Electronic Supplementary Material (ESI) for Lab on a Chip

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SUPPLEMENTARY DATA

Preparation of the layers and bonding were performed as described below:

Molds: The patterned molds were prepared on 6” Si wafers. SU-8 negative photoresist was used for the Source/NCV layer and Control layer and SPR220 positive photoresist (MicroChem) for flow layer molds. The channel heights (photoresist thickness) were controlled by rate of spin coating. Photoresist is then exposed to 365 nm UV light through the masks and subsequent baking and developing of the photoresist resulted in the patterned molds. These molds are then used to fabricate layers with features in PDMS.

Chips: All the layers were fabricated from PDMS (RTV-615 A&B Kit, Momentive Performance Chemicals). The mix ratio for the prepolymer to crosslinker used was 10:1 for all the layers. Parts A and B were mixed in a vacuum mixer (Thinky 2000) for 120 sec at 1200 rpm to avoid air entrapment. All the molds were surface treated with TMCS to keep PDMS from sticking to the molds surface.

The Source / NCV fill layer was fabricated by pouring RTV-615 on the mold and cured at 100^{o}C for 1h in a convection oven to produce ~4 mm thick patterned layer. The cured layer was peeled from the mold and manually punched for external connections. Flow layer and control layer molds were spin coated with RTV-615 ~30 μm and ~45 μm thick respectively, and cured separately. ~60 μm dia vias were punched on the layers to form layer to layer connections and then permenently bonded after alignment.

Fabrication of Normally closed valves:

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Normally closed valves were fabricated by post processing the normally open valves. The NCV fill channels crossing the bottom flow channel was filled with curable material, and flash cured with the valve in closed condition under pressure (Figure 2a). A low viscosity UV curable reactive acrylate monomer (ditrimethylolpropane tetraacrylate, SR355, Sartomer) mixed with 10% initiator (Esacure KT-046) was used as the UV curable filler material to fabricate NCVs. Curing was done by exposing the material to 365nm UV light (~275MW/cm2) for 2½min. NCV fabrication is performed at least a day after the fabrication of the chip to eliminate any undesired permanent bonding at the NCV resulting from residual surface activation during the chip fabrication.

Tuning the breakthrough pressure of the normally closed valves:

Since the static gain is directly dependent on the breakthrough pressure of the normally closed valve employed, it is possible to tune the gain to our requirement by simply controlling the BP of the valve. Breakthrough pressure of a NCV can be easily tuned during design and fabrication of the device and primarily depends on two parameters – (1) fill line pressure of the normally closed valve and (2) geometry of the valve. Higher fill pressure leads to bigger NCV structure which exerts more force on the valve and leads to a higher break through pressure. This is easier to understand when the NCV is visualized as flow channel blocked by a structure exerting certain force rather than an active pressure. Change in BP in relation to fill line pressure is shown in Supplementary Figure 1a. The cured NCV structure grows bigger, faster in the initial stages by spreading, making more contact and pinching into the bottom layer. This becomes unsustainable and the growth slows down since significantly higher pressures are required for the structure to grow beyond a certain

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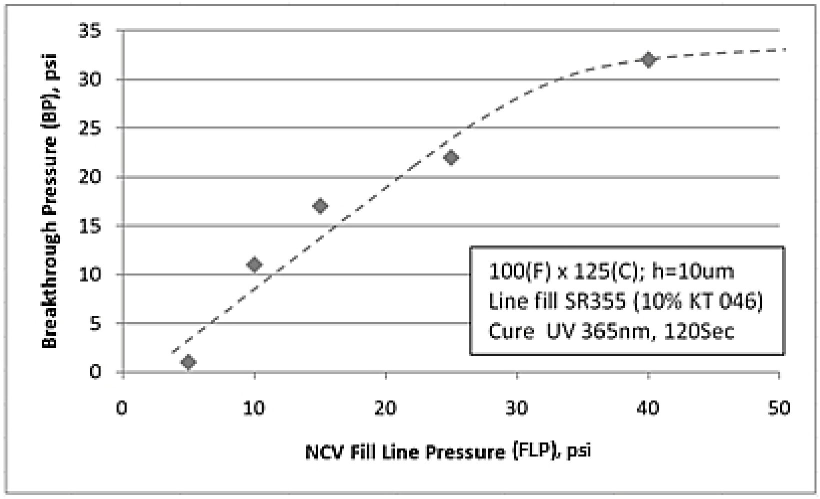

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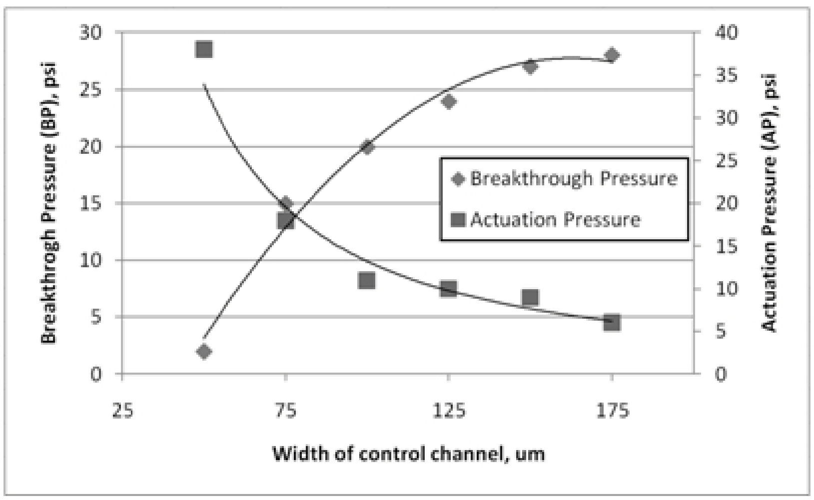

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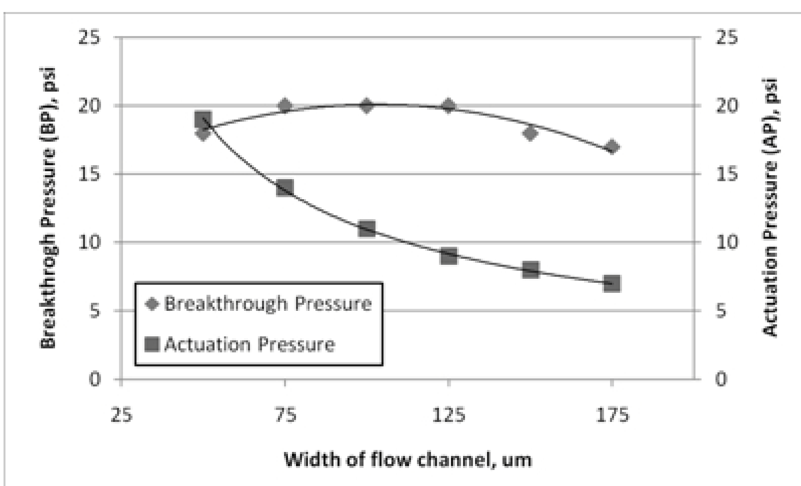

Supplementary Fig. 1. (a) Tuning the BP of a NCV by controlling the NCV fill line pressure (FLP).

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Increase in fill pressure results in a bigger, stronger NCV structure with more "pinch" which translates to higher BP. **(b)** Tuning the BP by varying the width of the control channel, and **(c)** Effect of varying the flow channel width on BP. With increase in flow channel width, the structure becomes stronger and exerts more force (increases the threshold force); however, the breakthrough pressure does not necessarily increase because of the increased force available resulting from increase in area pushed up by the flow channel.

size because of the constraining effect in the channel. The geometry of the valve from which the NCV is fabricated also influences the BP. Building the normally closed valves from bigger valves and thinner membranes leads to increase in BP for two reasons; (1) effective fill line pressure of the valves increases since the membranes deflect at lower pressures, and (2) the resulting valve structure is bigger, stronger and exerts higher force. Although the BP of the normally closed valve can be increased by increasing the size of the valve, we found that starting from a valve that has wider fill channel keeping the same flow channel cross section is a more effective method to increase the BP (Supplementary Figures 1b & 1c). This is due to the fact that a larger flow channel generates larger force at a given pressure (f=pa).

Hysteresis of static gain valve (SGV):

Figure 2 shows the difference in breakthrough pressure (BP = P_{flow}-$P_{control}$) for opening and closing of the SGV. We have observed that it takes a slightly higher (~3 psi) control pressure to close a SGV on a given flow pressure than to keep the SGV closed on the same pressure. We believe this is because when closing a valve on a flow, the flow pressure acts on both sides of the SGV membrane (upstream and downstream), whereas when a flow pressure attempts to push a SGV open, the pressure acts only on the upstream side of the valve membrane. Since we use signals much larger than 3 psi to drive the logic, this hysterisis has minimal to no effect on the fluidic logic elements described here.

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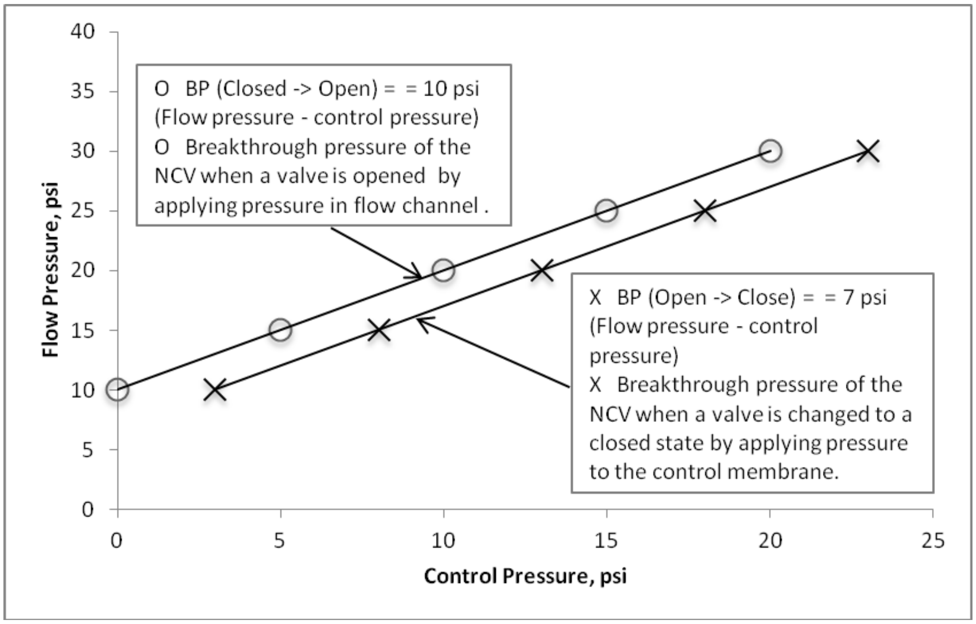

Supplementary Figure 2. Hysteresis data of a static gain valve.

Design:

Our devices were fabricated using standard multilayer soft lithography and consist of three functional layers – (1) Source / NCV fill layer, (2) Flow layer, and (3) Control layer. A fourth thick blank layer was used to seal the channels in the control layer. The cross sectional view of a gain valve is shown in Figure 1. Source/NCV fill layer (normally closed valve fill layer is ~4 mm thick and contains 45 µm high rectangular channel network (100 – 300 µm wide). This layer comprises of large chamber/channels and serve as large reservoirs for pressure source and drain for the entire chip by delivering the pressure simultaneously to all the source ports and connecting the drain ports to atmosphere. The NCV fill layer also contains the network of channels to fabricate all the normally closed valves. In this work all the external connections including pressure and atmospheric connections are made through punches (~700 µm) in this layer. Layer 2, the flow layer is 30 µm thick and consists of 15

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μm high, 100 μm wide rounded flow channels. This layer houses all the NCVs and and acts as the signal transfer layer; containing most of the logic circuitry. This layer also contains all the normally closed valves blocking the channel. The source port connections to the reservoir in the source layer, as well as any layer to layer connections for signal transport were made using ~60 μm vias. Layer 3, the control layer, is 60 μm thick and consist of 15 μm high squared channels. This layer contains the control membranes (300x300 μm, 45 μm thick) for the valves. The control channels receive the input signal from flow/signal transport layer (Layer 2) and deliver the signals to the membranes for the valve control. Layer 4 is a thick blank sealing (4 mm) layer that also acts as the substrate.

Testing:

Testing of the valves and circuits was performed by visual observation of the valves at the output under optical microscope. Controls were performed using a custom built instrument that has two independently controllable pressures and 50 solenoid valves. Devices were powered with the house pressure line modulated by computer controlled pressure regulators and solenoid valves. Iron Python programming on .NET 4 was used to write the operational instructions for the control of the control device. The operational speeds of complex circuits, such as the shift register were verified by video microscopy and observing the correctness of the output set of the instructions.

Oscillator – Frequency and amplitude control:

Amplitude and real time frequency control can be done by varying the (source) pressure **(Supplementary Figure 3a).** Frequency of the oscillator can be controlled by changing the

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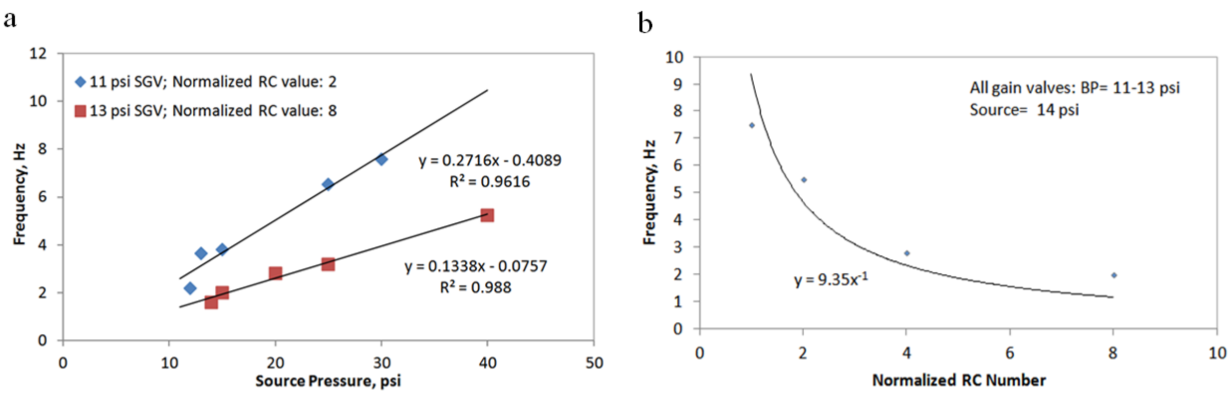
embedded resistance and capacitance (RC) (**Supplementary** F**igure 3b)**. The higher the RC, the lower the frequency and vice versa.



Supplementary Fig. 3a and b. Frequency change with RC and source pressure.

Flow rate measurements:

NOT gate: A high sensitivity flow meter (Omega FMA-1601A) was connected to the drain of a NOT gate to measure the air flow rate leaking to the atmosphere when the valve was open. The leak rate observed through the drain with source at 20psi was 0.2618 SCCM. The resistance of the drain determines how fast the output changes from 1 to 0 – larger the resistance, slower the switch, and smaller resistance faster the switch.

Shift Register: A flow meter (ALICAT M-5SLPM-D/5M) connected to the common drain line of the SR operating (pneumatically) with source at 25 psi (of which at least 26 of the 51 drains vent out at any given time) measured 0.29 SLPM through the drain to atmosphere.

Serial to parallel converter – Clock operation:

A gated latch was used to generate CLK and anti-CLK signals (Figure 4(d)). The input was vented to atmosphere with gate being controlled by a series of ON/OFF signals. When the gate was supplied with 0 (atm), the latch gives out 1 (p) on the inverted side and 0 (atm) on the

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buffered side of the latch. When the the gate was supplied with 1 (p), buffered side produces an output of 1 (p) and inverted side 0 (atm).