Electrical analogies applied on a volumetric micropump "highlighting of its fluidic resonant frequency"

Olivier Français and Samir Bendib
Group ESIEE, Cité Descartes, BP 99
93162 Noisy le Grand Cedex France
Tel: 01 45 92 65 86, Fax: 01 45 92 66 99
bendibs@esiee.fr, o.francais@esiee.fr

ABSTRACT

This paper deals with a simple way for optimising the design of a valve-less micropump. The method is based on electric analogies. The micropump is compared to an electrical circuit similar to a RLC circuit. By this way, the fluidic resonant frequency of the micropump can be evaluated despite a non-linear working due to the used of micro-valve. The results are applied on the design of an electrostatic micropump with a specific electrode shape in order to control the micropump resonant frequency. In order to validate the modelling, a prototype of electrostatic micropump is realised. The micropump is composed of three different wafers associated by bonding techniques.

KEYWORD list : Electrostatic Micropump, Electric Analogy, Modelling, Resonant frequency

1. INTRODUCTION

With MEMS, a lot of innovative applications had emerged in the field of microfluidic (Inkjet printer head, micromixer, microanalysis device) [1]. Micropump is one of the key success for controlling microfluidic transmission. But the apparent complexity of such a system induces heavy simulator based on FEM methods or a specific simulator [2]. A more simple method is the use of electrical analogies. Representing a micropump with electric networks enables the use of classic electric simulator such as Pspice. Simulations are obtained very quickly and enable parameter variations. This method has been used in order to evaluate the fluidic resonant frequency of an electrostatic micropump. The electrostatic excitation was supposed to be in a linear mode (similar to a pneumatic actuator).

2. DESCRIPTION OF AN ELECTROSTATIC VALVE-LESS MICROPUMP

In order to obtain a fluidic displacement, a volume chamber is associated to an actuator in order to modify its geometry. Usually, a diaphragm is used. Two symmetrical valves are designed to control the flow direction. The shape of the valve enables to obtain a greater flow in direct direction than reverse. The valves are connected to a tank or external tubes (Fig. 1).

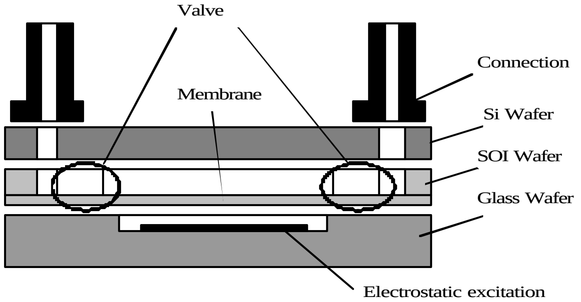

Figure 1 : Representation of the electrostatic micropump

Here, passive microvalves are used. Two kind of structures are developed :

- Nozzle-Diffuser (Fig. 2) : variation of the cross section generates loss pressure depending on the flow direction [3].
- Tesla Diode (Fig. 3) : variation of the geometry channel modifies the fluidic way [4].

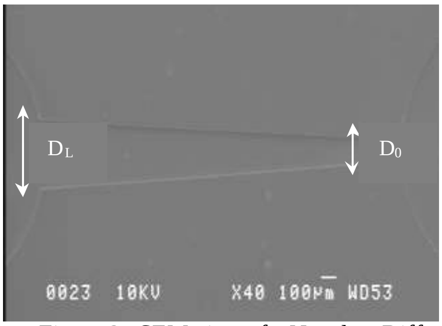

Figure 2 : SEM view of a Nozzle – Diffuser

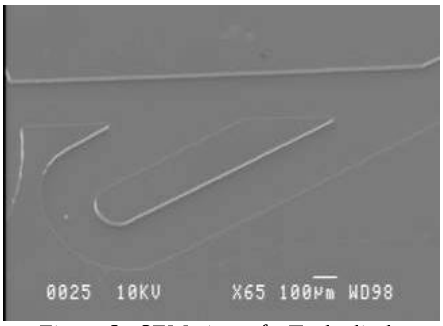

Figure 3 : SEM view of a Tesla diode

In the case of an electrostatic actuator, three wafers are needed:

- A Si Wafer or Pyrex wafer to close the micropump.
- A SOI Wafer to obtain the volume chamber (diaphragm) and the microvalves
- A Pyrex wafer to achieve the actuator.

3. ELECTRIC ANALOGIES OF MICROPUMP BEHAVIOR

The fluidic behaviour of a micropump is compared to an electric network [5]. The analogy is summarised in table 1 :

Fluidic parameters	**Electric equivalence**
Pressure (P)	Voltage V=P
Flow (ϕ)	Current I=P
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 section S_H)	Resistance $R = \frac{8\eta l}{\pi R_H^4}$ *(laminar flow)*
Compliance (Chamber volume variation versus pressure $C_m = \frac{dVol}{dP}$*)*	Capacitance $C_m = \frac{3\pi}{16E}\frac{R^6}{h^3}$ *(*silicon circular membrane: Radius R, thickness h and young's modulus E)

Table 1 : Electric equivalence with fluidic parameters

With this method, a tube becomes an [R,L] serial circuit with R the fluidic resistance and L the fluidic inertia. the volume variation of a component is modelled by a capacitor C. Here, the volume variation is generated by an electrostatic pressure which is comparable to a pneumatic pressure in the case of used of a small AC voltage around an DC offset voltage. By this hypothesis, the electrostatic pressure can be modelled by a simple voltage source.

For the valve, the asymmetric behaviour versus pressure has to be take into account. The modelling is more complex.

4. MICROVALVE MODELLING

The valves are characterised by their flow evolution versus pressure [6]. In the case of electric analogy, the equivalent representation is a current source driven by a voltage :

$$\phi = f(\Delta P) \Rightarrow i = f(\Delta U)$$

For the flow, two analytic equations are implemented in order to take into account the asymmetric behaviour of the micro-valve :

- **Direct flow :** The pressure applied on the valve is supposed to be positive. The flow value I_d is :
$$I_d = [F_d(\Delta U)/\Delta U] * (\text{abs}(\Delta U) + \Delta U)/2$$
Note : I_d=0 if ΔU<0

- **Reverse flow :** The pressure applied on the valve is supposed to be negative. The flow value I_r is :
$$I_r = [F_r(\Delta U)/\Delta U] * (\text{abs}(\Delta U) - \Delta U)/2$$
Note : I_r=0 if ΔU>0

F_d is the analytic approximated relation of the flow versus pressure in the direct mode and F_r in the reverse mode. ΔU represents the pressure applied on the valve. This analytic relation can be deduced from numeric simulation or measurement [7]. Here nozzle-diffuser and Tesla diode (fig. 4) are used in the realisation.

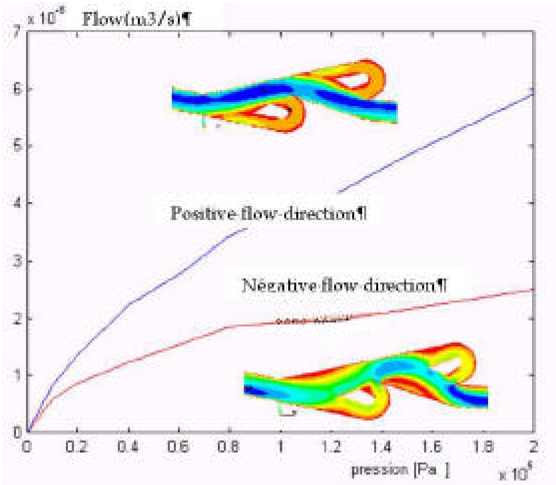

Figure 4 : Numeric simulation of a Tesla diode

5. IMPLEMENTATION OF THE ELECTRIC ANALOGY

From the analogy, an equivalent representation of a valve-less micropump has been implemented under Pspice simulator (Fig. 5). The schematic is composed of two branches (inlet and outlet) connected to a capacitor (Volume chamber).

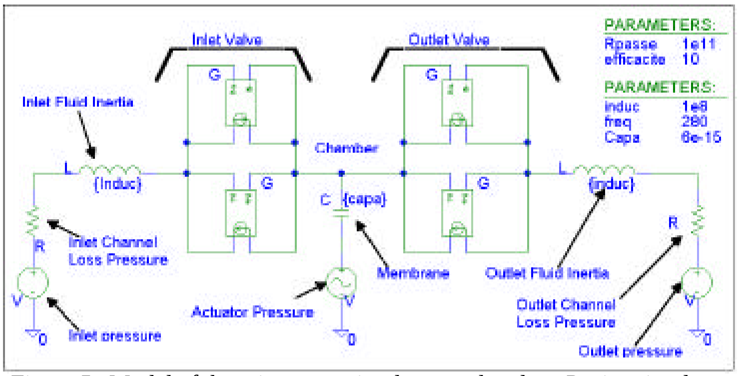

Figure 5 : Model of the micropump implemented under a Pspice simulator

The circuit obtained is very close to a RLC circuit. The results of transient analysis taking into account the non linearity of the valve has been compared with AC analysis (linear behaviour) of two linear simple representation(RC and RLC circuit) (Fig.2). “Linear mode” means that the valve are perfect and can be considered as a simple resistor R, with R the initial slope value of the valve characteristic.

Very close results are obtained. From the analysis of the results (AC analysis and transient analysis) the resonant frequency and the quality factor of the micropump can than be evaluated :

$$fo = \frac{1}{2\pi}\sqrt{\frac{2}{LC}} \text{ and } Q = \frac{2}{R}\sqrt{\frac{L}{2C}}$$

With R the average value of the resistor valve, if supposed perfect (efficiency of 1) [3].

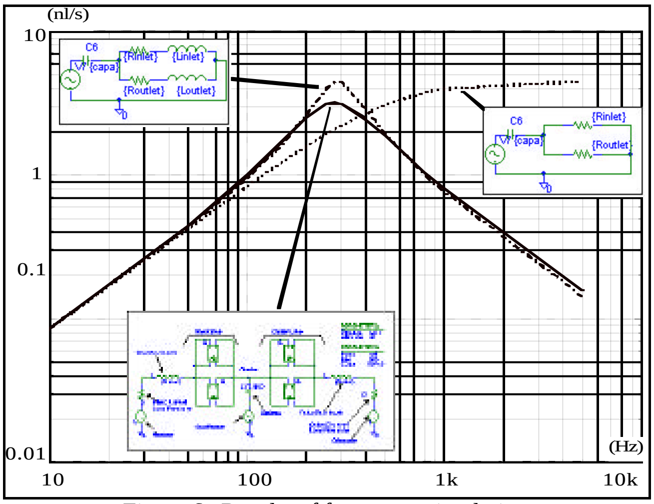

Figure 6 : Results of frequency simulation

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 ($\eta = 1e-3 Pa.s$). The average expected fluidic resonant frequency is 370 Hz.

So, from this results, the pressure chamber P_{ch} and outlet flow ϕ_{out} versus frequency can be expressed with reasonable approximation via the formula extracted from Fourier theorem applied to the electric network :

$$\phi_{out} = \frac{jC_m\omega}{1 - \frac{LC}{2}\omega^2 + j\frac{RC\omega}{2}} P_{exc} \qquad P_{ch} = \frac{jC_m\omega\left(\frac{R}{2} + j\frac{L\omega}{2}\right)}{1 - \frac{LC}{2}\omega^2 + j\frac{RC\omega}{2}} P_{exc}$$

With P_{exc} the amplitude of sinusoidal pressure applied on the membrane for generating the flow.

It's important to notice that using the micropump at its resonant frequency (with Q>1) will generate the maximum pressure chamber value, which is very important in order to used valve with no moving parts with an optimum diode efficiency.

6. INFLUENCE OF THE ELECTRODE SHAPE

Most of the electrode shapes are rectangular of circular. Here, an original excitation structure has been developed in order to obtain the desired the C_m value (Fig. 3) by using several electrode applied on a global diaphragm.

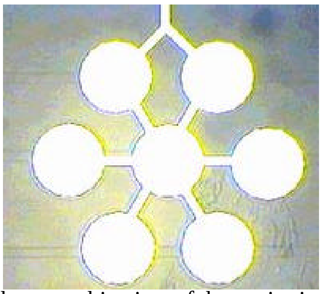

Figure 7: Photographic view of the excitation electrode

Instead of using one electrode on a circular membrane of radius R, seven electrodes are used on 7 membrane of a radius of approximately R/3. By this way, the compliance is divide by 100 :

$$C_{m1} = \frac{3\pi}{16E}\frac{R^6}{h^3} \Rightarrow C_{m7} = 7 * \frac{3\pi}{16E}\frac{(R/3)^6}{h^3}$$

Then, the volume stroke is divided by 100, but it can be compensated (if possible) by a greater excitation value (voltage multiplied by 10). In the same way, the resonant frequency and the quality factor are multiplied by 10. So the micropump performance can be controlled by modifying the electrode shape in order to obtain the resonant frequency and quality factor desired. The goal is to cumulate the fluidic resonant frequency of the micropump with mechanical resonant frequency of the diaphragm.

7. REALIZATION OF A PROTOTYPE

The micropump realisation is centred on the used of a SOI wafer in order 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).

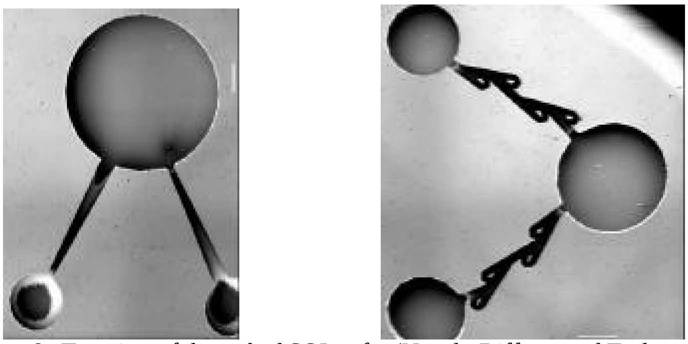

Figure 8 : Top view of the etched SOI wafer (Nozzle-Diffuser and Tesla valve)

For the SOI process, a first DRIE etching is done on the SOI (Fig. 9.1) for preparing an access window. Than the topside is etched until the SiO2 layer is reached (Fig. 9.2). A complete cleaning is done to remove the SiO2 (Fig. 9.3), 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 localisation (Fig. 10.1). Than a step of Aluminium sputtering enable to design the shape of the electrode. (Fig. 10.2) 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. 10.3) for the external connections.

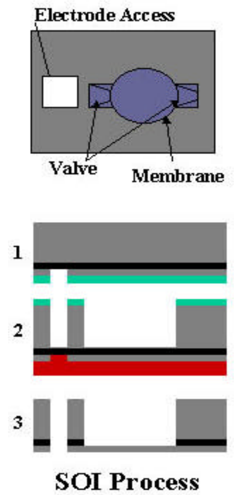

Figure 9: SOI process

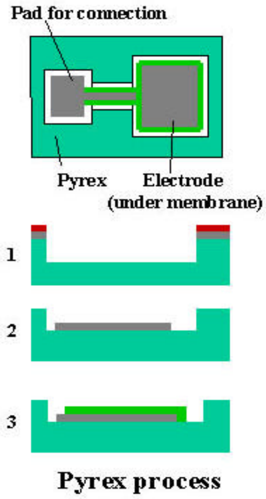

Figure 10 : Pyrex process

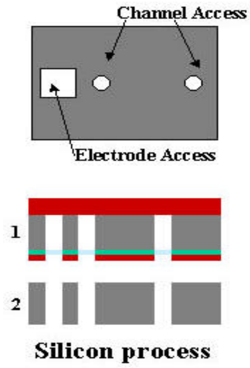

Figure 11 : Silicon process

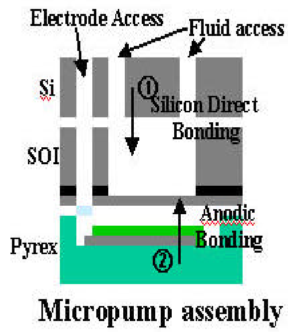

Figure 12:Bonding step

For the silicon wafer, a complete etch of the wafer is done by DRIE technique (Fig. 11.1). 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. 11.2). Finally, we do first a direct silicon/silicon bonding between the Si wafer (Fig. 12.1) and the SOI Wafer. Then an anodic bonding is achieved between the Si stack and the Pyrex wafer (380°, 450V) (Fig. 12.2). to obtain the complete structure.

The DRIE process is under optimisation in order to avoid the over-etching which appears during the complete top SOI etch (Fig. 13). This effect reduces the performance of the Tesla diode by reducing its geometry.

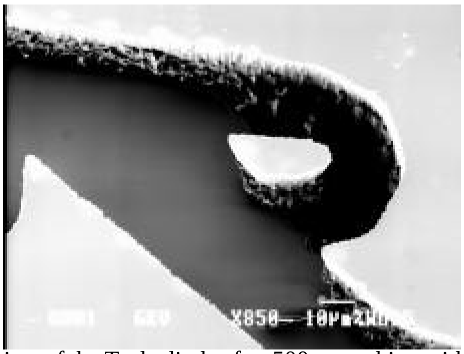
Figure 13: SEM view of the Tesla diode after 500µm etching with DRIE technique

Futur work will be done on the realisation on a piezolectric micropump with a specific process of AlN developped at ESIEE Group.

8. CONCLUSION

With the help of electrical analogies, micropump behaviour is found to be very similar to classical RLC circuit. This implementation method under a Pspice simulator enables to obtain very fast results. From the results, the fluidic resonant frequency is extracted and its behaviour versus the excitation geometry is studied. A method to modify the frequency characteristic is purposed and depicted. This modelling is associated to the realisation of a prototype. The process is based on DRIE technique and used a double bonding step.

Acknowledgements

This work is supported by the "Pôle Francilien des Microsystèmes" (PFM). The authors would like to thank the "Service des Moyens de la Microélectronique" (SMM) of ESIEE Group for help in the realisation of the prototype.

REFERENCES

[1] N. Giordano, J-T Cheng, *"Microfluid mechanics : progress and opportunities*", Journal of Physics Condensated Matter, Vol 13, pp 271 295, 2001.
[2] Qiulian Gong, Z. Zhou, Y. Yang, X. Wang, *"Design, optimization and simulation on microelectromagnetic pump"*, Sensors and Actuators, 83, pp 200-207, 2000.
[3] OLSSON A., STEMME G., STEMME E., *"Numerical and experimental studies of flat-walled diffuser elements for valve-less micropumps"*, Sensors and Actuators A, 84, pp. 165-175, 2000.
[4] Ron L.Bardell and Fred K. Forster, *"Impedances for design of microfluidic systems"*, Micro Total Analysis Systems '98 Workshop in Banff, Canada, 13-16 October 1998.
[5] BOUROUINA T., GRANDCHAMP J.P., *"Modeling micropumps with electrical equivalent networks"*, Journal of Micromechanics and Microengineering, vol.6, pp. 398-404, 1996.
[6] ANDUZE M., COLIN S., CAEN R., CAMON H., CONEDERA V., DO CONTO T., *"Analysis and testing of a fluidic vortex microdiode"*, Journal of Micromechanics and Microengineering, vol.11, pp. 108-112, 2001.
[7] M. Koch ,A.G.R. Evans and A. Brunnschweiler, *"The dynamic micropump driven with a screen printed PZT actuator*", Journal of Micromechanics and Microengineering, Vol. 8, pp 119–122, 1998.