MICROFLUIDIC SERIAL DAC FOR ANALOG PRESSURE GENERATION

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ABSTRACT

Soft polymer microfluidics often requires control methods for on-chip flow. Traditionally, this control is provided by push-up or push-down valves regulated by constant external pressures. We present an on-chip method to generate analog pressures from a single external pressure source. This microfluidic pressure DAC (Serial to Analog Converter) employs a serial DAC architecture and can be applied to both flow control and pressure control applications. The microfluidic serial DAC has a 30 psi dynamic range and displays a linear 4-bit output from 0-10 psi at a cutoff frequency of 3 Hz.

KEYWORDS

Microfluidic, serial DAC, pressure regulation.

INTRODUCTION

The use of multilayer PDMS (Polydimethylsiloxane) microfluidics for the application of biological and chemical sciences has increased drastically. Nowadays, microfluidic setups can be used to precisely manipulate chemical reagents [1], perform complex biological processes such as PCR (Polymerase Chain Reaction) [2], and culture mammalian and bacterial cells [3]. To control the flow of fluids inside a multilayer microfluidic device, the predominant method remains the push-down or push-up valve that uses constant external pressure sources to collapse the flow channels above or below [4]. Even though two layer PDMS pneumatic valves provide robust performance and relatively fast actuation times, they do not provide the ability to partially restrict a flow channel without increasing the amount of off-chip control hardware. As microfluidic components scale, the quantity and complexity of off-chip pneumatic control would become limiting.

A similar problem in electronics is solved by introducing the DAC, where a constant external (digital) voltage is converted into many (analog) on-chip voltages. Taking pressure in the fluidic domain to be the analogous quantity to voltage and flow rate analogous to current, it would be ideal to borrow the same idea from electronics and create an analogous structure which converts a digital, off-chip pressure to analog pressures. The serial DAC architecture lends itself nicely for this application since it has a simple structure that requires only valves and capacitors (Fig. 1a). Therefore, we present, in the rest of this paper, a microfluidic pressure serial DAC that acts effectively on any incompressible liquids. We demonstrate a 4 bit working pressure resolution with a cutoff frequency of 3 Hz, higher than all previously published microfluidic DACs [5, 6].

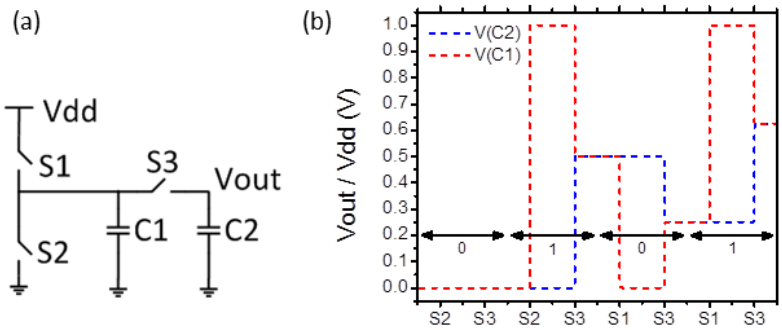


Figure 1. Operation principle of the electronic serial DAC. (a) Schematic of an electronic serial DAC. (b) Voltage on the two capacitors as a 4 bit digital code 1010 is passed to the DAC. Digital code is serially passed in starting from the LSB. Each event represents the opening and closing of a valve.

METHODS

Electronic serial DAC operates based on charge sharing. To send a bit, Vdd or Gnd is charged onto C1. Then, S3 initiates charge sharing. This process is repeated for each digit in a bit stream from the LSB (Least Significant Bit) to the MSB (Most Significant Bit) (Fig. 1b). For microfluidic serial DAC, switches are replaced by valves and capacitors by diaphragms (Fig. 2a). Pressure bits are passed in using similar valve actuation sequences. Instead of storing energy in electrical field, the fluidic capacitors store energy in the elasticity of PDMS membranes.

Fabrication uses the standard two layer soft lithography process. SU8 and SPR are used to pattern control and flow layer molds respectively. After lithography, the flow layer mold is baked overnight to facilitate reflow of the SPR resist, which produces a rounded cross section profile. Off ratio Sylgard PDMS is used to mold both layers on the silicon master. The layers are joined by thermal bonding at 80C. Push-up valves are employed to increase the dynamic range of the DAC to 30 psi (Fig. 2d). Finally, the two layer structure is plasma bonded to a glass slide. The cross section schematic and the top view of the fabricated device are shown below (Fig. 2bc).

To test the microfluidic serial DAC, all the cannels are first filled with water. Then, with a 10 psi external pressure source, a 4 bit digital code is passed into the DAC. This causes C2 diaphragm to deform. A 40X objective is used to focus on the center of the diaphragm before and after this deformation to record the vertical displacement of the membrane. Then, the external pressure source is applied directly to the membrane to reproduce the deformation as the source pressure value is adjusted. Such a test setup is used both to record the output pressure for each input digital code combination and the z displacement at the center of the membrane caused by different pressures.

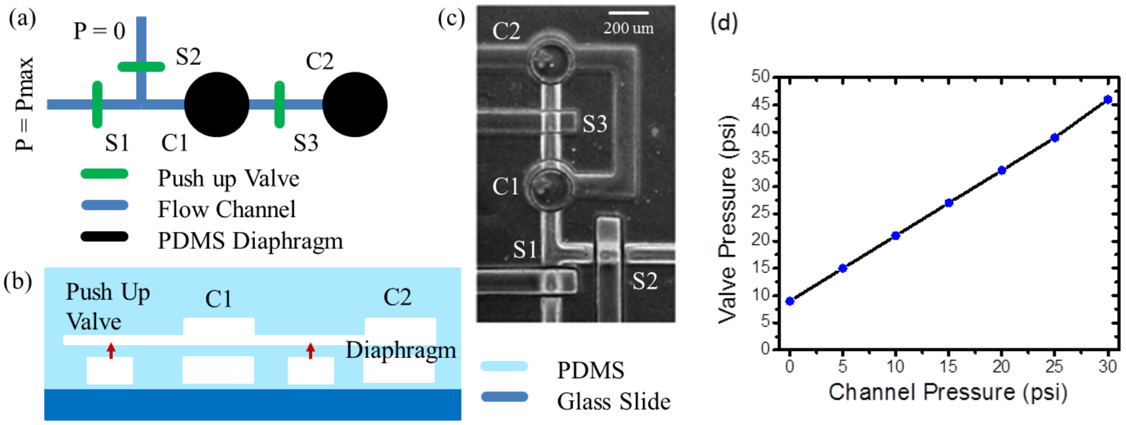
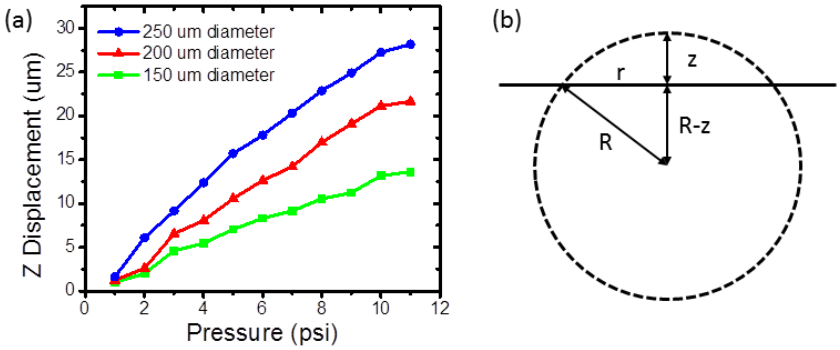


Figure 2. (a) Top view schematic of the microfluidic serial DAC showing membranes, flow channels, and valves. (b) Cross section view showing push-up structure. (c) Top view of fabricated PDMS device showing fluidic capacitors and switches. Switch numbers correspond to (a). (d) Dynamic range of the DAC depends on the ability to close pressurized flow channels. This DAC's dynamic range is at least 30psi.

RESULTS

Linearity of the DAC output is mostly affected by the linearity of the fluidic capacitors and how well C1 and C2 matches. To investigate linearity of the fluidic capacitors, we look at the dependence of extra volume of liquid stored for a selected pressure dV/dP. This dependence is further divided into dz/dP and dV/dz. Figure 3a shows that the center displacement of fluidic capacitor membranes are reasonably linear with respect to applied pressure for membranes whose diameters are 150, 200, and 250 µm. In addition, equation 4 shows that dV/dz is also linear when vertical displacement is smaller than the radius of the diaphragm, which is the case of the microfluidic DAC. Therefore, PDMS membrane in the microfluidic serial DAC acts as linear capacitors in the regime of our operation.



(c)

$$C_{fluidic} = \frac{dV}{dP} = \frac{dV}{dz}\frac{dz}{dP} \qquad (1)$$

$$V_{cone} = \frac{1}{3}\pi r^2 (R - z) \qquad (2)$$

$$V_{solid\ angle} = \frac{4}{3}\pi R^3 \frac{\Omega}{4\pi} \qquad (3)$$

$$\frac{dV}{dz} = V_{solid\ angle} - V_{cone}$$

$$= \frac{1}{6}\pi(z^3 + 3r^2 z) \qquad (4)$$

Figure 3. Linearity of PDMS membrane as microfluidic capacitors (a) Vertical displacement of the C2 membrane show linear response to pressure from 0-10psi. Different lines represent diameter of fluidic capacitor membranes. (b, c) Assuming circular membrane deformation assumes a spherical profile, the extra volume created by an incremental increase in z can be calculated (Equations 1-4). R is the radius of the imaginary sphere, r is the radius of the PDMS membrane, and Ω denotes solid angle created by R and R-z.

Mismatch in C1 and C2 often result from asymmetrical channels attached to these structures producing different parasitic capacitances. This mismatch can often be studied through simulation and compared to experimental data. By simulating the membranes and the channels using FEM (Finite Element Modeling), we confirmed the linearity of the volume verses pressure functions, as well as estimated the values of C1 and C2. The resulting C1:C2 ratios were 1.083, 1.174 and 1.5 for 250, 200 and 150 µm diameter membranes respectively.

We assessed the microfluidic serial DAC transfer function by investigating output linearity and frequency characteristics (Fig. 4). 4-bit digital input is used to create 16 analog output pressure levels between 0 and 10 psi. Devices with larger membrane diameters tend to display more linear output. This result is expected since larger membrane corresponds to larger linear capacitance and less parasitic effects from channels, which results in less mismatch. The vertical jump that occurs when the MSB is switched corresponds to a C1:C2 ratio of greater than 1, which is consistent with more channels attached to C1 and what we observed through simulation. Finally, the increase in output pressure corresponding to each input digital code as diaphragm diameter decreases can be explained by volume injection – the extra volume of liquid pushed into the fluidic chamber under the membrane when a valve closes. The injection of extra liquid results in more force applied to the membrane and thus a greater output pressure. To compensate sources of nonlinearity for an N-bit operation, 2N linearly spaced output levels can be selected from outputs using N+1 bits.

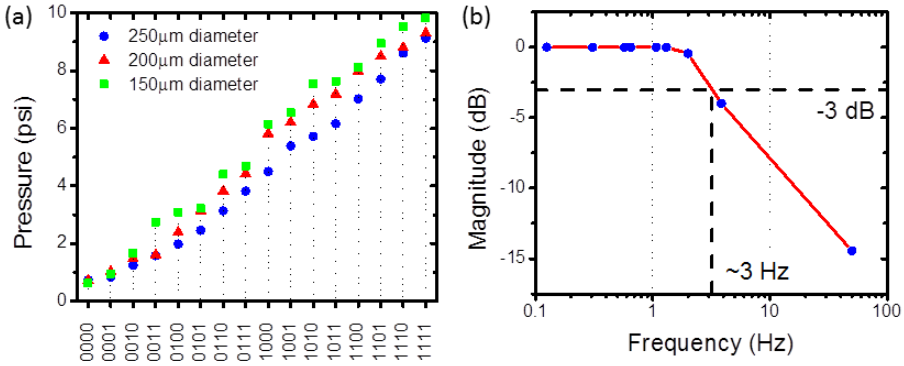


Figure 4. Microfluidic serial DAC measurement results (a) 4 bit digital input with various sized membranes from a 10psi off-chip pressure source. Larger diaphragms show more linear response. (b) Frequency response using a 10psi off-chip pressure source and an input 4 bit digital code of 1010. Cutoff frequency is extracted to be 3Hz.

Unlike other DAC architectures, the microfluidic serial DAC does not have an intrinsic resolution limitation. Theoretically it can achieve any resolution at the expense of speed. Therefore, tradeoffs between speed and resolution should be the criteria for selecting operation modes of the microfluidic serial DAC. As an example, a 4-bit digital input on a 200 µm membrane DAC produces a cutoff frequency of 3 Hz (Fig. 4b).

CONCLUSION

In this paper we demonstrate a microfluidic pressure DAC based on the serial DAC architecture. This device is compatible with standard 2 layer soft lithography. Therefore, integration of the serial pressure DAC into other 2 layer microfluidic devices will require no extra fabrication steps. The DAC can effectively provide more on-chip pressures with no addition of external pressure sources. It has a small form factor and demonstrates relatively linear transfer function, 3 Hz cutoff frequency, and a dynamic range of 30 psi.

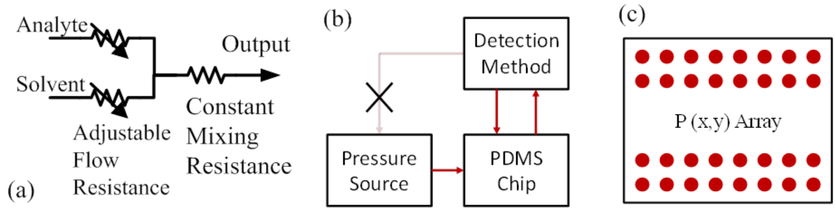


Figure 5. Possible applications for microfluidic serial DAC (a) Post fabrication adjustment of flow resistance (b) Close loop on-chip control (c) Analog pressure arrays using one external source.

Compared to previously published DACs that directly manipulates flow, the microfluidic serial DAC can be flexibly applied to flow-driven and pressure-driven applications. For flow driven applications, it can be used to adjust the flow resistance of each channel post-fabrication so that the concentration gradient does not depend on precisely matching channel geometries (Fig. 5a). Microfluidic serial DAC can also be used to provide close loop on-chip feedback of flow rates (Fig. 5b). Finally, physical or biological responses to different pressures can be studied with only one external pressure source using the pressure serial DAC (Fig. 5c).

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