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Electromechanical properties of pressure-actuated PDMS microfluidic push-down valves

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Abstract

Pressure-actuated PDMS valves have been characterized with respect to their electromechanical properties. Measurements of the valve opening and closing times, threshold pressures, and impedance spectra for closed valves can be used to assess the quality of the devices in general, determine their suitability for specialized applications, such as providing electrical isolated fluidic compartments for planar patch clamping, and specify ideal operating conditions. For our particular valve designs, we report valve opening times of the order of ten to hundred microseconds, making them suitable for rapid buffer exchange applications. They can effectively provide reversible electrical isolation between adjacent fluidic compartments with typical resistances of 5 GΩ in the closed state, which meets the gigaohm requirement for patch clamping applications.

Introduction

Microfluidics devices based on Polydimethylsiloxane (PDMS) have become an indispensable technology for the life sciences because they are quick, simple and inexpensive to produce through rapid prototyping and replication molding[14]. They also allow the facile incorporation of mechanically active features such as valves[9], pumps[6], and mixers[1]. Examples of applications and devices that rely on these active elements include cell sorting, flow cytometry[2], protein crystallization[3], microfluidic mixing[1], microfluidic cell culture on Braille-display controlled chips[4], drug discovery systems[5], and low-flow perfusion pumps[6]. Microfluidic patch clamping systems have a high potential to become an important tool for drug discovery[5], as they can provide a highly parallel platform to measure electrophysiological responses of single cells or single ion channels to chemical stimulation. To realize this potential, two key requirements must be met. First, cells need to be easily separated into electrically isolated compartments because the low currents involved in patch clamping require isolation in the gigaohm range[7]. Second, an effective reagent delivery system is needed that allows the rapid chemical stimulation of the cell through buffer exchange. In this note, we show that

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PDMS-based pressure-actuated push-down valves can meet these two requirements due to their superior electrical isolation and fast opening performance.

To this end, we present a comprehensive study of the electromechanical properties of pneumatically actuated PDMS valves in flow channels with integrated Au/Ti electrodes, including full impedance spectra for frequencies of up to 200 kHz. We have chosen to investigate push-down over push-up valves[8] for their inherent higher structural stiffness, which allows in turn faster valve opening for rapid buffer exchange applications.

Materials and Methods

Using conventional soft lithography replication molding techniques, we create two-layer silicone elastomeric chips with integrated pressure-activated valves[9,10]. The bottom layer contains 135 μm wide and 7.5 μm deep flow channels with rounded edges. They are separated from the upper control channel layer by a 40 μm thin membrane. Valves are formed at the intersections between the flow channels and the 130 μm wide and 10 μm deep control channels. They are actuated by pressurizing the control channel such that the membrane pinches off the flow in the channels underneath. The bottom of the chip is formed by 1 by 2 inch coverglasses that also carries the electrodes. The design layout of the chip is shown in Figure 1a. To fabricate the electrodes, the cover glasses are cleaned in piranha solution (3:1 solution of H_2SO_4 and 30% H_2O_2), and coated by vapor depositing 5nm of Ti followed by 55 nm of gold. The electrodes are patterned by conventional photolithography, using photoresist 9625 by Shipley and subsequently etched with Au etchant (Transene, TFA) and Ti etchant (HCl at 60 °C). The PDMS chip is then oxygen plasma bonded onto the patterned coverglass shown in Figure 1b, the electrodes wirebonded to external PC board contacts, and the assembled device is finally embedded with epoxy resin in an aluminum frame for mechanical stability and optical access[10], as shown in Figure 1c. The finished chip is prepared for use by priming the control channels with de-ionized water, which is necessary due to the permeability of PDMS to most gases. The flow channels are filled with aqueous 100 mM NaCl solution. The valves are actuated by applying air pressure to the fluid-filled control channels via a computer-controlled manifold.

Data on the dynamics of valve-opening and closing as a function of actuation pressure is acquired by applying a test voltage of 1 V to a pair of electrodes flanking the valve. The current through the valve during the opening and closing events is amplified by using a fast high-gain current amplifier (Femto, BW 10MHz, 100kV/A), followed by a 100-fold amplification and low pass filtering at 100 kHz using an instrumentation amplifier (Stanford Research Systems, Model SR560). The data is captured on a computer-controlled data acquisition card for further filtering, processing and analysis.

The impedance of the valves as a function of frequency is measured using a lock-in amplifier (Signal Recovery, 7265 DSP Lock-in Amplifier). The reference signal is applied to the electrodes flanking the valve with a voltage of 0.1 V (rms), while the frequency is swept across the frequency range of interest, from 1 Hz to 200 kHz. In this way data for open and closed valves, as well as control data for a dry flow channel were obtained.

Results and Discussion

Fig. 2 shows the complex impedance spectra for an open and a closed valve operating at an actuation pressure of 20 psi in 100 mM NaCl solution. For comparison, the impedance spectrum of a dry channel is also shown. Closed PDMS valves show impedances between 1 GΩ and 20 GΩ for frequencies ranging from 200 kHz to 1 Hz, and show a strong capacitive behavior. This contrasts sharply with impedances in the range from 50 MΩ to 200 MΩ for open valves. In comparison with the dry channel, however, it is noted that the impedance of the closed valves are generally lower over much of our frequency range. Overall, these observations suggest that PDMS valves can be used to reversibly isolate fluidic compartments on a chip with Gigaohm resistivity, as required, for instance, for parallel electrophysiological patch-clamp studies on microfluidic chips. In addition, a measurement of the impedance across a valve may provide a convenient way to assess the quality of a valve as a means of quality control for the manufacturing process. We also noted an aging effect that can result in a decrease in impedance of up to 15% when the chip is stored for more than a day with a filled flow channel. Therefore we suggest that the solution be vacuumed out before storage for subsequent reuse to minimize degradation of the PDMS walls and the valve membrane. We did not perform long term reliability tests of valve opening and closing because the embedded electrodes would only last for 3 to 6 hours of constant use.

Measurements of electric currents across the valve can also be used to measure the time it takes for the valve to open or close. For this aim, a DC voltage of 1V was applied to the two electrodes adjacent to the valve, and the current measured while the valve was repeatedly opened and closed. Figure 3a shows the trace of such a valve closing and opening, and Figure 3b a close-up of the rapid rise in current upon opening the valve. The most striking feature of these traces is that the valves open very rapidly – typically in less than hundred microseconds, whereas valve closing is significantly slower and often takes tens of milliseconds.

We also observe a large transient spike in the current when the valve is opened and ions are allowed to flow again. The transient spike in the current can be explained by looking at the electrochemical properties of the electrode – electrolyte interface. When a voltage is applied to the electrodes an electric double layer consisting of the Outer Helmholtz Plane (OHP) next to the electrode surface and a diffusive layer reaching into the solution is formed. These two layers can, from an electrical point of view, be approximated as two capacitors in series[11,12]. While the valve is closed, a double-layer is built up, charging the equivalent capacitors. When the valve opens, this charge is dissipated with a spike in the current. This picture is consistent with our observation that the height of the spike is closely related to how long the valve has been closed, i.e., how much of the double layer has been built up. Charge buildup reaches a plateau after six to eight seconds, which is sufficient for the ions to migrate approximately 10 μm at our field strength of roughly 300 V/m, resulting in a theoretical discharge of 150 pC in the spike. It is important to note that the spike magnitudes as a function of valve-closed times vary from valve to valve, and the time the valve has been operating for.

To further characterize the dynamics of valve opening, and closing, we measured the corresponding time constants as a function of actuating pressure. These times were determined from the current measurements as above, as the time from 10% to 90% of the maximum current. Ten replicates were averaged at each pressure, and the results are shown in Figure 3b and 3c. We find that the valve opening times vary relatively little with actuation pressure, except for a slight increase at the highest pressures. Valve closing, on the other hand, becomes substantially faster as the actuation pressure is increased. Perhaps at the moment of full closure, PDMS is most deformed and therefore more pressure is required to fully close it and more force related to elasticity is present at the point of max deformation.

The dramatic difference in time constants for valve opening and closing are likely caused by mechanical hysteresis of these valves. These hysteresis effects are demonstrated in impedance measurements of valve closure while first increasing and later decreasing the actuation pressure. Unlike Studer et. al.[13], we chose a quasi-static loading and unloading protocol in which the pressure was changed in 20-second time intervals from 0 psi to 25 psi, and back to 0 psi. This eliminates potential artifacts from the response of the external pressure-generating mechanism. The result is shown in Figure 3d. Minimum valve closing and opening pressures differed substantially. The valve closed when a pressure of approximately 11 psi was reached, and opened again when the pressure is decreased down to 8 psi. We interpret this result as sticking of the membrane to the bottom of the flow channel that allows some buildup of the solution near the valve wall and results in the quick opening. We believe that this explains the vastly different times for valve opening and closing.

This rapid mechanical opening of valve leads to a sudden disruption of the capacitive layers. This releases a typical spike charge of 150 pC which translates into nearly 9.47×10^8 ions accumulated over one electrode. This is more than sufficient compared to the total number of ions available in the aqueous 100 mM NaCl solution located on top of the measuring electrodes. Using the known electrophoretic mobility of the ions, we estimate that the Na^+ and Cl^- ions migrate at a rate of 1.8 and 2.8 μm/s, respectively, under an electric field strength of 333 V/m using a 1 V bias. This takes less than 5.5 s for the electrode to accumulate most of the ions within the channel of 10 nm of height, which is consistent with our experimental finding of a plateau time of 6-8 s.

Conclusions

We have studied the electromechanical properties of pressure-actuated PDMS valves. We have shown that they are effective in electrically isolating fluidic compartments on microfluidic chips and have in the closed state Gigaohm impedances over all relevant frequencies, as required, for instance, by parallel planar patch-clamping applications. In addition, such impedance measurements can also be used to characterize the valve for quality control applications.

We have used fast current measurements to characterize the dynamics of valve opening and closing, and report extremely fast valve opening in the ten to hundred microsecond range, whereas valve closing is significantly slower. This observation is consistent with a marked hysteresis in quasi-static valve opening and closing pressures. The rapid opening performance of these valves suggest that microfluidic platforms with pressure-actuated PDMS valves may be suitable platforms for rapid kinetic studies.

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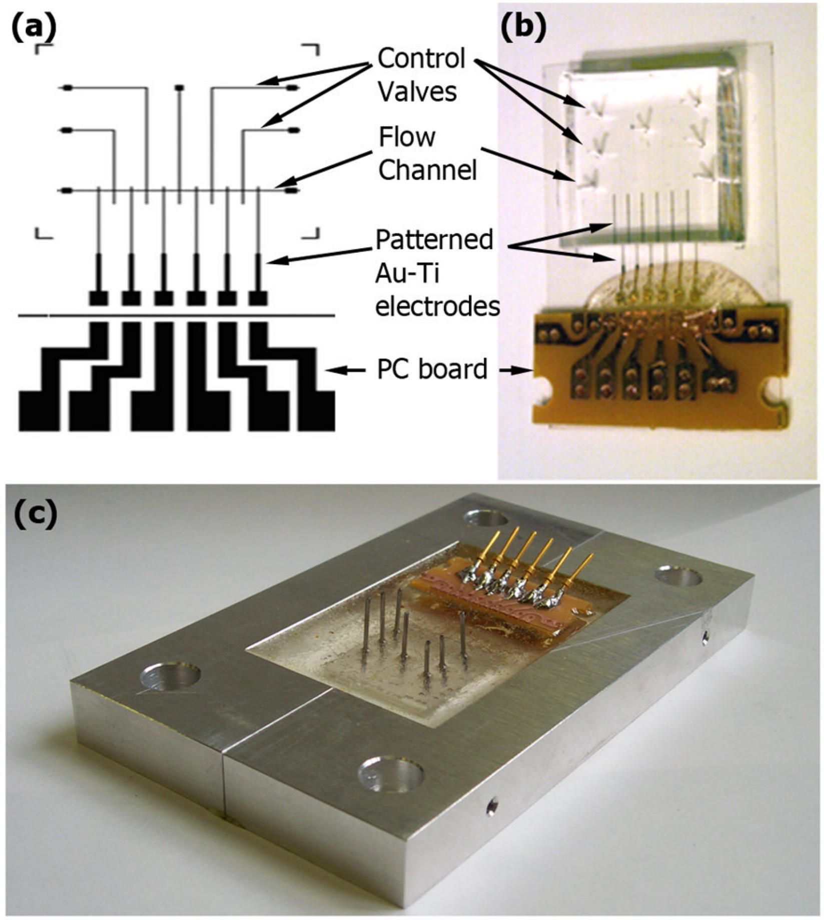

Figure 1.

(a) Layout of the microfluidic chip layout showing five valves, six electrodes, a main flow channel, and the external printed circuit board with contact pads. (b) The PDMS chip is oxygen plasma bonded onto the Au-Ti patterned coverglass. The electrodes are wirebonded to the external circuit board contacts. (c) Photograph of the finished device. The chip with its electric and fluidic interconnects is embedded in a block of epoxy resin for mechanical stability.

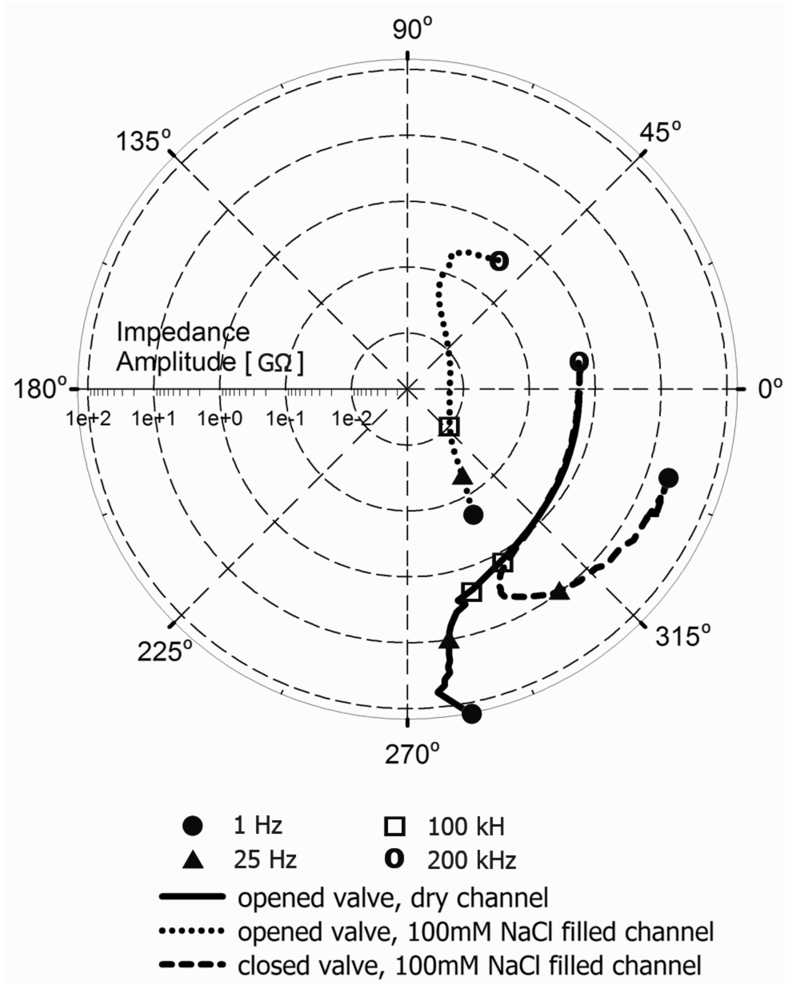

Figure 2.
Impedance spectra for open and closed valves, and a dry flow channel for comparison measured at 1 V. The data show Gigaohm isolation for closed valves over almost the entire frequency range of up to 200 kHz.

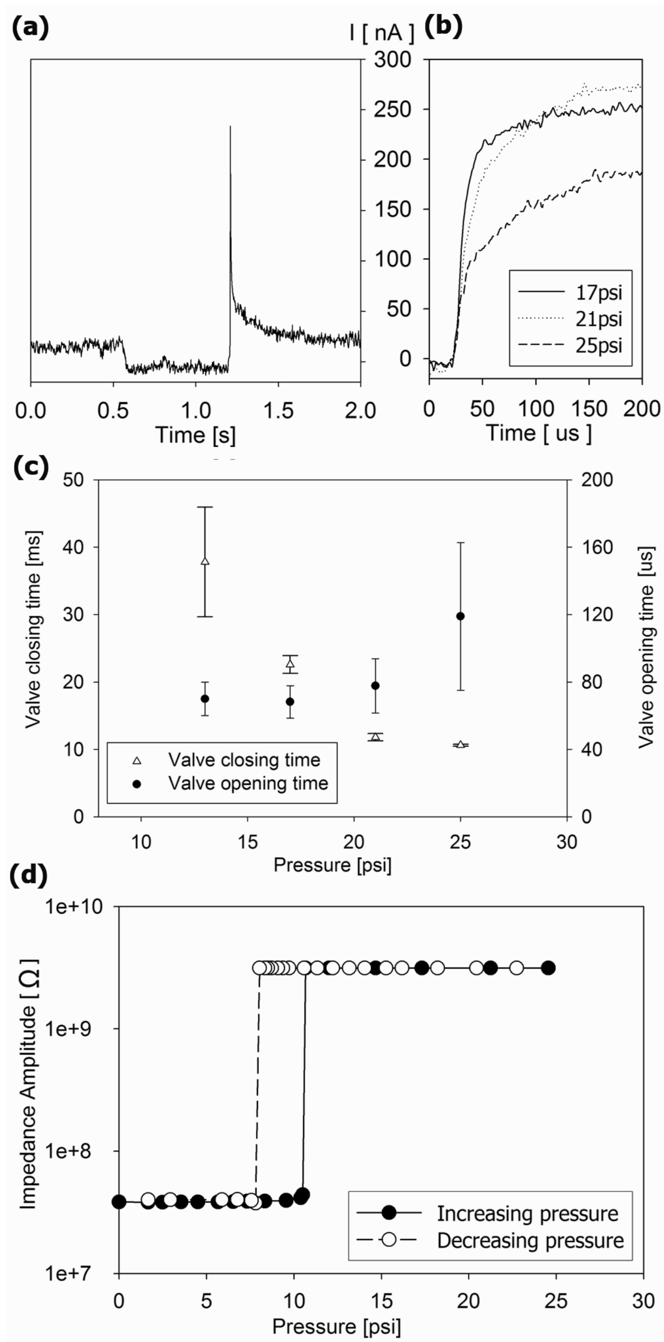

Figure 3.
(a) Measured current at a sampling rate of 1 MHz across a valve being closed and reopened. A typical spike is shown and this capacitive behavior is caused by the double layer ionic accumulation on the electrodes during the closed state. (b) Exploded view of the typical electrical spike from Figure 3a, showing that spike magnitudes vary from run to run using the same valve. (c) Valve opening and closing times as a function of applied valve pressure. Valve opening times can happen in the 100 μs range, 2500 fold faster than valve closing times, and depend on actuation pressures. (d) Measured hysteresis of the valve when valve pressure is stepwise increased and decreased. Each data point was measured using 1 V across the valve at a sampling rate of 50 Hz.