MICROMACHINED POLYMERIC MICROVASCULATURES: A THREE-DIMENSIONAL MICROFLUIDIC SYSTEM USING INCLINED SU-8 STRUCTURES AND LASER MACHINING

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Introduction

Microsystems-based approaches to micro total analysis systems (μ-TAS) for bio-chemical synthesis and analysis has enjoyed rapid growth from its initiation in the mid-nineties to the present day. As expected from its roots in conventional microsystems, many early-stage microfluidic devices were built from inorganic materials such as silicon or glass. More recently, there has been much interest in fabricating these devices from a variety of polymers. Among other advantages, polymers offer the ability to create biocompatible, low-modulus interfaces to tissue as well as the potential for extremely low-cost manufacture of microsystems. Examples of some of the more widely utilized polymers in microsystems include polyimides, photosensitive epoxies (e.g., SU-8), polydimethylsiloxane (PDMS), and polymethyl methacrylate (PMMA) [1-4].

Among these polymers, the photosensitive epoxy SU-8 has been utilized for the fabrication of high aspect ratio, three-dimensional (3D) structures at relatively low fabrication cost [2][5]. Utilizing this material in combination with advanced photodefinition exposure techniques, various microfluidic systems such as channels, filters, and mixers have been fabricated [6][7]. Other potential applications of 3D microfluidic structures include nerve or cell culturing systems [8][9]. For example, since the cytoskeletal protein of a cell in 3D cultures is quite different from that grown on a 2D surface, a 3D scaffold is essential to obtain tissue properties similar to those of a real organism [10]. However, a persistent challenge to the realization of these systems is the formation of a nutrient path for the cells throughout the *volume* of the culture. Essentially, the formation of a micromachined fluidic vasculature (i.e., microvasculature) is required. Typical approaches to such microvasculatures might involve lamination, multilayer casting, or other multilayer processes; however, such processes may suffer from interfacial adhesion and leakage as well as requiring relatively long processing times and complex fabrication procedures.

In this work, an alternative fabrication technique is developed for the fabrication of microvasculatures. This technique involves the combination of an inclined SU-8 structure process [6] and a normally-incident excimer laser ablation process. The inclined process uses a single coat of thick SU-8 for the channel wall and the channel cap as well as the inclined structures. Three-dimensional complexity is introduced into this layer using the double-exposure and single-develop technique previously described by the authors in [11]. This approach has several advantages. Since the device is produced from a unitary piece of SU-8, the number of photolithography steps is reduced. In addition, the inclined channel is itself an in-plane structure and can be formed in the same fabrication step of other channel components, thereby enabling easy connectivity with other microfluidic components. Finally, the unitary construction approach eliminates stacking or lamination of multiple layers, greatly facilitating the integration of these systems for applications such as a lab-on-chip. Combination of these fabrication techniques with laser ablation, as demonstrated in this work, enables the three-dimensional microvasculature required for future tissue engineering and interfacing applications.

Experimental

An appropriately-spaced tube array or parallel channel array is formed with an intentional angle of inclination, followed by masked excimer laser ablation at normal incidence. This approach allows variation of microfluidic ports up and down the third dimension with a single masked ablation exposure. The laser ablation forms fluidic exit holes on the sidewall with a planar spacing as well as a vertical displacement.

Figure 1 details the fabrication process. A chromium-coated glass plate is used as a substrate. After patterning of the chromium for channel definition, SU-8 photosensitive epoxy is coated on the plate to a thickness that will ultimately define the channel height. After the SU-8 is baked, the substrate is turned over and exposed at an angle of inclination in order to form latent images of the inclined channel walls through the thickness of the epoxy. This exposure is followed by a post-exposure bake on a hot plate to cross-link the SU-8 (a). Before developing, a low energy dose exposure is applied through a second mask to form the caps of the channels. The multiply-exposed structure is then post baked in an oven (b). A single develop step forms the inclined branch channels as well as the wide channels. Finally, excimer laser ablation (λ=193nm) through a metal shadow mask forms the vertically-distributed microfluidic ports (c).

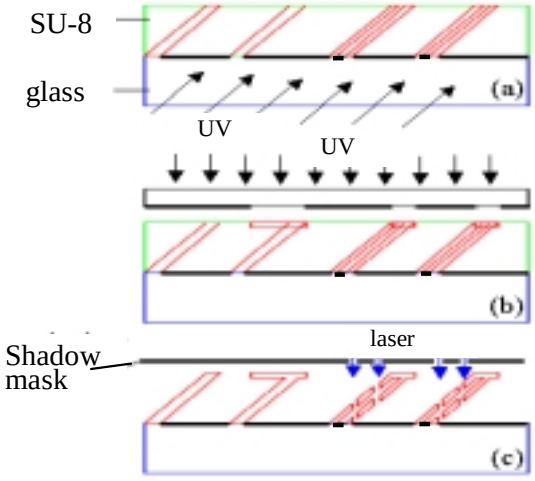


Figure 1. Fabrication Process

During exposure, the incident light is refracted at the boundary of the materials utilized since SU-8, glass, and air all have different refractive indices. To determine the refractive index of SU-8, a UV source is applied through a 15μm diameter window at multiple angles. Figure 2a shows a fabricated structure formed by multiple angle exposures in a 600μm thick layer of SU-8, followed by a single develop step. The measured refracted angles θ_r are 0°, 15°, 24°, and 31° for incident angles θ_i of 0°, 24°, 45°, and 62°, respectively, in Figure 2c. Curve fitting using Snell's law ($n_1 \sin\theta_i = n_2 \sin\theta_r$, in Figure 2b) gives a refractive index of approximately 1.7 for SU-8 [6].

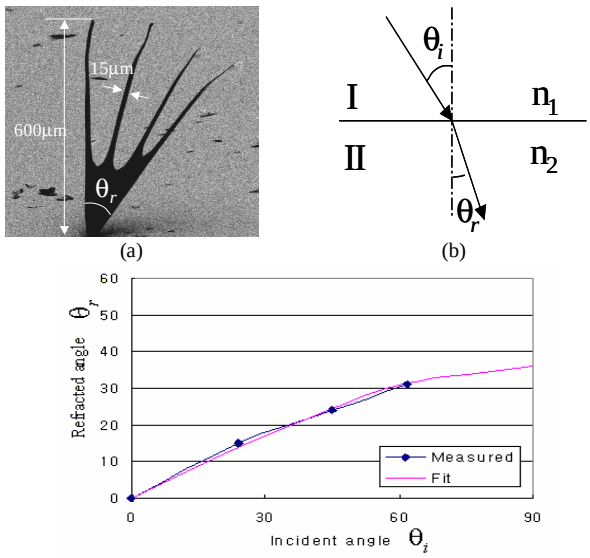
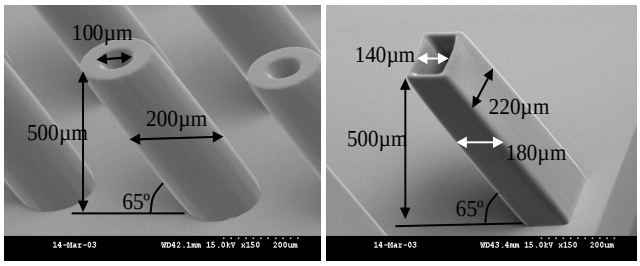
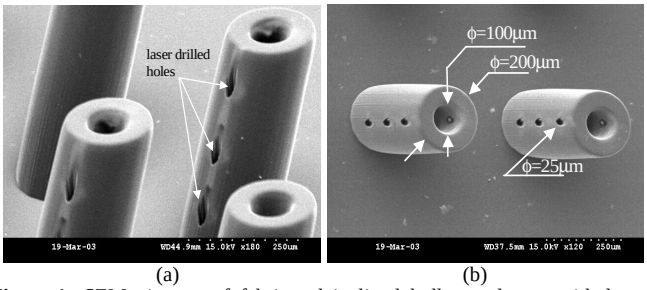


Figure 2. Angular dependence of exposure: (a) fabricated structure with different angle of incidence; (b) schematic diagram of ray trace; (c) refracted angle as a function of incident angle.



(a) (b)

Figure 3. Scanning electron microscope (SEM) pictures of fabricated SU-8 hollow columns: (a) circular column array; (b) rectangular column.

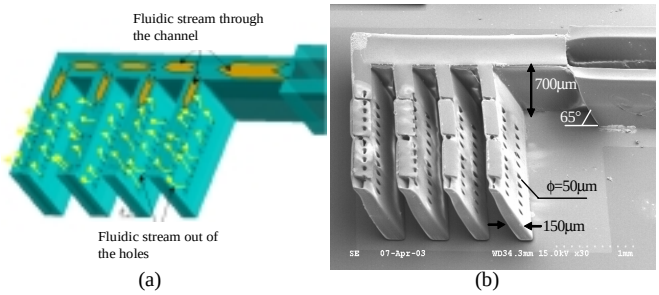


(a) (b)

Figure 4. SEM pictures of fabricated inclined hollow columns with laser drilled holes: (a) oblique view; (b) top view.

Figure 3 shows fabricated hollow columns; (a) a circular column array, (b) a rectangular column array. Both are 500µm tall and are inclined at an angle of 25º from the vertical.

Figure 4 shows a laser drilled inclined hollow column 500µm in height with three laser-drilled holes on the sidewall. The laser beam spot size was 25µm, the horizontal spacing between the holes was 50µm, and the vertical spacing (resulting from the interaction of the horizontal spacing with the angle of incidence) was approximately 100µm.



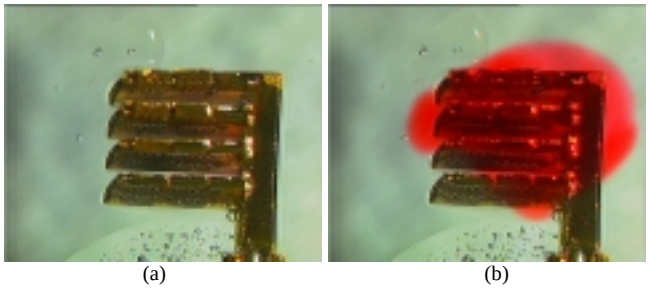
(a) (b)

Figure 5. Four inclined channel branches with laser drilled holes: (a) schematics; (b) an SEM picture of the fabricated structure.

Figure 5 shows a schematic view of the inclined channel array and an SEM of the fabricated device. The array has four inclined channel branches, each bearing laser-drilled holes. The height of the channel is 700 µm; the wall thickness of the channel is 50µm; and the widths of the branch channels are 50µm for the narrow channel and 100µm for the wide channel, respectively. The angle of inclination is approximately 25° from the vertical axis. The laser-ablated holes have diameters of 50µm and array pitch of 150µm. The fluid is supplied through the entrance of the wide channel and the fluid branches to the four smaller inclined channels. The left two branches have a larger channel width to take into account the pressure drop through the long fluidic microchannels.

Results and Discussion

The fabricated structures have been qualitatively tested to demonstrate their fluidic functionality. Figure 6 shows optical micrographs during two stages of a fluidic release test. The fabricated structures are immersed in deionized water, and red dye is introduced through the microfluidic channels, emerging from the laser-drilled orifices. Figure 6a shows the submerged structure prior to the introduction of the dye, and Figure 6b shows the structure while the dye is being released. The red dye emerges from the laser-drilled holes, and demonstrates good spatial uniformity except for the left half of the first row channel, which may be due to clogging.



(a) (b)

Figure 6. Red dye release through the arrayed holes in water: (a) before; (b) after.

Conclusions

A unitary microvasculature for tissue interfacing and engineering, based on high aspect ratio microfluidic tube and channel arrays for uniform liquid dispensing, was fabricated by a combination of inclined SU-8 channel patterning and normally-incident excimer laser ablation. A dilute solution of red dye released through the microfluidic structure possessed enhanced spatial uniformity, demonstrating successful liquid perfusion into water.

Acknowledgements

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