Design and realization of an electrostatic micropump used in a linear mode

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Abstract

This paper is focused on the modeling and realization of an electrostatic micropump composed of passive valves without mechanical part. The electrostatic actuator is used here in a linear mode by using a polarization (DC voltage) and activating the actuator around this polarization (ac voltage). The micropump modeling is based on electrical analogies. By this way, the implementation of the micropump under a Pspice simulator allows to define its resonant frequency from the flow behavior versus frequency of actuation. A realization is associated to the modeling. Three different wafers are needed to obtain the complete structure (by DRIE technique) and five steps of photolithography are sufficient to obtain the micropump.

1. Introduction

The developments of microfluidic devices have enabled a lot of new kind of applications in a lot of analysis device [1]. Micropump has a great part for controlling microfluidic transmission. For optimizing such a microsystem, using an FEM software is too heavy because of the coupling effect between mechanic, fluidic, and electric phenomena. This paper recalled the electric analogy for modeling a fluidic device [2] and used it to extract the resonant frequency of a micropump. Here, due to the use of a polarization voltage, the electrostatic actuator is modeled and used in a linear mode (equivalent to a pneumatic pressure).

2. Micropump description

The working of the micropump is based on electrostatic pressure to deflect a membrane. The deflection of the membrane modifies the chamber volume and generates a pressure variation, which activates the fluid displacement. By the use of passive microvalves [3], the fluid moves throughout the micropump in a direction imposed by them.

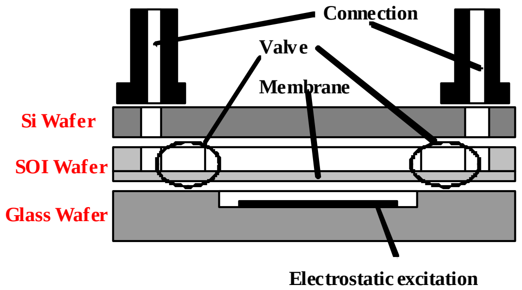

Fig. 1 : view of the valveless electrostatic micropump

The micropump structure is depicted in figure 1. It's composed of three different wafers :

- A Pyrex wafer to obtain the electrostatic actuator.

- A SOI wafer to obtain both membrane and valves (Fig. 4).
- A Si wafer to close the micropump and define the access.

3. Micropump modeling

In order to estimate the micropump performances, we have to model the electrostatic actuator and the fluid behavior versus pressure.

3.1 Electrostatic actuator

The pressure generated by an electrostatic actuator can be expressed by the formula :

$$P_e = \frac{\varepsilon_0 (U_{DC} + u_{ac})^2}{2(e - W_{DC} - w_{ac})^2} \qquad (1)$$

By supposing that the AC voltage (u_{ac}) is smallest than the DC voltage (U_{DC}) and that the position variation w_{ac} around static position W_{DC} doesn't influence the electrostatic pressure, the equation 1 can be decomposed in a DC part and in an AC part :

$$P_e = \frac{\varepsilon_0 U_{DC}^2}{2(e - W_{DC})^2} + \frac{\varepsilon_0 U_{DC}}{(e - W_{DC})^2} u_{ac} \qquad (2)$$

It means that by using a polarization U_{DC}, the variation of the electrostatic pressure can be considered as a linear pressure (first term in equ. 2) and becomes directly proportional to the AC voltage (second term in equ. 2). The electrostatic pressure can then be viewed as a pneumatic pressure and be modeled by a simple voltage source.

3.2 Fluidic behavior

The electric analogy [2] can be applied to a micropump structure, by this way a Pspice simulator can be used to simulate the micropump behavior. The equivalence is based on the used of simple electric components such as R, L or C. The analogy is depicted in table 1 :

Table 1. Electric equivalence of fluidic parameters

Fluidic parameters	**Electric equivalence**
Pressure (P)	Voltage V $\Leftrightarrow$ P
Flow (ϕ)	Current I $\Leftrightarrow$ ϕ
Inertia of fluid : density (ρ) in a channel (length l and hydraulic section S_H)	Inductance $L = \rho \frac{l}{S_H}$
Loss Pressure in a channel : (length l, dynamic viscosity η and hydraulic diameter D_H)	Resistance $R = \frac{32\eta l}{D_H^2 . S}$
Compliance $C_m = \frac{dVol}{dP}$	Capacitance $C_m = \frac{3\pi}{16E}\frac{R^6}{h^3}$ (Silicon circular membrane: Radius R, thickness h and young's modulus E)

The mechanical resonant frequency is not taken into account here but can be implemented if needed.

3.3 Particular fluidic component

For the valve behavior, the modeling must take into account the flow evolution with the pressure [3]. In this case, we use a current source driven by a voltage that corresponds to the differential potential of the current source. The flow is than implemented analytically in the current source I. To simplify, two current sources are used for each microvalve, one for the direct flow and a second for the reverse flow:

- Direct flow ($\Delta U>0$) :
  $I_d=[F_d(\Delta U)/ \Delta U]*(abs(\Delta U)+ \Delta U)/2$
  Note : $I_d=0$ if $\Delta U<0$
- Reverse flow ($\Delta U<0$) :
  $I_r=[F_r(\Delta U)/ \Delta U]*(abs(\Delta U)- \Delta U)/2$
  Note : $I_r=0$ if $\Delta U>0$

F_d is the analytic approximated relation of the flow versus pressure in the direct mode and F_r in the reverse mode. It means that the valve behaviors are not linear but depends on the pressure. ΔU

represents the pressure applied on the valve. This analytic relation can be deduced from numeric simulation or measurement. Here nozzle-diffuser [3] (fig. 4) and Tesla diode (fig. 4) are used in the realization.

4. Implementation and simulation results

A very classical software can be used to simulate the micropump (Pspice). The result of implementation is depicted in figure 2 with all the electric analogy defined in table 1.

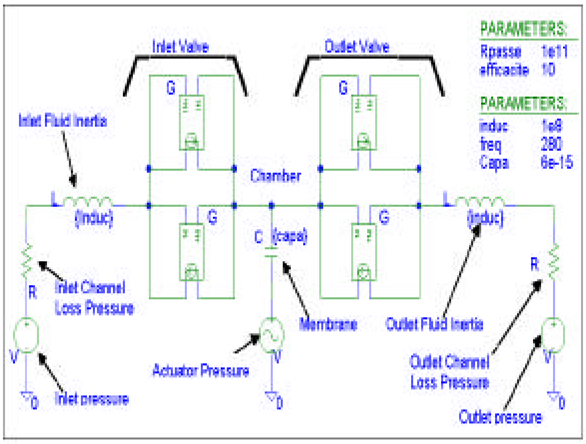

Fig. 2: Electric representation of a volumetric micropump

The circuit obtained is very close to a RLC circuit with two RL branches (the input and output channel) connected to a capacitor (the chamber). A simulation of the micropump flow versus frequency has been achieved by several transient analysis. A resonant frequency occurs and reflects the second order comportment of every fluidic system (Fig. 3). A comparison with electronic linear circuit (RLC type "second order" and RC type "first order") is added to the figure 3.

The micropump behavior is very closed to a capacitor connected to two RL circuits. We can than expressed the resonant frequency (fo) of the micropump as :

$$\boxed{fo = \frac{1}{2\pi}\sqrt{\frac{2}{LC}}} \qquad (3)$$

(with L and C defined in table 1 and represented in figure 2)

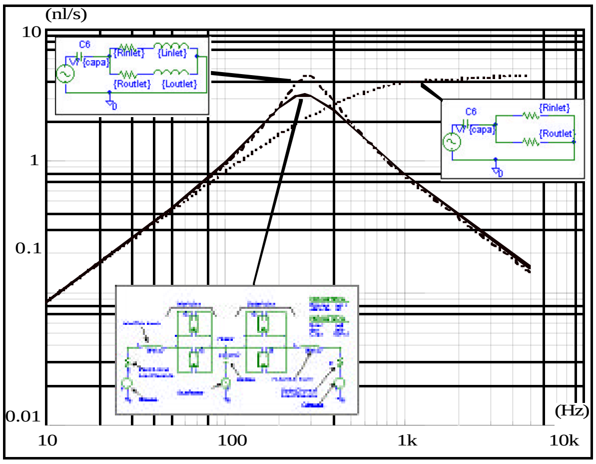

Fig. 3 : Frequency behavior of the micropump

To optimize the working of the micropump, the ac voltage of the electrostatic actuator will be used at this frequency. The variation of the flow will be obtain by controlling the ac amplitude. The average values of parameters used for the simulation correspond to membrane in silicon with a radius of 1400µm and a thickness of 16µm (Equivalent capacitor value of $6.25e^{-15}$). The channels have an average section of 500µ*150µm with a length of 2350µm (Equivalence Resistor of 3.4e10 and inductance of 6e7). The fluid used is supposed to be water ($\eta = 1e-3Pa.s$). The average expected fluidic resonant frequency is 370 Hz.

5. Realization of a prototype

The micropump realization is centered on the used on a SOI wafer to obtain both the membrane and the valve. The depth of the valve and channel is equal to the thickness of the top SOI wafer (500µm for our wafers), the thickness of the membrane is equal to the SOI (here 16µm are used).

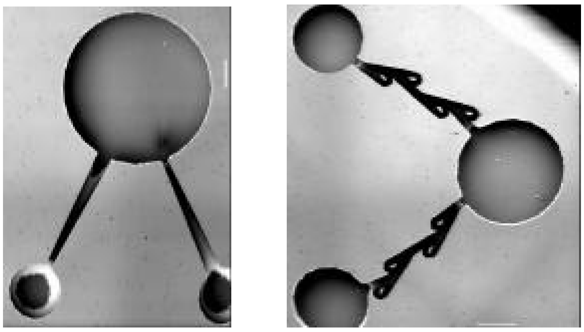

Fig. 4: Top view of the etched SOI wafer (Nozzle-Diffuser and Tesla valve)

For the SOI process, a first DRIE etching is done on the SOI (Fig. 5.1) for preparing an access window. Than the top side is etched until the SiO2 layer is reached (Fig. 5.2). A complete cleaning is done to remove the SiO2 (Fig. 5.3), the membrane and the valve are then obtained. For the electrostatic actuator, a Pyrex wafer is used. The Pyrex process starts with a $HF_{10\%}$ etching (with chrome protecting layer) of 5 µm to obtain the electrode localization (Fig. 6.1). Than a step of Aluminum sputtering enable to design the shape of the electrode. (Fig. 6.2) A last step of PECVD for Si3N4 deposition enables to protect the electrode which activate the membrane. This step can be shortened, it's a protection between the electrode and the membrane in case of short cut. This protective layer is etched by RIE technique (Fig. 6.3) for the external connections.

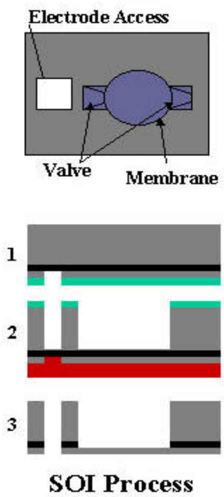

Fig. 5 SOI process

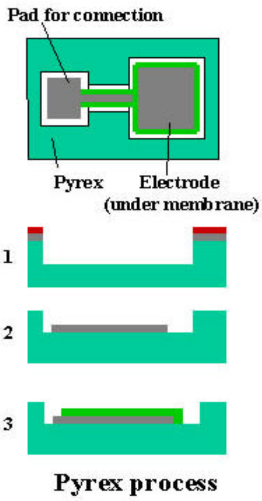

Fig. 6 Pyrex process

For the silicon wafer, a complete etch of the wafer is done by DRIE technique (Fig. 7.1). A 4000 angstrom layer of Al is used to protect the wafer during all the etch. Then a complete cleaning is done to obtain the cap (Fig. 7.2). Finally, we do first an anodic bonding between the SOI wafer and the Pyrex wafer (380°, 450V) (Fig. 8.1). Then a direct silicon/silicon bonding is achieved with the Si wafer (Fig. 8.2) to obtain the complete structure.

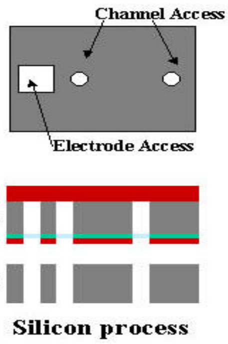

Fig. 7 : Silicon process

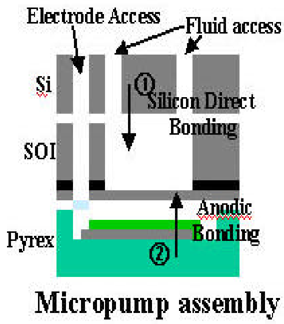

Fig. 8 :Bonding step

6. Conclusion

From the development of electric analogies applied to an electrostatic micropump, a micropump simulator (implemented under Pspice) has been achieved. From the simulation results and comparison to classical RLC circuit, a formula of the resonant frequency is presented from the electric equivalent parameters. Then, the realization of a prototype is depicted. The process is based on DRIE technique and used a double bonding step for the micropump assembly.

7. References

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