VIRTUALLY MONOLITHIC DEVICE FOR DIFFUSIVE MASS TRANSFER ENABLING HIGH VOLUME FLOW

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ABSTRACT

This work presents a virtually monolithic fluidic device made of silicone rubber (PDMS) with 150 mm long micro channels enabling a high volume flow. The leakage-free device is fabricated by stacking numerous structured PDMS sheets whereby no distinguishable bonding interfaces occur. This is not realizable on large areas by commonly used oxygen plasma bonding. It enables diffusive mass transfer between two enclosed compartments and can be adjusted to high volume flow by increasing the amount of layers.

KEYWORDS: silicone rubber, monolithic microfluidic device, PDMS bonding, high volume flow, diffusive mass transfer.

INTRODUCTION

Diffusive mass transfer via polymer membranes is used in application fields like gas and liquid separation or medical engineering. [1] For all those applications a high mass transfer and a high volume flow are necessary. The mass transfer efficiency can be increased by either reducing the diffusion length (membrane thickness and fluid height) or increasing the membrane area. Especially when it comes to medical devices and the use of blood as one fluid, large membrane areas are critical due to the restricted hemocompatibility of artificial surfaces. Therefore most devices are a compromise between mass transfer and volume throughput. This work overcomes this limitation by enabling mass transfer between two compartments with small heights, i.e. short diffusion length, while maintaining a high volume flow due to a high degree of parallelization.

THEORY

The aimed application for the device presented in this work is the diffusive mass transfer between whole blood and a second fluid, e.g. a ventilating gas. Therefore the device consists of two discrete compartments separated by a membrane. Both compartments are separately, fluidically connected. Thereby the inlet and outlet of each compartment are diametrically located. Here two distinctive structures for the two different compartments were designed which will be positioned above each other after the stacking. It is essential to avoid high shear rates and areas of zero flow within the blood guiding structure to increase the hemocompatibility. [2, 3] Therefore straight channels with a small height (several tens of microns) were designed to combine the above mentioned requirements with a short diffusion length. One layer features 40 parallel micro channels. To minimize the losses in membrane area even if the sheets are slightly misaligned the structure for the second fluid was designed as an open area with pillars as spacers. The device is completely made of PDMS due to its high gas permittivity and the simple structuring possibility by casting a mold.

EXPERIMENTAL

The microfluidic device (see Figure 1) is fabricated by stacking structured PDMS sheets which feature alternatingly either the micro channels or the open area with pillars. The leakage-free stack is achieved by a virtually monolithic bond between the sheets. There are several commonly used PDMS bonding techniques. [4] But most of them are not applicable in this case due to the large area of the sheets (168.2 cm^2). Therefore a homogeneous layer of uncured PDMS is applied before stacking as an adhesive.

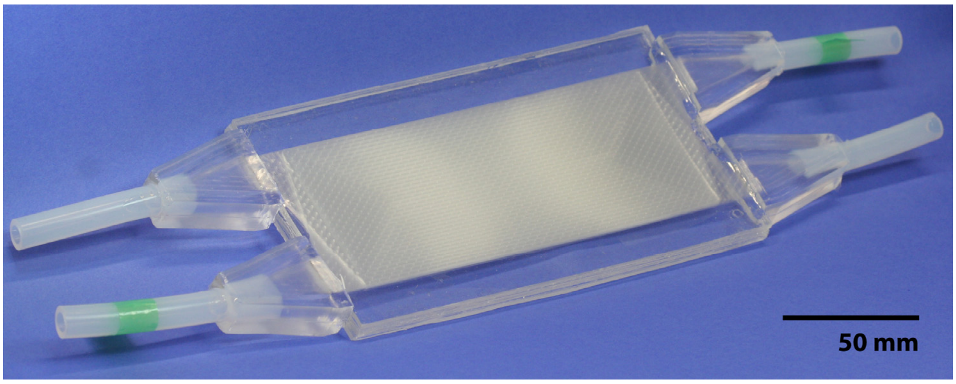

Figure 1: Picture of the fabricated PDMS mass transfer device made of 21 structured sheets embedded between two 2 mm thick PDMS base sheets. The inlet and outlet of each compartment are diametrically located

978-0-9798064-5-2/µTAS 2012/$20©12CBMS-0001

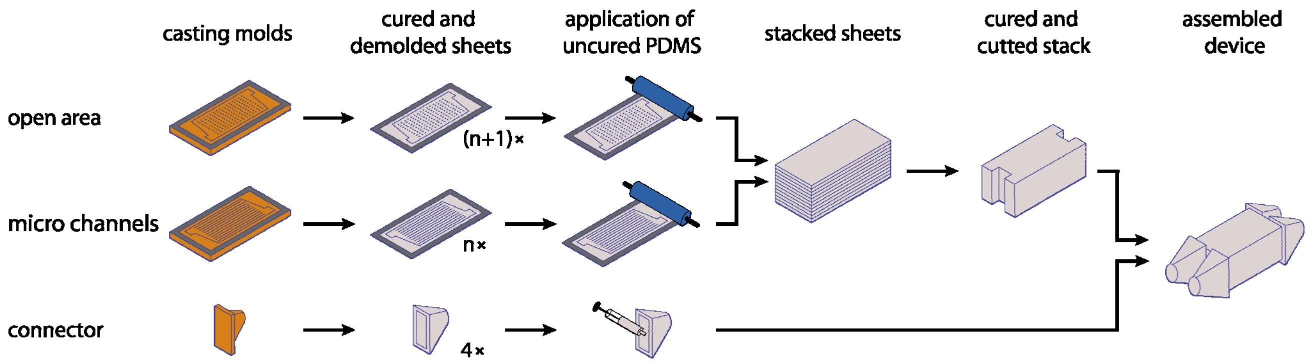

Figure 2: Schematic fabrication chain for a mass transfer device with two discrete compartments

Figure 2 shows the schematic process chain of a virtually monolithic stack of alternating sheets. The PDMS sheets are manufactured by curing PDMS in a mold during processing in a hot embossing machine. The molds consist each of a brass plate featuring the negative structures either of the micro channels or of the pillars and a second flat brass plate. In between the two plates a steel handling frame is inserted which defines the membrane thickness (at least 50 µm) and eases the stacking process. The addition curing PDMS (ELASTOSIL® RT 601, Wacker GmbH, Germany) is prepared as advised by the data sheet. [5] The open mold is filled with PDMS and evacuated in a desiccator to remove entrapped air bubbles. For ease of demolding the PDMS is covered with a polymer foil. The curing of the PDMS within the closed mold is accelerated in the embossing chamber by an elevated temperature of 70°C while a force is applied to achieve a homogeneous membrane thickness.

The stack is assembled on a handling plate which features pins for the alignment of the handling frames. First of all a 2 mm thick PDMS base sheet is aligned on the handling plate. The bonding to and between the following, structured sheets is realized via an approximately 5 µm thick film of uncured PDMS, which is applied selectively on top of the elevated structures of each sheet by a PDMS coated roller. The sheets are aligned on the handling plate with their structured side down using their handling frames. The handling frames and the adhesion between cured and uncured PDMS allow a bubble-free stacking of the sheets. As final layer of the stack serves again a 2 mm thick PDMS base sheet. Therefore both PDMS base sheets securely embed the thin membranes. Subsequently the handling frames are removed and the bonding via the applied PDMS films is carried out in an oven process with a maximum temperature of 130°C. After the bonding the interface between the sheets cannot be distinguished and thus a virtually monolithic device is realized (see Figure 3). The two compartments, defined by the set of sheets with the same structure, can be connected separately, since the distinctively structured sheets are chiral. The inlet and outlet regions need to be cut open with a blade for the fluidic connection. The developed connectors are also fabricated in PDMS and bonded to the stack in the same manner as the sheets among each other.

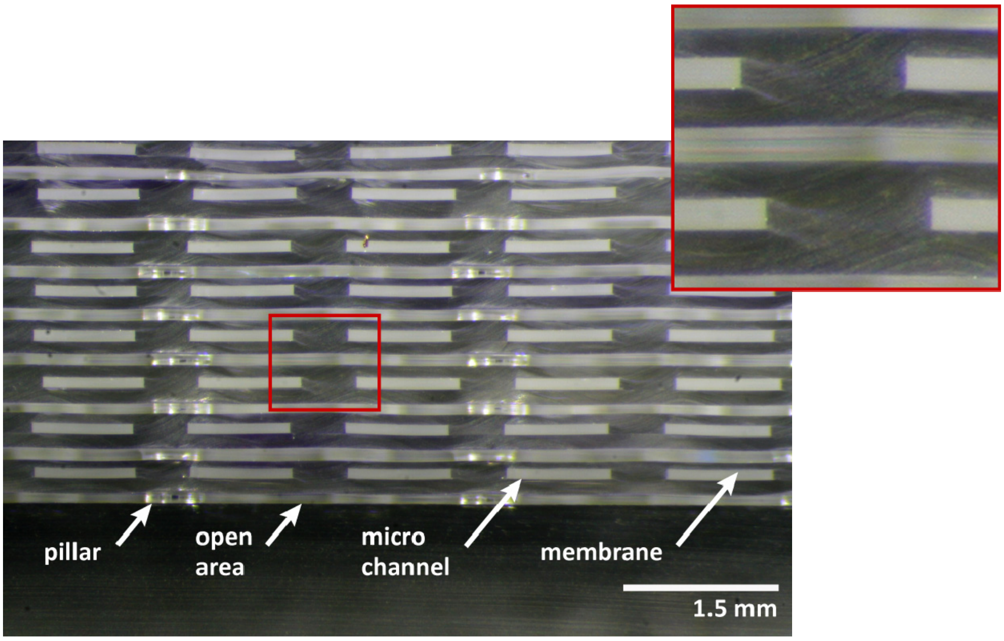

Figure 3: Cross section through a fabricated mass transfer device made of sheets with alternating pillar and channel structures and a detail view thereof. The membranes have a mean thickness of 100 µm. There is no visible interface between the bonded layers

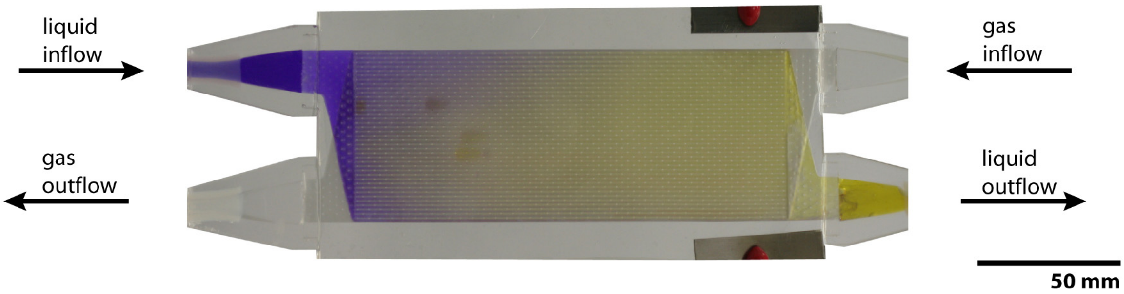

Figure 4: *Picture of an aqueous solution of a pH indicator (Bromocresol purple) flowing through the micro channels of the virtually monolithic device. Carbon dioxide flows through the second compartment of the device and diffuses through the membrane into the pH indicator and changes the pH value there*

The mass transfer within the fabricated device was demonstrated by leading a volume flow of 50 ml/min aqueous solution of a ph indicator (Bromocresol purple) through the micro channels and carbon dioxide through the second structure (open area). Since the carbon dioxide diffuses through the membranes, the color of the pH indicator changes from purple to yellow corresponding to the decrease of the pH value (see Figure 4).

RESULTS AND DISCUSSION

The developed process chain was successfully used to realize a leakage free device by stacking 21 structured PDMS sheets. The device features two discrete compartments which can be connected separately by commonly used tube connectors. The bonding of the sheets via uncured layers of PDMS as adhesive is reliable for an sheet area of 168.2 cm^2, although only 38.7% (open area) or respectively 55.3% (micro channels) of the sheet area contribute to the bonding as the uncured PDMS is selectively applied on the elevated structures. The two compartments have volumetric capacities of 10.7 ml (open area) and 7.1 ml (micro channels). Depending on the volume flow within the compartments pressure drops of 145 mbar (50ml/min water flowing through the micro channels) occur. Hereby no damage or delamination of the bonded sheets appears. The PDMS membranes in between the layers of the two compartments are thin and flexible. Therefore the pressure drop in one compartment influences the fluidic characteristics of the other compartment by bending and stretching of the membrane in between. The pressure drop for a flow of 50 ml/min of water through the micro channel structures rises for example up to 172 mbar for a gas flow of 1.2 l/min through the second compartment and a mean membrane thickness of 100 µm. Furthermore a pulsatile flow in one compartment e.g. induced by a peristaltic pump is recognizable in the initially non-pulsatile flow through the other compartment.

CONCLUSION

The presented device was successfully used for mass transfer applications in a reduced scale. The possible volume flow through the device can be easily raised by increasing the amount of stacked layers. So far there is no limit for the amount of layers obvious, in case the sheets have homogeneous thicknesses. The homogeneity of the sheet thickness is important for a homogeneous bond over the whole area of the sheets.

To decrease the influence of the pressure drop of one compartment on the fluidic characteristics of the other compartment more rigid membranes would be necessary. This could be realized by a reinforcement of the PDMS membranes, e.g. by fillers or by inserted gauzes. Hereby it is necessary to analyze the influence of the reinforcement on the gas permeability of the membranes.

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