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Active surface tension driven micropump using droplet/meniscus pressure gradient

Roxana Shabani [a], Hyoung J. Cho [a,b,*]

[a] Department of Mechanical, Materials and Aerospace Engineering, University of Central Florida, Orlando, FL 32816-2450, USA
[b] School of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon 440-746, Republic of Korea

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ABSTRACT

An active micropump with a simple layout and no moving parts is designed and fabricated which has on demand flow on/off capability. The micropump is based on droplet/meniscus pressure gradient generated by electrowetting on dielectric (EWOD). By altering the contact angle between liquid and solid using an electric field a pressure gradient was induced and a small droplet was pumped into the channel via a uniform flow rate. A surface tension based propellant method was introduced as a low power consumption actuation method in microfluidic devices. The liquid contact angle on the EWOD substrate was measured vs. electric potential and was used to obtain the capacitance of the substrate by fitting Young–Lippmann's equation. The capacitance of the EWOD substrate was also calculated to be $10 \pm 0.6\ \mu F/m^2$ by measuring the dielectric layer thickness which showed excellent agreement with the former method. EWOD setup parameters such as capacitance, saturation contact angle, hysteresis contact angle and onset voltage were discussed. A coupled theoretical–experimental model was developed to predict how much voltage is needed to start the micropump for different droplet sizes. The modeling results revealed that for droplets with a radius smaller than 0.4 mm the droplet will start going into the channel even when no voltage is applied. For any larger droplet, a certain voltage is needed to start the pump. It was also shown that decreasing the size of the input droplet and increasing the voltage will result in an increase in the pump flow. A model for describing the shrinkage of the micropump input droplet was developed, based on direct observations, which was in agreement with the forced wetting described in literature. This model was compared to the other models used to describe passively pumped droplets and evaporating microdrops.

1. Introduction

Micropumps and microvalves are the key components in handling small amount of aqueous samples [1–3]. Their importance is recognized, especially, in the field of analytical chemistry, biology and medicine in which massive and parallel screening of aliquots with the limited amount of usable samples is to be performed or a limited amount of dose needs to be supplied with good accuracy. In such applications, small amounts of biological samples or chemical reagents are introduced and transferred to analytical units by means of micropumps and microvalves, followed by chemical reactions and biochemical processes such as immobilization, labeling and detection [4,5]. Micropumps have been categorized by means of actuation methods applied to drive the flow rate. The electrostatic, piezoelectric, bimetallic, electroosmotic and electrowetting (EW) actuation methods have been reported [6].

The performance characteristics of micropumps for biological and chemical applications depend on critical parameters such as power consumption, flow rate, biocompatibility, disposability and durability of mechanical moving parts. Micropumps consisting of moving parts such as mechanical valves and membranes for controlling or actuating the liquid may be prone to mechanical failure, and their complicated structure and associated fabrication cost are prohibitive to integration [7]. Micropumps with low fabrication cost and minimal mechanical complexity are highly desirable for designing disposable biochips which could be easily replaced once the sample analysis is completed [8]. Therefore design and fabrication methods of micropumps with no moving parts are one of the central points of research in the field.

Among various actuation techniques, the surface tension-driven method was shown to be well suited for droplet based transport devices due to its favorable scaling effect [8–10].

The surface tension force is linearly proportional to the length of the interfacial line between the liquid, air and the solid (wetting line) in which a droplet forms the boundaries of the wetting

* Corresponding author at: Department of Mechanical, Materials & Aerospace Engineering, 4000 Central Florida Boulevard, University of Central Florida, Orlando, FL 32816-2450, USA. Tel.: +1 407 823 5014; fax: +1 407 823 0208.
E-mail address: hjcho@ucf.edu (H.J. Cho).

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area on the solid surface. By scaling down the size of the system homogenously, the surface to volume ratio of the system increases and the surface forces which are negligible on macroscale become dominant on the microscale.

Although passive surface tension based micropumps are shown to be suitable for many applications [8,9], the ability to control the surface wettability to induce and stop the flow on demand would be highly desirable. The control of surface tension, by a temperature gradient in thermocapillary and by an electric potential gradient in electrocapillary, is implemented for micropumping [2,3]. However, electrocapillary in the forms of EW and EWOD are considered more power efficient than the thermocapillary [4]. EWOD is the most promising method due to the electrochemical inertness of the substrate and the ability to work with the non-electrolyte aqueous solutions. In EWOD phenomenon, the wetting properties of a hydrophobic surface could be modified by applying an electric field without changing the chemical composition of the surface.

Although EW and EWOD have been actively studied for a discrete droplet manipulation [11–14], to our knowledge an active micropump for continuous flows which takes advantage of EWOD has not been reported. The alteration of wettability as a propellant method could be combined with a valve to form a pump. However, the design and fabrication of a valve that could work with the actuating method and form a complete device remains challenging [1,15]. Most of the developed active electrical microvalves are driven by mechanical actuators [16]. In the proposed micropump, the flow could be turned on and off by switching the voltage on and off. On contrary to the previous works which used active mechanical microvalves for pumping, our device does not require any moving parts and is driven purely based on wettability of the surface which is altered by the electric potential. The key concept in our device is the linkage of this wettability control and the droplet/meniscus pressure gradient as a propellant method for driving a liquid in a microchannel. The power consumption is expected to be very small due to a very small current (<0.01 mA) associated with EWOD.

The biocompatibility imposes a limit on the type of the liquids which could be used for actuation in biomedical devices or induced chemical reactions. Although secondary transport liquid has been suggested as a solution for pumping water based solutions [16], the prevention of two liquids from mixing has remained an issue. Using the proposed micropump, aqueous solutions can be driven without using any electrolyte or secondary medium.

The EWOD micropump with its simple design could be used as a sample loading component in a disposable biochip. For example, it could be used to substitute syringe pumps for injecting samples into the plasma separators. Syringe pump is commonly used to fill the plasma separators with a sample [17–23]. Substituting it with a small scale disposable micropump is especially important when small amount of a sample needs to be used such as a blood sample or expensive chemical samples. The EWOD micropump could be easily integrated with the reported blood plasma separators in literature. The separators based on the Zweifach–Fung effect [17–19], geometric singularities [20], or large output channel [21,22], indicate the modular integration with the proposed pump is possible.

2. Materials, design and fabrication

The idea of the micropump was developed by direct observation of alteration of a water droplet's contact angle on hydrophilic surfaces such as glass or a silicon wafer with a native oxide layer, and hydrophobic surfaces such as a bare silicon wafer, fluorinated surfaces, or polydimethylsiloxane (PDMS) layers. The droplets with different contact angles would have different Laplace pressures due to the difference in their surface curvatures. A pressure gradient could be induced by altering the liquid contact angle on solid surface. As a low power consumption method for controlling the hydrophobicity of the solids and therefore inducing a pressure gradient, EWOD was employed. The EWOD-based micropump could be turned on and off on demand without any mechanical part and could work with non-electrolyte aqueous solutions.

In designing the micropump, it is assumed that the liquid of interest is applied in the form of a droplet using pipettes and syringes, which is a common protocol in chemistry. The size of the micropump is designed to work best with sample volumes on the microliter scale. The micropump chambers and channels are cast in biocompatible PDMS layer with low cost and simple fabrication process for disposability. PDMS is widely used in biological diagnosis lab on a chip in which transparency is required for optical measurement [24]. A single PDMS film is used both as bonding layer to the PDMS layer with a microchannel and the hydrophobic layer of the EWOD substrate. There are also other novelties in the fabrication process such as using spin on glass (SOG) as the insulating layer that could be applied in a very short time in compare to normally used dielectric layers in EWOD devices such as silicon dioxide.

2.1. EWOD substrate

The EWOD substrate of the micropump consists of a conductive layer which is used as the bottom electrode and a dielectric layer which insulates the liquid from the bottom electrode. A hydrophobic layer is formed on top of the insulating layer to put the meniscus in a non-wetting state before applying the voltage. A silicon wafer was used as the conductive layer. Other conductive substrates such as indium tin oxide (ITO) coated glass slides may also be used as the bottom electrode when a direct optical observation through the substrates is needed.

The electrical insulation was tested with both non-electrolyte and electrolyte aqueous solutions. The PDMS layer alone could not completely insulate the electrolyte solutions from the bottom electrode but it could be used to form a defect free underlayer for SOG film which could be used as a main electrical insulator. For instance, when a droplet of 1% KCl solution was used (instead of DI water), the generation of bubbles and the leaky current were observed on the single layer of PDMS or SOG, while those were not observed on the SOG/PDMS layer.

Prior to the deposition of the insulating layer the substrate was cleaned via AMD (acetone, methanol and DI water) or RCA cleaning step. In order to maximize the efficiency of the EWOD the insulating layer must be kept thin while maintaining the function of electrical insulator. The PDMS (monomer mixed with curing agent with a weight ratio of 10 to 1) was diluted in toluene (volume ratio of 1 to 3) and spin-coated at 6000 rpm for 10 min to suppress the effect of residual surface defects [25]. Then SOG was coated at 3000 rpm for 40 s to form a leak-free electrical insulating layer which could withstand relatively high EWOD voltages (Fig. 1a). Direct EWOD in which the voltage is directly applied to a droplet on the substrate was used to test the insulating layer. An ohmic resistor of 1 MΩ was connected in series with the EWOD substrate. The large resistor protects the system against any short circuit and at the same time could be used to measure the current. Since the resistance is large, any small leakage current due to the defects in the insulating layer will result in a large voltage drop in the resistor and could be easily detected.

The hydrophobic layer on top of the insulating layer increases the contact angle and therefore increases the pressure inside the liquid due to the increased liquid–air surface curvature. This is one of the major design considerations in our device in which the accessible range of contact angle is enhanced before applying the electric