

Microcontact Printing-Based Fabrication of Digital Microfluidic Devices

Michael W. L. Watson,[†] Mohamed Abdelgawad,^{‡,§} George Ye,^{||} Neal Yonson,[†] Justin Trottier,^{||} and Aaron R. Wheeler^{*,†,§,⊥}

Department of Chemistry, University of Toronto, 80 St. George Street, Toronto, ON, M5S 3H6 Canada, Department of Mechanical Engineering, University of Toronto, 5 King's College Road, Toronto, ON, M5S 3G8 Canada, Institute for Biomaterials and Biomedical Engineering, University of Toronto, 164 College Street, Toronto, ON M5S 3G9 Canada, Department of Engineering Science, University of Toronto, 40 St. George Street, Toronto, ON M5S 2E4 Canada, and Banting and Best Department of Medical Research, University of Toronto, 112 College Street, Toronto, ON M5G 1L6 Canada

Digital microfluidics is a fluid manipulation technique in which discrete droplets are actuated on patterned arrays of electrodes. Although there is great enthusiasm for the application of this technique to chemical and biological assays, development has been hindered by the requirement of clean room fabrication facilities. Here, we present a new fabrication scheme, relying on microcontact printing (μ CP), an inexpensive technique that does not require clean room facilities. In μ CP, an elastomeric poly(dimethylsiloxane) stamp is used to deposit patterns of self-assembled monolayers onto a substrate. We report three different μ CP-based fabrication techniques: (1) selective etching of gold-on-glass substrates; (2) direct printing of a suspension of palladium colloids; and (3) indirect trapping of gold colloids from suspension. In method 1, etched gold electrodes are used for droplet actuation; in methods 2 and 3, colloid patterns are used to seed electroless deposition of copper. We demonstrate, for the first time, that digital microfluidic devices can be formed by μ CP and are capable of the full range of digital microfluidics operations: dispensing, merging, motion, and splitting. Devices formed by the most robust of the new techniques were comparable in performance to devices formed by conventional methods, at a fraction of the fabrication time. These new techniques for digital microfluidics device fabrication have the potential to facilitate expansion of this technology to any research group, even those without access to conventional micro-fabrication tools and facilities.

The work presented here falls under the broad heading of “microfluidics”, a multidisciplinary field of study characterized by the use of integrated devices to manipulate fluids in micrometer-length dimensions. Microfluidics first became popular

in 1992 with the demonstration of capillary electrophoresis separations in enclosed channels.^{1,2} The technology was rapidly accepted and promoted by the scientific community as a revolutionary tool that would facilitate the development of “labs-on-a-chip” and “micro total analysis systems”.^{3,4} Despite this enthusiasm, the technology was, initially, limited to a few laboratories with access to well-equipped clean room fabrication facilities, and only ~5 papers/year were published on the topic between 1993 and 1997.⁵ In the late 1990s, however, the field exploded, with ~75 papers/year published between 1998 and 2000.⁶ This surge can be attributed, in part, to the development of “soft” fabrication techniques by the Whitesides group at Harvard.^{7–12}

A key feature of soft fabrication techniques is the use of unconventional materials (relative to standards such as silicon and glass) to form devices with reduced spatial resolution. For example, the popular method of soft lithography is used to form poly(dimethylsiloxane) (PDMS) devices by casting against positive relief masters formed using ink jet-printed transparency film photomasks with feature resolutions of $\geq 20\ \mu\text{m}$. These tradeoffs, i.e., PDMS instead of glass and reduced resolution, are in many cases worth making, as soft fabrication techniques are fast, inexpensive, and require less specialized equipment relative to

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* Corresponding author. E-mail: awheeler@chem.utoronto.ca. Tel: (416) 946 3864. Fax: (416) 946 3865.

[†] Department of Chemistry.

[‡] Department of Mechanical Engineering.

[§] Institute for Biomaterials and Biomedical Engineering.

^{||} Department of Engineering Science.

[⊥] Banting and Best Department of Medical Research.

conventional clean room fabrication. In short, soft fabrication technologies make microfluidics accessible to virtually any scientist or engineer who wants to use it.

Recently, an alternative paradigm to conventional, channel microfluidics has been introduced, called digital microfluidics. In this method, fluid is manipulated as discrete droplets on a patterned array of electrodes. Droplets are dispensed, merged, mixed, and split in digital microfluidics by electrowetting^{13–16} and dielectrophoresis^{17–21} forces that are generated when an electrical potential is applied to sequential electrodes in the array. There is currently much enthusiasm for the technique,²² as the geometry of digital microfluidics devices seems a perfect match for low-volume, array-based biochemical applications. For example, digital microfluidics-based methods have recently been used to implement enzymatic assays^{23,24} and profiling proteomics applications.^{25–27} Despite this enthusiasm, digital microfluidics is currently in use by only a few laboratories, worldwide, which is analogous to the state of conventional microfluidics in the mid-1990s. This can be attributed, in part, to the materials (i. e., glass and silicon) and resolutions ($\sim 1\ \mu\text{m}$) conventionally used in digital microfluidics device fabrication.

Here, we introduce a new set of “soft” fabrication tools for digital microfluidics device construction, based on microcontact printing (μCP).^{28–33} In μCP , a disposable “stamp” is formed by casting PDMS onto a master composed of raised features of photoresist on a solid substrate. After curing, the stamp can be used to transfer a two-dimensional replica of the features to a second substrate by “inking” the stamp and placing it into contact with the desired surface. Once formed, stamps can be reused repeatedly to enable fast deposition of features with micrometer dimensions onto multiple substrates. Of critical interest here, aside from fabrication of the master (which, once formed, can be reused

to create multiple stamps), is the fact that μCP requires no special equipment or access to clean rooms.^{28–33}

We present here, for the first time, the use of μCP to fabricate digital microfluidics devices. In the course of our work, we developed three distinct fabrication procedures. In the “etch mask” procedure, a patterned self-assembled monolayer (SAM) of 1-hexadecanethiol (HDT) was stamped onto a gold surface, which protected the covered regions from subsequent exposure to gold etchant. In the “colloid printing” procedure, a suspension of palladium colloids was stamped onto a substrate, and the resulting pattern was subsequently made more robust by electroless deposition of copper. In the “colloid trap” procedure, a patterned SAM with mercaptosilane functionality was stamped onto a substrate, followed by trapping of gold colloids and electroless deposition of copper. Electrode patterns formed by each of these procedures were then further processed and assembled into digital microfluidics devices to dispense, merge, mix, react, and split submicroliter droplets of reagents.

In what follows, we (1) describe the new μCP -based fabrication methods for digital microfluidics devices, (2) demonstrate the use of each of these kinds of devices for droplet actuation, and (3) compare the performance of devices formed by the new methods to devices formed by conventional clean room fabrication. It is our hope that these new fabrication tools, which are fast, inexpensive, and do not require access to clean room facilities, will make the technology of digital microfluidics accessible to a wide range of scientists and engineers.

EXPERIMENTAL SECTION

Reagents and Materials. Reagents used outside of the clean room were purchased from Sigma Chemical (Oakville, ON, Canada) unless otherwise indicated. Toluene, octane, methanol, ethanol, 1-propanol, and octanol were from Caledon Laboratories (Georgetown, ON, Canada). Concentrated hydrochloric acid, nitric acid, and sulfuric acid were from Fisher Scientific (Whitby, ON, Canada), Caledon Chemical Laboratories (Georgetown, ON, Canada), and JT Baker (Phillipsburg, NJ), respectively. Sylgard 184 PDMS was purchased from Dow Corning (Midland, MI). Blue food color dye was from McCormick Canada (London, ON, Canada). Parylene-C dimer was from Specialty Coating Systems (Indianapolis, IN), and Teflon-AF was purchased from DuPont (Wilmington, DE).

Clean room reagents and supplies included SU-8 photoresist and developer from MicroChem (Newton, CA), Shipley S1811 photoresist and developer from Rohm and Haas (Marlborough, MA), AZ300T stripper from AZ Electronic Materials (Summerville, NJ), solid chromium and gold from Kurt J. Lesker Canada (Toronto, ON, Canada), CR-4 chromium etchant from Cyantek (Fremont, CA), and hexamethyldisilazane (HMDS), from Shin-Etsu MicroSi (Phoenix, AZ).

Preparation of PDMS Stamps for Microcontact Printing.

Stamps for μCP were formed in two steps: (1) fabrication of masters and (2) casting of PDMS. Glass microscope slides served as substrates for the fabrication of masters. Slides were cleaned in piranha solution (7:3 concentrated sulfuric acid/30% hydrogen peroxide, 10 min) then rinsed in deionized (DI) water, and dried. *Note: Piranha solution is extremely acidic and oxidizing. Great care should be taken in its use.* SU-8 photoresist was spin coated (1000 rpm, 30 s) and soft-baked on a hot plate (65 °C, 5 min,

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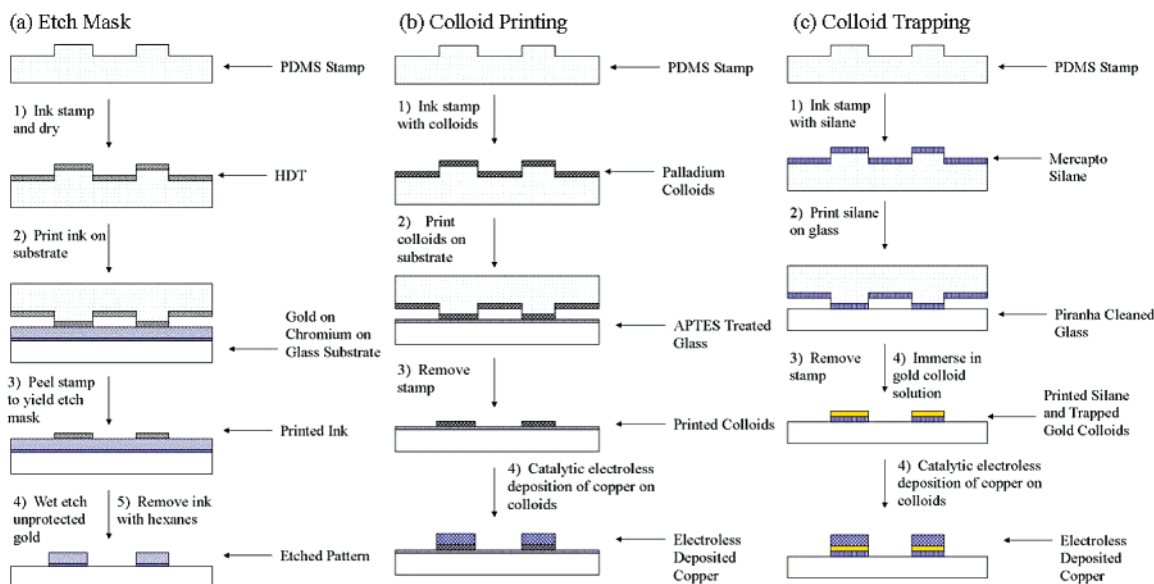


Figure 1. Three μ CP methods for fabricating digital microfluidics devices. (a) A patterned SAM of HDT serves as a contact etch mask for patterning a gold substrate. (b) Palladium colloids are printed onto a glass substrate pretreated with APTES. The amine groups promote colloid adhesion to surface. (c) Mercaptosilane is printed onto a glass substrate. Subsequently, gold colloids are trapped onto the patterned mercapto functionality. In (b) and (c), electrodes are made more robust by electroless deposition of copper.

followed by 95 °C, 15 min). SU-8 coated slides were exposed through a photomask using a Suss Microtek (Waterbury Center, VT) mask aligner (35.5 mW/cm², 365 nm, 8 s). Exposed slides were postbaked on a hot plate (65 °C, 1 min followed by 95 °C, 4 min) and then immersed in SU-8 developer (4 min). Feature thickness of 60 μ m was verified by profilometry. Finally, masters were rinsed with isopropyl alcohol and stored until use. We note that features on masters were spaced \sim 50–70 μ m from each other; this spacing is 1 order of magnitude larger than the 1–5 μ m spaces used for conventional digital microfluidics devices.

Patterned masters were used to create μ CP stamps by casting PDMS to form negative-relief features. Briefly, masters were exposed to methyltrichlorosilane vapor in a desiccator (20 min) and then positioned in a plastic petri dish. PDMS base and curing agent were mixed thoroughly (10:1 by mass), poured onto the master, and then degassed under vacuum until bubbles were not observed (30–45 min). The assembly was then cured in an oven (70 °C, 4 h); after cooling, stamps were gently peeled from the master, trimmed to size, and examined by microscopy for defects.

Etch Mask Method. The first soft fabrication method was adapted from previous work^{28,29} and is depicted in Figure 1a. In this method, HDT is used to selectively protect a gold substrate for wet etching. Device substrates were formed either (a) by electron beam deposition of chromium (10 nm) and gold (100 nm) onto a glass microscope slide or (b) from the preformed \sim 70-nm gold layers in a recordable compact disk (CD; Mitsui, Needham Heights, MA), in a method similar to the one reported by Daniel et al.³⁴ Prior to using the latter substrate, plastic protective layers were removed by immersing the CDs in concentrated nitric acid (30 s), followed by rinsing with copious DI water and drying.

Stamps were cleaned with hexanes and absolute ethanol and blown dry with nitrogen immediately prior to use. The solution

of HDT (5–10 mM in methanol, ethanol, or 1-propanol) was inked onto the surface of a PDMS stamp using a swab (Texwipe, Mahwah, NJ), and the solvent was allowed to evaporate in air or under a stream of nitrogen gas. After inking, the stamp was placed in contact with the gold-coated substrate for \sim 30 s to transfer a SAM of HDT to the surface. Light pressure was applied, taking care not to bend the stamp in order to reduce feature deformation.

Aqueous ferricyanide etchant was prepared, containing potassium hydroxide (1 M), potassium thiosulfate (0.1 M), potassium hexacyanoferrate(III) (40 mM), and potassium hexacyanoferrate(II) (4 mM). The SAM-patterned substrate was immersed in hot ferricyanide etchant (60 °C); depending on the age of the etchant bath and the size of the substrate, gold and chromium layers on glass substrates were etched in \sim 2–5 min, and the gold layer was etched in \sim 6 min on substrates formed from CDs. Following etching, devices were rinsed and swabbed with hexanes or dipped quickly (\sim 15 s) into piranha solution and then washed in DI water to remove residual HDT. Removal of HDT facilitated the coating of devices with hydrophobic dielectric polymer (described below).

Colloid Printing Method. The second soft fabrication method was adapted from previous work^{31,32} and is depicted in Figure 1b. In this method, a pattern of palladium colloids is formed on a surface and then made more robust by electroless deposition of copper. Device substrates were prepared by cleaning glass microscope slides with piranha solution (30 min), rinsing in DI water and absolute ethanol, and forming an amine-functionalized layer by immersion in a solution of (3-aminopropyl)triethoxysilane (APTES, 100 mM in absolute ethanol). We found that overnight treatment with APTES was required for high pattern fidelity; this stands in contrast to the original method,^{31,32} which stipulates a 1-h treatment. Palladium colloids were formed using established procedures³¹ and characterized using a Hitachi S-5200 electron microscope (Hitachi High Technologies America, Pleasanton, CA)

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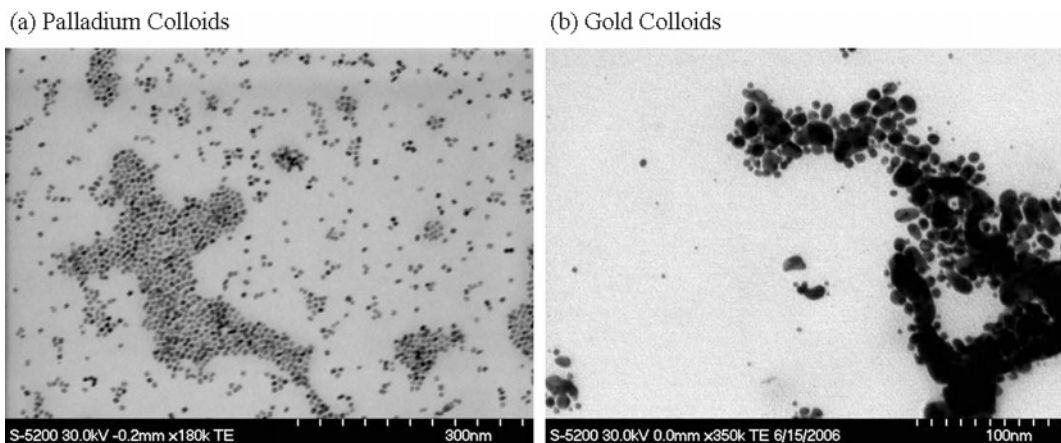


Figure 2. TEM micrographs of (a) palladium and (b) gold colloids used in digital microfluidics device fabrication. The palladium particles (a) had a mean diameter of 7 nm. Gold colloids (b) were not purified from the toluene mother liquor, which led to aggregation (prohibiting accurate measurement of particle diameter).

to have a mean diameter of ~ 7 nm (Figure 2a). A suspension of colloids (1.5 g/L in toluene) was inked onto the surface of a PDMS stamp, allowed to dry, and then printed onto the substrate.

The initial pattern of palladium was then used to catalyze the reduction of copper salts to form robust electrodes. A copper electroless plating bath was created by dissolving copper(II) sulfate (3 g), potassium sodium tartrate tetrahydrate (Rochelle salt) (14 g), and sodium hydroxide (4 g) in 100 mL of DI water. This solution was mixed 10:1 (v/v) with a second solution of 36% formaldehyde in DI water. Palladium-patterned substrates were immersed in the electroless plating bath (30–300 s, 45 °C) until fully developed (determined by visual inspection). After plating, devices were baked on a hot plate (100 °C, 1 h). This step, not reported in previous work,^{31,32} was found to be required for feature robustness.

Colloid Trap Method. The third soft fabrication method is depicted in Figure 1c and to our knowledge is the first such method reported for μ CP. In this technique, a patterned SAM containing thiol groups is deposited onto a surface and then used to “trap” gold colloids from suspension. As in method 2, the electrodes are made more robust by electroless deposition of copper. Device substrates were prepared by cleaning glass slides in piranha solution (30 min), followed by rinsing in DI water, and drying under a stream of nitrogen gas. PDMS stamps were inked with (3-mercaptopropyl)trimethoxysilane (MPTMS, 100 mM in octane) and were allowed to dry for ~ 10 min until they were no longer deformed by solvent-induced swelling. A patterned SAM of MPTMS was transferred to the glass substrate by placing the stamp on the surface for ~ 30 s. Pattern fidelity was reinforced by applying 6 kPa of pressure (i. e., positioning a 250-mL beaker containing 200 mL of water on top of the 6-cm² stamp).

Gold colloids were prepared as described by Brust and co-workers^{35,36} using a two-phase reaction of aqueous hydrogen tetrachloroaurate and tetraoctylammonium bromide in toluene, with subsequent reduction using sodium borohydride (Figure 2b). In previous work,^{35,36} gold particles formed in this manner were shown to have a mean diameter of ~ 8 nm. A suspension of colloids

(25.9 g/L in toluene) was decanted onto the MPTMS-functionalized slides, and colloid trapping was allowed to proceed for 3–5 min. Slides were rinsed in toluene and dried under nitrogen. Finally, the electrodes were made more robust by electroless deposition of copper, using a variation of the procedure described above but with a hotter plating bath (60 °C).

Clean Room Fabrication. Digital microfluidic devices were formed using conventional methods in the University of Toronto Emerging Communications Technology Institute (ECTI) fabrication facility. Glass slides were cleaned in piranha solution (10 min) and coated with chromium (10 nm) and then gold (100 nm) by electron beam deposition. After rinsing (acetone, methanol, DI water) and baking on a hot plate (115 °C, 5 min), the substrates were primed by spin-coating with HMDS (3000 rpm, 30 s) and then spin-coated with Shipley S1811 photoresist (3000 rpm, 30 s). Substrates were baked on a hot plate (100 °C, 2 min) and exposed through a photomask using a Suss Mikrotek mask aligner (35.5 mW/cm², 365 nm, 3 s). Substrates were immersed in MF321 developer for 3 min and then postbaked on a hot plate (100 °C, 1 min). After photolithography, substrates were immersed in gold etchant (50 s) followed by chromium etchant (30 s). Finally, the remaining photoresist was stripped in AZ300T for at least 5 min in an ultrasonic cleaner. Although electrode spacing of 1–5 μ m can be obtained using this method, spacings of 50–70 μ m were used here, for the purposes of comparison with devices formed by μ CP.

Application of Device Coatings. All devices (formed by soft or conventional means) were treated with one of three coatings: (1) 6 μ m of PDMS, (2) 1 μ m of parylene-C, or (3) 50 nm of Teflon-AF on 1 μ m of parylene-C. PDMS was deposited by spin-coating (10:1 base/curing agent diluted 1:1 by weight, in octane, 6000 rpm, 60 s), as was Teflon-AF (1% w/w in Fluorinert FC-40, 2000 rpm, 60 s). Parylene C was applied using a vapor deposition instrument (Specialty Coating Systems). Devices were coated globally, covering both the actuation electrodes and the electrical contact pads. To actuate droplets, the polymer coatings were locally removed from the contact pads by gentle scraping with a scalpel or the tip of a voltage probe. In addition to patterned devices, unpatterned indium–tin oxide (ITO)-coated glass sub-

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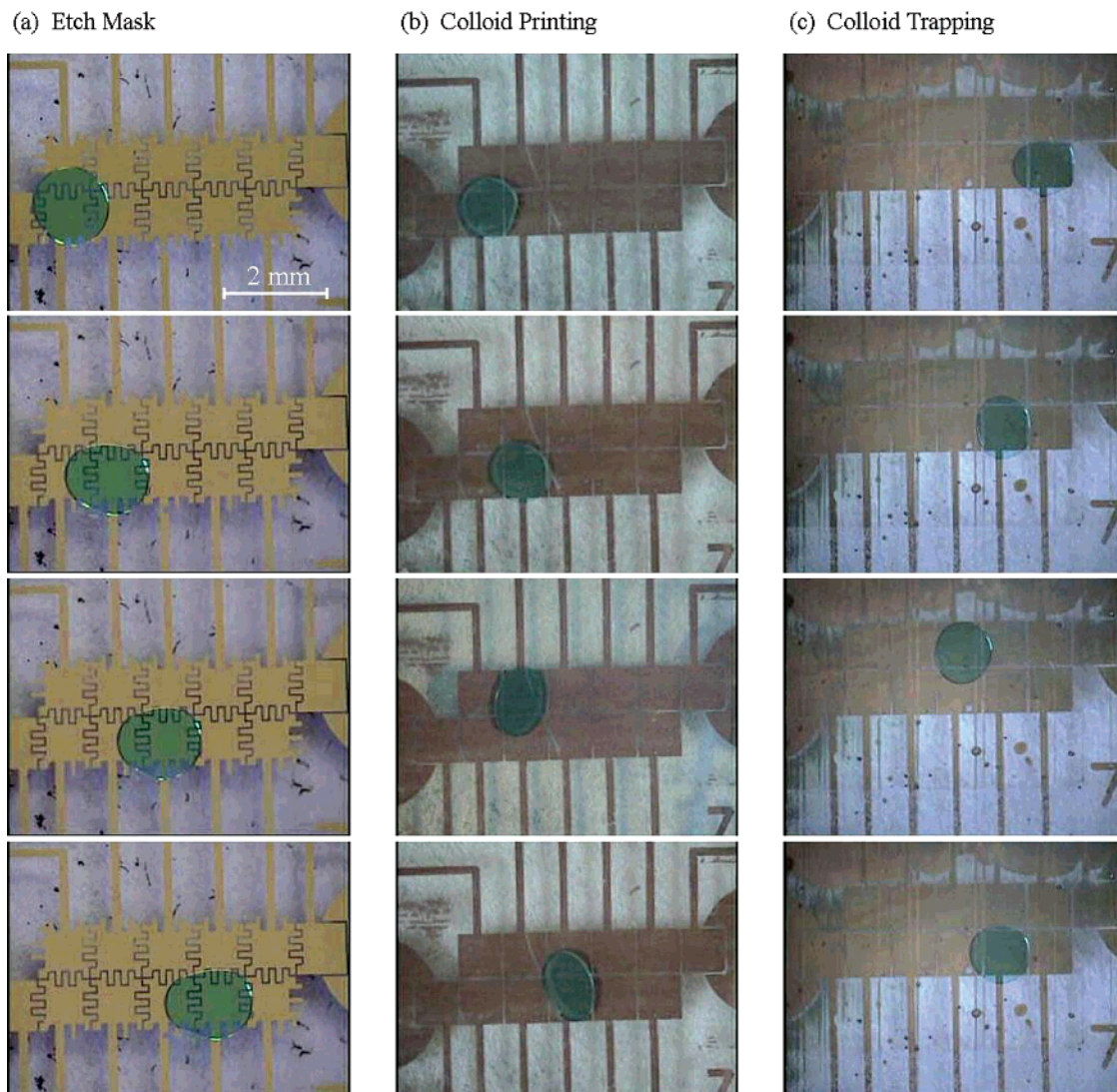


Figure 3. Video sequences (top to bottom) depicting actuation of droplets on digital microfluidics devices, formed by (a) etch mask, (b) colloid printing, and (c) colloid trapping methods. All droplets (300 nL) were moved using the same frequency (20 kHz) but with different voltages: (a) 100, (b) 140, and (c) 110 V. All chips were coated with parylene-C (1 μm) and Teflon-AF (50 nm), and ITO cover slides were separated by 140- μm spacers.

strates (Delta Technologies Ltd., Stillwater, MN) were coated with Teflon-AF (50 nm, as above).

Droplet Actuation. Devices were assembled with an unpatterned ITO/glass top plate and a patterned bottom plate separated by a spacer formed from one or two pieces of double-sided tape (~ 70 or $140\ \mu\text{m}$ thick, respectively). As described previously,^{13–16,23–27} droplets were sandwiched between the two plates and actuated by applying electric potentials between the top electrode and sequential electrodes on the bottom plate. Droplets were typically formed from blue food coloring dye in DI water (diluted 1:40) and passed through a $0.45\text{-}\mu\text{m}$ filter. Applied potentials ($75\text{--}200\ V_{\text{rms}}$) were generated by amplifying the output of a function generator operating at 20 kHz. Voltage application was manually performed on exposed contact pads on the bottom plate surface. 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. All devices had $1\ \text{mm} \times 1\ \text{mm}$ actuation electrodes, with an interelectrode gap of $70\ \mu\text{m}$. Some arrays were interdigitated to improve droplet overlap between electrodes.

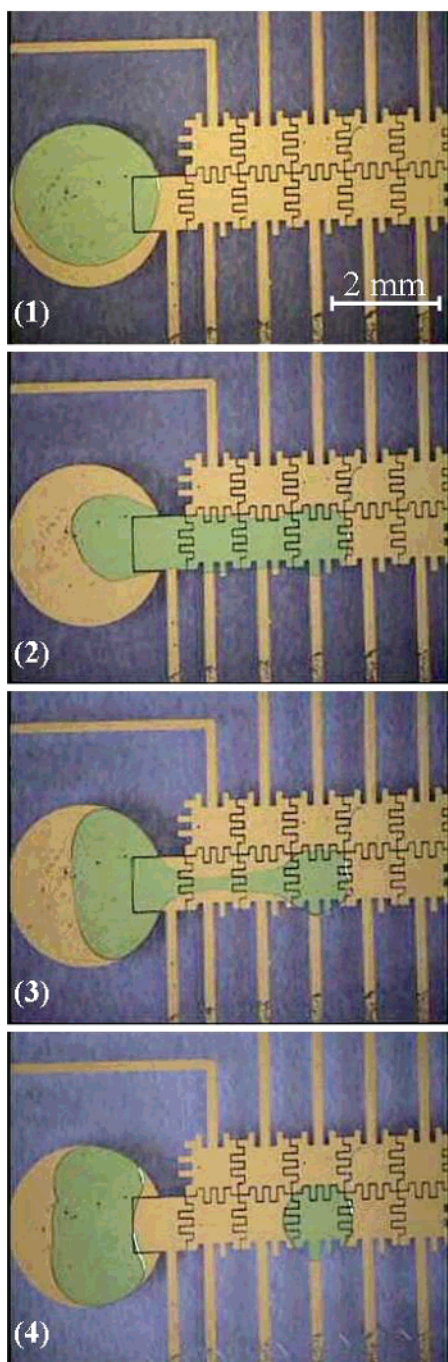
Comparison of Device Performance. A batch of 10 devices each were fabricated by both the etch mask μCP method and by conventional photolithography. In comparing device performance, a single droplet (300 nL) was pipetted onto devices and actuated over the array, repeatedly. Each electrode was tested 3–5 times; electrodes were only considered “operable” if capable of moving the droplet more than one time.

RESULTS AND DISCUSSION

Droplet Actuation and Device Optimization. Digital microfluidics devices were prepared by the three different μCP methods (summarized in Figure 1), assembled with a $140\text{-}\mu\text{m}$ spacer between top and bottom plates. Each type of device was capable of manipulating 300-nL droplets, with facile, smooth, and fast movement. These results (as for all of the results reported here) were confirmed using multiple devices formed by each method. Video sequences depicting droplet actuation on each kind of device are shown in Figure 3.

In general, devices formed by the etch mask method were more robust and reliable than devices formed by the colloid

(a) Dispensing



(b) Merging and Splitting

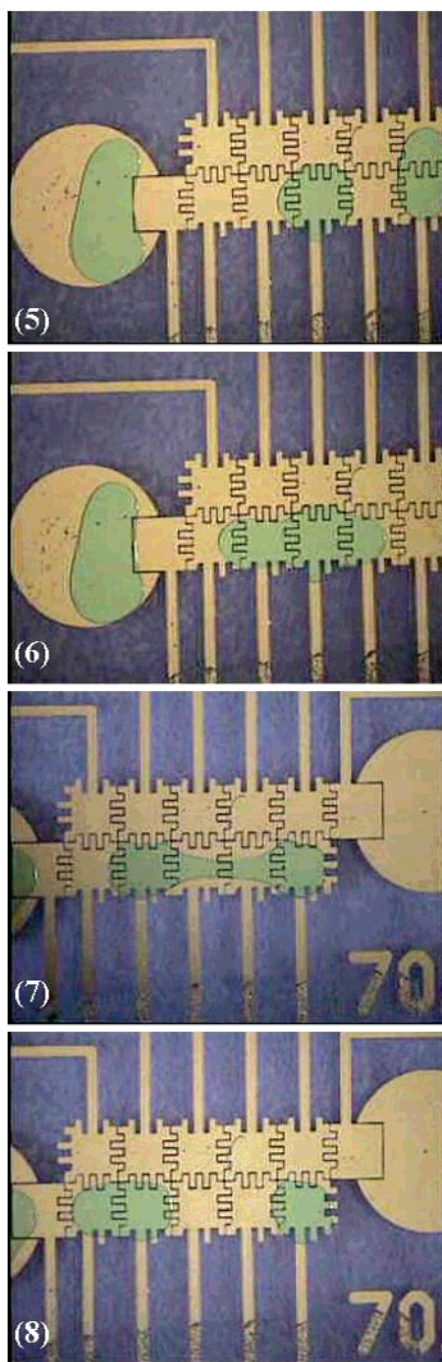


Figure 4. Video sequence (frames 1–8) depicting (a) dispensing and (b) merging and splitting. Droplets (~ 100 nL) were actuated by applying 75 V and 20 kHz.

printing or trapping methods. The fragility of devices formed by these methods was especially apparent during the necessary process of scraping the polymer coatings off of the contact pads (described above). On the devices formed by colloid printing or trapping, the contact pads were often damaged or removed, rendering the device useless for actuation. This problem could be solved by adding an extra mask/etch step to selectively remove polymer from the contact pads; we chose not to do so, in the spirit of developing rapid fabrication tools. These initial results persuaded us to concentrate our efforts on the etch mask method, which we used for the remainder of our work.

As others have reported,^{11,29} a drawback of μ CP-based etch mask methods is a tendency for the stamping process to be unstable—from run to run, the pattern of electrodes will sometimes be characterized by undesirable shorts between electrodes (i.e., too much ink is applied) or cuts in the circuit (i.e., too little ink is applied). With this in mind, we optimized the etch mask procedure for pattern-transfer fidelity. A particularly important parameter was ink composition. In agreement with previous work,^{28–30} we found that HDT formed a robust mask to protect gold from the ferricyanide etchant. However, while previous work used ethanolic HDT inks, we evaluated the performance of methanol, ethanol,

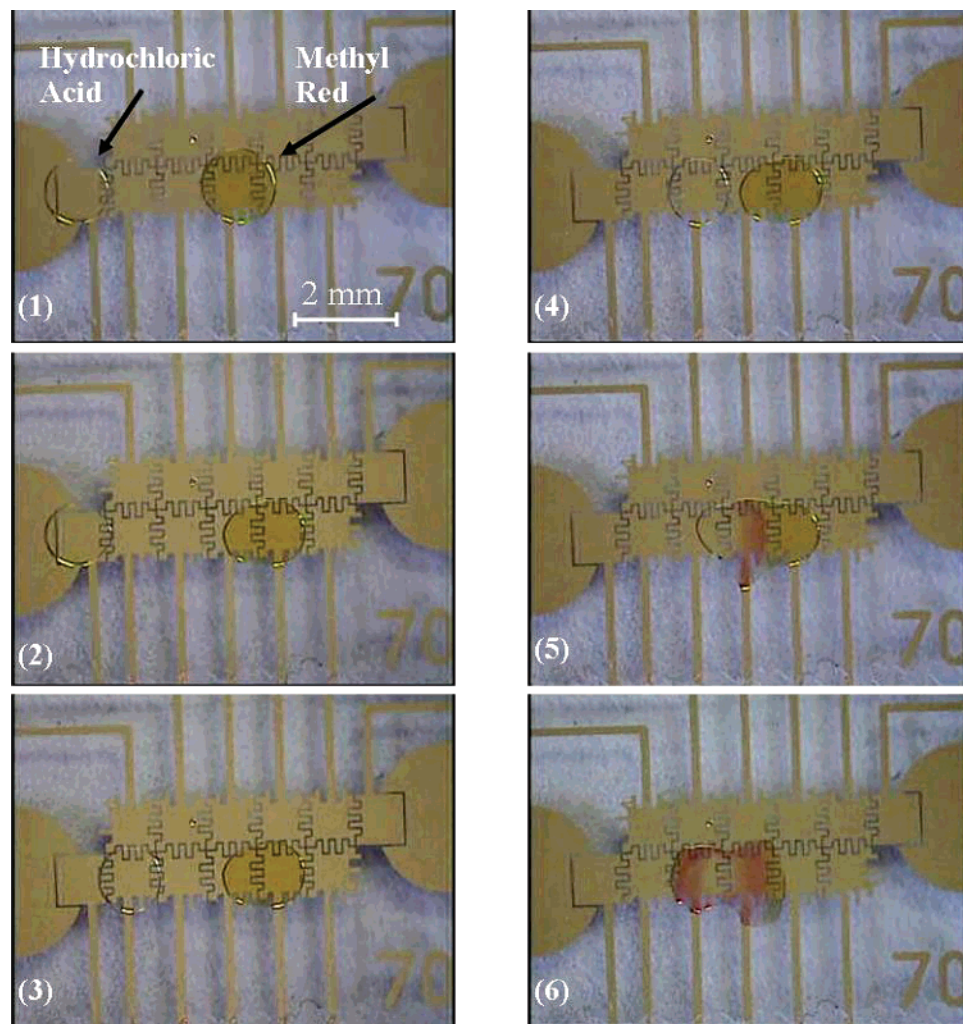


Figure 5. Video sequence (frames 1–6) depicting on-chip acidification of methyl red by hydrochloric acid. Each droplet was 300 nL and was actuated at 140 V and 20 kHz. After merging, the droplet was actively mixed by moving between two electrodes (frames 5 and 6).

and 1-propanol and found 1-propanol to be the best solvent for feature transfer. Ethanol- and methanol-based inks were found to cause undesirable effects such as precipitation of HDT and rapid, uneven evaporation, while 1-propanol-based ink reliably and smoothly transferred the desired pattern to the gold surface. In addition, the lower polarity of 1-propanol facilitated easier wetting of the hydrophobic stamp surface.

Stamping pressure was found to be another important parameter, as the conventional method²⁹ of simply placing the stamp on the surface led to poor pattern fidelity. We experimented with a variety of means to apply light pressure to the stamp (too much pressure causes the stamp to bend, which deforms the features) and found the best method to be tapping the top of the stamp with the blunt end of a swab for ~30 s. PDMS is transparent, and feature contact was visible through the stamp. This stamping technique produced very repeatable features with reliable fidelity.

In addition to electrode patterning, digital microfluidics device fabrication requires application of a uniform dielectric coating. (For electrowetting-driven droplet actuation, the force applied at a given voltage is inversely proportional to the square root of the thickness of the dielectric layer.) We evaluated the performance of devices with dielectric coatings formed from two materials: PDMS and parylene-C. Devices formed from either material were found to

Table 1. Comparison of Devices Formed by μ CP and Photolithography

device type	electrode performance, % ($N = 180$)	fabrication time, ^a min	accessibility ^b
microcontact printed	94	150	chemistry lab
photolithography	97	400	clean room

^a These fabrication times were recorded from actual experiments and reflect the time required to pattern electrodes in a batch of 10 devices. For both methods, an additional 60 min is required for PDMS deposition, or 200 min for parylene/Teflon-AF. ^b See text for details.

be capable of droplet actuation. Spin-coating PDMS is very fast and is thus a good match for rapid prototyping; however, bubbles and other irregularities were sometimes observed to form during the curing process. These features, which could be minimized with sufficient care during the deposition process, were observed to impede droplet actuation and thus reduced device reliability. Parylene-C-coated devices were more reliable. However, as droplet actuation on Parylene-C was significantly enhanced by application of a second coat of Teflon-AF (not necessary for PDMS, which is more hydrophobic than parylene-C), fabrication by this method

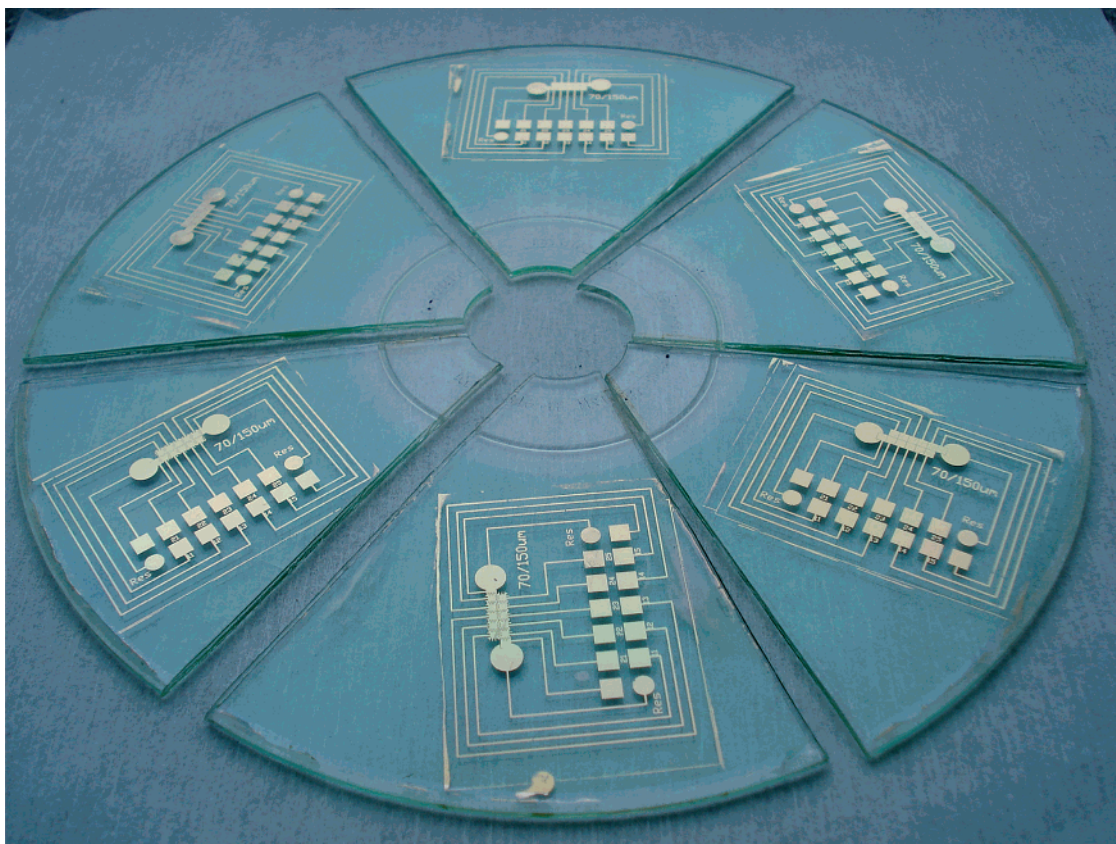


Figure 6. Digital microfluidics devices fabricated on a CD-R substrate. The gold surface was exposed by dissolving the plastic coating in nitric acid. The etch mask μ CP method was used to form electrode patterns, and devices were cut to shape using scissors.

required more time. We used both dielectric materials, depending on the goals of the experiment (i.e., rapid fabrication or reliable coating). Devices coated with parylene-C and Teflon-AF were used for the work reported below.

Full Complement of Digital Microfluidic Operations. After optimization, digital microfluidics devices formed by the etch mask process were evaluated for the capacity to perform the full suite of digital microfluidic operations: droplet dispensing, splitting, moving, and merging.¹⁶ The device design used for this work included circular reservoirs with an inset electrode, which aided in dispensing.^{23,27} Typically a 500-nL droplet was deposited into the reservoirs, and devices were assembled with a 70- μ m spacer (unit droplets dispensed under these conditions were \sim 70–100 nL). Video sequences depicting typical results are shown in Figure 4.

μ CP digital microfluidics devices proved compatible with all of the microfluidic operations that were evaluated. For dispensing, shown in Figure 4a, a reservoir droplet was pulled across three electrodes, was “necked,” and then was cut by activating the reservoir electrode. For merging, shown in Figure 4b (frames 5 and 6), two droplets were positioned with a target electrode separating them and combined by actuating the target electrode. For splitting, shown in Figure 4b (frames 7 and 8), a single, large droplet was divided by actuating electrodes on opposite sides of the droplet, separated by an unbiased electrode. These operations were then used to effect a reaction, depicted in Figure 5. In this experiment, one droplet was dispensed containing methyl red indicator (300 nL, 0.5 g/mL, yellow), and another droplet was dispensed containing hydrochloric acid (300 nL, 10 mM, color-

less). The two droplets were moved next to each other and then merged, causing methyl red to be protonated, yielding a pink product. Mixing was made more efficient by moving the large merged droplet between adjacent electrodes.³⁷

After conducting several similar experiments, we concluded that there were no qualitative differences between the performance of μ CP devices and devices formed by conventional means.

Comparison of Conventional and μ CP Devices. The two most critical parameters for digital microfluidics device fabrication are reliability and fabrication time. To evaluate the new fabrication method by these criteria, we fabricated two batches each of 10 identical devices with 18 actuation electrodes, formed by μ CP and by photolithography. All processes that could be performed in parallel (e.g., hot plate baking, resist stripping, sonicating, etc.) were done in this manner. Devices were evaluated in terms of droplet actuation reliability and time required to fabricate the batch. These results are summarized in Table 1.

When tested for droplet actuation, 97% (i.e., 174/180) of electrodes on devices formed by conventional means were found to support droplet movement. Devices formed by μ CP were found to be slightly less reliable, with 94% (i.e., 169/180) of electrodes supporting droplet movement. It is clear that both fabrication methods are reliable;³⁸ however, conventional, clean room fabrication slightly outperforms μ CP fabrication. When comparing the

(37) Paik, P.; Pamula, V. K.; Pollack, M. G.; et al. *Lab Chip* 2003, 3, 28–33.

(38) We note that neither of these techniques has a reliability matching the six-sigma tolerances common in industry, but this level of reliability matches that of fabrication techniques used in academia to form conventional, microchannel devices.

two techniques in fabrication time, μ CP is superior: i.e., ~ 150 min is required to fabricate a batch of 10 devices by μ CP, while ~ 400 min is required to fabricate the same number by conventional means. This difference in fabrication time effectively cancels out the difference in reliability. For example, in ~ 400 min, > 20 devices could be fabricated by μ CP, and those with nonperforming electrodes could be discarded.

Aside from device reliability and fabrication time, a significant advantage of μ CP fabrication is accessibility. Although the masters used in this work were formed in the ECTI clean room, all other steps were performed in a chemistry laboratory (as noted, masters could be used indefinitely to form multiple stamps, limiting the cleanroom fabrication to a one-time investment). We note that the resolution required for these masters (i.e., $50\text{--}70\text{-}\mu\text{m}$ spacing between electrodes) makes the technique attractive for non clean room fabrication such as conventional machining in aluminum.³⁹ Thus, with the new μ CP fabrication method, digital microfluidics should be accessible to scientists with access to generic chemistry laboratories equipped with a fume hood.

To further highlight the accessibility of the technique, we present preliminary data regarding the formation of devices from an inexpensive, widely accessible substrate: a compact disk. As shown in Figure 6, up to eight devices were formed on a single \$1 CD, such that the raw materials used to form each device required only a few cents. Devices formed in this manner were used to actuate aqueous droplets; movement was observed to be fast and reliable, with no discernible differences relative to the devices formed from gold-on-glass. We are currently optimizing this technique for higher device throughput. Regardless, we anticipate that the types of accessible techniques and materials described here will be useful for laboratories that wish to use

digital microfluidic devices but would not otherwise have the means to do so.

CONCLUSION

In this work, we introduce new methods for digital microfluidic device fabrication. We showed, for the first time, that μ CP can be used to form digital microfluidics devices, which are comparable in performance to devices formed by conventional means. Three different μ CP procedures were developed; the etch mask method, in which an HDT SAM is used to define a pattern of gold electrodes, proved to be the most robust and reliable. The digital microfluidics devices formed by the etch mask method were compatible with the full complement of digital fluidics operations: moving, dispensing, splitting, and merging. This work represents the first step in our ongoing goal to automate droplet actuation for high-throughput, biochemically relevant lab-on-a-chip tools. In addition to our work, we anticipate that the methods reported here will enable a wide group of scientists and engineers to join us in using the promising technology of digital microfluidics.

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(39) Zhao, D. S.; Roy, B.; McCormick, M. T.; et al. *Lab Chip* **2003**, *3*, 93–99.