RAPID, LOW-COST FABRICATION OF PARYLENE MICROCHANNELS FOR MICROFLUIDIC APPLICATIONS

Hong-seok Noh[a], Yoonsu Choi[b], Chi-fu Wu[a], Peter J. Hesketh[a] and Mark G. Allen[b]
School of Mechanical Engineering[a], School of Electrical and Computer Engineering[b]
Georgia Institute of Technology, Atlanta, GA 30332, USA
Tel.: (404) 385-2014, Fax: (404) 385-2011, E-mail: gte190t@prism.gatech.edu

ABSTRACT

This paper presents a rapid and low-cost fabrication method of parylene microchannels, so-called 'parylene micromolding'. Technical aspects of this new method are explored and some example products fabricated by this method are displayed. Among them, meander type channel, long spiral channel, electrophoretic channel, and dielectrophoretic channel are included.

INTRODUCTION

Recently, parylene has drawn considerable interest as a structural material for microfluidic components because of its excellent properties such as stress-free conformal deposition, chemical inertness, and biocompatibility. Many different parylene microfluidic components, for example, parylene microvalve [1], parylene micronozzle for electrospray [2], parylene flapping wing [3], parylene electrophoretic channel [4], and parylene gas chromatographic column [5] have been reported for the last few years.

For the fabrication of most devices [1-4] listed above, surface micromachining technique has served as a key technique to form enclosed parylene channel structures. This technique consists of parylene deposition, sacrificial photoresist patterning, another parylene deposition and the dissolution of the sacrificial photoresist (Fig. 1a). This fabrication technique however is a considerably slow process because the dissolution of sacrificial photoresist is a diffusion-limited process at the restricted solute-solvent interface. It has been reported that the dissolution of sacrificial photoresist take about 30 minutes per 1mm dissolution distance in acetone regardless of its width and height [6]. Also, post-releasing rinsing is always required to remove the photoresist residue remaining in the parylene channel. Consequently it may take several days to completely release several centimetre or longer microchannels, which are often required for many applications such as electrophoresis. It must be also noted that this surface micromachining technique is relatively high cost process because it involves several lithography and oxygen plasma etching steps.

Parylene/parylene thermal bonding technique was developed as alternative method to fabricate long parylene microchannel [7]. In this technique, bulk micromachined silicon microchannel is used as a mold for parylene deposition. Parylene copies the mold structure and forms a rectangular corrugation. Then another parylene layer deposited on a flat substrate is attached to it and bonded together by applying heat and pressure. Finally a free-standing parylene channel is obtained by removing silicon mold by KOH etching. This fabrication technique is comparatively fast and therefore greatly advantageous in fabricating very long microchannels such as gas chromatographic channels. However, high cost still remains unsolved because each parylene channel can be released by sacrificing silicon mold.

In this paper, we report recent progress in the fabrication technique of parylene microchannels. This new fabrication method consists of parylene/parylene thermal bonding technique and a novel release technique without dissolving the silicon mold. This method may be called 'parylene micromolding' because micromachined silicon mold can be reused. Parylene micromolding method is a rapid and low-cost fabrication technique of parylene microchannels. This technique can be applied for the fabrication of many microfluidic devices or disposable μTAS. Many aspects of this new technique are explored in this paper.

EXPERIMENTAL

Fabrication. Parylene micromolding technique is illustrated in Fig. 1b. Silicon microchannel molds were prepared by deep RIE. The width of the rectangular silicon microchannels was fixed at 100 μm and the depth was controlled (50 ~ 200 μm) by the number of standard Bosch cycles. After photoresist mask was completely removed by stripper and RIE, the silicon molds were dipped in soap solution (Micro-90, *Special Coating System*; Indianapolis, IN) and then dried. 10 μm parylene C (*Special Coating System*) was then deposited on silicon microchannel. The counterpart parylene layer was deposited on 25 μm thick stainless steel sheet (*Lyon Industries*, West Chicago, IL) after the same soap solution treatment. If electrodes are required for the application, thin gold electrode can be patterned on the parylene layer deposited on stainless steel sheet. Then two parylene layers were bonded together at 190°C in vacuum oven [5, 7]. After bonding

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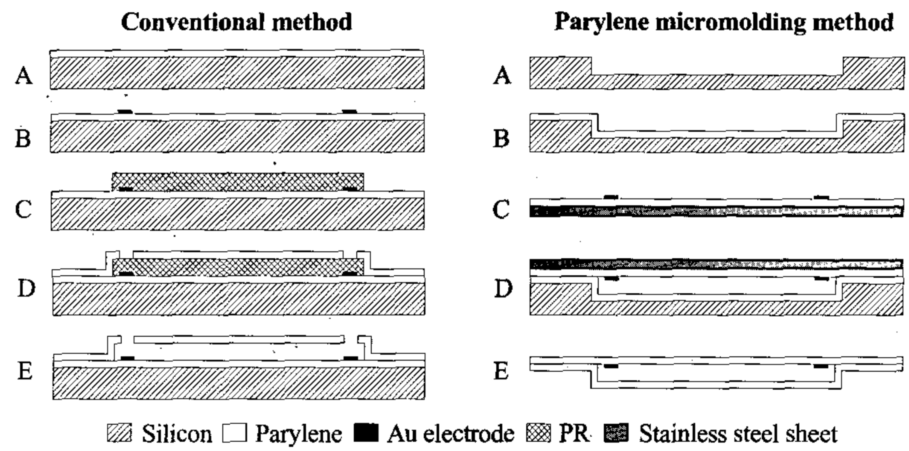


Figure 1. Conventional surface micromachining method and new 'parylene micromolding' method of fabricating parylene microchannel (**Surface micromachining method** - A: parylene deposition, B: electrode patterning, C: sacrificial PR patterning, D: parylene deposition and patterning, E: dissolution of PR, **parylene micromolding method** - A: silicon mold fabrication using deep RIE, B: parylene deposition, C: electrode patterning, D: thermal bonding, E: releasing).

the stainless steel sheet was peeled off leaving parylene channel in silicon mold and then the parylene microchannel was released from silicon mold by being lifted up.

Leakage Test. Since the final free-standing parylene microchannels have flexible thin film structure, tubing for fluid introduction is not trivial. For tubing, all the parylene microchannels were designed to have wider inlet and outlet than the main channel part. After parylene channels were released both inlet and outlet of the channel of each channel were punched with microneedle to make a hole and then polyimide coated silica microtubes (OD ~ 250 μm, ID ~ 100 μm, *Polymicro*, Phoenix, AZ) were inserted and sealed with small amount of epoxy resin. Leakage was checked visually by flowing dyed water through the channel using syringe pump. The maximum flow rate used for this test was 0.2 SCCM.

Mold Reusability. Used silicon molds were inspected visually under microscope to see if there was any parylene remnant. The visually clean molds were descummed completely by oxygen plasma etching (200mTorr, 200W, 30min). Then the silicon molds were treated with soap solution and reused for another parylene microchannel fabrication.

RESULTS AND DISCUSSION

Cross-Sectional Geometry. Through the parylene micromolding technique, the final parylene channels have the same cross-sectional shape as the silicon molds because parylene copies its molds on deposition. Therefore round channel can be obtained by using isotropically etched (HNA or XeF_2 etching) silicon molds and triangular or rectangular channel by using anisotropically etched (KOH or DRIE etching) molds as shown in Fig. 2a. However in this study we only used deep RIE etched silicon molds for rectangular channels.

The inner aspect ratio of parylene channel can be easily controlled by varying parylene thickness. In other words, parylene channels with different inner aspect ratio can be fabricated using the same silicon mold as shown in Fig. 2b. Moreover multiple layer channel wall, for example parylene/metal/parylene can be formed if it is required for the appication.

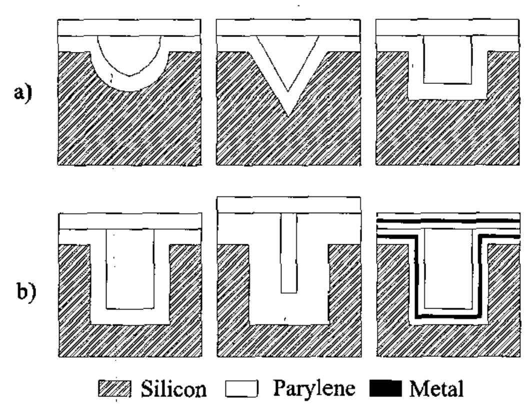


Figure 2. Cross-sectional geometries of parylene channels: a) the effect of isotropically and anisotropically etched silicon molds, b) Inner aspect ratio control by varying parylene thickness, and multiple layer channel.

Applications. Diverse kinds of parylene channels were fabricated by the parylene micromolding technique. Some examples are meander type channels and long spiral channels as shown in Fig. 3a. The process time was basically identical regardless of the design and length of the channel. Some applications require electrodes embedded in microchannels. To demonstrate this capability, electrophoretic and dielectrophoretic microchannels were fabricated (Fig. 3c and d). The electrophoretic parylene microchannels have simple linear gold electrode on reservoir area and the dielectrophoretic microchannels have interdigitated electrode array under the straight channels. For both electrophoretic and dielectrophoretic channels, Ti/Au (30nm/0.2μm) electrode were patterned by lift-off process. The electrophoretic channel was single channel of 4 cm length and the dielectrophoretic channel was multiple channel of 1 cm length.

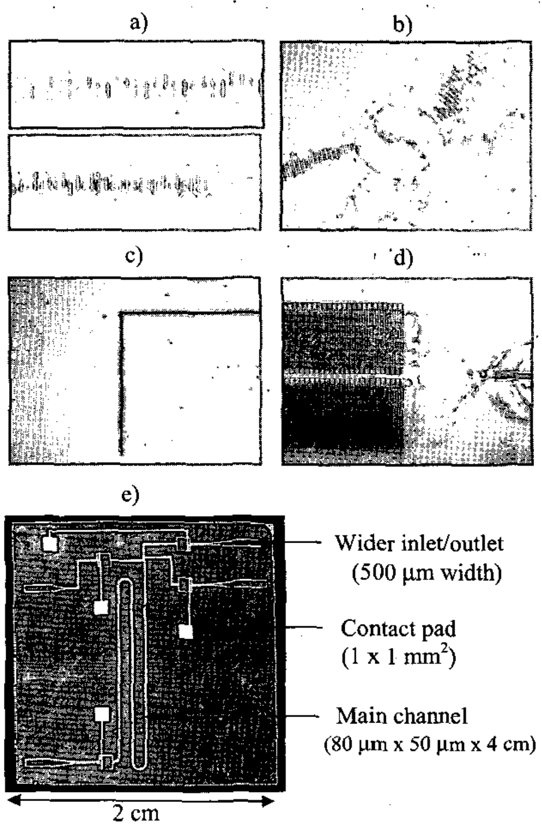


Figure 3. Diverse kinds of parylene microchannels fabricated by parylene micromolding technique (all channels have same dimension of 100 μm width, 50 μm depth, and 10 μm wall thickness): a) meander type channels, b) 1 m long microchannel, c) electrophoretic channel, d) dielectrophoretic channel, e) overall view of electrophoretic channel.

Channel Release. Releasing parylene channel highly depends on the aspect ratio of silicon mold. We have used 100 μm wide silicon channels with different depth from 50 to 200 μm to see this aspect ratio effect on channel release. It was found that parylene channels were released better when the depth of silicon mold was less than 100 μm (1:1 aspect raio).

Soap solution treatment for both silicon molds and stainless steel sheet turned out very effective for channel release. Although parylene does not have good adhesion on silicon and metal surface, while it is going through high temperature bonding process parylene comes to have much better adhesion on those surfaces. Hence, parylene channel can be deformed or destroyed during releasing. This problem was reduced greatly by treating silicon molds and stainless steel sheet with releasing agent, soap solution. Some of the molds were reused three times and still worked fine. The mold reusability depends on its aspect ratio, cleanness, and soap solution treatment.

Also stainless steel sheet was very effective for release process because it was peeled off easily after serving as a temporary substrate for parylene deposition and bonding. However the surface roughness caused delamination of the dielectrophoretic channels with complex electrode geometry, resulting in partial destruction on parylene channel. This problem could be avoided by using pyrex glass substrate instead although it required an additional ultrasonic agitation for release. Therefore, our conclusion of release experiments is that stainless steel sheet can be used for the fabrication of general microchannels or electrophoretic channels having simple electrode but that glass substrate is recommended for the fabrication of microchannels having complex electrode array such as dielectrophoretic channels.

Quality Inspection. Parylene deposition is known as pinhole-free conformal coating. To investigate the uniformity of parylene deposition in microchannels, a narrow (100 μm x 300 μm) silicon microchannel was was diced after being coated with 10 μm parylene. Fig. 4a shows the SEM image of the silicon microchannel cross-section. Parylene coating thickness was uniform across the channel. But the channel was deformed by dicing.

Surface roughness is another issue because deep RIE etched silicon molds have typical roughness on the wall. Parylene deposition basically copies the roughness of its mold but in our process, the overall roughness was reduced as shown in Fig. 4b because parylene deposition thickness (~ 10 μm) was much bigger than the scallop pattern roughness (~ 1 μm).

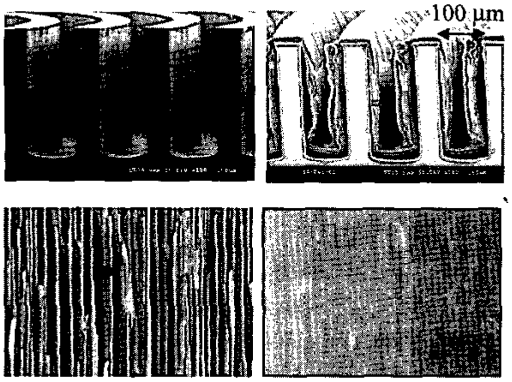
a)
b)


Figure 4. The SEM images of the silicon microchannel cross-section : a) parylene coating uniformity, b) surface roughness change by parylene deposition.

The above SEM image (Fig. 4a) of the parylene channel deformed by dicing implies the possibility of deformation during release process. Each released parylene channels were inspected under microscope and it was found that the chance of deformation was greatly reduced when the aspect ratio becomes less than 1:1. After the visual inspection dyed water was introduced through the channel to see if there was any leakage. Generally the microchannels that had passed visual check test did not have any leakage (Fig. 5).

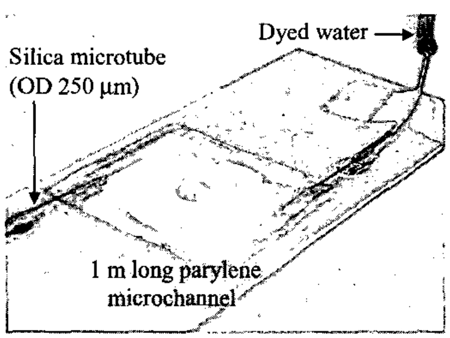


Figure 5. Tubing and leakage test.

CONCLUSIONS AND FUTURE WORK

We have developed a new fabrication method of parylene microchannels, which may be called 'parylene micromolding'. This method is faster and cheaper than conventional surface micromachining method. This method consists of parylene/parylene thermal bonding technique and a novel release technique without dissolving the silicon mold. Diverse kinds of channels such as meander type channel, long spiral channel, electrode-embedded electrophoretic and dielectrophoretic channels were able to fabricated by this method. Channel release highly depended on the aspect ratio of silicon mold. With less than 1:1 aspect ratio of silicon mold, we were able to achieve good release result without damage or deformation in parylene channels by the help of a release agent, soap solution. Thin stainless steel sheet was used as a temporary substrate for this method.

Currently we are applying this method to the fabrication of dielectrophoretic microchannel for the sample enrichment purpose. One of the future work is to investigate the deformation of parylene channel due to the pressure of inner fluid. This will be investigated both by ANSYS simulation and experimentally.

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