Designing, realization and characterization of a novel capacitive pressure / flow sensor

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SUMMARY

This paper reports the design, realization and characterization results of an integrated pressure / flow sensor for measuring flow-rates as well as pressures of common liquids in micro analysis systems. The sensing system comprises high accurate capacitive pressure sensors and a hydraulic resistor. An attractive feature is the simple realization process consisting of common micromachining techniques.

Keywords: Pressure sensors, Flow sensors, Modeling

THE PRESSURE / FLOW SENSOR

In behalf of micro total analysis systems [1] (μ -TAS), components are needed to steer and control fluid flows. Examples of these are passive or active valves and sensors for measuring flow rates and pressure [2,3]. The first need is to have a controlled flow or pressure source to feed the analysis system. For this, a combination of an active valve and a flow sensor in an electrical feed-back loop can be used if only the flow rate needs to be controlled [4]. In many cases however, it might also be interesting to monitor and control the delivered pressure to protect for example fragile sensors. In such a case, an extra pressure sensor is needed to sample the pressure level at the entrance of the system [5]. For sensing the delivered pressure from the pressure-reservoir, a second pressure sensor is inevitable.

By combining two pressure sensors and a known impedance connected in between, a pressure / flow sensor is obtained [6] which ideally fits the need for flow-rate as well as pressure sensing for a hydraulic power supply. Besides the simplicity of the sensor, it can be used both for conducting as well as non-conducting fluids. By using capacitive pressure sensors, the system can be designed to consume little energy. Compared to the thermal mass-flow sensors [7], the working range in flow-domain is large.

DESIGN

To meet the wishes in μ -TAS for low-power consumption, accuracy and stability, the pressure sensors were designed with a capacitive read-out. The working principle is shown in Figure 1. The pressure on both sides of a hydraulic resistor is sensed, relatively to atmospheric pressure. Because

the reference pressure is the same, the pressure drop over the hydraulic resistor is directly known from the two sensed values.

The capacitance change of the pressure sensors as function of the design parameters and applied pressure is computed both for round as well as square membranes, working in the linear and the non-linear range. By rewriting the results in a dimension-less form, the plots can be used more general due to reduction of parameters. The conversion from dimension-less to dimensional is given in Table 2. In Table 1 the definition of the used parameters is given.

Figure 1: Schematic cross-section view of the sensor

Table 1: Membrane parameters

parameter	notation	parameter	notation
pressure	p	radius coord.	r
deflection	w	angular coord.	θ
center deflection	w_0	x-y coord.	x, y
thickness	h	modulus of elast.	E
radius	a	Poisson's const.	ν
side length	$2*a$	pre-stress	σ

For small displacements, the membrane deflection only depends on bending stresses for which the following load - deflection relation holds [8] $Q = K_b \cdot W_0$

Table 2: Definition of dimension-less parameters

membrane theory	dimension-less parameter	dimensional elements
pressure load	Q	pa^4/Eh^4
deflection	W	w/h
center deflection	W_0	w_0/h
radius coordinate	R	r/a
angular coordinate	θ	θ
x-y coordinates	X, Y	$x/a, y/a$
deflection stiffness	K_d	$C_2 f(\nu)/(1-\nu)$
pre-stress	K_σ	$C_1 \sigma_0 a^2/Eh^2$

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For large deflections ($W_0 > 0.5$) the tensile stresses become noticeable which requests an extended approximation:

$$Q = K_\sigma \cdot W_0 + K_d \cdot W_0^3$$

The bending constants, K , are given in Table 3 and obtained from analytical as well as fitted numerical computations [9].

Table 3: Stiffness constants for round and square membranes

	K_b	K_σ	K_d
Anal ○	$\frac{64}{12(1-\nu^2)}$	$4.0 * \left(\frac{\sigma_0 \cdot a^2}{E \cdot h^2} \right)$	$\frac{2.67}{1-\nu}$
FEM ○	$\frac{64}{12(1-\nu^2)}$	$4.0 * \left(\frac{\sigma_0 \cdot a^2}{E \cdot h^2} \right)$	$\frac{2.67}{(1-\nu) * (1.026 + 0.233\nu)}$
Anal □	$\frac{49.6}{12(1-\nu^2)}$	$3.04 * \left(\frac{\sigma_0 \cdot a^2}{E \cdot h^2} \right)$	$\frac{(1.47 - 0.40\nu)}{1-\nu}$
FEM □	$\frac{49.6}{12(1-\nu^2)}$	$3.41 * \left(\frac{\sigma_0 \cdot a^2}{E \cdot h^2} \right)$	$\frac{(1.98 - 0.585\nu)}{1-\nu}$

For calculating the capacitance, the gap size between the fixed upper electrode and the deflecting lower electrode must be integrated over the electrode area:

$$c = \int_{A_c} \frac{\epsilon_0 \epsilon_r}{d_0 - w} dA$$

For these calculations the dimension-less parameters of Table 5 are introduced.

Table 4: Parameters for capacitance calculations

parameter	notation	parameter	notation
capacitance	c	gap distance	d_0
diel. constant	ϵ_0	radius coord.	r_c
rel. diel. const.	ϵ_r	x-coordinate	x_c
area	A	y-coordinate	y_c

Deflection W depends on the shape of the membrane. For round membranes, the function $W = W_0(1 - R^2)^2$ well suits both for linear (exact solution) as well as non-linear deflections. For square membranes, Timoshenko [8] suggests:

$$W = W_0 \cos\left(\frac{\pi}{2} X\right) \cdot \cos\left(\frac{\pi}{2} Y\right) \text{ although the shape function}$$

$$W = W_0(1 - X^2)^2 \cdot (1 - Y^2)^2 \text{ better fits the measured profiles (fully clamped membrane).}$$

Table 5: Dimension-less parameters for capacitance calculations

capacitance	dimension-less parameter	elements
spec. capacitance	C	$ch/\epsilon a^2$
gap distance	D_0	d_0/h
radius coordinate	R_c	r_c/a
x coordinate	X_c	x_c/a
y coordinate	Y_c	y_c/a

For a round membrane with an initial gap distance D_0 and circular electrode ranging from $R=R_{c1}$ to R_{c2} , the specific capacitance becomes

$$C = \int_{R_{c1}=R_{c1}}^{R_{c2}} \int_{\theta=0}^{2\pi} \frac{RdRd\theta}{D_0 - W_0 \cdot (1 - R^2)^2} = \pi \cdot \frac{a \tanh\left(\frac{\sqrt{W_0}(R_{c2}^2 - 1)}{\sqrt{D_0}}\right) - a \tanh\left(\frac{\sqrt{W_0}(R_{c1}^2 - 1)}{\sqrt{D_0}}\right)}{\sqrt{W_0 D_0}}$$

Whereas the other integrals for square membranes can be integrated numerically. With these results, plots are made which give size-independent information and can be used for optimizing the sensors for a specific working range. An example is given in Figure 2.

Figure 2: Load - capacity relations for a round membrane

The modeling of the hydraulic behavior is done by taking only a fully developed flow into account. Because the resistance channel is taken quite long compared to the depth, the neglect of entrance and exit-resistances will give no major differences.

Another assumption, is the situation of static pressure under the pressure sensors. So only a pressure-drop will occur in the small resistor channel. The parameters that are important for modeling hydraulics are given in Table 6.

Table 6: Parameters for hydraulic modeling

parameter	notation	parameter	notation
resistance	R	mass density	ρ
pressure	p	effective velocity	v_{eff}
flow-rate	ϕ	cross-section area	A
channel length	l	wetted perimeter	ϕ
viscosity	μ	Reynolds number	Re

Friction in the fluid causes energy dissipation which results a pressure drop over the channel [10,11]:

$$\Delta p = \frac{1}{8} \left(\frac{\rho v_{eff}^2}{Re} \right) \left(\frac{f_{Re,ph} \cdot \phi}{A} \right) \cdot l$$

REALIZATION

From this, the hydraulic resistance is calculated by using the relation between flow and pressure:

$$\Delta p = R \cdot \phi$$

So the resistance is defined by:

$$R = \frac{\mu}{2048} \cdot \left(\frac{f_{ReDh}^2 \cdot \phi^2}{A^3} \right) \cdot l$$

For a circular, and rectangular cross section this resistance becomes:

$$\circ \quad R = \frac{128}{\pi} \cdot \mu \cdot \frac{1}{d^4} \quad \text{with } d = \text{diameter}$$

$$\blacksquare \quad R = \frac{\mu}{512} \cdot \left(\frac{f_{ReDh}^2 \cdot (a+b)^2}{a^3 \cdot b^3} \right) \cdot l \quad \text{with } a, b = \text{wall sizes}$$

Values for the geometry factors f_{Re} vary from 56.91 for a rectangular cross-section with $b = a$ to 96.00 for $b/a \approx 0$. Because the channel shapes we use have values somewhere in between, we interpolated a range of known constants to extract the values we needed.

Combining the models for the pressure sensors with the hydraulic models, the static characteristics of the sensor can be predicted. For dynamic impedance calculations however, we need also to take the hydraulic capacitance of the sensors (membranes) and the inertia of the traveling fluid into account [12]. Similar to electronic circuits, the hydraulic scheme looks like Figure 3. The pressures P_1 and P_2 are absolute whereas ground indicates the atmospheric pressure.

Figure 3: Hydraulic impedance scheme

The hydraulic capacities C_{hyd} are calculated by:

$$\phi = C_{hyd} \frac{dp}{dt} \quad \text{so that} \quad C_{hyd} = \frac{dvol}{dp} \quad \text{with "vol" indicating the}$$

pumped volume by the membrane of the sensor. For the square membrane with a double-quadratic shape and side length $2a$

$$\text{this results: } C_{hyd} = \frac{4}{75} \frac{a^6}{Eh^3} (1 - \nu^2) \quad [m^5/N]$$

The inductance, L_{hyd} is defined by: $p = L_{hyd} \frac{d\phi}{dt}$ so that in

this case: $L_{hyd} = \frac{\rho l}{A}$ with l and A the length and cross-section area of the resistor channel respectively.

The 10x5x1.3 mm sensor consists of an integrated pair of pressure sensors and a hydraulic resistor, build by a wafer sandwich of (Hoya) pyrex glass - silicon - pyrex glass. Figure 4 shows a SEM picture of the cross-section.

Figure 4: Cross-section SEM picture of the sensor

The silicon intermediate contains the active parts of the pressure sensors. Membranes are made by an-isotropic KOH etching, combined with a time-stop to determine the wanted thickness. After this, the silicon-nitride insulation layer on the silicon membrane is patterned and the chromium-platinum electrodes are sputtered. The patterning of these electrodes is performed by a lift-off process.

For creating the fixed upper electrode, first a cavity is etched isotropically in the pyrex glass with HF. This cavity determines the gap-distance between the electrodes and thus the capacitive behavior. Patterned chromium with a resist layer on top is used as mask for HF etching but also as auto-aligned shadow mask during the following deposition of the chromium-platinum electrodes. Besides simplifying the process sequence, combining these steps also yields a well-defined, deepened electrode.

In the lower pyrex wafer we etched the hydraulic resistors and drilled holes for the fluid connections. The working range in the flow-region can be changed by choosing a wafer with different resistor sizes.

After all wafers are processed, the pyrex-silicon-pyrex sandwich is anodically bonded. Because of the strong attracting forces between the electrodes, due to the potential drop over the electrode pairs, both need to be held at the same potential level. For this, all electrodes at the top wafer are coupled and electrically connected to the silicon wafer. This worked-out well without disturbing the bonding process.

The connection of the upper and lower electrodes to the outer world can create a problem. Designs become more complex due to feed-through of electrical connections from one to the other wafer. By dicing the upper and lower wafers at a different position this problem is solved. After breaking the

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pre-etched silicon wafer, the lower and upper electrodes become accessible, as is shown in Figure 5.

Figure 5: Electric connection principle: A top view (half)
B side view

TESTING AND CHARACTERIZATION

For the first tests, a computer controlled set-up is build, consisting of an gain-phase analyser, translation table with syringe, to generate a flow with a minimum resolution of 16.7 pl. and a calibrated reference pressure sensor. A defined liquid flow is increased in steps, during which both pressure as well as capacity is measured. Figure 6 shows the fitted flow-rate capacity relation, obtained with demi water.

Figure 6: Measured flow-rate capacity relation

Final characterisation will be carried-out with use of a developed modified Martin oscillator circuit for reading the capacities. With this we expect to detect capacitance changes down to 50 atto Farad which will provide an extremely sensitive sensor system. By interfacing the electronics closely to the sensor, a strong reduction of noise (wiring) is expected, combined with the facility to obtain a digital output signal (frequency).

CONCLUSIONS AND FURTHER DEVELOPMENTS

The presented sensor integrates both a flow and pressure sensor which ideally suits the wishes for making a combined

pressure / flow control system for μ -TAS applications. Design functions are derived to predict the sensor's behavior both for stationary and dynamic operation. Because of the simple design, the sensor can be made with common micromachining techniques with a minimum of processing steps.

The first measurements show a good functionality of the sensor, although some improvement is needed in the electrical read-out and the sensitivity of the sensor, necessary for measuring small flows ($<1\mu\text{l/min.}$). A modified Martin oscillator circuit will be used to obtain a high resolution and to reduce noise by close interfacing.

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