ms

**Step5:**

Using □ = $t_{90}$ / ln(10) with ln(10) = 2.3026:
□$_{\mathbf{open}}$ = $t_{open}$ / 2.3026 = 165.387 / 2.3026 = 71.83 ms
□$_{\mathbf{close}}$= $t_{close}$ / 2.3026 = 496.179 / 2.3026 = 215.49 ms

| **Frequency (Hz)** | **$t_{open}$ (ms) (start→90%)** | **□$_{open}$ (ms)** | **$t_{close}$ (ms) (start→10%)** | **□$_{close}$ (ms)** |
|---|---|---|---|---|
| 0.25 | 330 | 143 | 830 | 360 |
| 0.5 | 153 | 67 | 538 | 233 |
| 1 | 240 | 104 | 323 | 140 |
| 10 | 74 | 32 | 150 | 65 |

**Table S5.** The temporal response of the pneumatic valve (55um flow channel device, 1 bar actuation) quantified using the electrical readout of the ionic current through 1M KCl by biasing 1V with different frequency at 1bar. The transition time $t_{open}$ (ms) (start→90%) and $t_{close}$ (ms) (start→10%) represents the time required to reach the near steady state and □ obtained by fitting the open→close and close→open transients with exponential response.

| **Pressure (bar)** | **Freq (hz)** | **$t_{open}$ (ms) (start→90%)** | **$t_{close}$ (ms) (start→10%)** | **□$_{open}$ (ms)** | **□$_{close}$ (ms)** |
|---|---|---|---|---|---|
| 1 | 0.5 | 147 | 575 | 64 | 250 |
| 2.4 | 0.5 | 151 | 610 | 66 | 265 |
| 2.8 | 0.5 | 140 | 590 | 61 | 256 |
| 3.2 | 0.5 | 141 | 580 | 61 | 252 |

**Table S6**. Time constant □$_{open}$ (ms) and □$_{close}$ (ms) for the 55 μm device constant frequency 0.5Hz at different pressures.