Rapid mask prototyping for microfluidics

B. G. C. Maisonneuve,^{1,2} T. Honegger,^{1,2,a)} J. Cordeiro,^{1,2} O. Lecarme,^{1,2}
 T. Thiry,^{1,2} D. Fuard,^{1,2} K. Berton,^{1,2} E. Picard,³ M. Zelsmann,^{1,2} and
 D. Peyrade^{1,2}

¹*Univ. Grenoble Alpes, LTM, F-38000 Grenoble, France*

²*CNRS, LTM, F-38000 Grenoble, France*

³*CEA, INAC-SiNAPS, F-38054 Grenoble, France*

(Received 6 January 2016; accepted 19 February 2016; published online 3 March 2016)

With the rise of microfluidics for the past decade, there has come an ever more pressing need for a low-cost and rapid prototyping technology, especially for research and education purposes. In this article, we report a rapid prototyping process of chromed masks for various microfluidic applications. The process takes place out of a clean room, uses a commercially available video-projector, and can be completed in less than half an hour. We quantify the ranges of fields of view and of resolutions accessible through this video-projection system and report the fabrication of critical microfluidic components (junctions, straight channels, and curved channels). To exemplify the process, three common devices are produced using this method: a droplet generation device, a gradient generation device, and a neuro-engineering oriented device. The neuro-engineering oriented device is a compartmentalized microfluidic chip, and therefore, required the production and the precise alignment of two different masks. © 2016 AIP Publishing LLC.

[<http://dx.doi.org/10.1063/1.4943124>]

INTRODUCTION

Since the seeding paper of Xia and Whitesides in 1998,¹ microfluidics has risen both as a powerful technology and as an independent research field. Thanks to the emergence of microelectronics fabrication machines, numbers of laboratories gained access to clean room facilities and to microfluidic chips fabrication. Eventually, every student or researcher who wanted to fabricate microfluidics devices needed to gain access to a clean room, to be trained and to wait for chrome or transparent masks to be fabricated or bought externally. Realistically, when designing and fabricating a microfluidic device for a new application, it is quite unlikely that the first design will be the most suited one, even with the help of accurate numerical simulations. Anticipating the designs flaws can be a difficult task, especially if the materials flowed through the device are mechanically complex (e.g., suspensions, emulsions, and blood) or multiphase (e.g., oil/water for droplet generation or resist in water for encapsulation). Therefore, a significant amount of time and/or resources can be wasted in debugging mask design. Partly for those reasons, there is a pressing need for lower cost, shorter timing, and easier ways to fully enable rapid prototyping of masks for microfluidic chips. Such prototyping process has to be fast, so when the design is flawed, a corrected mask can be fabricated within a couple of hours, and it has to be low cost, for every idea to be tested quickly, without the worry of wasting a significant amount of resources. Nowadays, 3D printing technology shows promising prototyping potential, however, commercially available products do not currently offer the capacity of printing molds with micrometer resolutions with a field of exposure (FOE) in the cm² range. There have been some successful attempts to perform mask-less UV photolithography directly on dry films² or SU-8^{3,4} with the resolution of tens of micrometer. However, such systems require the use of new films that are

^{a)} Author to whom correspondence should be addressed. Electronic mail: thibault.honegger@cnrs.fr

not commonly used in the microfluidic community (compared to the SU8 standard and wide-spread process) or complicated systems to replicate that are not commercially available.

Here, we present a facile approach for out-of-a-clean-room rapid prototyping of microfluidics device masks that relies on the classical SU8 processing. The process relies on the use of a modified commercial video projector to create chrome masks only in a matter of a few minutes. The rest of the fabrication process is kept similar to regular microfluidic fabrication processes (fabrication of masters using photolithography and SU-8, followed by polydimethylsiloxane (PDMS) casting and bounding). The overall process, from designing the features to fabricating the microfluidic device, can take less than a couple of hours, every part of the system is commercially available, and the technology merely requires training before use. The overall process can be seen in Figure 1. We first characterize the capabilities of the mask fabrication in terms of pixel size and field of view. Then, we demonstrate the efficiency of the process to fabricate masks for three microfluidic applications: drop generation by flow focusing,^{5,6} concentration gradient generation,⁷ and neuro-engineering/neurons culture.^{8,9}

MATERIAL AND METHODS

Video projector modification

The fabrication of the microfluidic chip was done using a customized commercial LCD video projector (EH-TW5200, Epson, Japan) with a 1920×1080 native resolution. The genuine projection lens of the video projector was replaced by a home-made microscope-type reduction optical system containing a tube lens and an infinity-corrected microscope objective.¹⁰ The tube lens is adjusted in order to be at least 100 mm from the DMD, and a 6 mm diameter pinhole was placed at the back of the microscope objective. A CCD camera couple to a beam splitter was placed at the output of the projector for aligning the projected mask and tuning the focus. Three different optical elements were chosen as the reduction optics. A $\times 0.5$ lens (Thorlabs, USA) was used for the largest field of view and two objectives with $\times 1$ and $\times 2.5$ magnification power (QV-series, Mitutoyo, Japan) for the smallest features. Finally, the light energy was selected using a band-pass filter $@450 \pm 20$ nm (Thorlabs, USA) to specifically insolate g-line resists. A picture of the experimental set up is available in supplementary Figure 1.¹¹ The modified videoprojector was mounted on a vertical aluminium holder that fits perpendicular to the sample holder. To ensure that the objective and the sample holder were perpendicular enough to maximise uniformity of the light, the holder of the entire videoprojector was optically adjusted before screwing by projecting a full resolution image of the LCD with a $1\times$ objective and adjusting the tilt with a fit of the image to a reference projected image on the stage. The distance between the objective and the mask depends on the objective, as it has to be placed in the focal plane of the objective: for the $\times 0.5$ lens, the focal distance used was 15.9 cm, and was 3 cm and 3.4 cm for the $\times 1$ and $\times 2.5$ objectives, respectively. The focus is adjusted by projecting an image on a chromed glass slide without photoresist and adjusting the height of the glass slide with a vertical micrometer elevator (Thorlabs).

Design rules

The masks were designed using an open source vector graphics editor (Inkscape). A matrix of 1920×1080 black pixels was used as a background, and white pixels were used to create

FIG. 1. Overview of the rapid fabrication process.

the features. The size of the features was chosen according to the magnification of the objective used and the size of the LCD pixels ($7\ \mu\text{m}$). The white pixels were aligned to the nearest pixel on the background to prevent any rasterization during the design exportation. The impact of poor rasterization is shown in supplementary Figure 2.¹¹ The design of the mask was finally exported as a bitmap with a resolution of 90 ppi.

Mask fabrication

Regular microscope glass slides were cleaned by immersion in a Piranha solution (made of H_2SO_4 and H_2O_2 at a ratio of 2 to 1, respectively) at 100°C for 10 min. A layer of chrome (100 nm thick) was deposited onto the clean glass slides using an evaporator MEB 550S (Plassys, France). An adhesion promoter (TI Prime, MicroChem, USA) was spin-coated onto the chromed glass slides at 3000 rpm for 30 s, before letting them on a hotplate at 110°C for 3 min. A positive photoresist (AZ-1512HS, AZ Electronic Materials, Germany) was then spin-coated onto the glass slides at 3000 rpm for 30 s, followed by a soft bake step of 3 min at 110°C . Using a $0.5\times$ objective and the video projector, the designs were exposed on the coated glass slides for 180 s. The masks were developed in a mixture of AZ developer (AZ Electronic Materials, Germany) and deionized (DI) water (1:1) for 30 s, before being washed with DI

FIG. 2. (a) FOE and size of the individual pixel for different objectives. (b) Pictures of the masks used to test the videoprojector capabilities. (c) Pictures of the some features (3×5 pixels) obtained with the different magnification. (d) Picture of the smallest features obtained (2×2 pixels) with the $\times 2.5$.

water. The chrome layer unprotected by the photoresist was finally etched using a ChromEtch solution (Technic, France) for 90 s.

SU-8 mold fabrication

The mold was fabricated using a silicon wafer as substrate. An adhesion promoter (Omnicoat, MicroChem, USA) was spin-coated onto the wafer at 300 rpm for 30 s, before letting it bake at 200 °C for a minute.

For the droplet generation and the concentration gradient generation devices, SU8–2050 (MicroChem, USA) was spin-coated onto the wafer at 3000 rpm for 30 before being soft baked (1 min at 65 °C, 6 min at 95 °C, and finally 1 min at 65 °C). Using the corresponding masks, the wafer was exposed to an appropriate dose of UV light (158 mJ/cm²) using a portable desktop UV LED exposure system (UV-KUB2, Kloeé, France). The wafer was then post baked (1 min at 65 °C, 6 min at 95 °C, and finally 1 min at 65 °C) before being developed in SU8 developer (MicroChem, USA). The wafer was finally rinsed with isopropanol.

For the neuron culture device, SU8–2002 was first spin-coated onto the wafer at 1000 rpm for 30 s, and then soft baked (1 min at 65 °C, 2 min at 95 °C, and finally 1 min at 65 °C). Using the first mask made previously (bottom layer of the microfluidic chip), the wafer was exposed to an appropriate dose of UV light (90 mJ/cm²). A post exposure bake was done (1 min at 65 °C, 2 min at 95 °C, and finally 1 min at 65 °C) before developing. SU8–2050 was then spin-coated onto the same wafer at 1667 rpm for 30 s and followed by another soft bake step (5 min at 65 °C, 16 min at 95 °C, and 5 min at 65 °C). Using a binocular, the second mask was aligned with the SU8 features already onto the wafer using alignment marks, before exposing the wafer to UV light (230 mJ/cm²). A post exposure bake step was carried out (4 min at 65 °C, 9 min at 95 °C, and 2 min at 65 °C) and the wafer was developed in SU8 developer again, before being washed with isopropanol. A hard bake step (150 °C for 15 min) was finally carried out.

PDMS microfluidic chip fabrication

The wafer was first silanized using vapors of a silanizing agent (trichloro(1H,1H,2H,2H-perfluorooctyl)silane) in a desiccator for 30 min. PDMS (Sylgrad 184, Dow Corning, USA) pre-polymer was prepared by mixing the base and the curing agent at a ratio of 10:1. The mixture was degassed, poured onto the wafer and cured at 80 °C for 40 min. For the drop generation device and the concentration gradient device, a clean glass slide was coated with PDMS and also cured for 40 min at 80 °C. The PDMS layer was cut to the required size, peeled off the wafer and the inlet/outlet zones were punched out. The device and either the PDMS coated glass slide or a clean microscope glass slide (depending on end application) were then plasma treated using a plasma cleaner (Harrick Plasma, USA) before being assembled at a clean bench. The devices were then sprayed and filled with a solution of 70% of ethanol and bring in a sterile environment. The ethanol was washed three times using sterile DI water and put under UV light for 30 min.

Drop generation protocol

The two fluids used for this application are sunflower oil, as the continuous phase, and DI water as the dispersed phase. The experiment was carried out with an inlet flow of 0.5 ml/min for both phases.

Concentration gradient generation protocol

The concentration gradient device required to use two fluids. The first one was DI water, and the second one was a solution of fluorescein in DI water (at the maximum desired concentration, here, 1 mg/ml). These two fluids were placed at their respective inlets, and a syringe pump was used to suck the fluids through the device at a flow rate of 500 µl/min. The repartition of the headloss within the device allowed the generation of the concentration gradient.⁶

Coating for the neuron culture device

The channels of the neuron culture device were coated with 0.1 mg/ml poly-L-lysine (Sigma Aldrich, USA) for 24 h in an incubator. The channels were then rinsed 3 times with Hank's Balanced Salt Solution (HBSS) (Life Technology, Thermo Fisher Scientific Inc., USA) buffered with 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES) (10 mM) and coated with 20 μ g/ml laminin (Sigma Aldrich, USA) for 2 h. The channels were washed again 3 times and filled 3 times with Neurobasal-B27 containing 2 mM glutamine and 100 U/ml penicillin/streptomycin (hippocampal culture medium). The microfluidic chips were placed in an incubator until use.

Neuron preparation and culture

Hippocampi were harvested from E18 OFA rats (Charles River Laboratories) and stored in ice-cold HBSS, buffered with 10 mM HEPES, pH 7.3. The tissue was digested by a 30 min incubation in 2 ml of HEPES buffered HBSS containing 20 U/ml of papain (Worthington Biochem.), 1 mM EDTA and 1 mM L-cysteine. Next, the tissue was rinsed three times with 8 ml of hippocampal culture medium. The cells were gently triturated in 1 ml of hippocampal culture medium, counted with a hemocytometer, and flowed into the device. The cells were maintained at 37 °C, 5% CO₂. All animal work was approved by the CEA and CNRS Ethics Committee of Animal Care, and abided by institutional and national guidelines for animal welfare.

Neuron seeding in device

Before seeding, the reservoir of the microfluidic chip was emptied without removing the media from the microchannel. For each inlet reservoir, 4 μ l of high density ($>8 \times 10^6$ cells/ml) dissociated neuron solution was placed near the entrance of the microchannel. The chip was returned to the incubator for 5 min in order to let the neurons adhere on the coated glass, and the seeding process was repeated 3 times to achieve a high cell density. At the end, the input and output reservoirs were quickly filled with hippocampal culture medium and chips were returned to incubator.

RESULTS

Overview and capability of the microfabrication process

The designs of the mask can be done with any software according to the pixel-real distance ratio for an objective (see Materials and Methods Section for details). The features are exposed on a chromed glass slide covered with positive photoresist (here, AZ1512HS, MicroChemicals) for the appropriate amount of time. Once developed, the chrome layer is unprotected where the mold casting features will be placed. The chrome is then chemically etched, and the residual photoresist is stripped (by acetone for AZ1512HS). Regular photolithography protocols are then used to produce the SU-8 molds of the device, before casting and curing PDMS onto them. The mask can therefore be produced in ~ 1 h.

The features are designed using white and black pixels on an insulated area of 1920×1080 pixels. The FOE and the size of the pixel depend on the objective that is mounted on the output of the video projector. Exposure time also depends on the objective magnification and follows the empirically determined equation: $t(s) = \alpha/\Gamma^2$, where Γ is the magnification of the objective and α is a parameter depending on the resist photosensitivity (for AZ 1512 HS, $\alpha = 45.3$ s). The performances of the process were assessed with objectives: $\times 0.5$, $\times 1$, and $\times 2.5$. Figure 2(a) plots the corresponding pixel sizes and FOE. Resolution can go down as ~ 3 μ m and a maximum FOE of 25.5×14.3 mm (with a resolution of ~ 14 μ m). The smallest features produced during this study were lines of three white pixels wide pitched by five black pixels, as shown in Figure 2(b). Using the different magnifications, the corresponding width of the lines were 40 μ m, 20 μ m, and 8 μ m, and the corresponding line spacing were found to be 70 μ m, 35 μ m, and 14 μ m for the $\times 0.5$, $\times 1$, and $\times 2.5$ objective, respectively. This technique offers a wide

combination of channel widths that are within the range of sizes commonly used for microfluidic applications (circa 10–100 μm). The projected modulated was uniform enough for all motifs on the glass slides to expose the Chromium after development on the entire FOV for each objective.

Microfluidic chip characterization

We have fabricated and observed “key features” for the production of microfluidic chips: microchannels, connections between microchannels (or between a microchannel and a microchamber) and curved channels. Figure 3 shows the chrome mask and SEM pictures of resulting Chrome mask, SU8 mold and PDMS features. Sharp edges and opened microchannels are produced by the video projection system, in manner of 2 h. Similarly, connections between microchannels and microchambers as well as curved channels and structures are shown in Figure 3. This is important as serpentine are an efficient way to increase the length of microchannels (to either increase residence time or head losses) while minimizing the size of the final device.

Microfluidic chip for droplet generation

Droplet generation microdevices offer attractive techniques to minimize the volumes of chemical reactions and incubation of bioreagents.¹² Several types of geometry have been reported,¹³ and the design and test routine is time and effort consuming when debugging new designs. Here, we focussed on showing the ability of the video-projector technology to produce masks that will enable researchers to fabricate “on demand” droplet generation devices. Figure 4(a) shows the design of a classical droplet design mask, and Figure 4(b) shows one of the fabricated microfluidic devices, filled with Rhodamine-B in order to visualize the features of the device.

FIG. 3. Design of the two layers of the microfluidic device. (a) Picture of the mask used for the bottom layer, (b) picture of the mask used for the top layer, (c) SEM images of the mask, the SU8 master, and the resulting PDMS device. The proposed technology allows clean and precise fabrication of microfluidic geometries.

FIG. 4. Drop generation device. (a) Design of the mask, (b) picture of a microfluidic device, filled with some rhodamine-B, (c) image of the generation of droplets (water in oil).

We have used this device to create ~ 0.94 pl (ellipsoids of $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m} \times 90\text{ }\mu\text{m}$) droplets of DI water suspended in sunflower oil (as shown in Figure 4(c)).

Microfluidic chip for concentration gradient generation

Generation of controlled concentration gradients of species in microfluidic devices has become an important tool for studying dynamic biological assays¹⁴ for chemotaxis on stem cells¹⁵ or neurons.¹⁶ In order to demonstrate the ability of our technology to fulfil the need of researchers, we produced a concentration gradient generation device. The device enables the creation of a gradient concentration thanks to a controlled repartition of headlosses within the device. Each inlet was filled with DI water and a solution of fluorescein in DI water.

Figure 5 shows the design of the complete mask and a fluorescent image of the concentration gradient of fluorescein in DI water.

Microfluidic devices for neuro-engineering and neurones culture

As an illustration of the capability of the rapid prototyping fabrication, we have designed and fabricate a compartmentalized microfluidic chip.³ Such chips were used to investigate the influence of the presence of flow on neurite development. One of the main challenges in designing and fabricating such chips is the capacity to adapt the design in case of culture failure. Since primary neurons are difficult to obtain (typically one

FIG. 5. Concentration gradient generation device. (a) Picture of a microfluidic device, filled with some Rhodamine-B, (b) design of the mask, (c) image of the concentration gradient generated (fluorescein and water).

experiment per week just after surgery), the delay between the fabrication of new masks is critical to avoid sacrificing animals. As mentioned previously, existing fabrication solutions are either expensive or time consuming (often both), and therefore, are not suited for such experiments. The process presented here is an alternative, as it is inexpensive and enables the user to go from the design of the desired chip to the PDMS device in a matter of hours.

We have fabricated a compartmentalized chip, aiming at culturing primary hippocampal neurons for an extended period of time (up to three weeks). The design of the bottom layer is shown in Figure 3(a) and is made of two main components: two plating microchambers, and a set of microchannels that connect the two microchambers together, where the neurites only will be able to sprout and extend. The SU8 mold resulting from the use of this first mask is $3\text{ }\mu\text{m}$ high. The upper layer presents identical geometry for the two microchambers but does not include the microchannels patterns (Figure 3(b)). This mask is used to increase the final height of the loading microchambers of the device to $100\text{ }\mu\text{m}$.

Hippocampal neurons were cultured in one of the chambers of the device, so the neurites could grow in the microchannel (Figure 6). The neurons were monitored for 21 days after seeding. Because of the fluidic resistance of the microchannels ($3\text{ }\mu\text{m}$ high), the two chambers of the device are fluidly isolated.⁸

DISCUSSION

Low cost approaches to produce photolithography masks have been reported in the literature,^{17,18} mainly by the use of overhead transparency. Although such transparent sheets are inexpensive, the high resolution laser printer is not and the minimum resolution is $\sim 10\text{ }\mu\text{m}$. The device presented here costs around 3000€ to build (with a single microscope objective) with micrometric resolutions (Figure 2(d)). Moreover, as a bench top method, our device fits easily in most labs, or on most lab bench, which is not the case with high resolution printers.

One of the future directions of the fabrication of molds for microfluidic chip prototypes should, and potentially will, be in the use of 3D printing to design such molds.¹⁹ However, to date and to our knowledge, both Fused Deposition Modeling (FDM) and StereoLithography

FIG. 6. Compartmentalized neurons culture device. (a) Design of the mask of the bottom layer of the device. (b) Picture of a microfluidic device, filled with some Rhodamine-B in the cell body chamber (right on the image) and some fluorescein in the axon chamber (left on the image). (c) Picture of the device, with some neurons in culture in the (10DIV) in the right chamber, and with some axons crossing all the way to the left chamber.

(SLA) commercially available machines have very limited resolutions to achieve proper microfluidics devices. The lowest resolution is $\sim 25 \mu\text{m}$ in depth for commercially available 3D printing machines using SLA. The FDM technology seems to reach its limits around $300 \mu\text{m}$ with micromachined nozzles. As a fact, microfluidics prototyping requires micrometer resolution, especially for neuro-engineering devices which require embedded microscaled structures to be functional or sufficient surface roughness for cell seeding, as shown in this work. For this particular reason, the classical spin coating/lithography process would remain the gold standard for the next decade to fabricate fully functional microfluidic chips, mainly because of their unique capacity to achieve micrometer resolution in both X-Y and Z resolutions.

One may also question the very use of molds versus direct 3D printing of channels. Soft lithography has been largely used by the microfluidic community, particularly because of PDMS casting. PDMS remains the best material to be used for microfluidic chips because of its gas porosity and its unique capability to maintain a viable environment for cells inside chips. To our knowledge and to date, there is hardly any potential replacement material that fits such critical requirement for the chip material, even less usable for injection molding or 3D printers (either for prototyping or mass production). Hence, PDMS microstructures casting would remain the gold standard for the next decade and rapid mask prototyping for microfluidic devices needs improvements in the ability to create devices at low cost.

Finally, our approach can be also seen as a complement to other approaches that may have limited access to micrometer resolutions, including 3D printing or micromilling. For example, a large ($>100 \mu\text{m}$) loading chip can be fabricated with those techniques, and the micrometer parts can be rapidly fabricated and challenged with the technique presented here.

CONCLUSION

The novel technology and process presented here show a possible answer to the ever growing need of a low cost rapid microfluidic prototyping. All of the parts required for the setup are commercially available, and the use of chromed glass slides as masks reduces the cost of the whole process compared to other available options. No complex or expensive software has to be used to draw and export the features to the video projector setup, which guarantee fast and easy access to the process. The fabrication of the mask takes far less than an hour and is of very limited cost. The use of several objectives allows a wide range of fields of exposure and

resolutions. Using this technology, we have fabricated three different devices of common applications in the field of work: drop generation/encapsulation devices, concentration gradient generation devices, and cell culture and study device. In the case of the cell culture and study device, we fabricated a multilayered, compartmentalized microfluidic device to seed and culture rat primary hippocampal neurons for three weeks. Various configurations of microfluidic devices can therefore be screened and tested in a quick and easy manner. This kind of rapid prototyping method is essential, especially for the experimental development of research areas such as neuronal network studies, where researchers want to test complex and numerous connectivity patterns to unravel the links between structure and function of these networks. We hope that this “Microfluidic FabLab” platform will enable rapid prototyping of microfluidics chip for both research and education purposes.

¹Y. Xia and G. M. Whitesides, *Annu. Rev. Mater. Sci.* **28**, 153 (1998).

²S. Zhao, H. Cong, and T. Pan, *Lab Chip* **9**, 1128 (2009).

³T. Wang, M. Quaglio, F. Pirri, Y.-C. Cheng, D. Busacker, and F. Cerrina, *Proc. SPIE* **7274**, 727420 (2009).

⁴S. E. Chung, W. Park, H. Park, K. Yu, N. Park, and S. Kwon, *Appl. Phys. Lett.* **91**, 41106 (2007).

⁵R. Dreyfus, P. Tabeling, and H. Willaime, *Phys. Rev. Lett.* **90**, 144505 (2003).

⁶S. L. Anna, N. Bontoux, and H. A. Stone, *Appl. Phys. Lett.* **82**, 364 (2003).

⁷S. K. W. Dertinger, D. T. Chiu, N. L. Jeon, and G. M. Whitesides, *Anal. Chem.* **73**, 1240 (2001).

⁸A. M. Taylor, M. Blurton-Jones, S. W. Rhee, D. H. Cribbs, C. W. Cotman, and N. L. Jeon, *Nat. Methods* **2**, 599 (2005).

⁹T. Honegger, M. A. Scott, M. F. Yanik, and J. Voldman, *Lab Chip* **13**, 589 (2013).

¹⁰J. Cordeiro, M. Zelsmann, T. Honegger, E. Picard, E. Hadji, and D. Peyrade, *Appl. Surf. Sci.* **349**, 452 (2015).

¹¹See supplementary material at <http://dx.doi.org/10.1063/1.4943124> for a picture of the experimental setup and a picture of the effects of poor rasterization of the design.

¹²S.-Y. Teh, R. Lin, L.-H. Hung, and A. P. Lee, *Lab Chip* **8**, 198 (2008).

¹³P. M. Korczyk, L. Derzi, S. Jakiela, and P. Garstecki, *Lab Chip* **13**, 4096 (2013).

¹⁴A. G. G. Toh, Z. P. Wang, C. Yang, and N.-T. Nguyen, *Microfluid. Nanofluid.* **16**, 1 (2014).

¹⁵S. G. M. Uzel, O. C. Amadi, T. M. Pearl, R. T. Lee, P. T. C. So, and R. D. Kamm, *Small* **12**, 612 (2015).

¹⁶N. Bhattacharjee, N. Li, T. M. Keenan, and A. Folch, *Integr. Biol. (Camb.)* **2**, 669 (2010).

¹⁷V. Pinto, P. Sousa, V. Cardoso, and G. Minas, *Micromachines* **5**, 738 (2014).

¹⁸D. Qin, Y. Xia, and G. M. Whitesides, *Adv. Mater.* **8**, 917 (1996).

¹⁹A. K. Au, W. Huynh, L. F. Horowitz, and A. Folch, *Angew. Chem. Int.* (published online 2016).