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A Microfluidic Capacitance Sensor for Fluid Discrimination and Characterization

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Abstract

A microfluidic device with embedded capacitive sensing is proposed. The purpose of the device is fluid discrimination and characterization on the basis of the dielectric permittivity. The device is fabricated in a hybrid technology which innovatively combines PDMS (PolyDimethylSiloxane) soft photolithography and screen printing techniques. A microchannel, realized in a PDMS layer, is placed in the fringe field of a sensing capacitor formed by electrodes screen-printed on a glass substrate. Fluids inside the microchannel affect the capacitance that is measured by a tailored electronic interface system. Experimental results obtained for different fluids injected in the microchannel demonstrate the ability of the system to discriminate the fluids and estimate their dielectric permittivity both as pure samples and as mixtures at varying solute fractions. This makes the device a promising building block for fluid mixing monitoring in microfluidic systems.

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1. Introduction

Recent research on μ TAS (Micro Total Analysis Systems) and LabOnChip systems has led to a large variety of microfluidic devices for chemical analyses and biological applications. These devices are made by one or more microchannels where fluids and tissue particles can be manipulated and analyzed. Exploiting the micrometric dimensions of the microchannels, such devices advantageously require very small quantities of samples and can be fabricated with small dimensions, becoming a promising solution for chemical or biological analysis of expensive materials or in-field measurements [1].

The present work proposes a microfluidic device with embedded sensing fabricated in a hybrid low-cost technology which innovatively combines PDMS (PolyDimethylSiloxane) soft photolithography and screen printing techniques. The device has been developed with the aim to discriminate and characterize fluids on the basis of the dielectric permittivity [2]. This is obtained by means of capacitance measurements taken from sensing electrodes

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buried into the PDMS along the microchannel and isolated from the fluid. The dielectric permittivity of different fluids or mixtures affects the capacitance of the sensing electrodes measured by a purposely developed electronic interface system. A sequence of fluids with known permittivity have been pumped in the microchannel and the generated capacitance variations have been measured in order to verify the possibility to discriminate the different fluids. Moreover a possible application of this device in the characterization of fluids solutions has been conducted using this system to estimate the dielectric constant of a two fluids solution for different solute fractions.

2. System description

2.1. Microfluidic device

The device consists of a Y-shaped microchannel with a series of electrodes placed along its length as shown in Fig. 1. The microchannel has been fabricated in a PDMS layer using a standard soft photolithography technique. The microchannel is 200 μm wide, 75 μm high, and 25000 μm long for a total volume of 0.375 nl. The electrodes have been deposited on a microscope glass slide substrate by screen printing a conductive silver-based ink (DuPont 5000). After printing and baking at 150°C for 10 min, an electrode dry thickness of 25 μm has been obtained. A 100- μm thick PDMS layer has then been deposited on the electroded face of the substrate. This forms a planar surface and intermediate sealing layer for the superimposed PDMS upper layer containing the channel. The intermediate layer has been baked for 10 min at 70°C to partially cure the PDMS. The upper PDMS layer has been placed on top by a visual alignment process, using the microscope. Finally, the obtained stack has been baked for 2 h at 80°C to ultimate the sealing between the PDMS layers. The obtained microfluidic device presents three pairs of planar electrodes with the microchannel in between. The inner electrodes pair works as the measurement section, i.e. the sensing capacitor, while the outer pairs are electric guard sections [3]. The adopted length of 2 mm for the measuring section is a good trade off between spatial resolution and capacitance sensitivity to fluid dielectric permittivity.

2.2. Electronic interface

In order to perform the capacitance measurements a tailored electronic interface system has been developed and connected to the electrodes on the microfluidic device, as shown in Fig. 2. The electronic circuit drives both the sensing capacitance C of the measurement section and the capacitances of the guard sections with a sinusoidal voltage V_p at frequency f_p and generates a DC output voltage V_{meas} proportional to the value of C at f_p . To perform this operation, the transduction circuit is composed by a transimpedance amplifier followed by a demodulation stage. The transimpedance amplifier sinks the current from the sensing capacitor by connecting the terminal M to virtual ground, and converts it into a sinusoidal voltage V_o whose amplitude is modulated by C . This kind of input stage has been chosen to minimize the effect on the measurements of the parasitic capacitances of the connecting

Fig. 1. Microfluidic device: (a) top view layout with microchannel and electrodes; (b) cross section; (c) top view picture.

Fig. 2. Block diagram of the complete system with the electronic interface connected to the microfluidic device.

wires that can be orders of magnitude larger than C . The information in the V_o signal is carried back to DC in the demodulation stage, where a multiplication by V_p followed by low-pass filtering and amplification is performed.

The electronic interface has been dimensioned in order to obtain an overall sensitivity on the capacitance variations $\partial V_{meas}/\partial C$ of 40 V/pF at an excitation frequency $f_p = 400$ kHz. The signal V_{meas} is sampled and stored by means of a 16-bit data acquisition system connected to a personal computer. A dedicated program written in LabVIEW allows the visualization of the time behavior of the measured capacitance.

3. Experimental results

The device has been placed in the slide holder of an inverted microscope to allow visual observation of the flow in the microchannel. The system has been tested pumping inside the microchannel test fluids while measuring the capacitance variations.

In a first test distilled water has been pumped into the microchannel while measuring the capacitance variations from the reference condition of the microchannel filled with air. Two kinds of different flow regimes have been generated: continuous water filling at constant flow rate and segmented air-water flow. As shown in Fig. 3a with the continuous filling a linear increase in the V_{meas} signal, i.e., of C , is obtained which demonstrates the linear response of the system when the microchannel in the measurement section is partially filled with two kinds of different fluids. In the segmented flow a step-like behavior of the V_{meas} signal is obtained, as shown in Fig. 3b, where the low and high signal levels are related to the measurement section filled with air and water respectively. From the height of these steps in V_{meas} a capacitance variation of about 8 fF between the air- and water-filled conditions can be estimated.

Fig. 3. Measured V_{meas} versus time and corresponding snapshot pictures with two different flow regimes of distilled water colored with blue ink for better visualization: (a) continuous flow; (b) segmented air-water flow. (c) Measured V_{meas} versus time for step injections of four different fluids, where the signal traces have been superimposed for better comparison.

Fig. 4. (a) Normalized capacitance variation ΔC^* as a function of dielectric constant of fluid in the microchannel obtained by FEM simulations. (b) Estimated dielectric permittivity of ethanol-water solutions with different water volume fractions.

A second test has been carried out by injecting in the microchannel four different fluids with known dielectric permittivity values. In Fig. 3c the comparison in the V_{meas} signal steps due to air-to-fluid capacitance variations is reported. As it can be seen, the step magnitudes are clearly different and ordered as expected, thereby demonstrating the possibility to discriminate the presence in the microchannel of fluids with different permittivities.

The possible application of the presented microfluidic device in the estimation of the dielectric constant of the fluid in the microchannel ϵ_{fluid} has been investigated. To this purpose, a calibration curve obtained by FEM (Finite Element Method) electromagnetic simulations has been proposed. In Fig. 4a the predicted capacitance variations are shown as a function of ϵ_{fluid} in the range $1 \leq \epsilon_{fluid} \leq 80$. The limiting values are the dielectric constants of air and water, respectively, since most of the fluids involved in possible applications of the device have ϵ_{fluid} within such a range. The capacitance variation is reported as a dimensionless quantity normalized to the air-to-water capacitance variation taken as the reference, defined as:

$$\Delta C^* = \frac{C(\epsilon_{fluid}) - C(\epsilon_{fluid} = 1)}{C(\epsilon_{fluid} = 80) - C(\epsilon_{fluid} = 1)} \quad (1)$$

Ethanol-water solutions with different solute fractions have been injected in the microchannel in order to obtain steps in V_{meas} similar to those shown in Fig. 3c. From the step amplitudes the different capacitance variations as a function of the solute fractions have been derived. By using the calibration curve, the dielectric constant of the solution have been estimated, obtaining the results shown in Fig 4b.

4. Conclusions

A microfluidic device with embedded capacitive sensing has been developed to discriminate and characterize small amounts of fluid samples on the basis of the dielectric permittivity. The device is fabricated in a hybrid low-cost technology which advantageously combines PDMS soft photolithography and screen printing techniques. The experimental results demonstrate the possibility to use the device to estimate the dielectric permittivity of fluids or mixtures in the microchannel.

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