Sensors and Actuators B 186 (2013) 343–352

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

High precision control of gap height for enhancing principal digital microfluidics operations

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ARTICLE INFO

Article history:
Received 2 April 2013
Received in revised form 30 May 2013
Accepted 6 June 2013
Available online 19 June 2013

Keywords:
Digital microfluidics
Gap height
Droplet transport
Droplet splitting
Variable volume dispensing
Capacitance measurement

ABSTRACT

A variable gap size actuation (VGSA) mechanism is integrated into the digital microfluidic (DMF) system. The VGSA mechanism serves to optimize the aspect ratio during performing different microfluidic operations by changing the gap height between the top and bottom plates. This in effect will have a direct impact on the four main DMF operations including droplet transport, splitting, dispensing and merging as they are greatly affected by changing the aspect ratio. Experimental results demonstrate that the VGSA mechanism significantly enhances the principal DMF operations by retaining the appropriate gap height for each operation which is also dependent on droplets volumes when using fixed electrode size. Specifically, varying the gap height precisely between the two plates will enable us to transport the droplets more reliably, control the volume of the dispensed droplet, carry out splitting and merging more effectively, facilitate motion of residual droplets resulting from splitting or partial evaporation, enhance mixing at faster rates, achieve accurate positioning of droplets regardless of their volume, and minimize evaporation without complicating the DMF system with the use of a filler medium. The proposed mechanism is realized by accurate positioning of the top plate over the fixed bottom plate, instead of maintaining a fixed gap height during the operation. In this work, an experimental setup is constructed for the proof of concept to meet precise alignment requirements of the two parallel plates using a feedback-controlled positioning system. Three different methods viz., visual, capacitance-based and encoder values, are used to measure the gap height between the two plates precisely. For practical lab-on-chip devices, micro-actuators in conjunction with capacitance measurement feedback can be used to position the top plate during the operation. In this way, the proposed VGSA mechanism will introduce a mean for optimizing the parameters controlling the DMF operations.

1. Introduction

Digital microfluidics (DMF) provides a promising platform for performing different chemical and biological applications [1,2]. Researchers nowadays are moving towards performing more tests on the DMF platform and every day new applications appear to be applicable on the DMF chips. The small size of the DMF platform makes this technology favourable for portable devices since it can be implemented into a handheld battery-powered device [3]. For this reason, the DMF platform characteristics make it compatible to work as a point of care testing devices as these devices offer the ability of testing near the patient.

Electrowetting on dielectric (EWOD) has gained a lot of interest for actuating droplets in the microscale [4]. A lot of research has been done to improve droplet actuation on discrete electrodes of the DMF systems. In order to study the droplet motion and the forces involved in actuation in the DMF system we need to know more about the electrical and fluid dynamics properties that affect the droplet motion.

Based on EWOD, several configurations have been used to manipulate droplets on a single plate [5,6] or between parallel plates [7,8] of DMF systems. Each configuration has some advantages and disadvantages. The main advantages of the open DMF systems is that it allows having direct access to the droplet, direct droplet dispensing, and lower friction by removing the upper plate. This in effect leads to higher droplet velocities. However, the uncontrolled evaporation and incapability of these systems to split the droplets are considered as the main disadvantages that limit the use of open systems in certain applications. The closed systems on the other hand, are more versatile as they can effectively handle all four basic and crucial microfluidic operations including transport, splitting, dispensing and merging [9] with controlled evaporation using silicone oil as a filler medium [8].

Different approaches have been adopted in the published research to improve these operations, for example, by improving the electrode shape design [10], use of different dielectric

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http://dx.doi.org/10.1016/j.snb.2013.06.029

materials in fabrication [11], varying electrode configurations in open systems [12], pre-charging for reducing the threshold voltage for actuation [13], active matrix actuation to decrease the number of addressing connections [14], and manipulating droplets on large array of small electrodes of thin film transistors (TFT) [15].

In this work, a mechanism for controlling the gap height between the top and the bottom plate is introduced by integrating a *xyz* feedback controlled micro-stage to demonstrate a new technique for enhancing the four basic microfluidic operations. The same technique can also be used to switch between an open and closed DMF system to benefit from the advantages of both on a single platform. The effect of the gap height on the microfluidic operations have been investigated in the past, but a mechanized gap height manipulation has not been examined as a way of improving the DMF performance and applicability to date. For example, Chen et al. [16] used aluminium foil as a flexible spacer between the plates to study the effect of changing the gap height within a small range (16–32 microns). However, this change cannot be used as an integral feature of the DMF system. Moreover, larger gap height changes are required to have a noticeable difference on the DMF operations and this might be the reason why no complete droplet motion has been achieved in their work.

2. Effect of changing the gap height on the DMF operations

Manipulating the droplets between two parallel plates is affected by several geometrical and electrical aspects. In the literature, the gap height is defined by the thickness of the spacers used and it remains constant during performing the microfluidic operations. The aspect ratio (h/L), where h is the gap height between the two parallel plates and L is the side length of the electrode, is considered as one of the important parameters that affect droplets actuation. The size of the electrode cannot be modified once the chip is fabricated. However, modifying the aspect ratio can be feasible by changing the gap height. Meanwhile, there is a preferable gap height range for performing each operation.

Accordingly, the following section will illustrate the strong relation between the gap height and the different DMF operations.

2.1. Transport

DMF system relies mainly on moving the droplets on discrete electrodes. Successive droplet motion is attainable as long as the droplet meniscus can reach the vicinity of the neighbouring electrodes. There is no limit on the maximum droplet volume that can be transported as the droplet can be stretched on more than one electrode. However, there is a minimum droplet footprint area required for having sequential motion of the droplets. This area is determined by the aspect ratio and the droplet volume. Though, as long as the aspect ratio and the gap height are defined by fixed spacers, there will be a limited capability to operate on droplets with defined volume and footprint area lower than a certain limit (where the diameter of the droplet is smaller than the electrode side length). Some techniques are used for increasing the overlap area between two electrodes by modifying the electrode design such as using inter-digitated electrode design [7].

Major forces acting on the droplet during motion will change significantly by changing the gap height and footprint surface area of the droplet. The shear force from the two parallel plates is one of the opposing forces that will increase by decreasing the gap height. This force can be accounted by the following equation [17]:

$$F_s = (2\pi r^2)\frac{6\mu U}{h} \tag{1}$$

where r is the radius of the droplet, μ is the viscosity of the droplet, U is the velocity of the droplet and h is the gap height between the two parallel plates. The friction force can increase by decreasing the gap height due to the increase in the droplet radius. This force can be calculated by the following equation [8,17]:

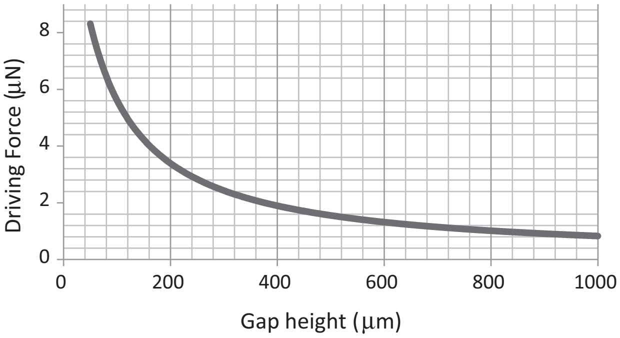

Fig. 1. The driving force acting on a non-conductive droplet versus the gap height.

$$F_f = 4\pi rU\zeta \tag{2}$$

where ζ is the contact-line friction. Likewise, the driving force on non-conductive droplet will increase by decreasing the gap height as shown in Fig. 1. This force is calculated by using the electromechanical model at different gap heights [18]. The electromechanical model is used as it accounts for the changes in the driving force when the gap height is modified in terms of the change in the droplet capacitance. The parameters used in generating this model are listed in Table 1.

According to the previous equations, changing the gap height and the droplet footprint area, in terms of the droplet radius, are going to affect the major forces acting on the droplet.

2.2. Splitting

Droplet splitting is considered as one of the critical DMF operations as there are strict electrical and geometrical considerations have to be addressed for performing successful splitting. The splitting process is used for different purposes such as dilution and changing the solution concentration [19], and purification after particle separation [20].

Previous studies showed the effect of the gap height on having successful splitting and mentioned that the gap height should be lower than a certain value to perform successful splitting [21]. Another study explained the splitting stages such as pinching, necking and cutting and verified that these steps occur at different aspect ratios [9]. Furthermore, the minimum voltage required for splitting must be exceeded in order to have two equal splitted volumes [22]. An approximate estimation for the maximum gap height required for splitting was found to be [23]:

$$h < -L\ \cos\theta_o \tag{3}$$

where θ_o is the contact angle when there is no applied voltage. Similarly, the electrical constraint for splitting can be defined by a

Table 1
The parameters used in the electromechanical model.

AC voltage used for actuation	100 V_{pp} (35.35 V_{rms})
Frequency of the AC signal	1 kHz
Electrode side length	2 mm
Droplet resistivity[a]	18 MΩ cm
Droplet permittivity[a]	80
Hydrophobic layer thickness[b]	50 nm
Hydrophobic layer permittivity[b]	2.1
Dielectric layer thickness[c]	1.5 μm
Dielectric layer permittivity[c]	2.56

[a] DI water.
[b] Teflon AF1600.
[c] S1813 dielectric layer.