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Highly integrated COP monolithic membrane microvalves by robust hot embossing

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ABSTRACT

This paper presents an in-plane pneumatically actuated membrane-type microvalve, entirely made of Cyclic Olefin Polymer (COP). The body of the valve is fabricated following a robust hot-embossing method with SU-8 master moulds, producing devices with repetitive dimensions at wafer-level. Sealing is performed by applying a suitable solvent on the COP membrane, rendering monolithic devices, free from assembly errors. Various design parameters have been studied to obtain different working regimes, with maximum flow rates of 8.5 ml/min being successfully regulated and fully stopped. Owing to its fabrication method and characteristics, these devices represent a reliable and low-cost solution for the integration of microfluidic control in mass-produced lab-on-a-chip devices.

1. Introduction

Microvalves are critical for fluid flow control and thus, one of the most important components for the realization of fully integrated Lab-on-a-Chip (LoC) systems [1–5]. High potential applications for precise volume handling include chemical analysis, gas/liquid sample injection, flow regulation and gas or liquid sealing [6].

Microvalves are basically categorized into active and passive, the former being best suited for autonomous LoCs. Actuation principles include pneumatic [7–12], thermopneumatic [13–17], thermomechanical, piezoelectric [18–21], electrostatic [22–26], electromagnetic [27–32], electrochemical and chemical [33–39] and capillary force [40–43].

Amongst these, pneumatically actuated membrane valves have been successfully used in many applications due to their low cost and simple fabrication. A variety of devices has been demonstrated for silicon [44–46] and glass–silicon [47,48] as well as for less traditional materials such as elastomers [49–52] and polymers [53–56]. Within the latter, cyclic olefin polymer (COP) has recently emerged as an attractive material [57,58] due to its high optical clarity (into deep-UV range) [59], high bio-compatibility [60,61], low autofluorescence, low water absorption [62–65] and good chemical resistance, also against organic solvents [58,62,63].

Although valves represent one of the most researched topics upon microfluidics over the past 30 years, there is not yet any example that can be truly integrated in complex LoC systems, which is robust, simple, versatile, low-cost and free from assembly errors. In this paper, a simple and monolithic active valve is presented, showing wide linear flow regulation capabilities and low closing pressure. The valves have been fabricated by a robust hot embossing protocol, showing industrial-quality dimensional control; its combination with COP provides low-cost and ready integration at laboratory level that is compatible with mass-production. Finally, a reliable solvent-based bonding method is introduced, which renders planar, strong sealing of the actuation membrane, allowing control of micrometric clearances for valve performance enhancement. Hence, a highly versatile valve concept and a direct prototype-to-mass-scale fabrication method are presented, which can be highly useful for the LoC research community and industry.

2. Device architecture and working principle

An image of the developed active-type microvalve is presented in Fig. 1. As it can be observed, two different heights are defined,

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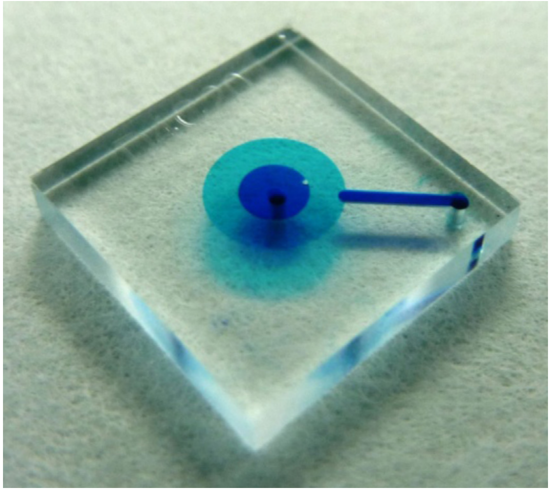


Fig. 1. Image of the finished microvalve in a 1 cm^2 dye, filled with a blue-colored solution, which highlights the different parts of the structure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

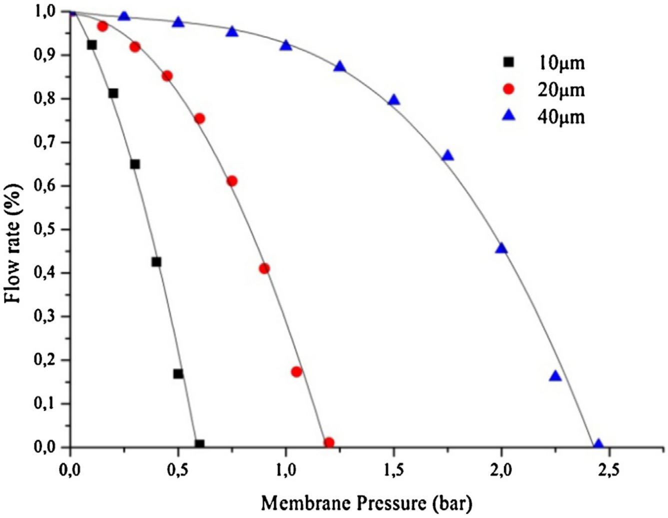
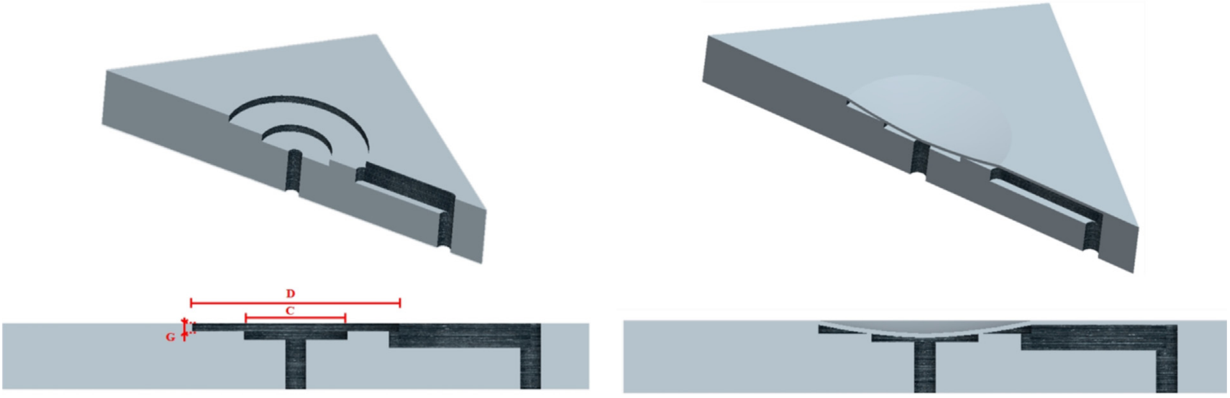


Fig. 3. Theoretical variation of the valve's flow profile, for a given valve seat (0.7 mm) and valve diameter (2.5 mm), as the gap size is reduced (▲ = 40 μm, ● = 20 μm, ■ = 10 μm).

Fig. 2a. On one hand, the valve chamber is delimited by the outer diameter (*D*) and the clearance between the membrane and the valve seat (gap or *G*). On the other hand, the valve seat is delimited by the inner diameter (*C*). The membrane that seals the device regulates the flow through it by deflecting and reducing the fluidic section under the action of an external pressure source. Thus, upon application of pressure, the membrane deflects and the fluidic path gets narrower, consequently reducing the flow rate. When sufficient pressure is applied, Fig. 2b, the membrane collapses against the seat, stopping the flow and closing the microvalve. Owing to this construction, the valve can achieve extensive flow modulation and close at relatively low pressure.

In general terms, the valve's flow rate profile depends on the rate of increase of fluidic resistance per unit membrane displacement. This can be modelled using total pressure drop equations [66], which provide an estimate of the pressure drop across each part of the device (microfluidic channel and valve) as a function of geometry. According to these, for a given seat diameter the initial gap size will influence the maximum flow rate, the percentage pressure drop across the valve and its rate of increase as the membrane deflects. Hence, if the gap is initially large, the pressure drop at the valve will be small for low values of membrane deflection, giving a parabolic flow rate decay. Past a certain level of deflection, the resistance at the valve will become dominant, resulting in a linearly decaying flow rate, as predicted by Poiseuille's equation [67]. For smaller gap sizes, the valve dominates over a wider range, resulting in a rather linearly controllable flow rate. Fig. 3 depicts such behaviour, as predicted by the equations. With respect to the seat diameter, its effect is easier to predict, simply resulting in a proportional change in closing pressure due to a change in the value of membrane deflection per unit actuation pressure [68]. Hence, from the previous, we can select the maximum flow rate and its regulation profile through the gap size and the pressure range through the seat diameter.

The effect of these design parameters on the valve's behaviour has been demonstrated through a design array, having a diameter of 2.5 mm, two different seat diameters (0.7 mm and 1.0 mm) and three gap heights (10 μm, 20 μm, 40 μm). In order to realize these architectures, a robust membrane bonding technique, which allows narrow gaps without collapse and a highly repetitive hot-embossing method have been developed. The resulting valves feature a low foot-print, monolithic construction with excellent dimensional control and neatly defined micro-sized features.



(a)

(b)

Fig. 2. (a) Schematic drawing and cross-section of the normally-open microvalve, without the diaphragm. (b) Cross-section of a COP microvalve with a COP diaphragm in its closed state.