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Near-IR nanosecond laser direct writing of multi-depth microchannel branching networks on silicon

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ABSTRACT

Multi-depth microchannel network is fabricated on silicon using near-IR nanosecond laser direct writing followed by chemical etching. An 11-level branching network, for which the depth ranges from 20 to 200 μm, is designed and fabricated to be used as a mold for PDMS replica. The bifurcation of the microchannels is designed according to Murray's law so that the total cost function is minimized. The detailed fabrication procedure and parameters are presented, and method of roughness control using both laser processing parameters and etching parameters are discussed. The efficient manufacturing of such microchannels with minimal roughness can pave new roads for realizing microdevices with multi-depth microchannels. Such devices have proven use in environmental/biomedical applications such as artificial lungs.

1. Introduction

Microchannel devices are a promising alternative to the current inefficient gas exchange membranes used for artificial lungs [1–9]. The inefficiencies of current gas exchange membranes are caused by the non-physiological features of the gas exchanger module, which is composed of bundles of loosely-packed microporous hollow fiber membranes [10]. In order to enhance the gas exchange performance of artificial lungs while maintaining biocompatibility, microchannels are considered as artificial capillaries allowing intimate contact with the blood flow via a gas permeable membrane [11–13]. The short diffusion path and the large surface to volume ratio of microchannels result in efficient gas exchange thus allowing devices to be smaller in size [14]. In the fabrication of such microchannel networks, a wide range of microchannel size with reasonable resolution is necessary. Indeed, it is possible to build multi-depth microchannel networks using well-known lithography and etching techniques; however, the mask based lithographic technique is inefficient in terms of cost and time, and it is difficult to lithographically vary the depth of multi-depth structures.

Laser direct writing, on the other hand, is a promising alternative method which can be used to easily fabricate the multi-depth microchannels, especially because it does not require any masks or a clean room environment [15–19]. A variety of lasers can be used for fabrication of microfluidic structures onto silicon: from nanosecond lasers to ultra-short (femtosecond or picoseconds) lasers as well as from IR lasers to ultraviolet (UV) lasers. Our group recently showed that multi-depth microchannel networks could be successfully fabricated using femtosecond laser direct writing onto silicon [20]. Although femtosecond lasers or UV lasers are currently the best options for micromachining, since they result in minimal peripheral thermal damage with low debris formation [21–30], successful manufacturing of the networks using conventional near-IR nanosecond lasers can be of high impact due to wide availability and low cost of nanosecond laser systems.

In this paper, the method for fabricating multi-depth microchannels by a combination of laser direct writing using near-IR nanosecond laser and acid etching is presented and discussed. We first design the multi-depth microchannels according to Murray's law so that the total cost function is minimized. A near-IR nanosecond laser is used to engrave the multi-depth channels onto silicon which is then chemically etched to achieve the desired precision. The fabricated microchannel network is then repeatedly used as a mold to create polydimethylsiloxane (PDMS) replicas. We present detailed fabrication procedure of an 11 level multi-depth microchannel and we discuss, in detail, the parameters required for minimizing the roughness of the channels.

2. Design

The branching structure is designed according to Murray's law which states that the radius of the parent vessel (r_0) and the radius of the daughter vessel (r_1 and r_2), and the branching angles (θ, ϕ) have

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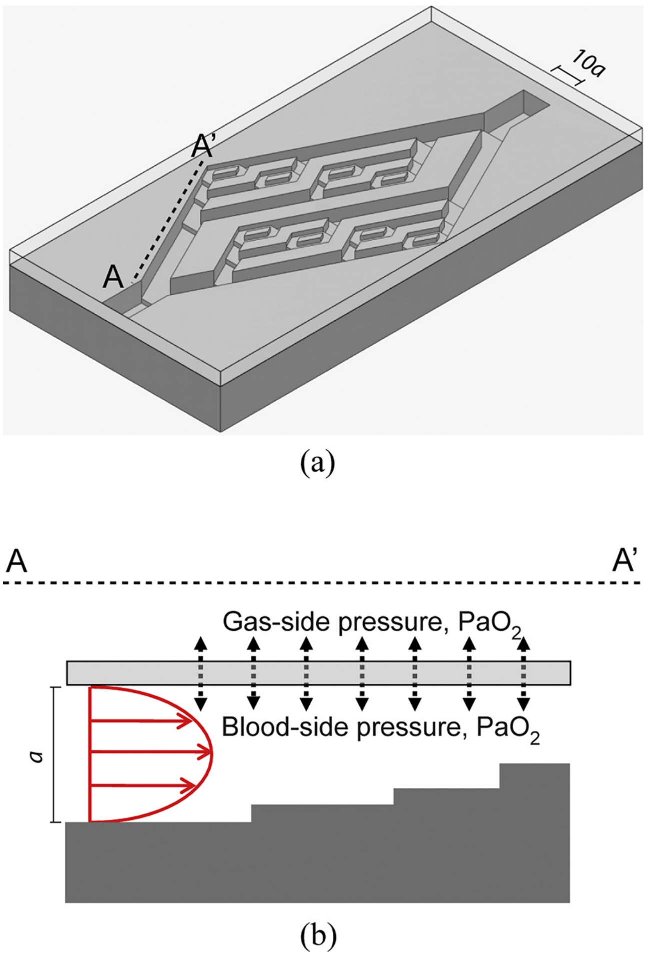

Fig. 1. (a) Schematic of a 4 bifurcated multi-depth microchannel network (b) Side view of blood flow and gas transfer in the microchannel. Gas exchange occurs through the thin PDMS membrane on top of microchannel.

following relationships:

$$r_0^3 = r_1^3 + r_2^3, \tag{1}$$

$$\cos\theta = \frac{r_0^4 + r_1^4 - r_2^4}{2r_0^2 r_1^2}, \tag{2}$$

$$\cos\varphi = \frac{r_0^4 + r_2^4 - r_1^4}{2r_0^2 r_2^2}. \tag{3}$$

Such law is necessary so that the cost function, that is, the same of the energy cost of the blood in a vessel and the energy cost of pumping blood through the vessel is minimized. Using such relationship, a multi-depth microchannel network, as illustrated in Fig. 1(a), can be designed where the channels become shallower and narrower at each bifurcation. The figure shows a 4 bifurcation sample resulting in 5 different channels with different depth and since the aspect ratio is approximately 10:1, when the depth is a the width of the channel becomes $10a$.

To apply Murray's law to rectangular cross-sections, hydraulic diameter ($D_h \equiv 4 \times$ area/perimeter) is used, instead of the radius. Here, the flow into the channel can be assumed to be two dimensional, and it is proportional to the hydraulic diameter since the channels have high aspect ratios. Therefore, it is reasonable to express Murray's law in terms of depth, for example, symmetric bifurcation with the same daughter depth ($d_1 = d_2$), and parent depth (d_0), Murray's law can be reduced to:

$$d_0 = 3\sqrt{2d_1} = 3\sqrt{2d_2}, \tag{4}$$

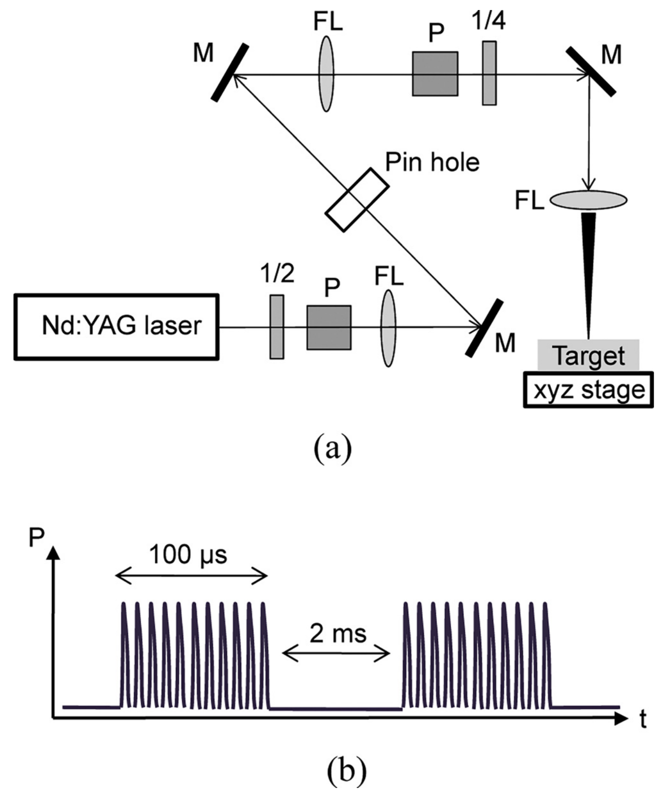

Fig. 2. (a) Experimental system schematic: polarizer (P), a half-wave plate (1/2), a quarter-wave plate (1/4), focal lens (FL), and mirror (M). (b) Temporal profile after modulation: 100 μs pulses consist of 11 pulses with 200 ns pulse width.

$$\cos\theta = \cos\phi = 3\sqrt{4/2}. \tag{5}$$

The ratio of the length to the depth is designed to be approximately constant for the entire length of each branch for a respective generation so that all paths from the inlet to the outlet of the network have the same length resulting in the same pressure drop. A cross-sectional view of the multi-depth microchannel structure is presented in Fig. 1(b). The top of the channel is to be sealed with a gas permeable PDMS membrane where gas diffusion occurs between the blood flowing inside of the microchannel and the surroundings via the partial pressure difference between the gas-side and the blood-side.

3. Fabrication

3.1. Laser setup

The schematic of the laser machining setup is shown in Fig. 2(a). A Q-switched Nd: YAG laser (TRW DP-11) operating at 1064 nm is used as the nanosecond ablation laser. The laser was set to a repetition rate of 500 Hz and a pulse width of 100 μs (duty cycle of 5%). The 100 μs pulses were modulated to produce a series of 200 ns pulses with 10 μs interval as shown in Fig. 2(b). The repetition rate of 500 Hz was chosen since this repetition rate was the highest possible (for high fabrication efficiency) while maintaining the beam shape shown in the figure. When the repetition was modulated to a higher value using the Q-switch, the rectangular pulsed beam shape began to deform resulting in inconsistent laser ablation. The average power of the incident beam on the silicon sample was controlled using a combination of a half-wave plate and a polarizer. A quarter-wave plate and a polarizer were used to circularly polarize the beam at the target. At focus (far-field), the beam shape at the center with a symmetric diffraction is near-Gaussian, and a pin-hole was used to filter the diffraction spots surrounding the bright central lobe. Using 100 mm focal length objective, the focal spot size of