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SHORT COMMUNICATION

Low-cost, rapid-prototyping of digital microfluidics devices

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Abstract An innovative and simple microfabrication method for digital microfluidics is presented. In this method, devices are formed from copper substrates or gold compact disks using rapid marker masking to replace photolithography. The new method is capable of forming devices with inter-electrode gaps as small as 50 μm. Saran™ wrap (polyethylene film) and commercial water repellants were used as dielectric and hydrophobic coatings, respectively, to replace commonly used and more expensive materials such as parylene-C and Teflon-AF. Devices formed by the new method enabled single- and two-plate actuation of droplets with volumes of 1–12 μL. Fabricated devices were successfully tested for droplet manipulation, merging and splitting. We anticipate that this fabrication method will bring digital microfluidics within the reach of any laboratory with minimal facilities.

Keywords Digital microfluidics · Electrowetting · Rapid prototyping · Microfabrication · Rapid marker masking

1 Introduction

Digital microfluidics is a relatively new technology for manipulating liquid droplets on electrode arrays by means of electrowetting (Pollack et al. 2000; Lee et al. 2002) and/or dielectrophoresis (Washizu 1998; Gascoyne et al. 2004). It has recently emerged as a useful tool in biochemical applications such as PCR (Chang et al. 2006), enzyme assays (Taniguchi et al. 2002; Srinivasan et al. 2004), and proteomics (Wheeler et al. 2004; 2005; Moon et al. 2006). In addition, the technique shows promise for mechanical microactuation (Kang and Kim 2006; Moon and Kim 2006) and on-chip cooling of electronics (Paik et al. 2005).

Despite the current enthusiasm for digital microfluidics, the arduous fabrication procedures required to form devices has limited the technology to research groups with access to well-equipped clean-room facilities. This is analogous to the status of conventional channel microfluidics prior to the development of soft lithography in the mid-1990s (Qin et al. 1996; Duffy et al. 1998; McDonald et al. 2000), which contributed to an explosion in popularity of microchannels for a wide range of applications in many disciplines. Since that time, a variety of creative techniques have been developed to make microchannels even more accessible to all who wish to use them, including using printed circuit boards (Sudarsan and Ugaz 2004), laser printed polyester films (Do Lago et al. 2003;

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Bao et al. 2005), and liquid phase photopolymerization (Khoury et al. 2002; Hutchison et al. 2004). These techniques and others have had a profound effect on the field of channel microfluidics, and we speculate that a fast, accessible, and inexpensive method for forming digital microfluidics devices will have a similar impact on this promising technology.

We recently developed new rapid prototyping techniques for digital microfluidics using microcontact printing (Watson et al. 2006) and laser printing on printed circuit board substrates (Abdelgawad and Wheeler 2007). These are innovative methods, but are not ideal: the former requires the fabrication of an elastomeric stamp (requiring photolithography) and the latter is limited by the low resolution of commercially available laser printers. Here, we present a new technique, representing our concerted efforts to achieve the simplest possible device prototyping method.

An ideal prototyping method would be fast, would rely on inexpensive materials, and would not require access to expensive/technically complicated facilities. In response to this challenge, we divided the process for digital microfluidics device fabrication into three steps: electrode patterning, dielectric coating, and hydrophobic treatment. Electrode patterning is conventionally implemented using photolithography and etching of specialty/expensive materials such as gold (Roux et al. 2006), chromium (Paik et al. 2003), or doped silicon (Wheeler et al. 2004, 2005). Here, we replaced these materials with two inexpensive and accessible substrates: printed circuit boards (Abdelgawad and Wheeler 2007) and compact disks (CD) (Angnes et al. 2000; Lowinsohn et al. 2006; Watson et al. 2006). Additionally, we used ink masking to pattern electrodes (Manica and Ewing 2002) in place of photolithography, effectively trading a UV exposure system for an ink pen. The second step of device fabrication, dielectric coating, is conventionally accomplished by vapor deposition of parylene (Pollack et al. 2000; Srinivasan et al. 2004), thermal growth of silicon oxide (Wheeler et al. 2004, 2005), or spin coating of poly (dimethylsiloxane) (PDMS) (Kuo et al. 2003; Abdelgawad and Wheeler 2007). In place of these expensive/specialty materials, we opted for a method developed by Chuang et al. (Chuang and Fan 2006), using plastic sheets (commercially known as Saran™ wrap) as a dielectric coating. In the final fabrication step, devices are made hydrophobic, typically by spin coating Teflon-AF (Pollack et al. 2000; Pollack et al. 2002; Wheeler et al. 2004, 2005) or other fluoropolymers (Yi and Kim 2004). Here, we report replacing Teflon-AF (which is expensive, and requires a legal agreement with DuPont) with water repellant used for car windshield treatment (Carre and Shanahan 1995).

This work represents our best efforts to develop a fast and inexpensive method for fabrication of digital microfluidics devices. We anticipate that this method will make digital microfluidics accessible to all who wish to use it, regardless of financial resources or access to clean-room fabrication facilities.

2 Experimental

2.1 Materials

Two substrates were used for fabrication of digital microfluidics chips: Pyralux® AP7156E double-sided copper-clad laminate (DuPont Electronic Materials, Research Triangle Park, NC) and gold compact disks (Mitsui, Needham Heights, MA). Fisher (Fisher Scientific Limited, Ottawa, ON) and Sharpie (Sanford Corporation, Oak Brook, IL) permanent markers were used to draw and mask electrode array designs. Copper was etched in ferric chloride (CE-100, Transene Company Inc, Danvers, MA) and gold was etched in gold etchant (Sigma Aldrich, Oakville, ON). Other fabrication materials included Saran™ wrap (SC Johnson Canada, Brantford, ON), silicone oil (DMS-TO1, Gelest Inc, Morrisville, PA), Rain-x® water repellant (SOPUS Products, Houston, TX), and isopropanol (Fisher Scientific, Whitby, ON). Materials used for two-plate droplet actuation included Indium-Tin-Oxide (ITO) coated glass slides (Delta technologies, Stillwater, MN), Teflon-AF 1600 (DuPont Canada, Mississauga, ON) and Fluorinert FC-40 (Sigma-Aldrich). Materials used in device testing included food color dye (McCormack Canada, London, ON), bromothyl blue indicator (Sigma-Aldrich), and HCl (Fisher Scientific).

2.2 Fabrication of etch masks

The gaps between actuation electrodes in digital microfluidic devices are typically ~5–100 μm (Wheeler et al. 2004, 2005; Chang et al. 2006; Zhao and Cho 2006; Abdelgawad and Wheeler 2007). As features of this size are difficult to draw, we developed a two-step fabrication process for forming contact etch masks for device fabrication, depicted in Fig. 1. In the first step, an outline of the electrode array (without gaps) is drawn on the surface of a substrate; in the second step, gaps between electrodes are formed using the corner of a razor blade. With practice, an etch mask with 30 electrodes can be formed in 10 min.

Through extensive trial-and-error, we observed several factors that contributed to robust etch masks. First, different marker types are not equal (Manica and Ewing 2002); for example, while the ink in Fisher permanent markers resists dissolution in copper and gold etchants, the ink in Sharpie markers resists gold etchant only. Second, etch masks are most robust when drawn in two coats, allowing the ink to

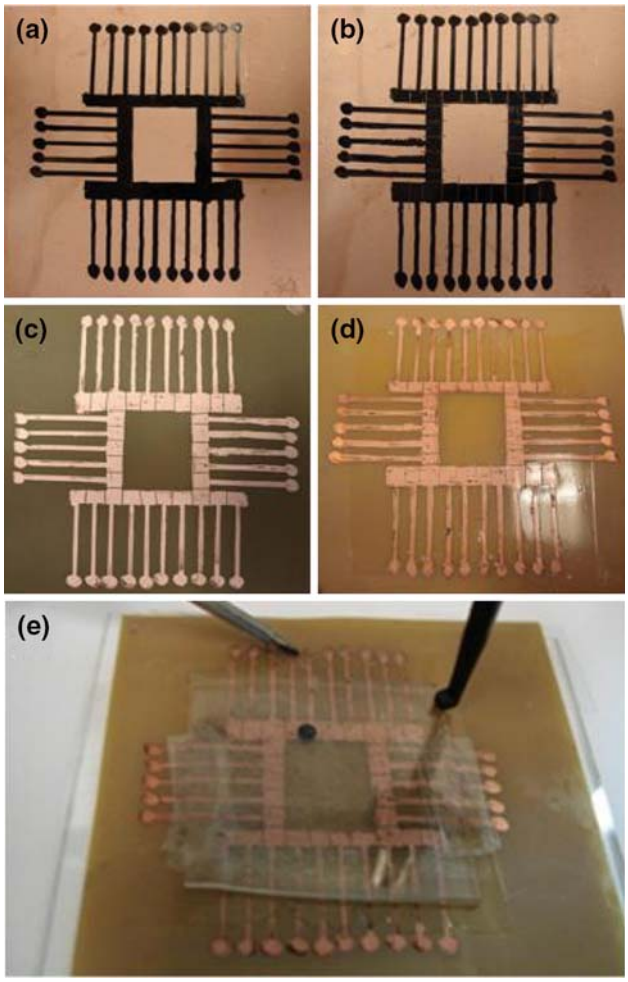

Fig. 1 Fabrication process. **a** Design is drawn with a permanent marker. **b** A razor blade is used to form gaps between electrodes. **c** Copper is etched in ferric chloride solution and ink is removed using an acetone dampened wipe. **d** Saran™ wrap is applied to device surface and treated with Rain-x®. **e** Picture of assembled two-plate device. A similar procedure is used to fabricate devices from compact disk substrates

dry between them. Both coats should be applied in short strokes with lighter pressure in the second coat to avoid removing ink from the covered areas. Third, when forming gaps between electrodes, it is not recommended to use more than one blade stroke, as the result will likely be two marks with a metal island between them. With practice, the scratches can be formed rapidly and reproducibly, without the aid of a magnifying lens. As shown in Fig. 2, devices formed in this manner have well-defined inter-electrode gaps of 50–60 μm (measured using a Wyko optical profilometer, Veeco Instruments Inc., Woodbury, NY).

2.3 Fabrication of electrode arrays

Devices were formed from two kinds of substrates: copper sheets and gold CDs. The fabrication of devices formed from copper sheets was straightforward; after applying an ink etch mask (as described above), substrates were immersed in ferric chloride (40°C ~1–2 min) to remove the exposed copper. Gold CDs required pre-treatment in concentrated nitric acid (1 min) to remove the thin plastic film covering the gold layer, prior to applying the ink mask. After cutting to size and applying the mask, gold devices were immersed in gold etchant (room temperature ~20 s). After etching either kind of substrate, the ink was removed using a methanol or acetone dampened tissue (note that acetone is more effective, but warps the plastic on CD substrates). While the thick copper layer (9 μm) is very robust, the gold layer on the compact disk is very thin (50–100 nm) (Angnes et al. 2000), and care must be taken to avoid unintentional scratches on the surface.

2.4 Dielectric coating and hydrophobic treatment

We used two methods for applying Saran™ wrap (15 μm thick polyethylene) as a dielectric layer. The first method was adapted from Chuang et al. (Chuang and Fan 2006), in which the wrap was simply placed on top of the electrodes; in the second method, the wrap was thermally annealed onto the electrodes to increase the durability of the coating.

In the first method, Rain-x® water repellant was applied to a piece of Saran™ wrap by wiping with a dampened tissue (this is easiest when the Saran™ wrap is wrapped around a glass slide). After drying, a second coat of Rain-x® was applied, and the wrap was cut to fit the electrode array size. A few drops of silicone oil were dispensed onto the surface of the array, and then the wrap was placed onto the oil-coated device using tweezers (note that the wrap need not be stretched). The film of oil helps prevent the trapping of air bubbles, and reduces the likelihood of the wrap wrinkling on the device surface. In most cases, Rain-x® treatment was used; however, droplets could be actuated (albeit less robustly) on un-coated Saran™ wrap, as well.

In the second method, a piece of Saran™ wrap without pre-treatment was placed on top of a silicone oil-coated electrode array as described above. The device was then annealed in an oven (120°C, ~5–10 min), forming a seal between the wrap and the substrate. Devices were then spin-coated with Rain-x® (2,000 rpm, 1 min) and baked on a hot plate (100°C, 15 min). In an alternative process, Rain-x® was diluted in isopropanol (1:5 by weight), dispensed onto the Saran™ wrap coating (by pipetting or dip-coating), and then baked on a hot plate (100°C, 15 min). Chips formed by either process were comparably capable of droplet actuation (note that the latter does not require a spin-coater).

For two-plate actuation, top plates were formed from ITO glass slides coated either with Saran™ wrap and Rain-x® (annealed as in the second method described above), or

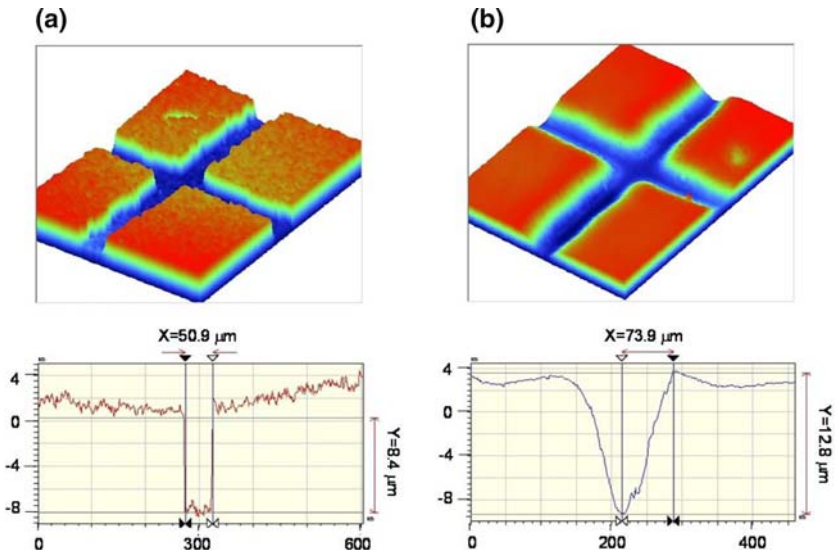

Fig. 2 Profilometer scans of devices on copper substrates **a** before saran™ wrap coating and **b** after saran™ wrap coating. As shown in **a**, the reported fabrication technique can achieve inter-electrode spacing of 50–60 μm. Saran™ wrap coating reduces the sharpness and aspect ratios, as shown in **b**

were spin-coated with Teflon-AF (Teflon-AF resin in Fluorinert FC-40, 1:100 wt:wt, 2,000 rpm, 1 min, followed by baking on a hot plate at 160°C for 10 min). Coated ITO slides were affixed to the top of patterned devices with 2 or 3 pieces of double-sided tape (75 μm thick each).

2.5 Device operation

As shown in Fig. 1e, driving potentials were manually applied via exposed contact pads on the device surfaces. We note that a control box can also be used to automate droplet manipulation; here, we used manual application to match the spirit of low-cost digital microfluidics. Potentials (400–800 V_{RMS}) were generated by amplifying (using a PZD 700 amplifier, TREK Inc., Medina, NY) the output of a function generator (model 33220A, Agilent Technologies, Santa Clara, CA) operating at 18 kHz. The total cost of this equipment (function generator and amplifier) is ~$5,000; however, we note that a low-current, high-voltage DC power supply could also be used (~$1,000). Droplet actuation was monitored and recorded by a CCD camera mated to an imaging lens (Edmund Industrial Optics, Barrington, NJ) positioned over the top of the device. Movies depicting droplet actuation can be viewed online in the electronic supplementary material.

3 Results and discussion

3.1 Inter-electrode gaps

The most critical feature in digital microfluidic devices is the dimensions of the gaps between the actuation electrodes. As shown in Fig. 2a, gaps of ~50–60 μm can be formed by the new rapid prototyping method; these dimensions are well suited for devices formed from CDs (with ~100 nm thick gold electrodes). In devices formed from PCB substrates (with ≥9 μm thick copper electrodes), however, these gaps form deep trenches, which have been reported to obstruct droplet movement when coated by a conformal dielectric layer (e.g., vapor deposited parylene-C) (Gong and Kim 2005; Abdelgawad and Wheeler 2007). This phenomenon was not observed in devices formed by the methods reported here; droplet motion was smooth and unobstructed in both single- and two-plate devices. As shown in Fig. 2, the Saran™ wrap coating reduces the sharpness and aspect ratios of the gaps between electrodes, which apparently contributes to facile droplet movement.

3.2 Single plate actuation

Single plate actuation is the simplest device configuration used in digital microfluidics. Advantages of this format include straightforward access to droplets (for analysis, etc.), the capacity to move large droplets with a small footprint, and increased mixing efficiency (Cooney et al. 2006; Yi and Kim 2006). As depicted in Fig. 3a, gold and copper devices were used for single-plate actuation by applying high and ground potentials (400–600 V_{RMS}, 18 kHz) to sequential electrode pairs. As shown in Fig. 3b, c, 10 μL droplets were manipulated on 2 × 2 mm electrodes covered with annealed Saran™ wrap. Although the non-annealed coating is easier to apply, in that configuration, silicone oil evaporates over time, causing unreliable device performance (e.g., air bubble formation, dielectric breakdown and arcing). Annealed Saran™ wrap constitutes a more reliable dielectric layer, resulting in more durable devices. We note that in either configuration (annealed or non-annealed), the coating can be easily removed and replaced. This is a valuable feature, as most failures in digital microfluidics result from prob-

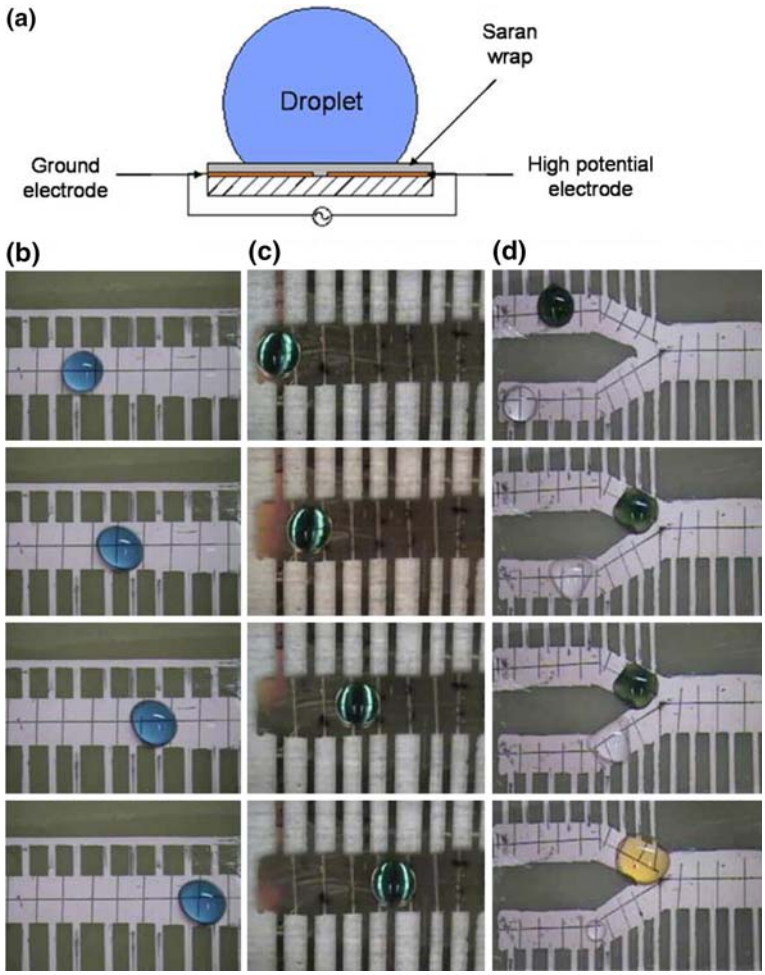

Fig. 3 Droplet actuation on single plate devices. **a** Actuation scheme; **b**, **c** actuation of 10 μL blue colored water droplets; and **d** merging two droplets, 8 μL each, containing 40 mM HCl and bromothyl blue. The droplets were actuated at 500 V_{RMS} (18 kHz); devices in **b** and **d** were formed from copper substrates, and the device in **c** from a CD substrate. All devices were coated with annealed Saran™ wrap and Rain-x®

lems with the coating (e.g., dielectric breakdown, non-specific adsorption to the surface, etc.). In the work reported here, we regularly used devices for many days, with multiple changes of the plastic covering.

To demonstrate the capacity to perform reactions on chips formed in this manner, droplets containing HCl (40 mM) and bromothyl blue indicator (0.9 mg mL^{-1}) were merged and mixed, causing the indicator to be protonated, yielding a yellow product (Fig. 3d). In addition to DI water, devices were capable of actuating aqueous buffers and solutions of proteins and DNA, when used with a thin film of silicone oil on top of the dielectric/hydrophobic coating. In all cases, droplet movement was facile and fast, with comparable performance to devices formed by conventional means.

3.3 Two plate actuation

Two-plate actuation, in which droplets are sandwiched between two plates, is the most common format in digital microfluidics. Advantages of this format include reduced evaporation and the capacity to dispense and split droplets (Cho et al. 2003). As depicted in Fig. 4, gold and copper devices were used for two-plate actuation by applying ground and high potentials to the ITO-glass slide and successive electrodes on the patterned array, respectively. Actuation voltages were 400–500 V_{RMS} (18 kHz) for devices mated to Teflon coated ITO-glass pieces (Fig. 4b, d), and 800 V_{RMS} for devices mated to Saran™ wrap coated ITO-glass pieces (Fig. 4c). The increased actuation voltage required for the latter is attributed to the additional 15 μm thick dielectric coating contributed by the Saran™ wrap on the ITO slide. Despite the increased actuation voltage, the latter method is attractive given the significant expense of Teflon-AF. Droplet size was ~1 μL for 2 × 2 mm electrodes with 150 μm spacing between the device and the ITO slide. Droplet splitting (Fig. 3d) was achievable on two plate devices with Teflon coated ITO slides at 700 V_{RMS} for 150 μm spacing between device and ITO slide.

3.4 Comparison to conventional devices

An important consideration for any new fabrication method is a comparison of device performance relative to

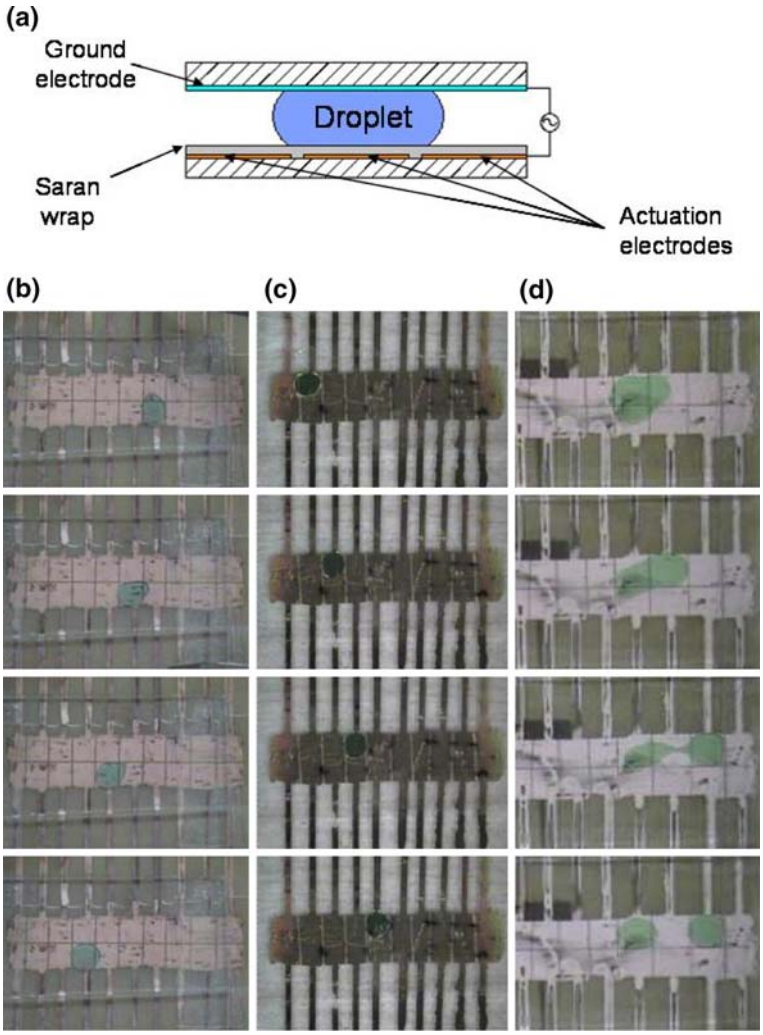

Fig. 4 Two plate actuation. **a** Actuation scheme; **b**, **c** actuation of blue colored 1.2 μL water droplets; and **d** splitting a 2 μL droplet . Devices in **b** and **d** were formed from copper substrates mated to an ITO-glass piece coated with Teflon-AF, and the device in **c** from a CD substrate mated to an ITO-glass piece coated with Saran™ wrap and Rain-x®

that of devices formed by conventional means. Although we did not conduct quantitative studies here, we note that qualitatively, devices formed by the new methods were capable of droplet manipulation with comparable velocity, efficiency, and reproducibility as devices formed using clean-room methods. We note that the rapid prototyping methods do have limitations: (1) droplet volumes cannot be much smaller than 0.5 μL, as there are practical limits to the sizes of electrodes (~1 mm) and inter-electrode gaps (~50–60 μm) that can easily be formed; and (2) actuation voltages are necessarily large, because of the thick dielectric (Saran™ wrap) layer used in place of much thinner dielectrics on devices formed by conventional means. For some applications, these limitations will make the new fabrication methods less attractive, and for other applications, the advantages of rapid prototyping and the use inexpensive, accessible materials will make the methods presented here a useful addition to the microfluidic toolbox.

4 Conclusion

Here, we present a very simple, accessible, and low cost fabrication technique for digital microfluidics. Devices were formed from circuit board substrates and gold compact disks using rapid marker masking in a procedure that is capable of producing devices with 50–60 μm spacing between actuation electrodes. Saran™ wrap (15 μm thick polyethylene film) was used as a removable dielectric coating, and Rain-x®, a commercial water repellant, was used as a hydrophobic coating. We demonstrated single-plate and two-plate actuation to move, merge, and split 1–12 μL droplets. We anticipate that the new fabrication technique will make the promising technology of digital microfluidics accessible to all who wish to use it, which should greatly expand the rate, range, and scope of applications thereof.

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