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A novel volumetric silicon micropump with integrated sensors

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A B S T R A C T

We present a novel peristaltic micropump based on piezoelectric actuation and active valves that combines high fluidic performances of a volumetric pump and the integration of sensors. The latter are localized directly on the membranes that consequently are used for pumping as well as for sensing. This achievement was possible thanks to an original fabrication process based on a SOI (Silicon On Insulator) wafer, enabling additional MEMS technological steps such as photolithography or ion implantation to be performed on the membranes.

1. Introduction

Numerous applications in the fields of biology, medicine or electronic cooling, among other fields, require the use of micropumps. In the last few years, many solutions based on various technologies have been proposed [1]. Depending on the required characteristics, many approaches are possible that differ mainly by the actuation mode and by the type of valve. The predominant principle is the piezoelectric actuation for its low power consumption and the high force it provides. Piezoelectric devices can be divided into two main families depending on they are equipped with passive [2] or active valves.

Peristaltic micropumps that are based on a piezoelectric actuation and active valves can provide a constant flow rate whatever the backpressure applied at the outlet [3]. These volumetric pumps are able to deliver very precise amounts of liquid. Despite these excellent fluidic performances, the need for a monitoring of the flow remains a major issue for many applications, in order to have a feedback control on the delivery or to detect malfunctions like occlusions or leakages. Up to now, this monitoring has been achieved with sensors that are external to the micropump, and very few studies have described integrated sensors. For example, in [4], a micropump with check valves is described, in which a pressure sensor consisting of an additional membrane with piezoresistive strain gages is processed.

We present here a novel micropump that combines the high fluidic performances of a volumetric micropump and built-in sensors. The technological solution is a peristaltic pump with piezoelectric actuation and active valves. An important added-value comes from the integration of sensors based on a piezoresistive strain gage technology directly on the silicon membranes that are consequently used for pumping as well as for sensing. This achievement was possible thanks to an original fabrication process based on a SOI (Silicon On Insulator) wafer, enabling additional MEMS technological steps such as photolithography or ion implantation to be performed on the membranes.

2. Design and fabrication process

Because of the fragility of their membranes, the integration of sensors in micropumps is a technological issue. Thanks to an original fabrication process described hereafter and to the use of a SOI substrate, we could add piezoresistive strain gages on the membranes of the micropump.

To start the fabrication, a 200 mm silicon wafer is structured through photolithographic and DRIE etching steps: three fluidic chambers, fluidic channels connecting the chambers and the inlet and outlet of the pump are etched (Fig. 1a bottom). The diameter and depth of the chambers are respectively 7.5 mm and 30 µm, the depth of the channels is 30 µm and the diameter of the inlet/outlet is 600 µm. The final dimension of the micropump is 30 × 11 mm^2.

Next, a SOI wafer is sealed by molecular sealing (Fig. 1a and b). As this step requires a high temperature (1100 °C) as do other steps later on in the process, it is essential to bond in vacuum conditions, otherwise plastic deformation or even rupture of the silicon membranes can happen.

Then the top wafer is thinned by grinding and etching, and, thanks to the buried oxide of the SOI wafer that acts as an etch stop layer, the thinning is perfectly controlled. Three membranes suspended upon the fluidic chambers described previously are

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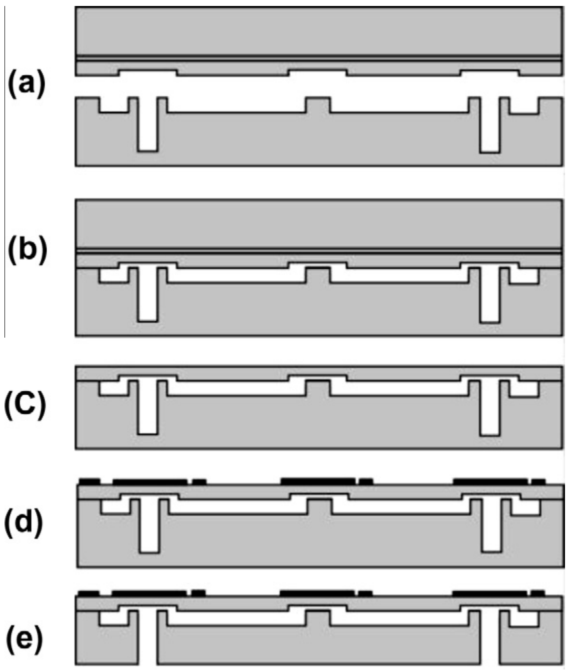

Fig. 1. Micropump fabrication process.

obtained, and their thickness, 100 μm, is defined very precisely by the device layer of the SOI. The central membrane is used for the pumping, while both side membranes work as inlet and outlet valves (Fig. 1c).

One major advantage of this fabrication process is that, at this stage, the top surface of the micropump is perfectly flat. This is an essential requisite to integrate sensors, as additional standard MEMS technological steps like photolithography, etching or ion implantation are feasible.

First the sensors, which consist of resistances in a Wheatstone bridge configuration, a classical design in MEMS technology for pressure sensing, are fabricated by Bore implantation at a concentration of 10^{17} to 10^{18} at/cm^3. This technology ensures better measurement performances than metallic sensors (sensitivity ×50). Then a metallic layer is processed to define the power supply lines of the piezoelectric actuators and of the sensors (see Figs. 1d and 2).

Finally, the fluidic inlet and outlet of the backside are opened by silicon etching (see Fig. 1e). Obviously the micropump is closed during whole fabrication process, so that any pollution of its interior such as dust or chemical contamination is avoided.

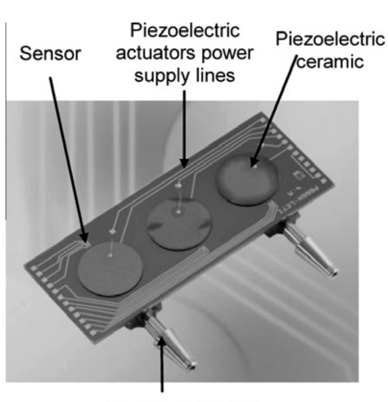

Fig. 2. Final packaged micropump.

Three 6.4 mm diameter piezoelectric ceramic discs are then glued onto each membrane. The electrical connections to the power supply lines are achieved by wire bonding. Finally, fluidic connectors are added in order to get the final component ready for use (Fig. 2).

3. Experimental results

3.1. Material and methods

The peristaltic pumping relies on the ability of the micropump to transfer a small amount of liquid from its inlet to its outlet. This is performed by the successive motion of the three membranes in a particular sequence. We used the "6-phase" sequence proposed in [5] and described in Fig. 3. The micropump was operated by applying a square 200 Vpp voltage to the three piezo ceramics. The signals were generated by two synchronized function generators (Yokogawa FG120) whose outputs were amplified by a specially designed voltage amplifier (gain: ×10). To generate pressure, a pressure regulator was placed either downstream or upstream (Sensortechnics VSOEPS10-50-15). The flow rates were measured with a flowmeter (Sensirion SLG1430-480) for flow rates lower than 40 μl/min and with a graduated tube for higher ones. The input of the inbuilt sensors was powered with a 1.25 Vdc voltage; the output was amplified by 10 using an instrumentation amplifier and recorded on an Analog to Digital data acquisition system (National Instruments DAQ 6229). The whole system was controlled by Labview® software. All the experiments were conducted with water.

3.2. Fluidic behaviour

The relationship between the flow and the actuation frequency was investigated and the results are shown in Fig. 4. For increasing frequencies, the flow rate varies in the typical way of peristaltic micropumps. First it goes up in a linear way, from less than 2 μl/min to more than 200 μl/min. Then a maximum is reached at 40 Hz when it begins to decrease owing to the damping fluidic forces.

One of the most important characteristics of a micropump is its ability to withstand pressure, otherwise it is difficult to ensure a stable flow rate when the fluidic conditions are likely to change. Fig. 5 depicts the measurements for downstream pressures in the range 0–300 mbar. The experiment was repeated for various

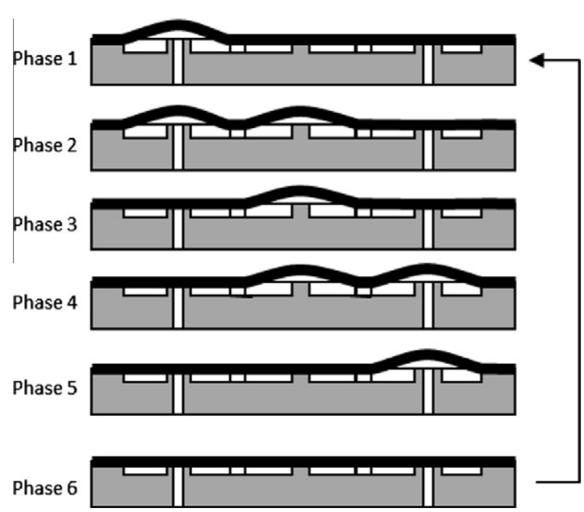

Fig. 3. 6-Phase actuation cycle.