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Improving the performance of electrowetting on dielectric microfluidics using piezoelectric top plate control

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ABSTRACT

An intelligent EWOD top plate control system is proposed in this study. The dynamic top plate is controlled by a piezoelectric (PZT) cantilever structure. A High resolution laser displacement sensor is used to monitor the deflection of the top plate. The gap height optimization and the top plate vibration significantly improve the droplet velocity and decrease the droplet minimum threshold actuation voltage. The top plate vibration induced actuation velocity improvement is magnitude and frequency dependent. 100 μm and 200 μm vibrations are tested at 25 Hz. Vibration frequencies at 5 Hz, 10 Hz, and 20 Hz are tested while the magnitude is 200 μm. Results show greater improvements are achieved at larger vibration magnitudes and higher vibration frequencies. With a vibrated top plate, the largest reduction of the actuation voltage is 76 V_{RMS} for a 2.0 μl DI water droplet. The maximum droplet instantaneous velocity is around 9.3 mm/s, which is almost 3 times faster than the droplet velocity without top plate vibration under insufficient driving voltages. Liquid that has different hysteresis such as acetonitrile with various concentrations are used as a control to show its compatibility with the proposed DMF chip. Contact line depinning under top plate vibration is observed, which indicates the underlying mechanism for the improvements in actuation velocity and threshold voltage. The top plate control technique reported in this study makes EWOD DMF chips more reliable when used for the clinical point-of-care diagnostic applications.

1. Introduction

Electrowetting on dielectric (EWOD) digital microfluidics (DMF) is one of the most promising lab-on-a-chip techniques [1]. With friendly interfaces to computers and microcontrollers, batch processing of droplet actuation [2], merging [3], splitting [4], position detection [5–7], droplet composition identification [8,9] and even volume controlled dispensing are all possible on a DMF chip [6,10]. EWOD DMF chips can be fabricated on low-cost substrates such as glass [11,12], printed circuit board (PCB) [10,13–15], polyimide film [16] and paper [17]. As the cost and size of the DMF chip decreases, the EWOD system can be integrated with portable electronics for point-of-care diagnostics [11,12,18]. Generally, a robust and clinically practical DMF device should have properties such as disposable DMF electrode card, efficient droplet actuation, low actuation threshold voltage, and high dielectric break down voltage.

Efforts have been made to lower the threshold voltage and speed-up droplet actuation. These efforts include reducing the liquid-dielectric interfacial tension [19], using the materials that have larger dielectric constant [19,20], using an oil environment [19–24] and decreasing the dielectric insulator thickness [19,20]. However, using an oil environment may contaminate the diagnostic chemicals; thinner dielectric layers are vulnerable to pinholes and dielectric break down. The droplet actuation velocity is mainly dependent on the roughness of the hydrophobic surface, the composition of the droplet, and the strength of the electric field. The droplet actuation velocity can be improved by using a single-plate topology to avoid the extra friction from the top plate [25]. Also, it can be improved using a silicone oil environment in a chamber to eliminate the contact angle hysteresis [26]. Additionally, modulating the driving voltages are reported to increase the actuation velocity such as using a single pulse [27], pulse train [28], AC waves [14] and pulse-width modified voltages [29–31].

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The top plate introduces more frictions and therefore requires a higher actuation threshold voltage. Another uncertainty introduced by the top plate is the aspect ratio [32], which is the ratio of the gap height to the droplet pitch. The aspect ratio has been reported in its significant influence on droplet kinetics [33,34]. Homogeneous gap height cannot provide optimized droplet operation if the droplets have various volumes. Conventionally, a double sided tape is used as the spacer for the dual-plate configuration [11,12,35]. The thickness of a layer of the standard commercially available double sided tape is roughly 50–75 μm. Adjusting the gap height by adding or removing the tape layers is too coarse for optimizing the system's performance. Thus, a continuously adjustable gap height is desired. So far the finest gap height control using a DC motor [33] suffers from a limited resolution (50 μm). In this study, the traditional DMF system is optimized using a quasi-static top plate to accurately adjusting the gap height and gently adding top plate vibrations. A precise top plate positioning technique is achieved by using two bimorph piezoelectric (PZT) cantilever beams. A cantilever beam is a rigid structure which has only one end anchored and another end is used to support the load. Cantilever structures can be found in both large constructions (such as bridges, buildings and aircrafts) [36,37] and small microelectromechanical systems (MEMS) [38,39]. The PZT plate can resolve sub-micron displacements. Piezoelectric actuators are widely used for accurate positioning tasks [40,41]. Controlled by the PZT actuator, the top plate can be precisely positioned and vibrated.

For more than 100 years, scientists have been fascinated with vibration induced droplet motions [42,43]. Vertical and horizontal harmonic vibration of the supporter can break the balance of the droplet and induce a liquid movement. The oscillating magnitude, frequency and phase dominate the vibration induced behaviors [42]. Different from the external substrate vibration, more powerful internal droplet oscillations can be created by surface acoustic waves (SAWs) [44–51]. However, the major concerns of using SAWs as actuators are the unpredictable rapid fluid flow and integration issues of the vibration source with the silicon and glass substrates in EWOD [52]. Substrate vibration was used to actuate a droplet on a surface with chemically wettability gradient [53]. A promoted droplet motion on a chemical gradient surface is realized by controlling a sandwiched structure which is similar to the popular DMF topology. In Daniel's study, a droplet ratchet-like motion is observed by continuously squeezing and relaxing the droplet. The contact line was depinned during the vibration and moves to the surface with lower interfacial energy. In electrowetting, a double layer of charges near the liquid-solid surface is formed by the electric field applied to the electrode [54]. The charge double layer lowers the surface energy which helps spread the liquid on the surface. Therefore, it is possible to use top plate vibration to overcome the surface hysteresis and lower the actuation voltage.

In this study, a PZT controlled DMF top plate is used to accurately define the gap height and provide vibrations to optimize the droplet operations on the proposed DMF system. The droplet actuation threshold voltage and velocity are tested with various top plate heights and top plate vibration magnitudes and frequencies.

2. Materials and methods

2.1. System design

Precise gap height control can be realized using two PZT cantilever beams. The EWOD chip (37.5 mm × 37.5 mm with 27 electrodes) is fixed on a PCB platform (Fig. 1(a) and (b)). The top plate is mounted to two PZT plates which are fixed by two binding posts. The on-chip chromium pins are connected to stranded wires using silver conductive epoxy. The top plate ITO (indium-tin-oxide) layer is grounded all the time for proper droplet operations. A high voltage module purchased from EMCO (EMCO F40, Schweiz, Switzerland) is used as the high voltage source to provide the driving voltages to the PZT chip and the EWOD electrodes. The great benefit of using EMCO and the simple CMOS gate arrays as the EWOD driving circuit is saving the space of using bench function generators & amplifiers. Laser displacement sensor (Z4M-S40, Kyoto, Japan) and its manufactural amplifier (Z4M-W40, Kyoto, Japan) are used to monitor the PZT displacement. The laser displacement sensor can perform high resolution (100 nm), broad bandwidth (1 kHz) and contactless displacement measurement. Fast and precise displacement data can be acquired without affecting the mechanical vibration properties of the structure. The output voltage from Z4M-W40 is 0–200 mV, a second stage amplifier is required to levitate the voltage level for the ADC (ADC, 0-3.3 V) (Fig. 1(c)). A desktop PC (ASUS, Intel i5 2.53 GHz, RAM 8 GB) is used for data collection and sending feedback driving voltages to the DAC & MCU module. The DAC translates the digital driving voltages to 0–2.54 V. An additional linear DC high voltage amplifier is developed to modulate the 0–2.54 V to 0–200 V to drive the PZT plates. The feedback loop can be automatically controlled by the software built in the PC, or visually controlled by a person if needed.

A novel modular design is introduced to the EWOD system. The EWOD electrode control system is integrated into two portable modules (Fig. 1(b)); one is the relay array, the other one is the control hub. The EWOD chip is mounted on a PCB platform and connected to the relay array module with standard flexible flat cables (FFC). EWOD electrode driving voltages are obtained from the drains of the high-voltage CMOS transistors (Fig. 1(d)). Various frequencies of the actuating voltage can be obtained by toggling the gates of the transistors with different rates [5,8,13] (DC pulses at 10 kHz and various voltages).

2.2. The DMF EWOD chip fabrication

Devices were fabricated in the cleanroom facility of Nevada Nanotechnology Center at University of Nevada, Las Vegas. The fabrication reagents includes Schott Boro Float glass substrate with Chrome coated (100 nm) microfluidic blank slides (with positive photoresist coated, Telic, Valencia, CA, USA), Teflon-AF solution (amorphous fluoroplastic resin in solution, 400S2-100-1, DuPont, Mississauga, ON, CA), photoresist developer RD6 (Futurrex, INC., Franklin, NJ, USA), Chromium etchant (Sigma-Aldrich, Co., MO, USA), photoresist remover (Microposit Remover 1165, Rohm and Haas Electronic Materials LLC, MA, USA), indium tin oxide (ITO) coated glass (Adafruit INC., NYC, USA). Open source integrated circuit (IC) layout tools Electric VLSI [55] is used to pattern the mask of the electrode array. GDSII output files from Electric VLSI are sent to Infinite Graphics INC. (MN, USA) for plotting (25,000 dpi). During the photolithography process, the substrates are covered by the patterned photomask and exposed to a UV light source for 45 s and then developed for 1 min in RD6. Substrates are then immersed in the Chromium etchant for about 15–20 s. Then the substrates are washed by DI water and dried out using nitrogen gas. The remaining photoresist is removed by Microposit Remover 1165.

It is more challenging to realize the droplet actuation, merging and splitting in an air environment rather than in an oil environment. The oil environment in the EWOD chip, to some extent, is more tolerant to dust. Also, without an oil environment, the two major microfluidic kinetic resists, the contact line pinning and contact angle hysteresis (CAH), become much more significant to prevent the droplet from being actuated. To realize a smooth actuation in air, larger electrostatic force is required. A morphological representation of the electrostatic force is the contact angle change. Obviously, the driving voltage has to be limited within the dielectric material break down voltage. Among all the candidate insulator