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SHORT COMMUNICATION

# Paper-based digital microfluidics

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**Abstract** In this paper, a new fabrication method for digital microfluidics is proposed. In which, paper, graphite, and adhesive tape are used as substrate, electrodes, and dielectric layer, respectively. The graphite is sprayed over a template on the paper substrate. Two different water repellants are used as the hydrophobic layer, which replace with expensive materials such as Teflon-AF®. The paper substrate is low cost, available, and flexible. The proposed device is disposable, and its fabrication procedure is simple, fast, and low cost which allows creation of a new device for each individual experiment. Therefore, problems such as adsorption and dielectric breakdown will not occur in this type of digital microfluidics. This device can perform two types of droplet operations, merging and moving on droplets in volumes of 15–50 μL.

**Keywords** Digital microfluidics · Paper-based · Low cost · Graphite electrode

## 1 Introduction

Microfluidics technology is developed in response to the need for handling and manipulating small volumes (microliter or picoliter) of fluids (Miller and Wheeler 2009; Cho and Moon 2008). The devices that are fabricated based on this technology are mainly used in biochemical tests and point of care diagnostics which they need full control on reagent and minimum material consumption such as chemical and enzymatic reactions (Taniguchi et al. 2002; Ito et al. 2003), immunoassays (Rastogi and Velev 2007; Sista et al. 2008), DNA-based researches (Wulff-Burchfield et al. 2010; Liu et al. 2008), and proteomics (Wheeler et al. 2004, 2005).

There are two major types of microfluidics: channel-based microfluidics and digital microfluidics (DMF). Channel-based microfluidics is appropriate for fluid handling due to its mature and robust process and also low reagent consumption, and high resolution (Abdelgawad 2009). DMF is based on electrowetting on dielectric (EWOD) phenomenon (Pollack et al. 2000; Lee et al. 2002; Cho et al. 2003). A DMF device is composed of electrode arrays which are coated by a dielectric layer and a hydrophobic material. When voltage is applied to an electrode which is in contact with a droplet, the surface tension and as a result the contact angle of the droplet with surface changes. This results in changing the shape of the part of droplet which is in contact with the actuated electrode and makes it move toward the actuated electrode (Paik et al. 2003a; Karuwan et al. 2011).

There are two configurations for DMF devices: open DMF (single-plate) (Washizu 1998; Yi and Kim 2005; Cooney et al. 2006) and closed DMF (two-plate) (Pollack et. al 2000, 2002; Cho et. al 2003). In closed DMF configuration, droplets are sandwiched between two plates and the top plate acts as the ground electrode, which is usually formed by a transparent conductive layer such as indium tin oxide (ITO) while the bottom plate consists of an array of actuating electrodes. In open DMF configuration, all of the electrodes, including ground electrode, are patterned on a single substrate (Choi et al. 2012). Closed DMF can support dispensing, moving, splitting, and merging

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operation (Pollack et al. 2002; Cho et al. 2003) while open DMF can only support moving and merging operations (Berthier 2008). Open DMF, however, can move larger droplets, assist fast mixing, have better access to samples, and have a simpler fabrication process (Cooney et al. 2006).

In DMF, each droplet can be handled and addressed individually without any need for pumps, valves, channels, and mechanical mixers, and samples can be collected after process is done to be used in other processes, as well. Thus, different processes can be carried out on a device simultaneously (Choi et al. 2012).

However, the conventional fabrication process of a DMF device is a bottleneck for DMF accessibility in laboratories. Therefore, developing low cost and accessible microfabrication techniques is crucial to make this technology, more widespread (Abdelgawad and Wheeler 2008).

As described, a DMF device has four major parts: substrate, electrodes, dielectric layer, and hydrophobic layer. Traditionally, glass or silicon is used as the substrate, and the metal layer is deposited on the substrate and patterned by photolithography. The next step of the process is deposition of the dielectric layer. This step can be accomplished in different manners, depending on the dielectric material. Vapor deposition of parylene, amorphous fluoropolymers, chemical vapor deposition of silicon nitride, or spin coating of PDMS or SU-8, or thermal growth for silicon oxide. Finally, a hydrophobic coating is applied to the dielectric which is usually Teflon® AF (Choi et al. 2012).

Clean-room-based processes such as photolithography, vapor deposition, thermal growth, and spin coating make DMF fabrication a costly, time-consuming, and hard to achieve process and decrease its superiority over channel-based microfluidics. Some studies have attempted to develop a low cost and rapid process to fabricate a DMF device. In Gong and Kim (2008a, b), printed circuit board (PCB) substrate is suggested instead of glass or poly silicon substrate, due to its lower cost, mass production capability, multilayer wiring, and flexible substrate possibility. However, using PCB as the substrate has certain drawbacks, e.g., there will be deep trenches between electrodes and the PCB surface will be rough. Such problems cause resistance against the droplet movement.

Studies have suggested various ideas for patterning of the electrodes on the substrate. In Watson et al. (2006), a reusable PDMS stamp is used to transfer a pattern on a gold surface and then etch out the uncovered part of gold. The PDMS stamp also has some drawbacks such as undesirable short circuits between electrodes and stamp bending. Another method is proposed in Abdelgawad and Wheeler (2007) which uses laser printer to pattern the PCB board, while the laser toner serves as a mask for etching. This technique is more robust than PDMS stamp and makes high-throughput fabrication possible. The problem is that the charge transfer of the printer depends on the type of the substrate. With a copper-coated substrate, this charge is not sufficient to pull toner particles from the drum to the substrate, since these printers are optimized for paper. Another technique uses a permanent marker to create a mask for metal layer outline patterning, after the outline patterning of electrodes is done with razor blade (Abdelgawad and Wheeler 2008).

In Abdelgawad and Wheeler (2008), new substances are proposed for dielectric and hydrophobic layers. They used food wrap as the dielectric layer and commercial water repellant, Rain-X®, as the hydrophobic layer.

In this paper, in order to present a simplified and cost-efficient fabrication process for DMF devices, a paper-based open-DMF process is proposed using paper as the substrate. Paper is very low cost, available in different types, biocompatible, disposable, and intrinsically flexible. In addition, paper is compatible with the lamination process and most of common printing methods such as screen printing and inkjet printing can be applied to it. These features give a great potential to paper-based DMF for simple, fast, and massive patterning of conductive electrodes. Paper has capillary action; thus, it has been used widely in paper-based microfluidics biomedical assays (Martinez et al. 2008; Klasner et al. 2010; Chitnis et al. 2011). Therefore, paper-based DMF can be merged with conventional paper-based microfluidics to create hybrid devices which enjoy benefits of both channel-based microfluidics and DMF.

Here, we used graphite as electrodes. Graphite powder is sprayed on the substrate over a template. According to Abdelgawad and Wheeler (2008) which uses food wrap as the dielectric layer and commercial water repellant as hydrophobic layer, here adhesive tape and commercial water repellants are used as dielectric and hydrophobic layers, respectively.

A low cost and practical DMF device needs a low cost and simple to implement high-voltage electrode actuator. In this paper, a small and low-cost actuator is designed to realize a real integrated device.

## 2 Experimental

### 2.1 Materials

Paper (80 g, A4-size, Pelican®) is used as the substrate. A fire-proof transparency film is used to pattern the template. Electrodes are sprayed over the template by graphite spray (Graphit 33 Kontaktchemie®). Clear adhesive tape (Janson®) with 35 μm thickness is applied as the dielectric layer. Two different hydrophobic materials are used as hydrophobic layer: (1) Nevosil®Si-7100 (Ultrakim home page) which is a silicon additive hydrophobic material and (2) Avam® rain repellent (Avam home page) which is similar to Rain-X® (Abdelgawad and Wheeler 2008).

### 2.2 Preparing the template, electrode, dielectric, and hydrophobic layers

Figure 1 illustrates the fabrication process steps. The first step is preparation of the template. As mentioned above, the template is made of a transparency film (Flame Resistant Polycarbonate-FRPC). A laser cutter (Boao Laser®, model: BMD75) is used to pattern the transparency film to produce the desired template. The setting of laser cutter is obtained after a lot of try and errors, since the transparency film gets constricted due to laser heat. The final setting obtained for laser cutter is: Current: 9 A, Voltage: 20 V. The laser radiation with this setting is repeated for five times with 1.5 cm/s movement speed. The fabricated template is reusable and washable.

Figure 1a, b illustrates two different templates which were used to pattern electrodes on paper. One of them is a simple rectangle which works as ground electrode template, and the other one works as a template to pattern actuation electrodes. To deposit the electrode layer, the template is placed over the paper and fixed to avoid graphite leakage under the template. Figure 2a, b shows the actuation and ground electrode templates, respectively. In the next phase, graphite is sprayed over the template. We used step and repeat to deposit the actuation electrodes on the paper. The graphite has to be sprayed from a determined distance (40–50 cm above the paper) and with minimum pressure. Here, minimum pressure means the minimum force applied to the nozzle that makes the graphite out of the tube. This minimum force can be achieved by pushing the nozzle approximately 2 mm when the spray tube is full. If the distance between the paper and spray is lower and high pressure is applied for spraying, the paper will get wet, and this might cause short circuits between the electrodes. The size of each actuation electrode is 3 × 3 mm, and the inter-electrode gap is 300 µm in average (the term in average used since the borders are not exactly sharp). The gap between ground electrode and actuation electrodes is between 450 and 550 µm. Figure 3a shows a sample of properly patterned electrode. Figure 4 shows the microscopic view of an inter-electrode gap. As can be detected in Fig. 4, some graphite powder has leaked beneath the template. At first glance, it seems there is a possibility of short circuits due to graphite leakage beneath the template, but if the graphite is sprayed properly, there will be no electrical contact between electrodes. Our measurements showed that there was no conductivity between electrodes. The attracting point is that the leakage of graphite into the inter-electrode gap can work as an inter-digit pattern for the device and can make the droplet movement easier (Pollack et al. 2000; Paik et al. 2003b).

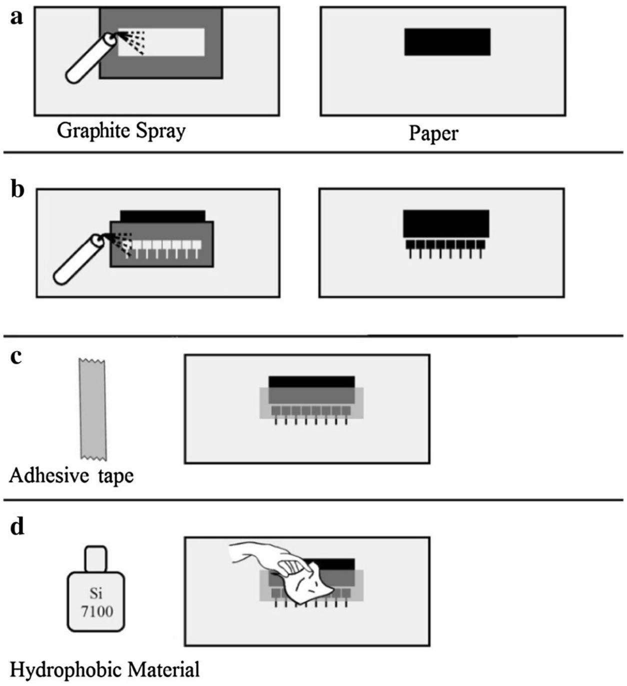

**Fig. 1** Fabrication process scheme of the paper-based DMF device. **a** Graphite is sprayed over the template to pattern ground electrode on the paper. **b** Spraying graphite to pattern electrodes. **c** Pasting adhesive tape as the dielectric layer. **d** Wiping hydrophobic layer by a tissue

The next step of fabrication is fairly easy. As shown in Fig. 1c, a piece of adhesive tape is cut and pasted over the patterned electrodes. The size of the tape has to be long enough to cover all actuation electrodes and a fraction of the ground electrode which have to be under the droplet. Figure 3b shows the DMF device after pasting the dielectric.

Finally, the hydrophobic layer is treated over the adhesive tape. The hydrophobic substance (either Nevosil® Si-7100 or Avam® rain repellent) is wiped over the dielectric layer with a tissue (As shown in Fig. 1d) and will be ready after 7–10 min.

### 2.3 Actuation voltage

To actuate the droplets, variable voltage supply was designed for the device. Approximately, 700 V AC is needed to actuate droplets over the thick dielectric layer. However, generating this voltage can be an issue. It should be noted that there is no need for a high voltage source with a high output power, since no current is passing through the electrodes. Thus, a high voltage generator that has a very

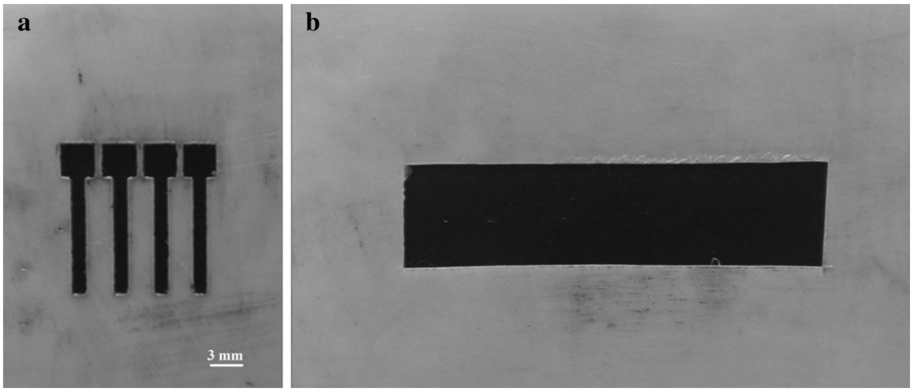

**Fig. 2** The templates made by transparency film and patterned by laser cutter. **a** Template for patterning actuation electrodes. **b** Template for patterning ground electrode

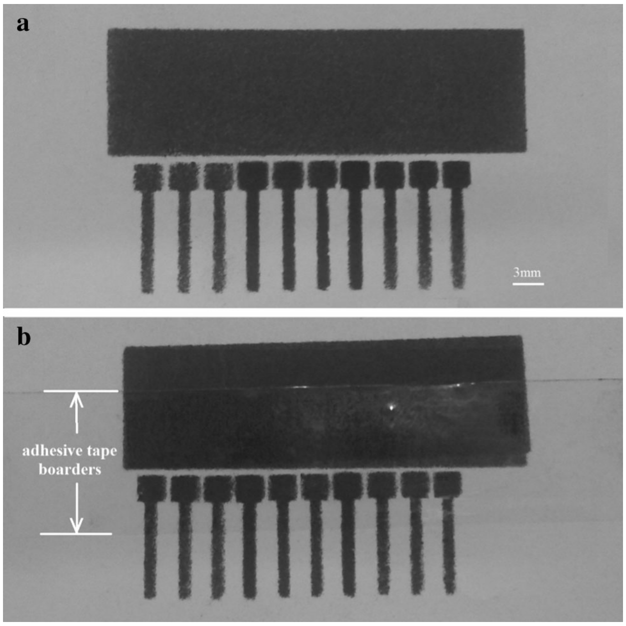

**Fig. 3** Electrode pattering on the paper. **a** Device after electrode patterning**. b** Laying the adhesive tape as the dielectric layer

**Fig. 4** Inter-electrode graphite scattering

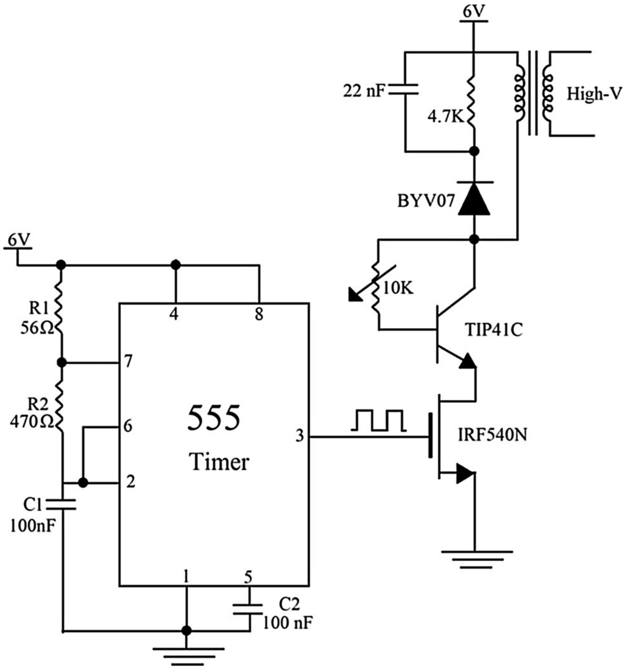

**Fig. 5** A simple variable high voltage generator

small output current is sufficient to actuate the electrodes, which is also safer than a high power supply. Figure 5 shows the designed high-voltage supply circuit which costs lower than 10$. It is portable and can be powered on with a 6 V battery. The transformer that is used in this circuit is a switching flyback transformer used in CRT display. The 555 timer IC is designed to work in astable mode in which, the circuit works as an oscillator, generating a square wave, with specific frequency, and duty cycle set with $R_1$, $R_2$, and $C_1$. The oscillation frequency is 14.5 kHz. This square wave is applied to a MOSFET device (IRF540N) to load the transformer. The TIP41C is used to change the output voltage value between about 100 V to 1000 V. Other parts are used to protect the circuit.

## 3 Results and discussion

### 3.1 Observations

Figure 6 shows the performance of the proposed paper-based DMF device. Figure 6a shows the schematic diagram of proposed DMF device in top view and cross-sectional view. The experiments are performed using different volumes of water droplets. The volume of droplet is measured by a micropipette. The minimum and maximum amount of the droplet which could be moved by the proposed device is 15 and 50 µL, respectively. Figure 6b shows the 15 µL droplet movement and Fig. 6c shows the 50 µL droplet movement on the proposed paper-based DMF. Figure 6d shows an on-chip reaction between droplets of NaOH and phenolphthalein. When two droplets

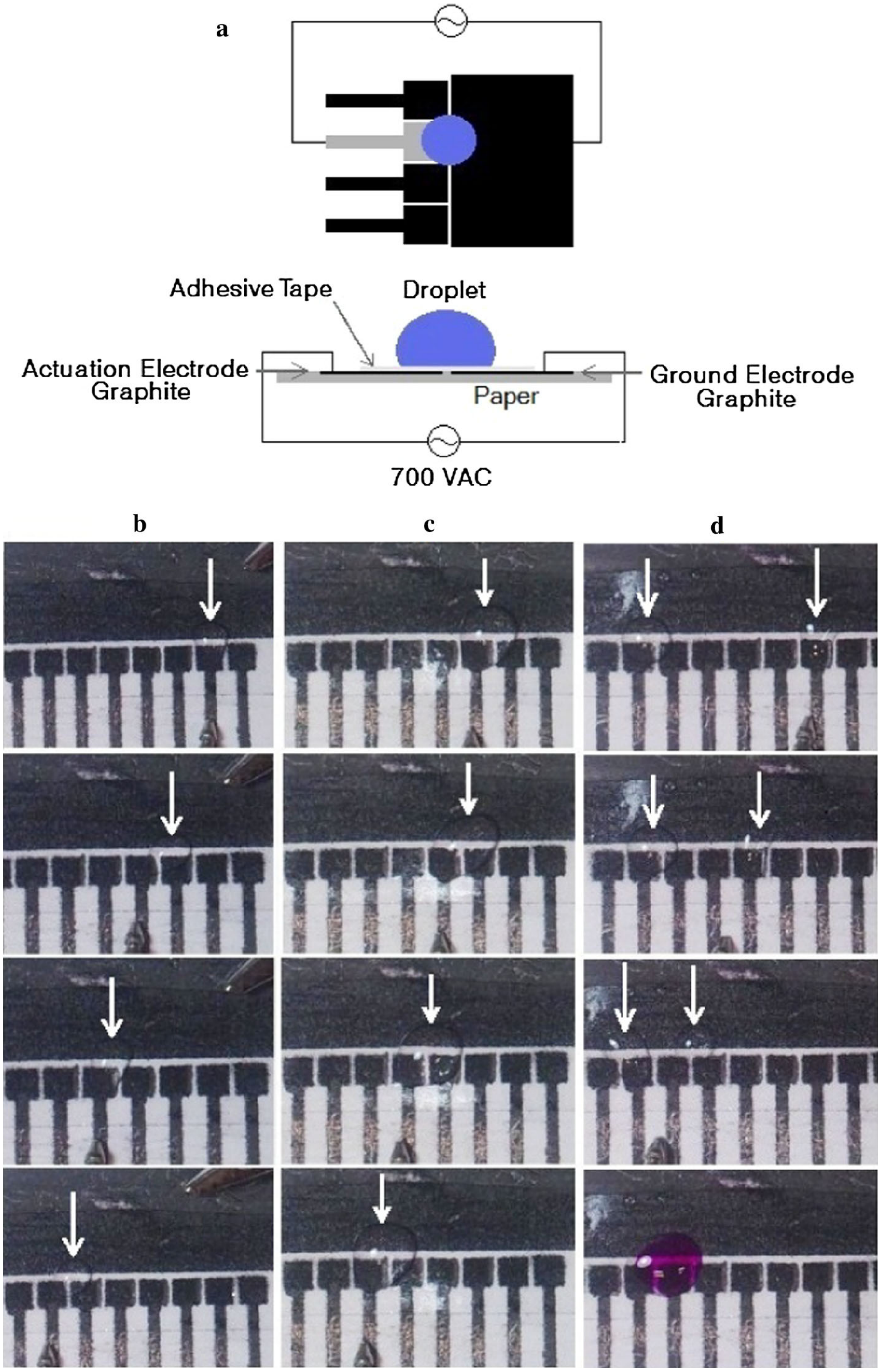

**Fig. 6** Paper-based DMF device performance with Avam® rain repellant as the hydrophobic layer. **a** Schematic view of an open DMF. With applying voltage to an electrode, it will be actuated (the electrode which is shown in *gray color*). This electrical field changes the surface tension of the electrode and the droplet moves toward the actuated electrode. **b** Movement operation of a 15 µL droplet. **c** Movement operation of a 50 µL droplet. **d** Demonstrate a reaction on DMF device between NaOH and phenolphthalein (The location of the droplets is shown by *white arrows*.)

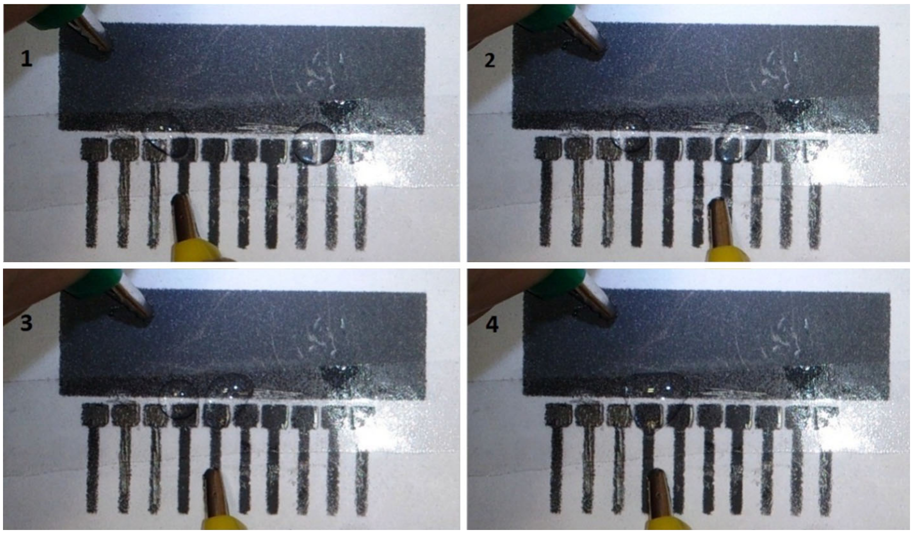

**Fig. 7** Merging operation of paper-based DMF device with Nevosil® Si-7100 as the hydrophobic layer

merge, the color changes to fuchsia. Device in the Figure 6 uses Avam® rain repellant as the hydrophobic layer. Figure 7 shows the merging operation on a paper-based DMF with Nevosil® Si-7100 as the hydrophobic layer. Nevosil® Si-7100 shows better performance in treatment; the Avam® rain repellent is hard to treat since it has a different behavior when contacting with adhesive tape. It does not spread on the dielectric layer and thus it cannot be treated all over the dielectric, as well. However, Avam® rain repellant (or any other commercial rain repellant) has lower cost and higher availability. We cured the hydrophobic substances after wiping, in a heater with 110 °C and 5 min where no considerable changes were observed in the operation of the device. Droplets are actuated manually. Manual actuation reduces movement speed of the droplet and faster droplet movement can be achieved by using a controlling circuit. The measured speed of the droplet movement in Fig. 7 is 0.18 cm/s. The hydrophobic substance can be used at least for three sequential experiments before needing retreatment. Our observation shows that droplet moves easier between the electrodes with higher amounts of graphite leakage.

### 3.2 Comparison with other works

Paper-based DMF is low cost, disposable, and easy to fabricate. It is convenient to fabricate a new device every time we want to hold an experiment, and thus paper-based DMF devices may not confront with dielectric breakdown, material sedimentation, and adsorption.

Patterning of the electrodes is one of the major issues in fabrication of DMF devices. As mentioned before, most of the studies use mask and etching to pattern the electrodes. By using the template and spraying process, electrodes are patterned on the substrate directly and only in one step. Another problem which shows itself in PCB-based DMF devices is the deep trenches between electrodes that may hinder the droplet movement (Abdelgawad and Wheeler 2008). Paper-based DMF has no trench at all, because graphite electrodes can penetrate in the paper. It seems this feature is not feasible in any other non-clean-room fabrication methods.

The DMF devices fabricated with the proposed paper-based process can be used for common biological applications such as DNA amplification, proteomics, and cell assays. However, there are some drawbacks in the proposed method in comparison with conventional devices. One is temperature limitation which makes it unsuitable for experiments which need high temperature (over 200 °C). In addition, physical resistance of paper is not good, which can be improved by using paperboard. Another drawback of our proposed method is that high-grade dielectric materials cannot be used. Electrode resolution limitation, droplet volume limitation, and developing close paper-based DMF are some other problems, which need more to be investigation more thoroughly.

## 4 Conclusion

Paper-based digital microfluidics is proposed as a new fabrication process in this paper. Graphite is patterned through a template on paper substrate, to form the actuation electrodes. Adhesive tape is used as dielectric layer and two different hydrophobic materials, Avam® rain repellant and Nevosil® Si-7100 water repellant, are used as hydrophobic coating. A low-cost high-voltage supply is designed specifically to actuate the paper-based DMF electrodes.

The proposed device works successfully for droplet movement and merging with a speed of 0.18 cm/s, and it can move droplets with volumes of 15–50 µL.

Paper as a substrate has some benefits. It is low cost, flexible, and available. The fabrication process of the proposed device is totally out-of-clean-room, and a new device can be fabricated fast and easily. In contrast to PCB, paper is intrinsically compatible with all type of printers, and hence, there is a potential to print conductive electrode with printer to perform mass production. Also, paper-based DMF can be merged with conventional paper-based microfluidics.

The proposed device is a proof of concept of paper-based DMF. Reducing the size of the electrodes and inter-electrode gap with using finer patterning methods such as printing and reducing the applied voltage with using thinner dielectric layers are cases of interest for future works.

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