Low-cost and flexible film-based digital microfluidic devices

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Published in Micro & Nano Letters; Received on 12th June 2019; Revised on 18th November 2019; Accepted on 29th November 2019

This work proposed a low-cost and rapid fabrication approach for flexible thin film-based digital microfluidics. In this approach, the carbon electrodes were screen-printed on the surface of a polyester film using carbon resistive ink. Then, a layer of polyethylene was applied to seal the polyester film with electrodes. Finally, a surface treatment was conducted to enhance the hydrophobicity. Compared with the conventional fabrication approaches for digital microfluidic devices using metal electrodes deposition on glass/silicon substrate, the proposed fabrication technique for polymer-based digital microfluidic device is simple, low-cost, flexible, and without the requirement of sophisticated photolithography procedure, metal deposition instruments and cleanroom environment. The proposed polymer-based digital microfluidic device has a total thickness <200 µm. The whole device is transparent, flexible and bendable. A series of tests were also conducted for the manipulation of water droplets using electrowetting on the fabricated digital microfluidic devices. The proposed fabrication technique for flexible film-based digital microfluidics could have wide potential point-of-care applications in biological and medical filed.

1. Introduction: Microfluidics has been widely used in biological and chemical fields for various applications. Unlike conventional microfluidic devices handling continuous flow with microchannels, valves and pumps, the digital microfluidics (DMF) is handling the discrete liquid droplets with the volume of microlitre or even picolitres [1]. Each of these droplets is an isolated capsule for biological or chemical reactions. The complicated droplets merging, splitting, mixing and dispensing process could also be conducted with the DMF devices for various applications. Typical DMF devices usually consist of several layers: substrate layer, electrode layer and dielectric layer. With the different layer configurations, the DMF devices are usually classified into open (droplet exposed in open-air) and close (droplet sandwiched between two substrates) configurations. DMF has a broad range of applications in cell handling [2, 3], DNA amplification and detection [4, 5].

The most commonly seen DMF device usually included the substrate layer, electrodes, dielectric layer and the hydrophobic coating/layer [6]. For the choice of substrate, various materials have been used based on different applications. The most commonly used substrates include PCB board [7], ITO glass [8], silicon/glass wafer [9], and even paper [10] could be used as the substrate for the low-cost approach of DMF. For electrodes, based on the choice of substrate, electrodes could be fabricated with gold [11], copper [12], silver [13] and carbon materials [14]. For the electrode fabrication process, sophisticated instruments, e.g. photolithography/etching instrument [15] and metal sputter [16] were commonly used. The dielectric layer is used for the electric isolation between electrodes and fluid droplets. The dielectric layer has a much more border choice of materials, e.g. PTFE [17], Parylene C [18] and SiO_2 [19]. For the patterning of the electrodes and isolation layer, previous fabrication approach usually involved a complicated procedure with sophisticated microfabrication instruments, which has a barrier for users with limited background in microfabrication.

In this Letter, we proposed a low-cost and rapid fabrication method for flexible thin film-based DMF devices. The polyester film was used as the substrate material with the screen-printed carbon electrodes, and another thin polyethylene film was used as the dielectric (isolation) layer with a surface treatment process to enhance the hydrophobicity. A series of droplet manipulation tests were also conducted in this Letter. Compared with the conventional approach for the fabrication of DMF, the proposed method is simple, low-cost, rapid and without the requirement of sophisticated microfabrication instruments. In addition, the fabricated devices are also optically transparent and bendable. The proposed fabrication approach could have board application potentials in point-of-care diagnoses.

2. Fabrication

2.1. Materials and instruments: The carbon resistive ink (C-200) for the screen printing of electrodes were sourced from Applied Ink Solutions, Massachusetts, USA, with surface resistance around 30 Ω/square/mil. The material used in this Letter to enhance the hydrophobicity on the dielectric layer is Rain-X water repellent, ITW Global Brands, Texas, USA. The mineral oil was sourced from Sigma-Aldrich, Missouri, USA. A polyester film used as the substrate was sourced from Microseal 'B' Adhesive Sealing Films, Bio-Rad Laboratories, California, USA. The adhesive sealing film was originally designed for the sealing of 96-well plate in PCR process, and the film has a total thickness around 50 µm. The polyester film has a wide working temperature range along with good biocompatibility. The polyethylene film (cling wrap, W300N) used as dielectric (isolation) layer is from The Glad Products Company, California, USA, with a thickness around 12 µm.

The printer used for the ink-jet printing of film used for screen-printing is Stylus Photo R230, Seiko Epson Corporation, Japan. The function generator (UTG9002) was soured from Uni-Trend Technology Co., Ltd, China. The high voltage amplifier (ATA-2161) is from Agitek Co., Ltd, China. The hotplate used for the baking of screen-printed electrodes is Cimarec+, Thermo Fisher Scientific, Massachusetts, USA. Hardwood frame with a 200 mesh resolution (200 threads crossing per square inch) shown in Fig. 1 was used for the screen-printing process. For carbon-based electrode printing, the squeegee moved across the screen to fill and transfer the pattern of electrodes through the unblocked stencil.

2.2. Fabrication process: The fabrication process for the proposed DMF device is shown in Fig. 2. A layer of 50 µm-thick polyester film was used as the substrate for the screen-printing process.

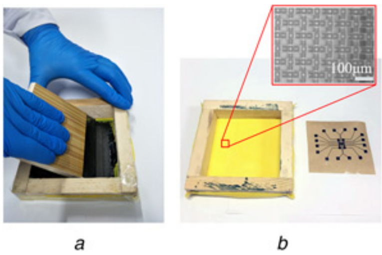

Fig. 1 *Images of the screen-printing process of the carbon electrodes*
a Squeegee across the screen for the electrode printing
b Printed carbon-based electrodes on polyester film

The polyester film was originally used as the adhesive seal film for the 96 well-plate in the thermal PCR process. In the screen-printing process (Fig. 2*a*), the hardwood frame with 200 mesh was used. For the preparation of the patterns on the mesh, the patterns were printed on a transparent film using an inkjet printer and then transferred on the mesh with a conventional photolithography process. The carbon resistive ink was then printed on the polyester film using the screen-printing process through the unblocked stencil (insert in Fig. 1). After printing, the polyester film with printed patterns was baked on a hotplate at 80°C for 10 min.

After the printing of electrodes on polyester film, a CO_2 laser system was used to cut the substrate into the desired shape (76 mm × 76 mm, size of standard glass slides). In the wiring process, the silver conductive paste was used for the connection of wires to bond pads. Before the attachment of the isolation layer, several drops (∼150 µl) of mineral oil were applied on the printed electrodes, in order to enhance the bonding between the substrate and the isolation layer. Finally, the isolation layer (polyethylene, 12 µm in thickness) was laser cut, aligned and attached to the mineral oil-covered electrodes. In order to enhance the hydrophobicity, the Rain-X water repellent was spin-coated (∼200 µl, 500 rpm) on the surface of the isolation layer and naturally air-dried to finish the fabrication process of the film-based DMF devices.

The laser confocal microscope images were obtained for the screen-printed carbon-based electrodes on polyester film. The confocal microscope image was shown in Fig. 3, the average thickness of the printed electrodes after the drying process is around 10 µm, and the measured average spacing between electrodes is around 340 µm. The edge of the screen-printed electrodes is relatively rough, compared with metal deposition or etching method using

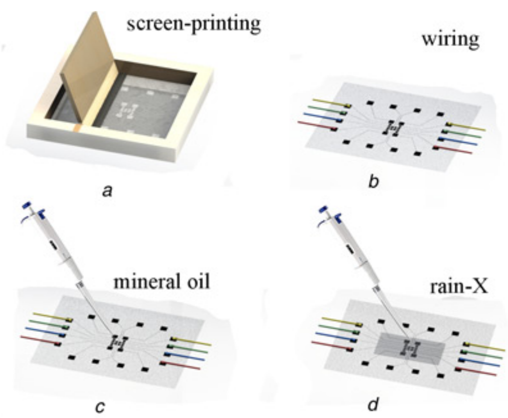

Fig. 2 *Schematic of the fabrication procedure for the flexible film-based DMF devices*
a Screen-printing process
b Wiring
c Apply mineral oil on substrate
d Apply Rain-X on the polyethylene isolation layer

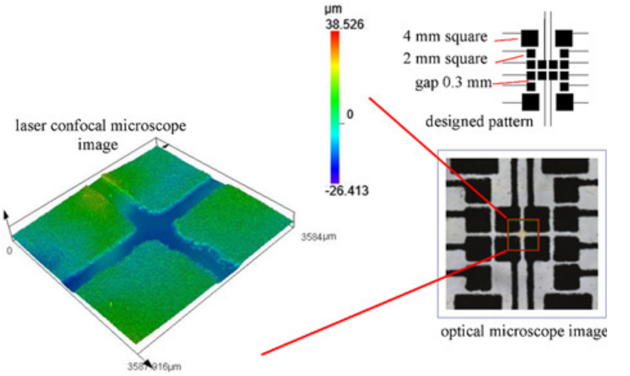

Fig. 3 *Surface profile measurement of the screen-printed electrodes on polyester film*

photolithography, which is one of the drawbacks of the low-cost approach. However, the spacing and quality of the electrodes could be further improved with a finer mesh.

3. Result and discussion: The system setup for the test of film-based microfluidics is shown in Fig. 4. The function generator provided a sine wave with a frequency of 1.1 kHz. The signal from the function generator is then amplified with a high voltage amplifier, resulting in a voltage output range from 0 to 700 V (peak-to-peak value). Each bonding pad (16 in total) on the proposed DMF device was connected to a series of relays controlled by a microcontroller (Intel MCS-51) for the programmed voltage supply in a designed sequence.

Fig. 5 shows a droplet movement process of a single drop of DI water (∼10 µl) with green dye. The voltage applied for the droplet manipulation is 630 V (peak-to-peak) with a frequency of 1.1 kHz. As shown in Fig. 5, the droplet was programmed for a back and forth motion on eight carbon electrodes. The red arrow in the image shows the direction of the movement. The droplet moved

Fig. 4 *System setup for the testing of film-based DMF*

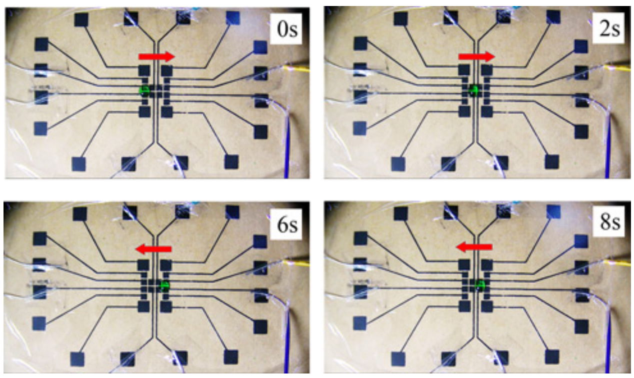

Fig. 5 *Droplet movement on the DMF device (multiple images with times)*

Micro & Nano Letters, 2020, Vol. 15, Iss. 3, pp. 163–165
doi: 10.1049/mnl.2019.0382

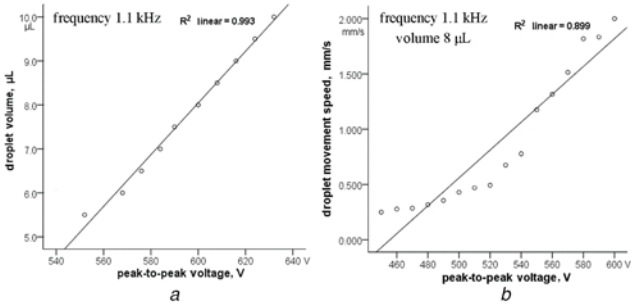

Fig. 6 *Driving voltages for the droplet with various volumes and moving speed*
a Minimum peak-to-peak voltage required to trigger droplet movement with various volumes
b Time required to complete droplet (8 µl in volume) movement under various driving voltage

intermittently, with an average speed around 1 mm/s. Video footage for the droplet motion is also provided as the supplementary file with this Letter.

The minimum peak-to-peak voltage required to trigger the droplet movement with various droplet volumes is shown in Fig. 6*a*. Generally, the minimum voltage increased linearly with the droplet volume, from 550 to 630 V corresponding to droplet volume from 5.5 to 10 µl. The droplet moving speed is also obtained with various driving voltages (shown in Fig. 6*b*). The droplet has a volume of 8 µl. The movement speed could increase from 0.25 to 2 mm/s with the peak-to-peak voltage increased from 450 to 600 V. For both of the analysis conducted in Figs. 6*a* and *b*, the driving frequency was set at 1.1 kHz. Compared with the previous studies on DMF, due to the low-cost fabrication approach used in this Letter, the fabrication precision of the electrodes and the thickness of the isolation layer result in a relatively higher (100–150 V) driving voltage.

4. Conclusion: This Letter proposed a novel method for the fabrication of a low-cost DMF device using screen-printing on thin polyester film. Compared with the conventional fabrication approach on glass- or silicon-based DMF, the proposed method is more accessible, rapid, low-cost and disposable. In addition, the fabricated DMF device is also optically clear, flexible and bendable. The proposed fabrication method for low-cost DMF could have board potential applications in rapid and point-of-care detection and diagnosis.

5. Acknowledgment: This work was supported by the National Natural Science Foundation of China (grant no. 51804014) and Beijing Natural Science Foundation (grant nos. 2182055, 3192024).

6 References

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