

## MICROFLUIDIC DEVICES FOR GAS FLOW CONTROL

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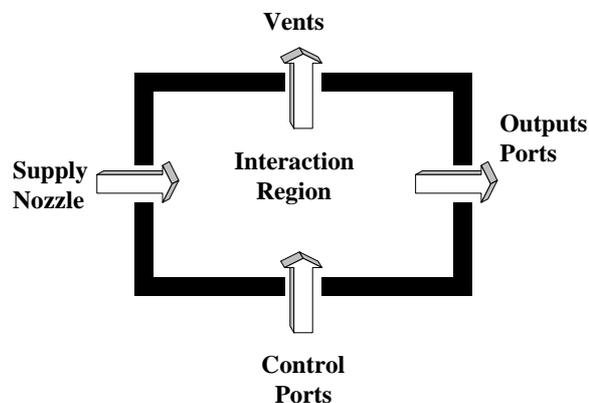
### ABSTRACT

*This paper is focused on the study of microfluidic devices implemented in silicon. Microactuators with no moving parts, microfluidic amplifiers, were integrated with microchannels. The operation of the obtained devices was analyzed in terms of gas flow control and division. Considering flow control, the devices presented proportional and symmetrical behavior with high proportional flow gains (output flow/control flow), similar to fluidic amplifiers with supply hydraulic diameters higher than hundreds of microns. For operation with flow division, a transition to a linear behavior between the supply flow and supply pressure is observed and the devices presented symmetrical output characteristics. Also, in this case, at moderate supply pressures, the results of numerical simulation indicate the possibility of internal choked flow, at the output of the supply nozzle, and supersonic regime in the interaction region.*

### INTRODUCTION

The miniaturization of fluidic devices finds many applications in several areas including medicine, biology, and chemical analysis, to mention only a few examples [1-6]. The miniaturized devices can be fabricated using microelectronics technology and other specific microfabrication techniques [7]. The obtained microdevices can present several advantages [8], as low cost batch fabrication, improved dynamic operation, operation with small sample quantities, reduced dead volume, etc.

In this paper we focused on the miniaturization of fluidic amplifiers [9 - 13], fabricating microactuator devices with minimum hydraulic diameters in the range of  $\sim 35 \mu\text{m}$ , which can be considered microfluidic amplifiers ( $\mu\text{FA}$ 's). These types of devices with no movable parts, schematized in Figure 1, have at least four basic functional parts: supply nozzle, control ports, output ports, and an interaction region. The flow emerging from the supply port generates a jet, which interacts with flows from the control ports in the interaction region. As a result, the jet from the supply nozzle is directed to one of the outputs, depending on the pressure or flow of the control inputs. The vents can be used to decrease the internal pressure and also to isolate the effects of output loading from control flow characteristics.

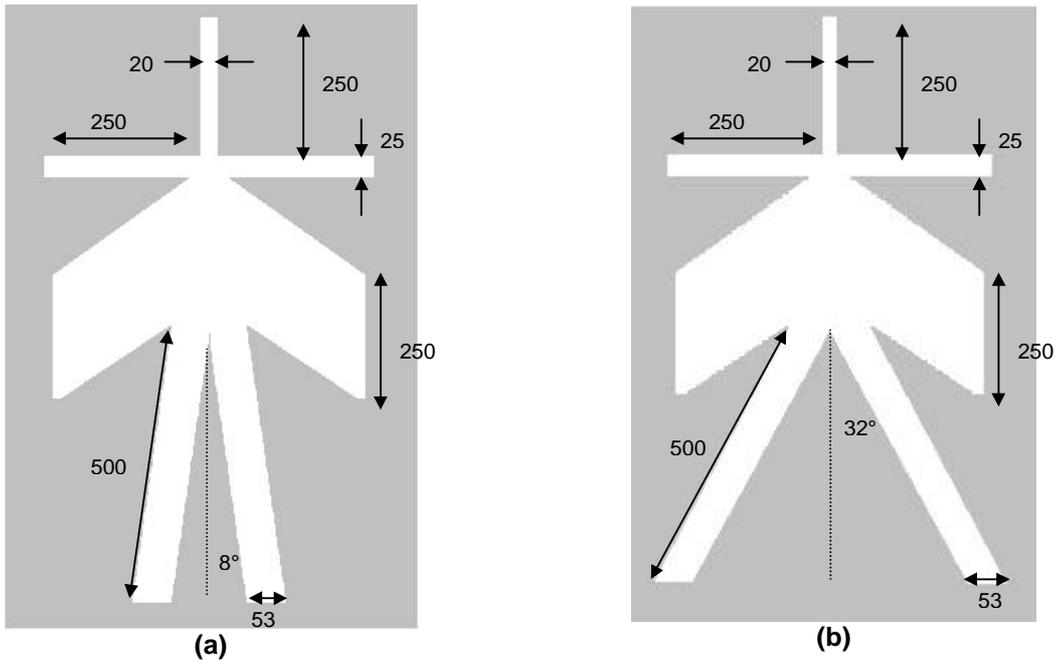


**Figure 1** - Schematic representation of a fluidic amplifier.

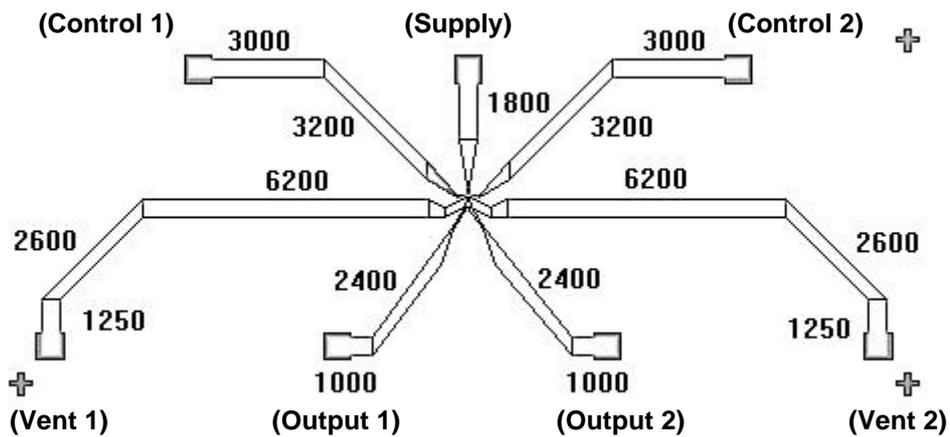
We scaled the fluidic amplifier proposed by Sugaya et al. [14] to divert the refrigerant of a freezer-refrigerator and added vents to it, in order to obtain a jet deflection type fluidic amplifier, as presented in Figure 2. Two configurations with splitter angles of 8° (Figure 2a) and 32° (Figure 2b) were implemented for comparison.

In order to facilitate the access to the microfluidic amplifier, we added interconnection channels. The complete device, displayed in Figure 3, can thus be considered a microfluidic circuit which could be integrated with other fluidic devices and/or microsensors.

The implemented devices were analyzed in terms of gas flow control and flow division operation. Numerical simulation was used to investigate the internal flow behavior.



**Figure 2** - Jet deflection type microfluidic amplifiers implemented in this work with splitter angles of: (a) 8° and (b) 32° (dimensions in  $\mu\text{m}$ ).

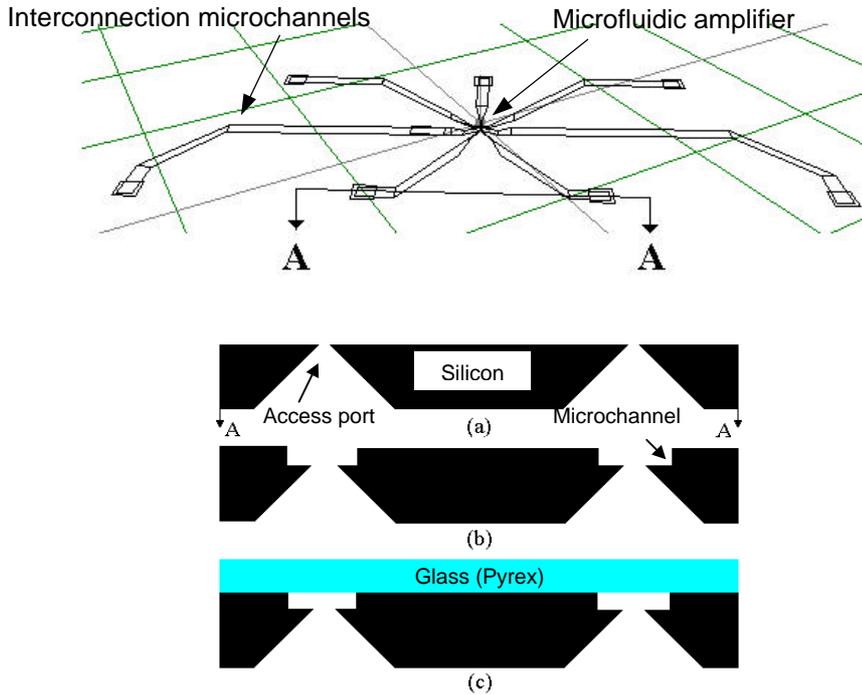


**Figure 3** - Complete microfluidic device implemented, including the microfluidic amplifiers, as the active part, and interconnection microchannels (dimensions in  $\mu\text{m}$ ).

### EXPERIMENTAL

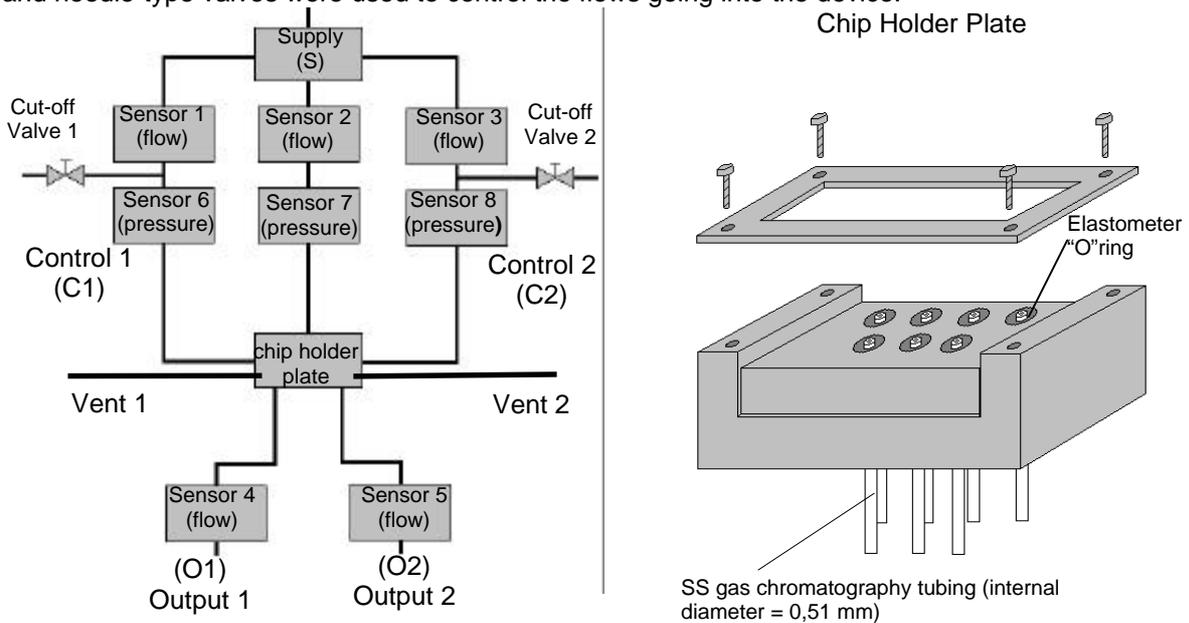
The devices were fabricated using silicon wet etching (KOH based solution) to open access ports from the back side of wafers. High density plasma dry etching ( $\text{SF}_6$  based) was used to open the microchannels on the front side. Anodic bonding between silicon and glass (Pyrex 7740®) permitted to

seal the microchannels. Details of the fabrication sequence, illustrated in Figure 4, are presented in references [11] and [15].



**Figure 4** - Schematic representation of a microfluidic amplifier cross section illustrating the fabrication process proposed by Furlan and Zemel [6][9][11]: a) access ports opened with silicon wet etching, b) microchannels defined in silicon with plasma etching, and c) sealing with glass using anodic bonding.

The devices thus fabricated were mounted on a chip holder plate connected to a pneumatic circuit, Figure 5, establishing the connections to nitrogen supply lines (supply and used control input) and to atmosphere (exits and vents). Thermal mass flow meters (MKS-500 and MKS-100 models 1179A and 2179A) monitored the mass flow rate at supply, control and output connections. Pressure sensors (SDE - 16-5 V/20 mA) were also used to monitor pressure at supply and control connections. Cut-off and needle-type valves were used to control the flows going into the device.



**Figure 5** - Schematics of the pneumatic circuit used for tests and detailing of the chip holder plate.

The gas flow behavior inside the devices (microfluidic amplifier without interconnection channels) for flow division operation was simulated using the commercial FLOTRAN (ANSYS 5.4) package. The simulation details are described in reference [16].

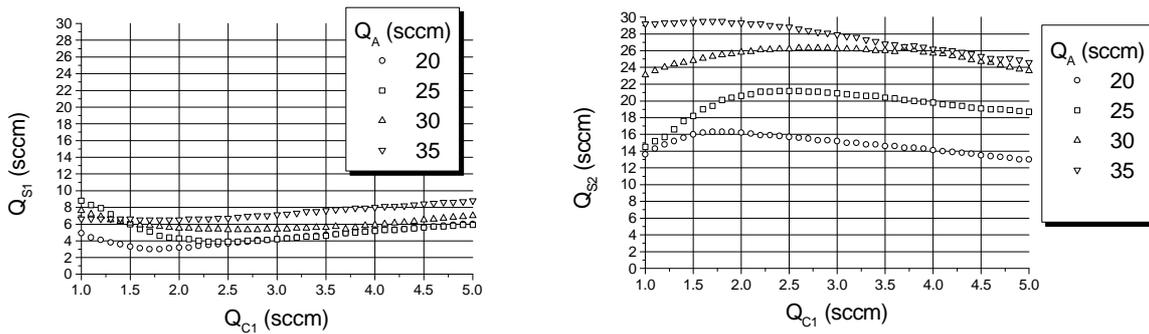
## RESULTS AND DISCUSSION

The implemented devices were analyzed in terms of possible applications, including flow control and flow division.

### Flow control operation:

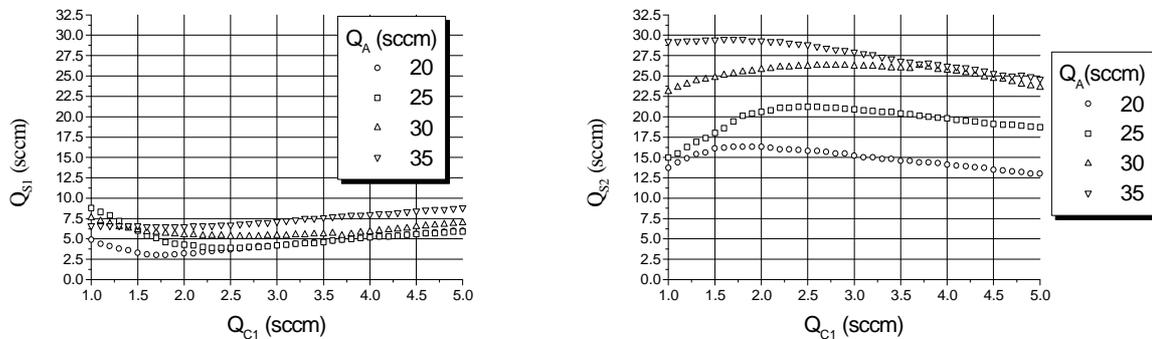
Figure 6 presents the characteristics of flow control of the jet deflection microfluidic amplifier with a splitter angle of  $8^\circ$ . In this case only one control input ( $C_1$ ) is being activated, with the other ( $C_2$ ) open to atmosphere, working as a vent. The supply flows correspond to Reynolds numbers lower than  $\sim 600$ , indicating operation in the laminar regime.

Increasing control flow 1 ( $Q_{C1}$ ),  $Q_{S1}$  decreases and  $Q_{S2}$  increases in a proportional way. For a certain control flow range ( $Q_{C1} < 2.5$  sccm) a linear behavior is observed, allowing to define a flow gain ( $\Delta Q_S/\Delta Q_C$ ) and the device can be really considered an amplifier. Increasing further the control flow the output flow control degrades. In this case  $Q_{S1}$  starts to increase, and  $Q_{S2}$  reaches a maximum and then starts to decrease, as the main jet reaches the vents. The increase in  $Q_{S1}$  can be explained by the fact that the main jet reaches a maximum deflection and the control flow also contributes to the flow through the output. Additionally, internal flow disturbances in the interaction region can contribute to this degradation. A very symmetrical behavior is observed when control input 2 is activated and control input 1 is open to atmosphere.



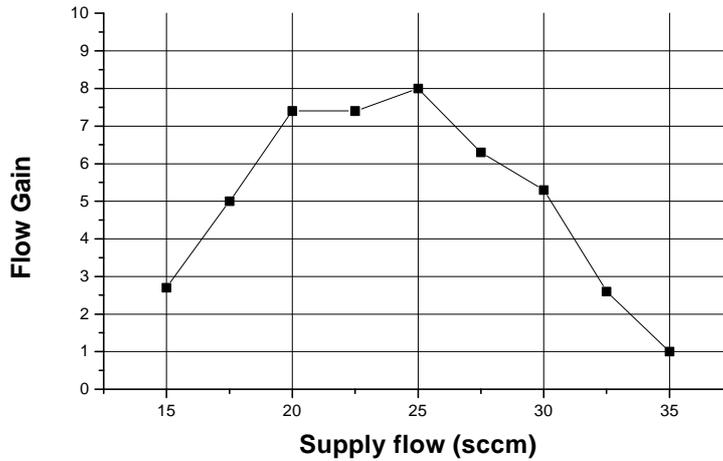
**Figure 6** - Output flow as a function of control and supply flow for a jet deflection microfluidic amplifier with a splitter angle of  $8^\circ$ . The not used control input ( $C_2$ ), vents and outputs were open to atmosphere.

A similar behavior can be observed in Figure 7, where the results were obtained for the device with a splitter angle of  $32^\circ$ .



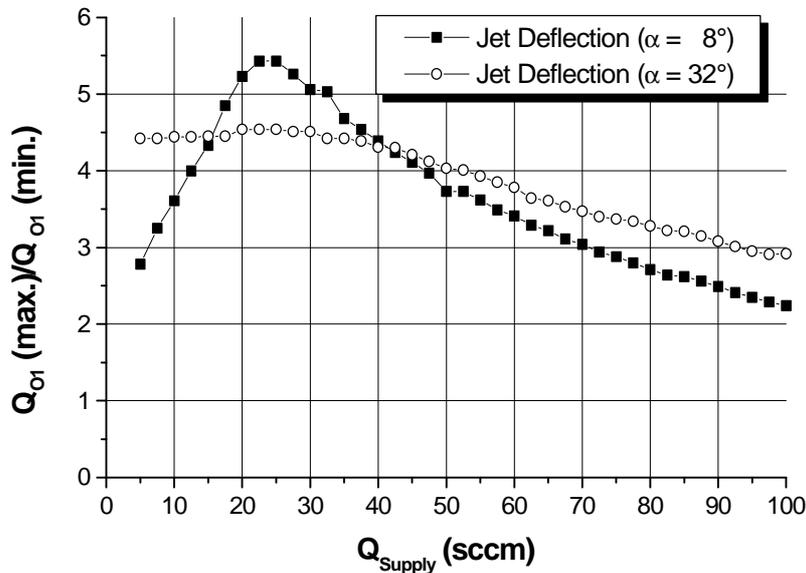
**Figure 7** - Output flow as a function of control and supply flow for a jet deflection microfluidic amplifier with a splitter angle of  $32^\circ$ . The not used control input ( $C_2$ ), vents and outputs were open to atmosphere.

The maximum flows gain obtained for both devices is about 8 corresponding to a supply flow of 25 sccm. This gain is in the range obtained for larger microfluidic amplifiers, using one only amplification stage. Also, it is a function of the supply flow, as displayed in Figure 8.



**Figure 8** - Flow gain of the microfluidic amplifier as a function of the supply flow.

Figure 9 presents the behavior of the ratio between  $Q_{O1}(\max)$  and  $Q_{O1}(\min)$  for both devices. It can be seen that the device with a splitter angle of  $32^\circ$  presents better characteristics for operation with low supply flows, probably because the splitter results better defined, resulting a best flow division at the outputs, probably without flow oscillations.



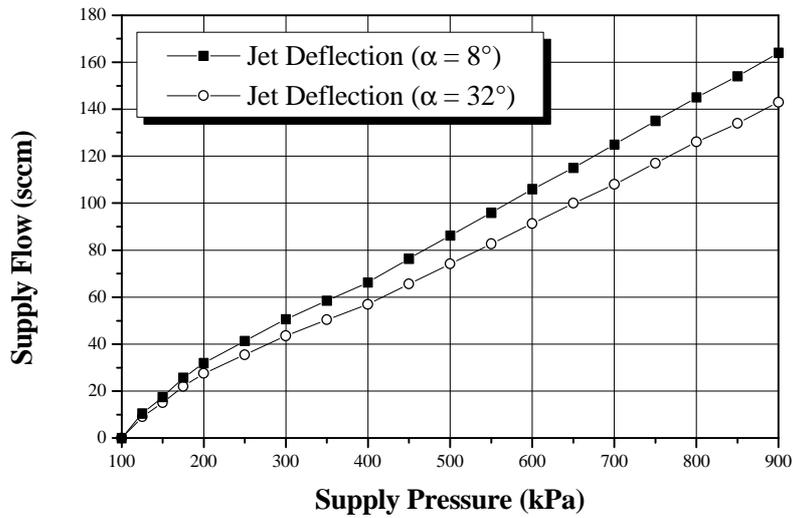
**Figure 9** - Flow ratio considering conditions of maximum deflection as a function supply flow. Only one control input was used and the other was open to atmosphere, together with vents and outputs.

Thus, the implemented microfluidic devices can be used for control flow applications, presenting proportional and symmetrical behavior with high flow gains, similar to fluidic amplifiers with supply hydraulic diameters higher than hundreds of microns.

Vented Flow Divider Operation:

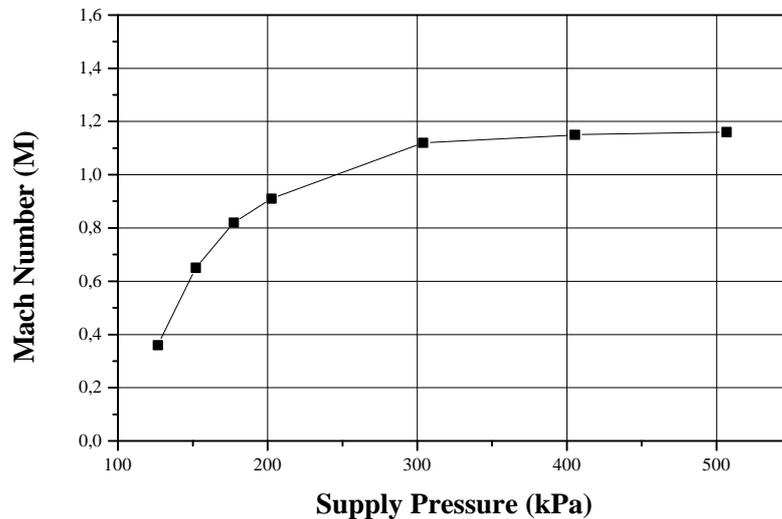
Figure 10 shows the behavior of the supply flow as a function of supply pressure for both implemented devices (splitter angles of  $8^\circ$  and  $32^\circ$ ). In this case control inputs and vents are open to

atmosphere and the devices operate as vented flow dividers. Also, in this analysis we extended the range of the supply flow (and associated supply pressure) and the Reynolds numbers reached values close to 3000.

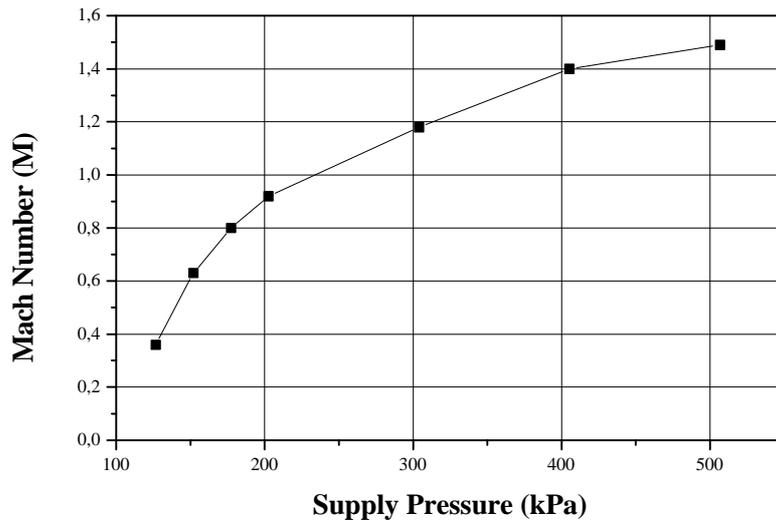


**Figure 10** - Supply flow as a function of absolute supply pressure for both jet deflection microfluidic amplifiers implemented, with splitter angles of  $8^\circ$  and  $32^\circ$ . Control inputs, vents and outputs were open to atmosphere.

For supply pressures higher than 200 kPa a transition to a linear behavior between the supply flow and pressure is observed. Numerical simulation analysis of the active part of the devices, at these operation conditions, indicate the possibility of choked flow at the output of the supply nozzle, Figure 11, and supersonic flow in the interaction region, Figure 12. These flow mechanisms may be associated with the observed transition.



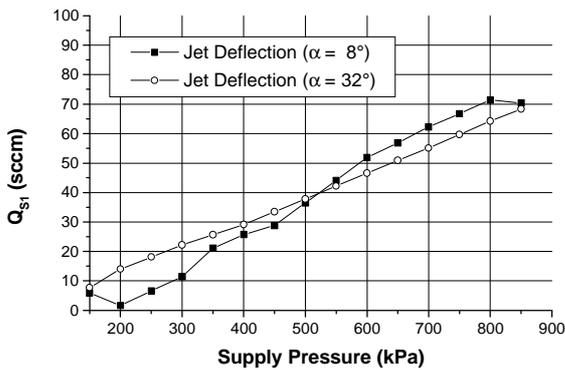
**Figure 11** - Mach number at the output of the supply nozzle as a function of supply pressure, obtained by numerical simulation, for the active part of a device with a splitter angle of  $8^\circ$ . Control inputs, vents and outputs were open to atmosphere.



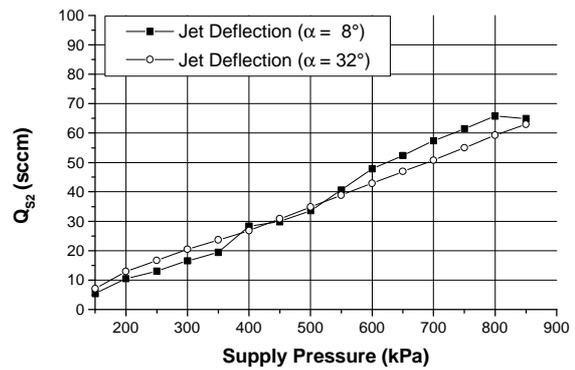
**Figure 12** - Mach number at the interaction region as a function of supply pressure, obtained by numerical simulation, for the active part of a device with a splitter angle of  $8^\circ$ . Control inputs, vents and outputs were open to atmosphere.

Although the simulated structures do not include the interconnection microchannels, the range of pressure necessary to obtain transonic flow is of  $\sim 250$  kPa, as observed in Figure 11. The occurrence of supersonic flow in the interaction region, in Figure 12, indicates the possibility of discontinuities in the flow, as shock wave formation.

Figure 13 shows the correspondent output flows of both devices, where a symmetrical behavior can be observed. The device with a splitter angle of  $32^\circ$  resulted more symmetrical in terms of output, for the entire range of supply pressures, probably because its splitter results better defined during fabrication.



Output 1



Output 2

**Figure 13** - Output flows as a function of absolute supply pressure for both jet deflection microfluidic amplifiers implemented, with splitter angles of  $8^\circ$  and  $32^\circ$ . Control inputs, vents and outputs were open to atmosphere.

Thus, the operation as a flow divider can be accomplished with symmetrical output characteristics. At moderate supply pressures ( $\sim 350$  kPa) the results of numerical simulation indicate the possibility of internal choked flow, at the output of the supply nozzle, and supersonic regime in the interaction region.

## CONCLUSIONS

Jet deflection microfluidic amplifiers were implemented in silicon, in a configuration with interconnection microchannels, forming a kind of miniaturized fluidic circuit. The implemented devices were analyzed in terms of applications involving flow control and flow division.

Considering flow control, the devices presented proportional and symmetrical behavior with high flow gains, similar to fluidic amplifiers with supply hydraulic diameters of hundreds of microns. The flow gain is a function of supply flow. The use of a splitter angle of  $32^\circ$  at the output of the microfluidic amplifier resulted in better characteristics than those obtained with a splitter angle of  $8^\circ$ , for operation with low supply flows, probably because of fabrication aspects.

For operation with flow division, a transition to a linear behavior between the supply flow and supply pressure is observed and the devices presented symmetrical output characteristics. At moderate supply pressures the results of numerical simulation indicate the possibility of internal choked flow, at the output of the supply nozzle, and supersonic regime in the interaction region.

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