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Supplementary Information: The Reversible Capillary Field Effect Transistor: A Capillaric Element for Autonomous Flow Switching

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PART I SUPPLEMENTARY FIGURES

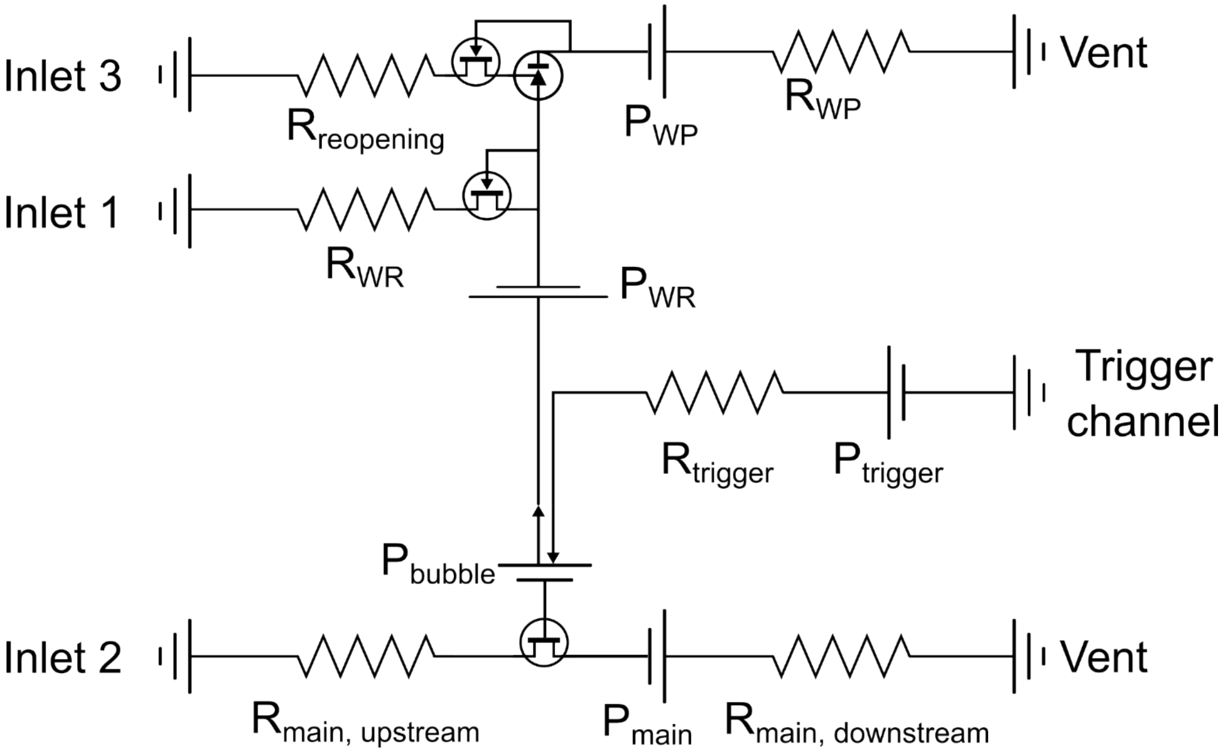


Fig. S1 Extended circuit diagram. This figure provides a more complete and complex representation of the whole rcFET circuit. The rcFET is represented here by the FET symbol in the main channel (running horizontally along the bottom). This FET has three "gate" pressures acting on it – the trigger and reservoir pressures acting towards the main channel and the natural countering pressure that is generated by the bubble that these expand into the main channel. The 2LTV is represented by a Silicon Controlled Rectifier symbol, with the flow from Inlet 3 acting as the gate. Inlets 1 and 3 are cut off from their downstream circuitry by secondary FETs, which represent the secondary dgcFETs .

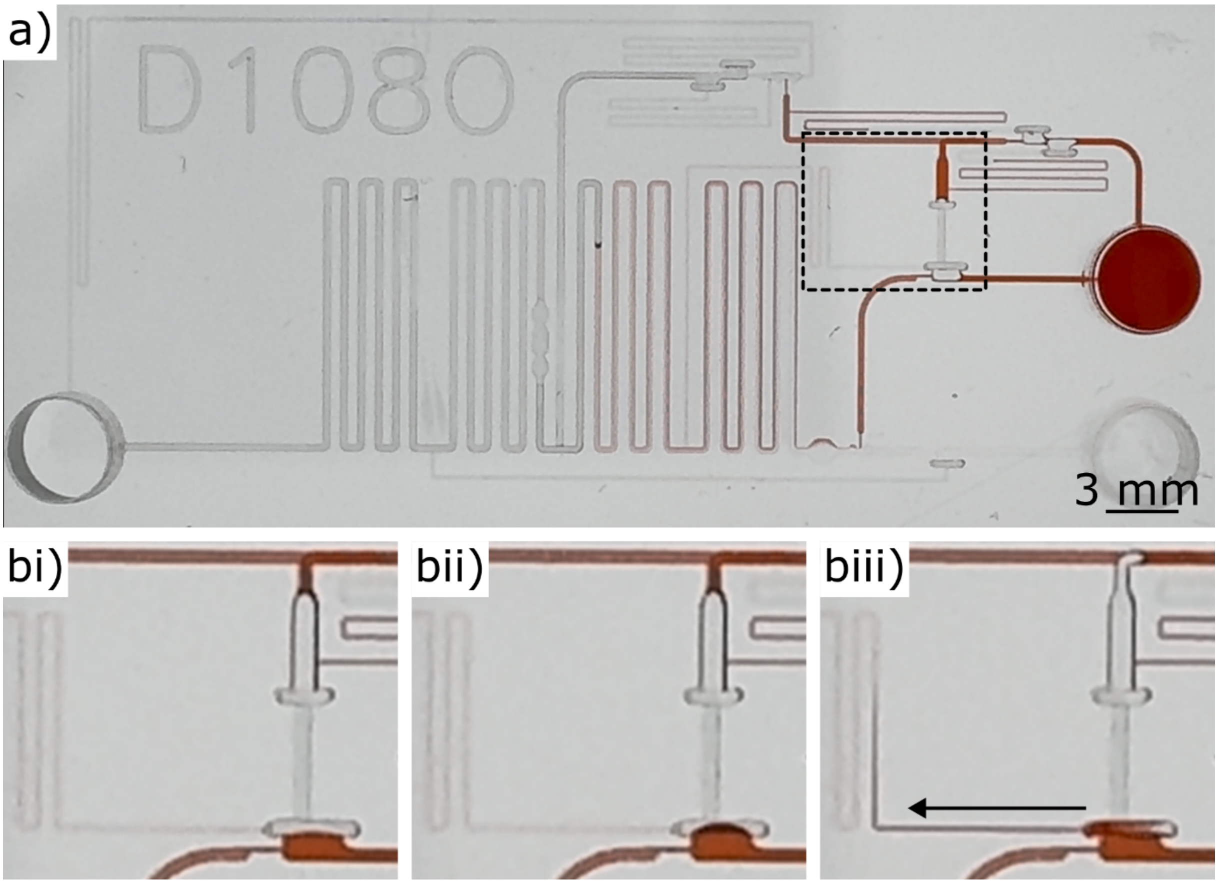


Fig. S2 Void failure due to overpulling of the withdrawal reservoir. a) rcFET in closed state showing the overall chip. The black dashed box shows the area enlarged in (b). bi) rcFET reopening caused by the withdrawal of liquid from the reservoir. bii) Continued withdrawal of liquid from the reservoir results in the liquid at the rcFET's main channel/void interface moving into the void volume. biii) Extreme overpulling of the withdrawal circuitry cause the void volume to fail, releasing liquid into the void. This causes the liquid from the main channel to connect to the liquid in the trigger channel, resulting in backflow through the trigger channel and potential short-circuiting of the circuit.

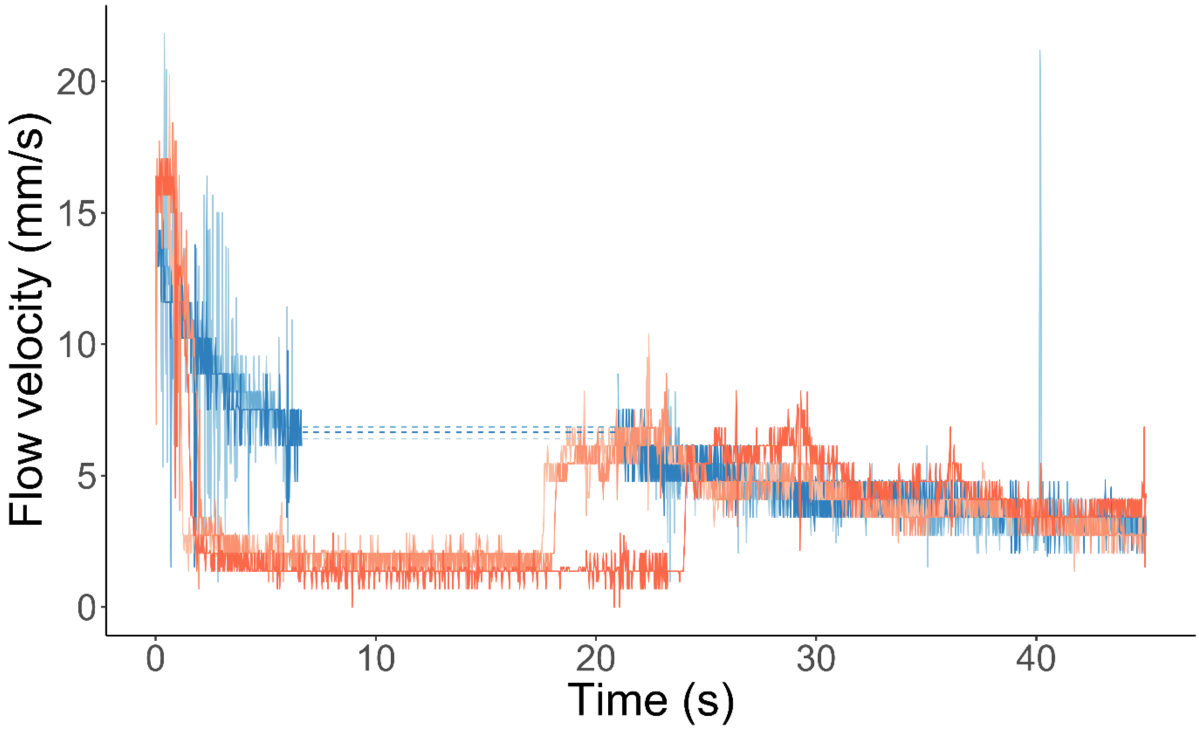


Fig. S3 Non-smoothed flow velocity for the rcFET and control reopening experiments showing the raw velocity data analysed by the flow tracking software. The significant noise is likely due to three main factors – the inherent noise in the flow velocity, the resolution and framerate limitations of the recording device (iPhone), and variation in the meniscus identification of the flow tracking software. Note that the rcFET experiments had the reopening manually triggered, which caused the reopening to start at different times.

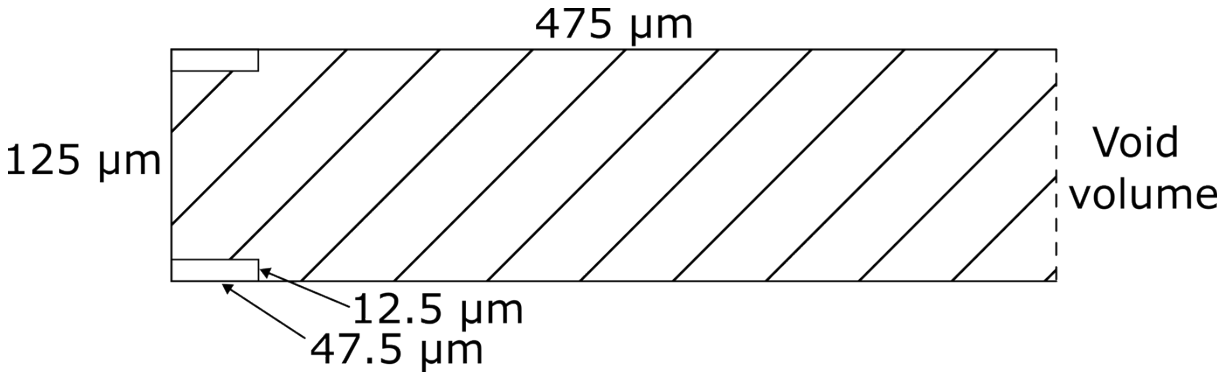


Fig. S4 Cross-sectional view of the main channel of an rcFET showing an approximation of the residual flow paths. The crosshatching represents the area the occluding bubble fills, while the boxes in the lefthand corners represent the residual flow paths, assumed to be each 10% of the width and heigh of the overall channel. Rearranging the resistance equation (Equation 1), the specific resistance of these channels can be determined

$$\frac{R}{12\mu L} = \frac{1}{h^3 w}\left(1 - 0.63\frac{h}{w}\right)^{-1} \#(Eqn\ S1)$$

Using the overall channel dimensions (which are 200 µm wider at the rcFET than a standard 275 µm wide channel) gives a specific resistance of 1.29×10^{15} *m^{-4}. The smaller residual channels then have a specific resistance of* 1.29×10^{19} *m^{-4} each. With two residual corners, this would represent a 5,000-fold increase in the resistance provided by the rcFET when closed over its open state.*

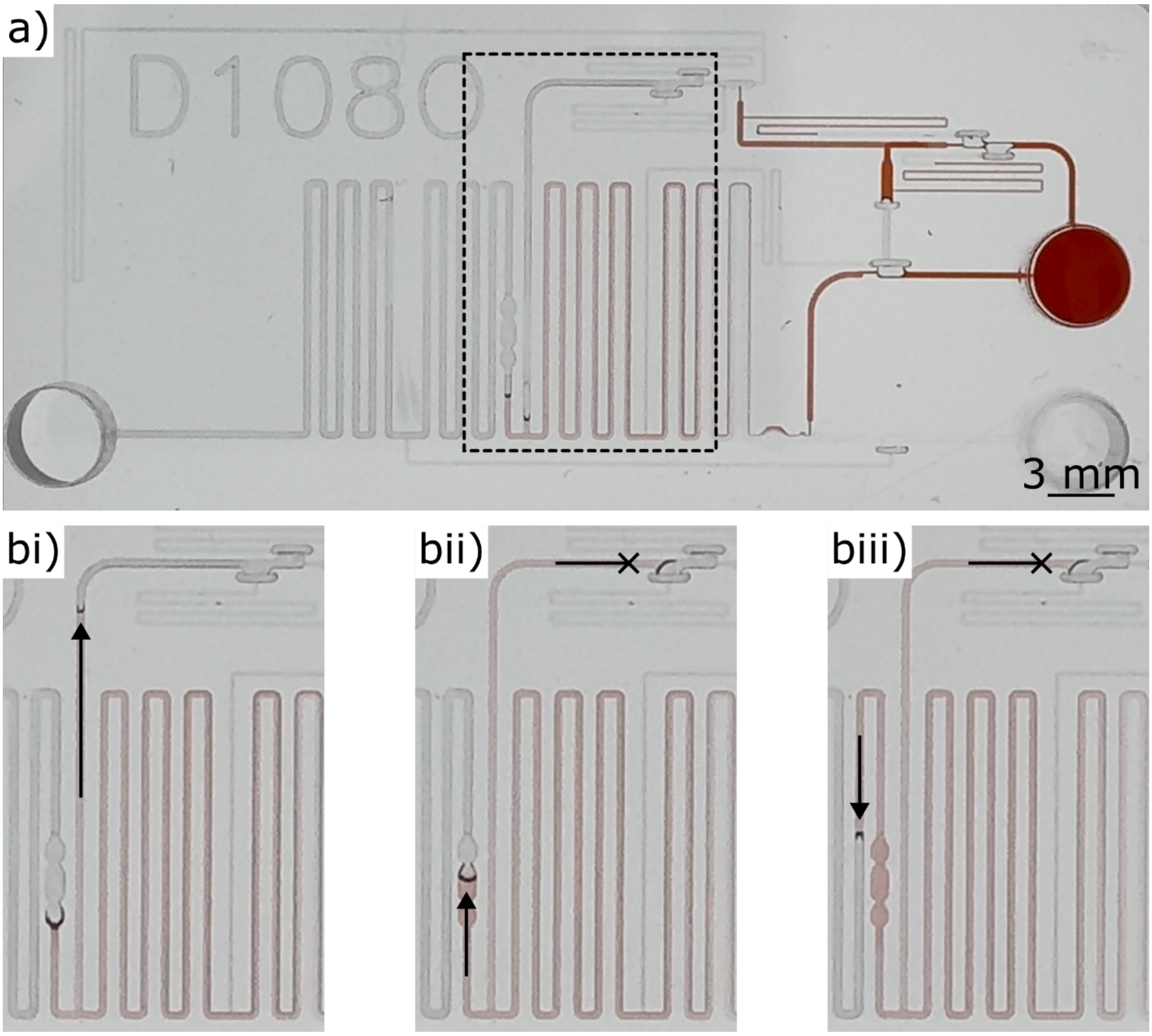


Fig. S5 Flow disruption caused by the dgcFET in the withdrawal triggering circuitry. a) The flow in the main channel branches off into the withdrawal circuitry. The black box shows the area enlarged in (b). bi) The flow break structure in the main channel disrupts the flow, allowing the liquid to travel down the withdrawal circuitry. bii) The disruption to the continuous geometry of the dgcFET causes the flow in the withdrawal circuitry to stop and the flow in the main channel to continue. biii) The flow break structure fails to stop the flow in the main channel again, allowing the flow to continue while the liquid in the withdrawal branch is stopped. This prevents the withdrawal circuitry from triggering the reopening and the rcFET fails to reopen.

PART II – SUPPLEMENTARY VIDEOS

Video S1 – rcFET Basic Operation

“rcFET Basic Operation” contains a video result demonstrating the fundamental operation of the rcFET valve. This includes the filling of three inlets. Videos were recorded using an iPhone 15 Pro Max at 4k with 60 fps.

Part 1: Filling of withdrawal reservoir

Inlet 1 is filled first to prefill the withdrawal reservoir of the rcFET with liquid before the rest of the circuitry is activated. This inlet causes the liquid to fill the withdrawal reservoir and up to the two-level trigger valve that will later be triggered to activate the withdrawal. Inlet 1 is cut off by a dual-gate cFET once the filling is complete to prevent excess liquid being drawn later.

Part 2: Main channel activation

Filling inlet 2 activates the main channel. Liquid flows past the rcFET, travelling initially at a high speed until the rcFET closing is triggered by the liquid reaching the trigger channel. This causes the liquid speed to drop significantly.

Part 3: Reopening trigger

Filling inlet 3 triggers the reopening of the rcFET. The inlet 3 liquid flows past a dgcFET structure and then connects to the 2LTV of the withdrawal pump. The dgcFET closes to prevent excess liquid being drawn from inlet 3, and the liquid enters the high pressure withdrawal pump. This causes liquid to be withdrawn from the reservoir, reopening the rcFET. This results in the liquid flow in the main channel picking up speed as the resistance is reduced.

Video S2 – Liquid Mixing Control

“Liquid Mixing Control” contains a video result demonstrating rcFET's ability to control the upstream mixing ratio of two liquids by turning off and on flow. Videos were recorded using an iPhone 15 Pro Max at 4k with 60 fps.

Part 1: Filling of withdrawal reservoir and connection to main channel

The filling of the first inlet performs two actions - filling the rcFET withdrawal circuitry and setting up the inlet's connection to the main channel via a two-level trigger valve.

Part 2: Initial liquid mixing and closing of the rcFET

Filling inlet 2 activates the main channel and connects the two inlets. The approximately equal inlet pressures cause the flow from each to be even, resulting in the colour ratio in the observation chamber being even. Upon closing of the rcFET by the trigger channel, the hydraulic resistance of the red channel is significantly increased and the clear liquid dominates.

Part 3: Autonomous reopening

Once the liquid in the main channel reaches the branch leading the reopening trigger, it splits and fills both branches. The liquid in the main channel branch is disrupted by the flow break structure, resulting in the liquid preferentially flowing through the reopening branch. Once this reopening branch connects to the two-level trigger valve, it self-seals by the secondary dual-gate cFET and the withdrawal pump causes the rcFET to reopen. This results in the liquids in the observation chamber returning to an approximately equal ratio.

Part 4: Closing of the base cFET

Finally, the liquid in the main channel reaches the trigger channel for the base cFET, connected to the second inlet channel. Once this trigger channel causes the cFET to close, the second inlet is cut off and the red liquid dominates the observation chamber.

Video S3 – Simultaneous rcFET and cFET Activation

"Simultaneous rcFET and cFET Activation" contains a video result demonstrating the simultaneous reopening of an rcFET and closing of a cFET utilising the same withdrawal pump/trigger channel. Videos were recorded using an iPhone 15 Pro Max at 4k with 60 fps.

Part 1: Filling of withdrawal reservoir and connection to main channel

The filling of the first inlet performs two actions - filling the rcFET withdrawal circuitry and setting up the inlet's connection to the main channel via a two-level trigger valve.

Part 2: Initial liquid mixing and closing of the rcFET

Filling inlet 2 activates the main channel and connects the two inlets. The approximately equal inlet pressures cause the flow from each to be even, resulting in the colour ratio in the observation chamber being even. Upon closing of the rcFET by the trigger channel, the hydraulic resistance of the red channel is significantly increased and the clear liquid dominates.

Part 3: Simultaneous reopening and closing activation

By utilising a combined high pressure channel for both the withdrawal pump of the rcFET and trigger channel of the cFET, both valves are actuated at the same time. This results in a rapid switching within the observation chamber from clear to red liquid.

Video S4 – rcFET Parallel Reopening

"rcFET Parallel Reopening" contains a video result demonstrating the parallel reopening of three rcFETs simultaneously utilising a single withdrawal pump. Videos were recorded using an iPhone 15 Pro Max at 4k with 60 fps.

Part 1: Prefilling of Inlets 1−3

The first three inlets are filled with liquids which filled their respective withdrawal reservoirs and connections to the main channel. All three withdrawal reservoirs are connected by two-level trigger valves to the same withdrawal pump.

Part 2: Connecting the liquids to the main channel

Filling the fourth inlet causes the two-level trigger valves to trigger, resulting in liquids from the first three inlets mixing with the fourth inlet liquid. Each of the first three inlets are sealed off in turn by their rcFETs closing, resulting in transient changes to the ratios of liquids in the main channel.

Part 3: Parallel reopening

When the liquid in the main channel fills the reopening trigger branch, the withdrawal pump becomes connected to all three withdrawal reservoirs simultaneously. This causes each rcFET to reopen at the same time and allows liquid from inlets 1-3 to begin flowing freely into the main channel again.

Video S5 – Flow Oscillation Using rcFETs

"Flow Oscillation Using rcFETs" contains a video result demonstrating the use of rcFETs to autonomously control the mixing ratio of three liquids over time. Videos were recorded using an iPhone 15 Pro Max at 4k with 60 fps.

Part 1: Initial filling

Filling of the outer two inlets prefills their respective withdrawal reservoirs and primes the two-level trigger valves connected to the main channel.

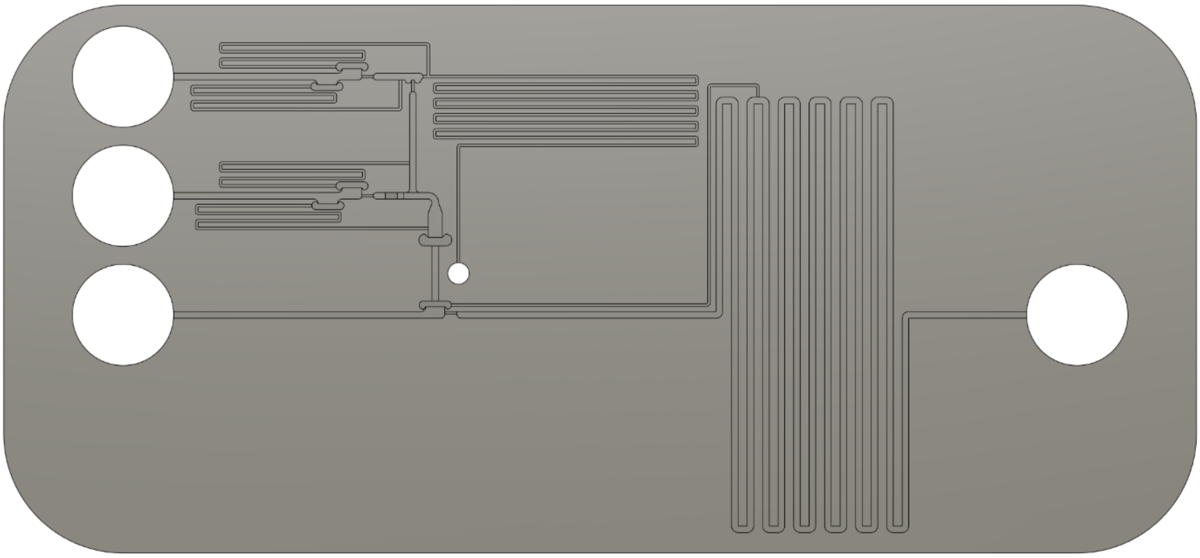
Part 2: Main channel activation

Filling the central inlet triggers the two-level trigger valves and allows the three liquids to flow into the observation chamber, developing a steady ratio. The ratio of the three liquids in the observation chamber is disrupted by the sequential closing of the rcFETs, resulting first in two liquids dominating the chamber, then the water alone dominating.

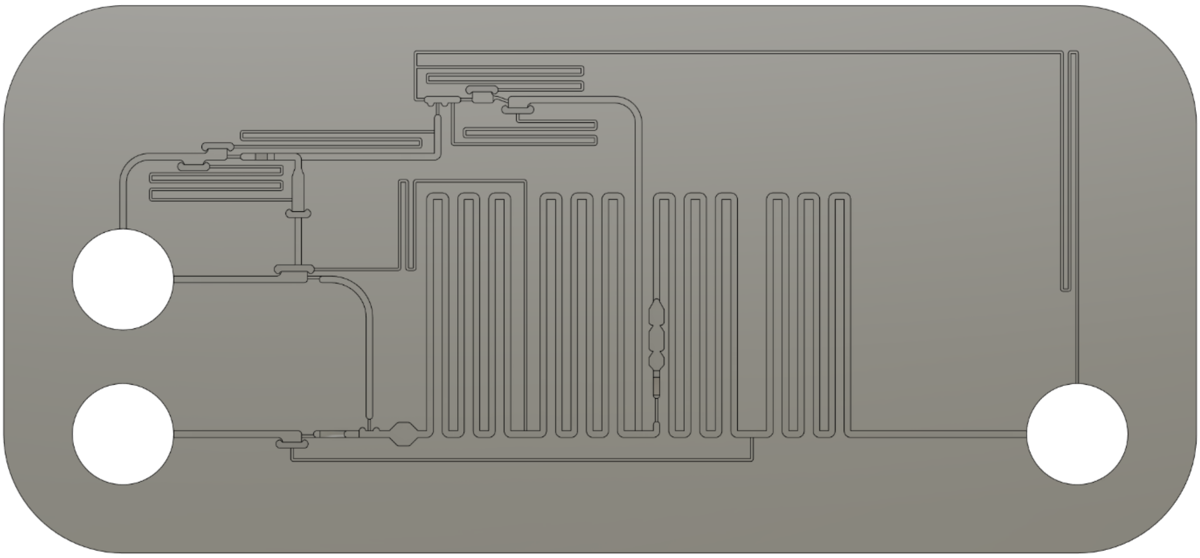
Part 3: Sequential Reopening

Once the main channel flow reaches the withdrawal trigger branches, the reopening of the rcFETs causes the ratios of the liquids within the observation chamber to return to its initial state.

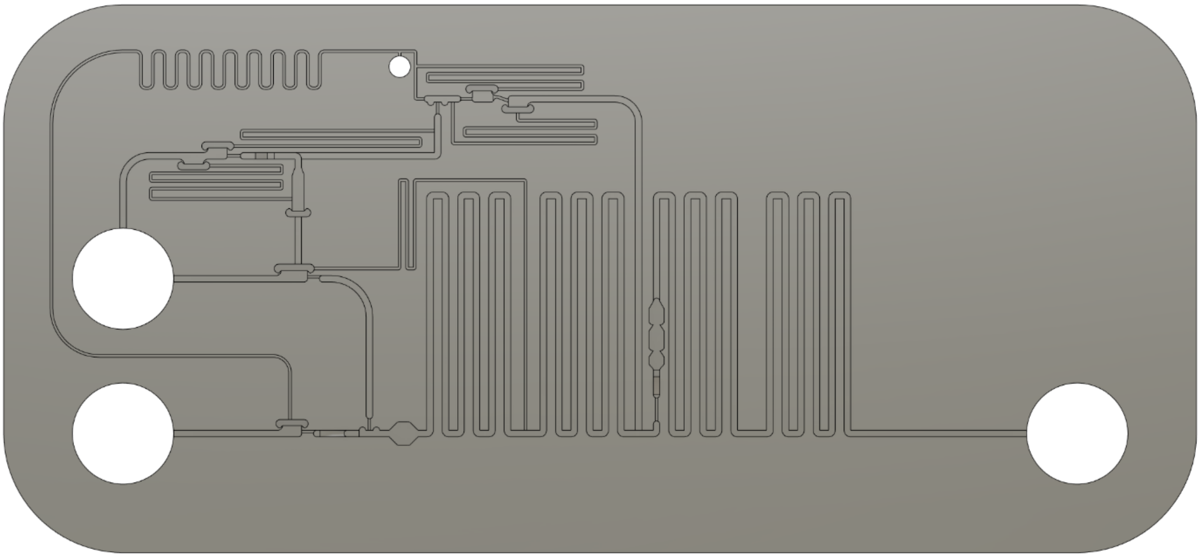
PART III: SUPPLEMENTARY CAD FILES



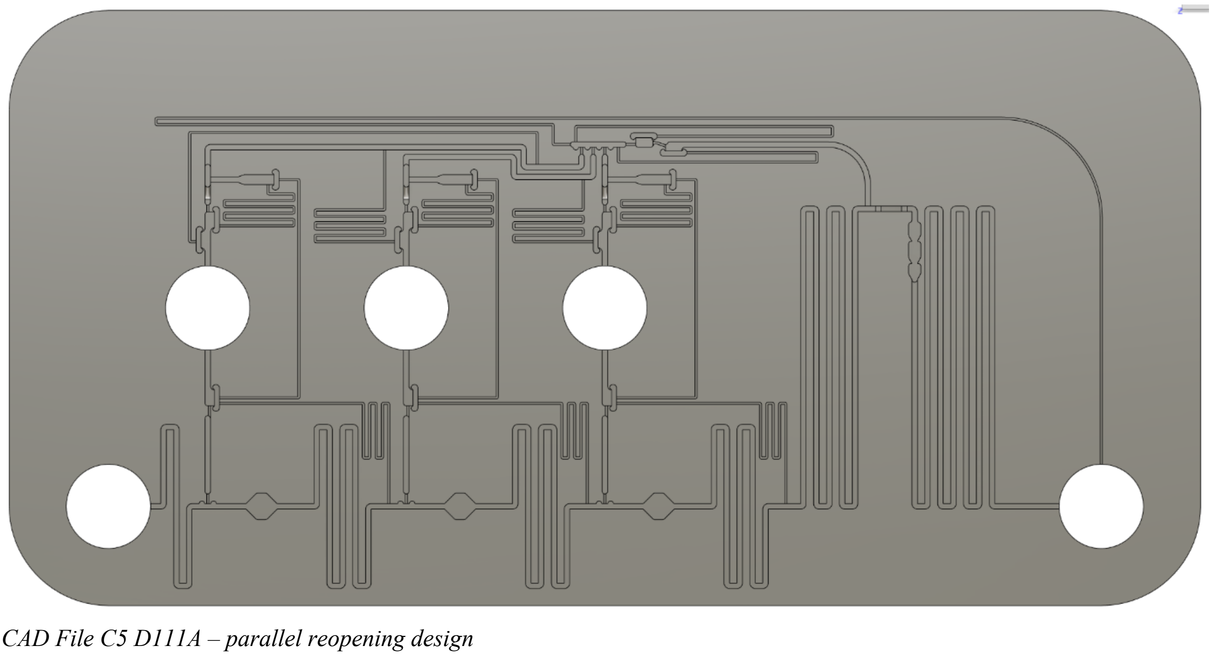
CAD File C2 D106H – proof-of-principle design



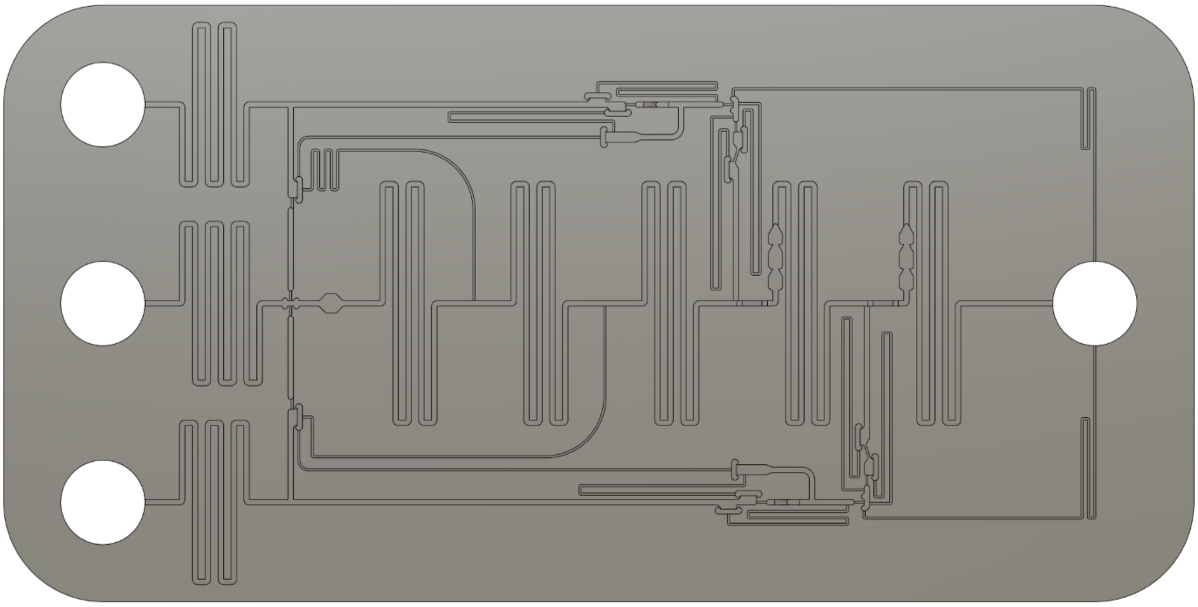
CAD File C3 D108Q – liquid mixing trial



CAD File C4 D115 – simultaneous activation design



CAD File C5 D111A – parallel reopening design



CAD File C6 D112 – flow oscillation design