PEN MICROFLUIDICS: FROM DESIGN TO BONDED THERMOPLASTIC CHIPS IN UNDER 30 MINUTES

Omid Rahmanian[1] and Don L. DeVoe[1,2]
Department of Bioengineering[1], Department of Mechanical Engineering[2]
University of Maryland, College Park MD 20742, USA

ABSTRACT

Here we report a rapid and simple approach to prototyping thermoplastic microfluidics in which a desired microchannel design is simply drawn directly on a thermoplastic substrate using a dry erase marker. The deposited ink selectively masks the substrate for patterned exposed to vapor-phase solvent, resulting in solvent uptake by the thermoplastic substrate and irreversible swelling of the exposed surface. Volumetric expansion of the surface results from rearrangement of mobile polymer chains within the polymer matrix and can be precisely tuned by adjusting the solvent exposure conditions to achieve a desired growth height. Furthermore, at the end of the orogenic growth process, the solvent-permeated surface can be permanently bonded to a cap layer, forming fully enclosed channels. Finally, the water-soluble ink remaining in the channels is simply washed away by a brief water flushing step.

KEYWORDS

Desktop manufacturing, rapid prototyping, orogenic microfabrication

INTRODUCTION

There is growing interest in simple and rapid desktop manufacturing processes that can decrease the cost, time, and effort of microfluidic system prototyping and fabrication. Though a variety of material including silicon, glass, and thermoplastics can be used for prototyping in both research and commercial settings, polydimethylsiloxane (PDMS) is the most widely used substrate due to the relative ease and speed of fabrication by soft lithography[1] techniques. However, low stiffness and mechanical robustness, high gas permeability, high water absorption, and incompatibility with many common solvents[2] limits the use of PDMS in many instances. Thermoplastic substrates have emerged as a leading material system for microfluidics devices due to their extremely low water absorption, resistance to polar solvents, optical transparency, and overall robustness. Variety of techniques including hot embossing, injection micromolding, laser ablation, and direct micromachining are currently available for manufacturing of microfluidic chips with flexible geometric control and high resolution patterning of thermoplastics, however all these methods require significant investment of time, infrastructure, and labor. Therefore there is a particular need for a true desktop manufacturing process for thermoplastic substrates adaptable for both research and commercial purposes.

Here we describe a new process enabling rapid desktop manufacturing of sealed microfluidic chips fabricated from homogeneous cyclic olefin copolymer (COC) substrate, termed orogenic microfabrication. Unlike traditional thermoplastic microfabrication, which involves removal or displacement of bulk polymer from the substrate, the orogenic process selectively raises the surface of bulk substrate by irreversible solvent swelling. During this unique fabrication process, regions of the surface masked with a material that serves as a barrier to solvent transport into the substrate are prevented from swelling, resulting in patterned depressions within the raised surface regions. In this paper, we utilize high-resolution pen nibs as ink mask deposition tools. Since the deposited ink mask defines the microchannel geometry, the desired patterns are defined by simply drawing the microchannel designs directly onto a COC substrate prior to solvent exposure and surface growth. Lateral channel dimensions are controlled by the deposited ink pattern, while channel height can be controlled by selected solvent exposure time as well as sealing pressure. Since the bulk surface is swollen with solvent at the end of the growth process, sealing of the channel is realized simply by mating the substrate with a second COC chip with pre-drilled fluidic access ports. The facile orogenic method is a simple approach for realizing sealed thermoplastic microfluidic chips in a rapid manner. The design-to-device process takes less than 30 minutes and uses ordinary equipment available in any research laboratory or commercial manufacturing sites. Using hand-drawn patterning as well as computer-generated design deposited using a robotic pen-plotter we demonstrate the utility and ease of fabrication of “pen microfluidics” process.

FABRICATION

Mask patterning. Ink from commercial wet-erase marker was used as masking layer for all experiments. High-resolution masking was performed using Pigma Micron pens with a 200 μm diameter nib. For simple straight channels a straight-edged guide was used to assist in drawing the mask by hand. For precise patterning, a 3-axis robotic stage was modified with a pen holder, allowing direct and automated transfer of a computer-generated mask layout to the COC chip.

Microchannel fabrication. The masked COC substrate was positioned face down at the top of the glass chamber, with a sheet of dicing tape used to hold the chip in place. The solvent volume was selected to define a 5 cm gap between the liquid solvent surface and the COC chip. After exposure to solvent vapor for the desired time, the COC chip was promptly removed from the solvent dish and brought into contact with a mating COC sealing layer. The resulting multilayer chip was then run through a desktop laminator to apply consistent pressure to the mating surfaces, resulting in a permanent solvent bond. Before bonding, fluidic access ports were milled in the COC sealing chip using a 125 µm diameter end mill. Interfacing between the ports and syringe pumps was realized by inserting needle tubing segments into the ports.[4]

RESULTS AND DISCUSSION

Microchannel patterning via orogenic growth. Solvent swelling of amorphous thermoplastics has been extensively studied for a variety of bulk materials. However, with the exception of investigations of solvent permeation through thin polymer films,[5] localized surface swelling at the nano/microscale remains virtually unexplored. Here we take advantage of patterned solvent swelling in COC substrates for microchannel fabrication. We recently established that for a particular grade of COC (Zeonor 1060R), large and permanent surface swelling can be controllably achieved by cyclohexane absorption, [3] using a variety of masking materials to realize growth heights above 50 µm. In the present work we have explored application of the orogenic process to microchannel fabrication using commercially available ink deposited from a pen as a masking layer. The basic process is described in Fig. 1. Ink from a pen with a fine-tip felt nib is written onto a COC surface by manual or computer-controlled deposition, followed by exposure to solvent vapor for a specified time required to grow the surface outside of the masked regions by the desired channel height. The solvated surface is then brought into contact with a mating sealing layer comprising a COC chip with pre-drilled fluid ports, resulting in a permanent solvent bond between the layers due to the presence of solvent within the field of the microchannel substrate. Uniform sealing pressure is achieved by running the chip through a desktop laminator. Depending on the desired channel height, the process entire process from mask patterning to sealed chip is typically completed within 30-60 min.

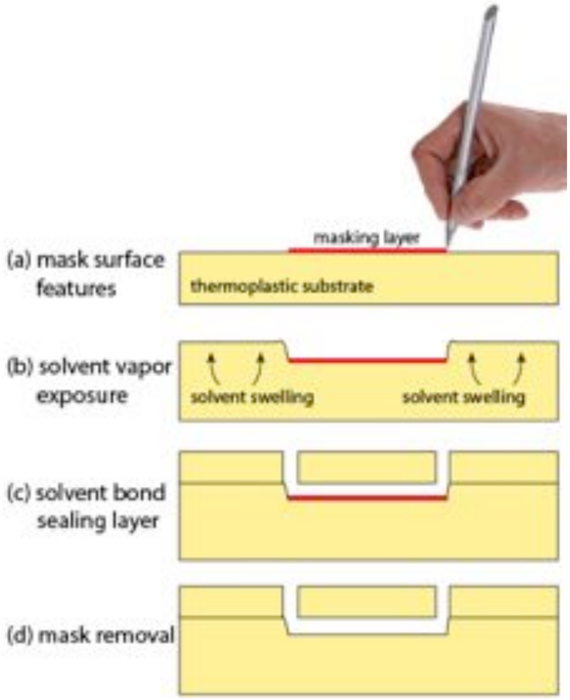

Figure 1: Overview of the pen microfluidics fabrication process. (a) An ink mask is drawn on a COC chip surface. (b) Vapor-phase solvent exposure results in patterned growth of the COC surface by solvent swelling. (b) Bonding is realized by bringing the patterned surface into contact with a sealing layer followed by solvent bonding using a desktop laminator. (d) The water-soluble ink masking layer remaining within the sealed microchannel is removed by pumping aqueous buffer through the channel.

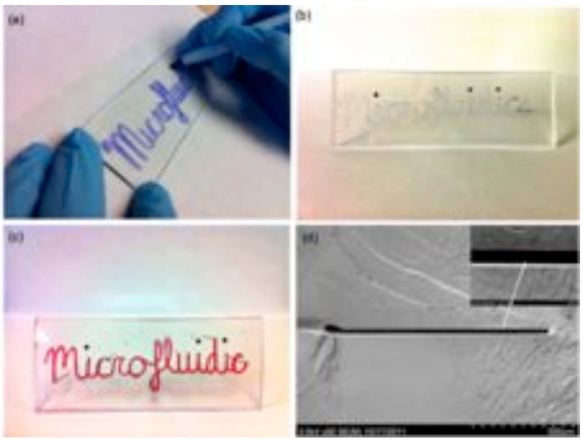

Figure 2: (a) Manual writing with a wet-erase pen onto a COC chip, followed by 15 min orogenic growth and solvent bonding, (b-c) injection of water through the resulting microchannel network, and (d) cross-section of the sealed microchannel.

Channel Width. Lateral dimensions in the orogenic process are defined by mask linewidths, and only limited by the pen nib dimensions. Using wet-erase markers linewidths below 2mm could be reliably formed by manual writing while lines of ~600µm could be achieved with the aid of a straight edge. After drawing the ink mask, exposed the chip to solvent vapor for 15 min, and sealing the channel, the water-soluble ink was removed by flushing the channels with DI water (Fig. 2b,c). The resulting channel height was determined to be 29 µm from SEM imaging, as shown in Fig. 2d. To achieve smaller mask linewidths, wet-erase marker ink was removed from the native casing and injected into a refillable fiber-tip marker with a reported 200 µm nib diameter. After mask drawing, orogenic growth, and chip bonding, the ink was flushed with DI water and the channel cross-section imaged by SEM. The resulting microchannel was found the be 23 µm high and 188 µm wide (Fig. 3)

While higher-resolution markers with nib dimensions as small as 30 µm are available, our tests with markers smaller than 200 µm were inconsistent due to irreproducible ink deposition.

Channel Height. In our previous work exploring the fundamental aspects of orogenic growth using cyclohexane as a solvent for COC, short solvent exposure times below 5 min were found to produce consistent submicron growth heights, while 60 min exposure yielded an average growth height of 51 µm, with nearly linear growth between 5-60 min.[3] However when using the ink mask method, maximum channel heights

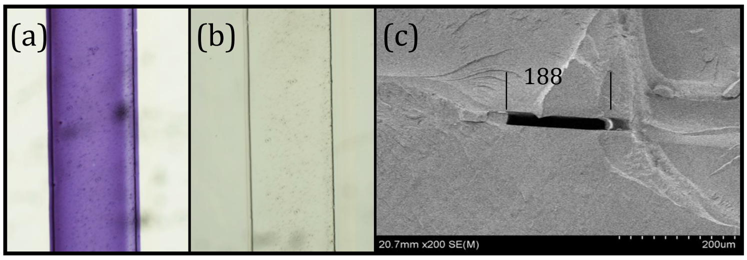

Figure 4: Bright field images of a microchannel formed in a COC chip by orogenic growth with a manually-drawn ink mask (a) immediately after microchannel sealing and (b) following buffer rinsing to remove the water-soluble ink. (c) Cross-sectional SEM image of a typical microchannel, 180 µm wide and 23 µm tall.

of 19±1µm were measured, with no increase in channel height observed for solvent exposure times longer than 15 min when a constant pressure of 350 psi was applied for 1 minute for channel bonding. Orogenic growth is a result of absorption of solvent into the polymer, resulting in a deformable matrix. The pressure used during the bonding process immediately after solvation thus leads to polymer flow, reversing some of the growth occurred during solvent exposure, forcing the swollen layers of substrate back into the bulk polymer. Our initial results indicate that decreasing the bonding pressure will result in deeper channels, with 80-100 micron channel heights easily achieved by minimizing the bonding pressure and time.

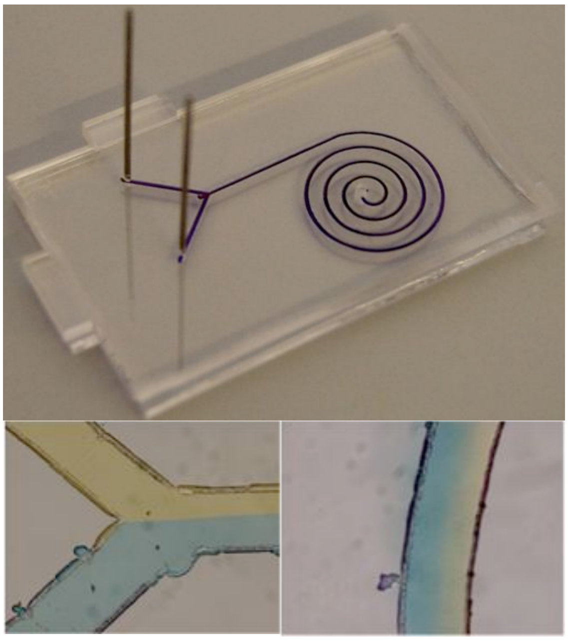

Figure 3: Spiral diffusive micromixer fabricated using a pen plotter for computer-controlled mask deposition. (a) Image of the fully bonded chip before flushing ink from the enclosed microchannel, and images of dye solutions (b) at the confluence of the injected dye streams and (c) within an arm of the spiral showing formation of a smooth dye gradient.

A central goal of this work was to demonstrate the pen microfluidics technique as a low-cost desktop manufacturing platform suitable for adoption by any research group seeking to develop thermoplastic microfluidics without significant infrastructure investment. While manual mask drawing may be suitable for some simple microfluidic applications, automated robotic control over pen motion is necessary for most real-world microfluidic systems where pattern accuracy and precision are important considerations. In order to achieve this goal, a high-end 3-D stage axis was modified and used as a pen plotter to transform computer-generated designs into masking layers. A spiral diffusive micromixer was fabricated using this approach to showcase the applicability of pen microfluidic method in fast prototyping of complex microfluidic devices. Figure 4 illustrates the fabricated chip with needle inserts prior to washing of the masking layer. Efficient diffusive mixing was achieved downstream the spiral when two colored dyes were injected from inlet needle ports.

CONCLUSION

In this paper we presented a facile microfluidic device fabrication method utilizing commercially available inks as masking layer in orogenic growth of thermoplastic substrates. The true sealed thermoplastic-only chips are made with minimum manufacturing requirements of only plastic, a pen, and a solvent dish. The fabrication approach combines channel formation and bonding into a single step, where the solvent permeated surface can be permanently bonded to a cap layer, forming fully enclosed channels. The simplicity of this approach allows any user to draw channel features directly on a thermoplastic substrate using standard wet-erase marker ink with a total cycle time below 30 minutes from initial design to final device. This process offers a unique and exceptionally rapid approach to thermoplastic microfluidic prototyping.

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CONTACT

* Don L. DeVoe, tel: +1-301-405-8125; ddev@umd.edu