IONIC LIQUID ELECTROFLUIDIC PRESSURE SENSORS WITH EMBEDDED ANALOG AND DIGITAL CIRCUITY FUNCTIONS

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ABSTRACT
This paper reports a novel method to integrate pressure sensors with analog and digital circuitry functions into microfluidic systems based on ionic liquid (IL) electrofluidic circuits. The developed pressure sensors possess electrical readout and can be seamlessly embedded into the microfluidic systems. The entire device is fabricated using an elastomeric material, polydimethylsiloxane (PDMS), and the electrofluidic circuits are achieved by IL filled fluidic networks. The analog functions are constructed based on Wheatstone bridge circuits with output of the additive or subtractive results of the pressurized variable resistors. The digital functions are built using the electrofluidic circuits with on-off logic gates, of which the states are regulated by the applied pressures. The experimental results demonstrate the designed functions are successfully achieved, making it possible to develop an integrated microfluidic system with capabilities of precise pressure monitoring and further feedback control.

KEYWORDS: ionic liquid, electrofluidic circuit, microfluidic pressure sensor, analog and digital circuitry functions

INTRODUCTION
Microfluidic technology plays an essential role in the micro total analysis system (μTAS) with multiple manipulation and analysis capabilities in the decades [1]. A complete system should be the integration of actuators and sensors, and several actuation schemes of microfluidics have been developed for on-chip sample manipulation. However, the observation and sensing of microfluidics still heavily rely on optical methods, which have drawbacks including: expensive instrumentation, professional operation, and difficulties of scaling up and further signal processing. Moreover, it needs tedious interfacing to integrate sensors and implement feedback control in the existing microfluidic systems. Therefore, an advanced sensing method is highly desired. In this paper, we propose a new concept – ionic liquid (IL) electrofluidic circuits. The circuits efficiently achieve the analog and digital operations of pressures within the microfluidic systems and transfer the results to the electrical readout. Furthermore, the circuits can be seamlessly integrated with microfluidic systems made of elastomeric material, polydimethylsiloxane (PDMS). We use this concept to bridge the gap between microfluidic systems, pressure sensors, and basic electrical circuits, providing better monitoring and control capabilities to microfluidic systems.

DEVICE DESIGN
The device is composed of two PDMS layers: an electrofluidic circuit layer and a microfluidic channel layer, which are separated by a PDMS membrane. Electrofluidic circuits are constructed by filling ionic liquid into the electrofluidic channels with various geometries. Figure 1 shows the three basic electrofluidic components used to construct the electrofluidic circuits in this paper, including: constant resistor, variable resistor, and on-off logic gate. An electrofluidic channel filled with ionic liquid can be treated as a constant resistor at low frequency (in the order of hundred Hz). The resistivity of the resistor can be altered by changing the channel dimensions. A variable resistor can be constructed with a channel bonded to an elastic membrane, which can be deformed by pressure application. The resistance change of the variable resistor is linear to the pressure applied on the membrane and can be exploited as a pressure sensor [2]. Furthermore, on-off logic gate is achieved using a channel with a rounded cross-section and an elastic membrane. When the pressure is applied on the membrane, the electrofluidic channel can be fully closed by the membrane. As a result, the electrical connection is opened, and logic gate is switched from the conductive to the non-conductive states. The pressure threshold to close the channel is defined as the operation pressure, which is determined by the geometries and the mechanical properties of the channel and the membrane.

Figure 2 shows the electrofluidic channel designs for pressure sensors with analog and digital circuitry functions. The analog functions are achieved by taking advantage of the electrical characterization of the Wheatstone bridge circuit. The device is constructed using one constant electrofluidic resistor and three variable electrofluidic resistors for pressure sensing as shown in Fig. 2(a). An AC voltage, $V_r$, is applied across one diagonal of the bridge, and the output voltage, $V_o$, is measured across another diagonal. According to the operation of the Wheatstone bridge circuit, the change of the output voltage is proportional to the addition of the change of the opposed resistors or the subtraction of the change of the neighboring resistors. Because the resistance change is linear to the pressure change, the output voltage represents the addition of pressure $P_a$ and $P_b$ or the subtraction of $P_a$ and $P_b$. The digital functions are constructed using various arrangement of the on-off logic gates in the electrofluidic circuits. For the AND function, two logic gates are connected in parallel and then connected to a constant electrofluidic resistor with relatively large resistance. An AC voltage, $V_o$, is applied across the entire circuit, and the output voltage, $V_{o2}$, is measured across two parallel arms with the logic gates. Consequently, the output voltage equals applied voltage only when both gates are turned off, defined as state 1. Otherwise, conductive electrofluidic wire makes $V_o$ be ap-
proximately zero, defined as state 0. For the XOR function, two series connections of an on-off logic gate and a constant electrofluidic resistor are arranged in parallel as shown in Fig. 2(c). An AC voltage, \( V_a \), is applied across the entire circuit, and output voltage, \( V_s \), is measured across two terminals between logic gates and resistors. The output voltage \( V_s \) presents state 1 when only one gate is turned off, because one terminal is grounded and the other is connected to \( V_a \). In contrast, closing or opening both channels results state 0, because two terminals are both grounded or both equal to \( V_a \).

**EXPERIMENTAL**

The device was fabricated using the well developed multilayer soft lithography process (MSL). The devices were demonstrated to process the designed circuitry functions by various pressure applications and the electrical signal measurements. A personal computer with a data acquisition (DAQ) system (PCIe-6363, National Instruments, Austin, TX) and LabVIEW programs (Version 2009, National Instruments) was utilized to apply square wave voltage with amplitude of 2.5 V, frequency of 2.5 Hz and measure the output voltages of the electrofluidic circuits. For the analog addition function, pressure \( P_a \) was fixed at a value and pressure \( P_b \) was changed from 0 to 20 psi with the increment of 5 psi. In the experiments, three pressures \( P_a, 0, 5, \) and 10 psi, were sequentially applied to measure the output voltages under various \( P_a \). For the analog subtraction function, the measurement was done by a similar method as the addition operation. For the digital operation, four combinations of the pressures were used to demonstrate digital functions, AND and XOR. While the pressure exceeded the operation pressure, 5 psi, the channel was entirely closed and the state of the input was defined as 0; otherwise, the open state, electrically conductive state, of the input was defined as 1. Four sets, \((0, 0), (1, 0), (0, 1), \) and \((1, 1)\), were chosen to be applied on \((P_a, P_b)\) or \((P_c, P_d)\).

**RESULTS AND DISCUSSION**

Figure 3 shows the results of the analog addition and subtraction operations with various pressure combinations. The output voltage becomes a step shape when \( P_a \) is fixed, and \( P_b \) or \( P_c \) changes by 5 psi at one time. In the figure, horizontal red dot lines are drawn passing the same output voltage levels. These lines show the output voltages are the same while the addition or the subtraction results are the same even in the different combination of the applied pressures. Furthermore, these lines also represent that output voltage changes by 0.4 V once the analog calculating result of applied pressures is altered by 5 psi. As a result, the Wheatstone bridge electrofluidic circuit has been demonstrated to successfully perform the analog calculation of applied pressures.
Figure 4 shows the output voltages at different states for AND and XOR digital operations when applying various combinations of applied pressures. For the AND operation, zero output voltage, state 0, is measured while two applied pressures are both zero. As there is only one channel closed, the output voltage is slightly above 0 V (< 0.2 V), which is also defined as state 0. Once both on-off logic gates are pressurized to be switched off, the output voltage is raised to 2.15 V, which is the state 1. The results show that there will be output voltage only when both pressure sensors are pressurized, demonstrating the AND logic operation capability of the device. Furthermore, for the XOR operation, there will be output voltage when only one of the sensors is pressurized. The result demonstrates the digital function of XOR works well as designed.

**CONCLUSION**

The pressure sensors with fundamental analog and digital functions have been successfully constructed using the electrofluidic circuits in this paper. Two analog functions, addition and subtractions, have been implemented by the construction of the Wheatstone bridge circuit. Also, two digital functions, AND and XOR, have been built by the designed electrofluidic circuit with on-off logic gates, which are made by rounded electrofluidic channels. The proposed electrofluidic circuit concept is successfully demonstrated to efficiently transfer the pressure information to the electrical signal. Furthermore, the sensors and pre-processors can be seamlessly integrated into the microfluidic systems. The concept is promising to integrate these functions to build a large-scale electrofluidic circuit-based system with capabilities of precise monitoring and advanced feedback control capabilities.

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**REFERENCES**


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