A Hydrophobicity Controlled Nanofluidic Pump

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ABSTRACT

In this paper, we present a nanofluidic device utilizing electrically controllable surface tension as the driving force to deliver fluid flow in the order of nano liters per minute or even smaller, without a dedicated actuator. This nanofluidic pump is capable of pumping a continuous liquid column. It also has a built-in metering feature to precisely determine the flow rate without an additional flow sensor. The physics of this micro/nano flow actuation is based on electrowetting-on-dielectric (EWOD) and depicted by Young-Lippmann equation. The device was prototyped by silicon and Pyrex 7740 glass to form a closed microfluidic channel, where the hydrophobic and hydrophilic electrode pads were fabricated alternatively along the fluid path. The experimental results show that water can be electrically actuated successfully to flow in the microchannel at a flow rate of 18 nl/min under a potential of as low as 20 V. This is very attractive for applications which require an ultra miniaturized metering pump operated at a low power.

Keywords: nanofluidic, pump, electrowetting–on-dielectric (EWOD), surface tension, hydrophobicity.

1 INTRODUCTION

From the beginning of the 1990s, the manipulation of fluid flow at micro/nano scale has been intensively investigated and surface tension has been proven to be a dominant force to provide micro flow control. Surface tension actuation of fluid motion needs approaches to actively control the interfacial energies in the system. Many methods for surface tension control have been studied and reported including the mechanical (surface roughness effect [1,2]), chemical (electrochemical effect [3]), opto-(photochemical effect [4]), thermal (thermocapillary effect [5, 6]) and electrical (electrowetting [7, 8], electrowetting-on-dielectric (EWOD) [9, 10]) method. However, precise control, further miniaturization and high power consumption etc., have been challenging tasks in fluids handling.

We demonstrate in this paper a method fully utilizing the electrically controllable surface tension as driving force in the micro/nano scale to deliver fluid flow without a dedicated actuator. It overcomes the limitations of the conventional pumps or actuators like the relatively bulky size, high driving voltage, high power consumption, further miniaturization difficulty, etc., which are mainly imposed by the actuators. It is very attractive for the applications which require an ultra miniaturized metering pump operated at a low voltage, such as environmental monitoring, chemical analysis systems, implantable medical devices, drug delivery systems and diagnostic systems [11].

2 DESIGN AND FABRICATION

Figure 1 shows a schematic cross-sectional view of the nanofluidic pump. This pump consists of a microchannel which is connected to a liquid reservoir. The top substrate is preferably made of Pyrex 7740 glass in order to visualize the flow motion in the channel. The bottom substrate can be either silicon or glass. Electrode pads are fabricated on both the top and bottom of the microchannel along the fluid path. Indium-tin-oxide (ITO) is deposited and patterned as the electrodes due to its transparency to facilitate visualization. A thin layer of hydrophobic coating is patterned to cover alternative ITO electrodes. These hydrophobic areas become hydrophilic by applying an electric field across the bare ITO electrode in contact with the liquid and the electrode underneath the hydrophobic coating, as shown in Figure 1.

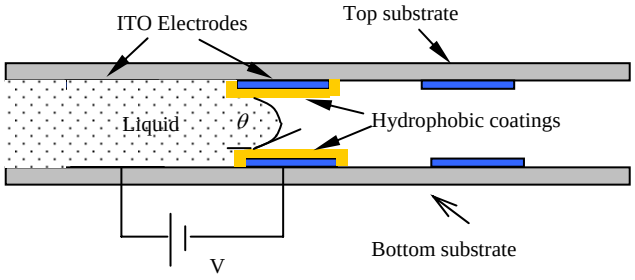

Figure 1. A schematic cross-sectional view of the nanofluidic pump.

The physics of this micro/nano flow actuation is based on electrowetting-on-dielectric (EWOD) effect and depicted by Young-Lippmann equation [12]. The microchannel surface (glass, native oxide and ITO) is naturally hydrophilic while the hydrophobic layers alternately coated on top of the ITO electrodes serves as the insulation layer to block the electron transfer under the threshold potential. Once the liquid fills up the reservoir, it will propagate into the microchannel because of capillary forces and pass over the bare ITO electrode until it stops at the 1st hydrophobic pad. As shown in Figure 2, upon applying an electrical field across the hydrophobic layer, a free charge distribution is built-up at the liquid-solid interface to generate an electrostatic force to pull the liquid column forward. After passing through the electrified hydrophobic area, the liquid column will continue to propagate under the effect of capillary forces till it meets the next hydrophobic electrode. Applying an electric potential again between this electrode and the previous one will start another propagation cycle. Throughout the pumping sequence, the liquid column driven by surface tension or electrostatic forces automatically gets rid of any unwanted air bubbles that may be present in the system.

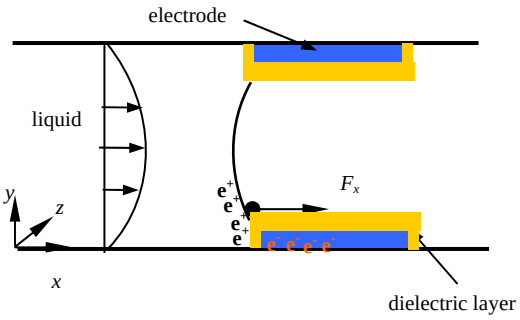

Figure 2. Charge distribution at the liquid meniscus upon application of electric potential and the electrostatic force (F_x) pulling on the meniscus.

A proof-of-concept prototype which was a chip level device, was fabricated starting with the bottom substrate. A thin layer of silicon dioxide of 500 nm thickness was thermally grown on a 4-inch (100) silicon wafer. A thin layer of conductive ITO was deposited and patterned by a lift-off process to form the electrodes along the length of the substrate at a pitch of 10 μm. A fluoropolymer, Cytop, was spin-coated at 3000 rpm to form a 700-nm thick layer over the electrodes. After baking and patterning, the residual Cytop was removed by oxygen plasma etching to form a hydrophobic Cytop coating on alternate electrodes. Cytop also served as an insulator. Then, a microchannel (100 μm wide and 20.2 μm high) was fabricated with SU-8 across the electrodes. On the top glass substrate, ITO electrodes and Cytop coatings were formed using the same method as for the bottom silicon substrate. Diamond drilling was used to make two holes in the glass substrate to form the inlet and outlet for the liquid. After dicing, the top and bottom substrates were placed on a customized bonder and aligned. Applying a certain pressure, the top and bottom substrates were bonded firmly at a temperature of 150°C. Subsequently, the bonded chip was attached onto a PCB electrically connected through wire bonding. The electrodes were individually addressable via the multiplexer electronics as shown in Figure 3.

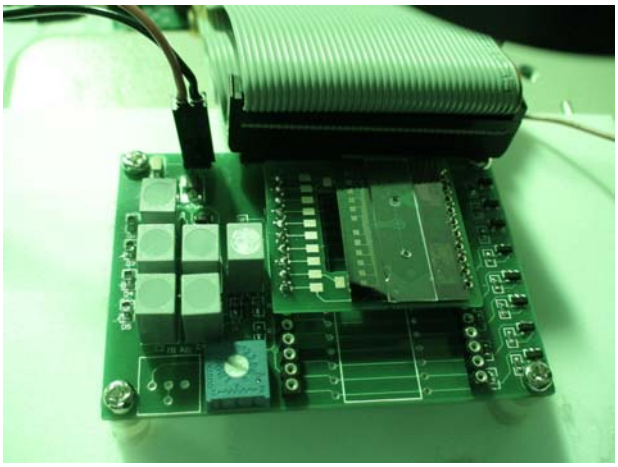

Figure 3. The completed nanofluidic pump attached to a PCB can be individually addressed by a multiplexer.

Since the electrodes can be individually activated consecutively, the volume of liquid pumped through the channel can be precisely controlled. The smallest volume of liquid which can be delivered in one propagation cycle is equal to the volume of the channel between two consecutive hydrophobic electrodes. Thus, the pumped fluid volume can be precisely determined without an additional flow sensor for metering the liquid flow. This is an innovative built-in digital metering feature of this nanofluidic pump which is not available in the other fluidic devices reported to date.

3. TESTING AND DISCUSSIONS

To test this device, it was first mounted on the glass stage of a stereo zoom microscope using polyimide tape. The positive terminal of a dual-channel DC power supply was connected to the Cytop-coated electrode while the negative terminal was connected to the bare electrode. A reservoir of water was introduced at the inlet of the pump and the experiment was videorecorded through a microscope and a CCD color video camera by a video cassette recorder at room temperature for subsequent image analysis.

Figure 4 shows one captured video image of the propagation of the water column through the microchannel. The water from the reservoir at the inlet of the microchannel initially propagated into the channel, driven by capillary forces, but was stopped at the 1st hydrophobic electrode, as shown in Figure 4(a). The leading edge of the liquid meniscus was used as a reference for the

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determination of displacement and velocity along the microchannel as its motion was much more easily observed. The liquid meniscus began to propagate when the applied potential reached 20 V as shown in Figure 4(b).

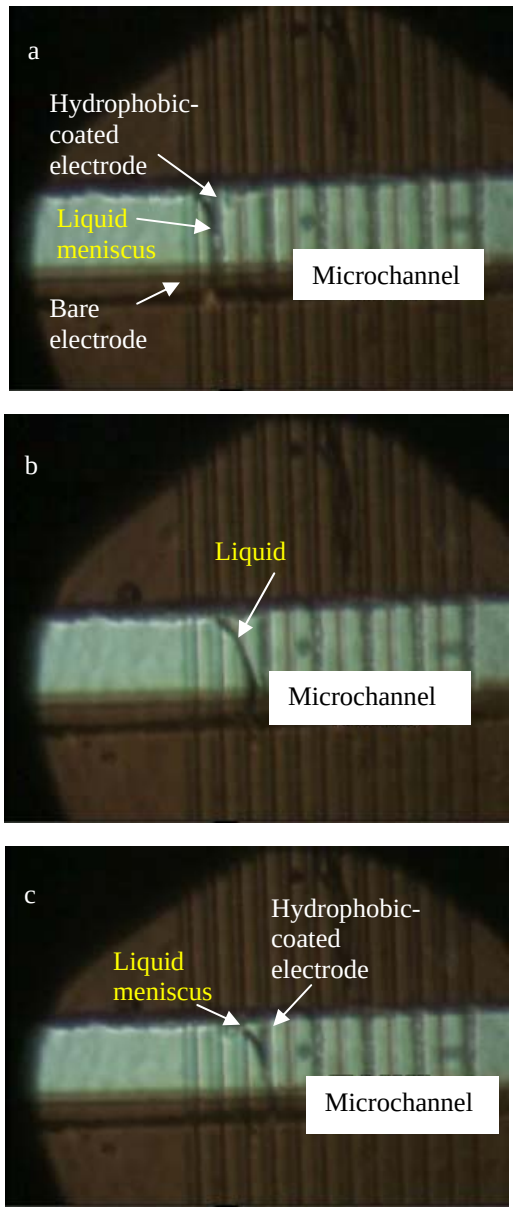

Figure 4. Video images showing the progressive advancement of the liquid meniscus along the microchannel from hydrophilic electrode to hydrophobic electrode.

Subsequently, the liquid stopped at the 2nd Cytop coated ITO electrode (the 4th electrode from left) as shown in Figure 4(c). Upon applying the electrical potential again across the 3rd and 4th electrodes, the liquid meniscus continued to propagate over the Cytop coated ITO electrode in the same manner as that described earlier.

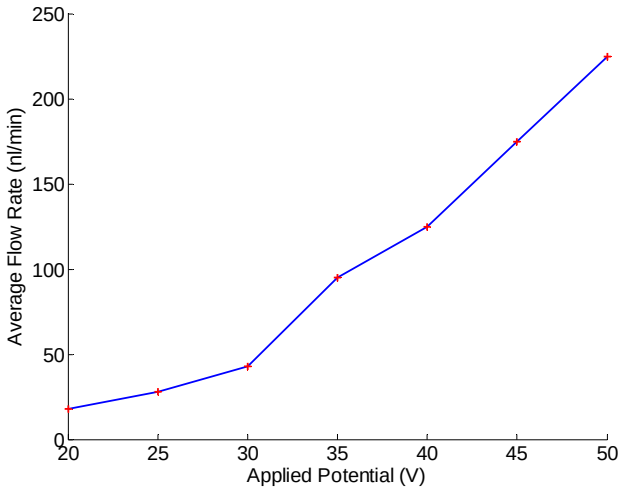

Figure 5. Plot of the measured time-averaged flow rate of liquid column as a function of applied potential. The experimental data are indicated by (+) and connected by solid lines.

Figure 5 shows the plot of the measured time-averaged flow rate of the liquid column as a function of applied voltage. The average flow rate was computed by measuring the time it took for the liquid meniscus to clear the length of the activated electrode pads and then dividing the pumped liquid volume over that period of time. It was observed that the liquid column did not begin to propagate until the applied potential reached 20 V. With the fabricated pump, a minimum average flow rate of 18.0 nl/min was measured at 20 V while a maximum flow rate of 225.0 nl/min was measured at 50 V with a standard deviation of approximately 9.0 nl/min.

4. CONCLUSIONS

In summary, we have demonstrated a micro/nanofluidic pump which can deliver liquid in the range of nano liters per minute. It has an innovative built-in metering feature which enables it to deliver a precise flow rate of liquid without a dedicated flow sensor. Its low power consumption (about 8 mW at 20 V) and the low voltage make it very attractive for applications which required an ultra miniature metering microfluidic pump. By optimizing the dielectric thickness and further miniaturizing the key dimensions of the microchannel and the pitch of electrode pads, the device performance characteristics can be tailored to suit the application required.

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