Application Note: Smash-Simulation of a Surface Micromachined Capacitive Pressure Sensor

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1 The Pressure Sensor System

The presented example is a capacitive pressure sensor system. The physical pressure is detected by a circular pressure element whose upper plate is deflected if it is exposed to an external gas or fluid pressure. The deflection results in a change of capacitance C_S between upper and lower plate. The readout circuit compares C_S with a reference capacitance C_R which is not sensitive to pressure changes. It is based on the switched capacitor technique. The system is depicted in Figure 1.

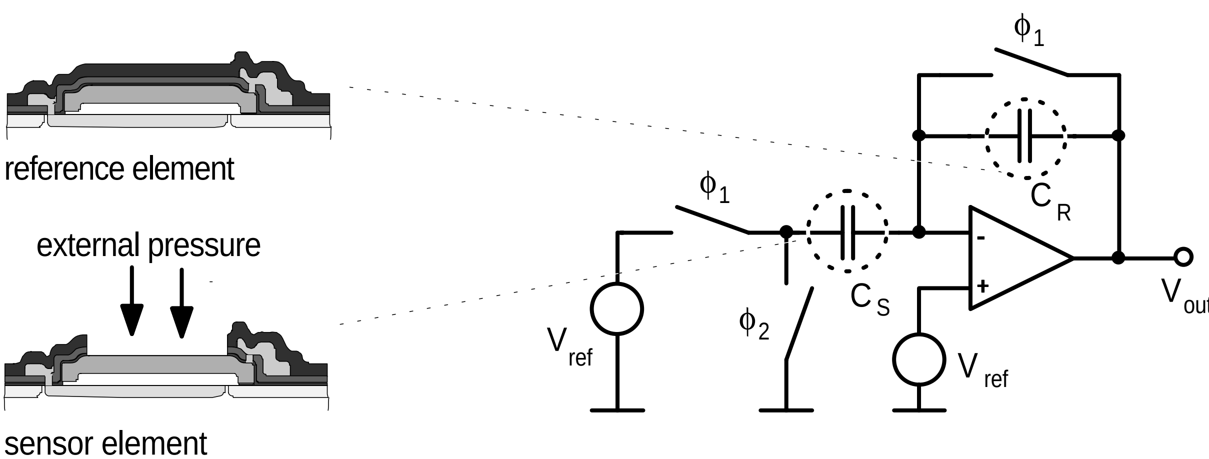

Figure 1: Surface micromachined capacitive pressure sensor system.

Note that mechanics and electronics cannot be separated for simulation purposes. This is for two reasons: the system is a transducer between mechanics and electronics and is thus heavily dependent on the electro-mechanical interference. Moreover, the time constants of mechanics and electronics are in the same range. Thus, dynamic interference cannot be neglected.

The mode of operation is as follows: the external pressure causes the deflection of the upper plate and thus a change of the sensor capacitance. The sensor capacitance in turn is part of the readout circuit which compares the sensor capacitance with a reference capacitance and prepares an output signal. For simulation purposes, the circular, upper plate of the sensor element can be described through the following partial differential equation:

$$\frac{\partial^2 u}{\partial t^2} = -\frac{Ed^3}{12\rho(1-P^2)} \cdot \left(\frac{\partial^4 u}{\partial r^4} + \frac{2}{r}\cdot\frac{\partial^3 u}{\partial r^3} + \frac{1}{r^2}\cdot\frac{\partial^2 u}{\partial r^2}\right) + w$$

u is the displacement, E the modulus of elasticity, d the thickness of the plate, ρ the density of the plate material, P poisson's factor, r the (radial) spatial variable and w the excitation. The above partial differential equation will be solved for every time step of the underlying circuit simulator.

2 Generating ABCD models

We apply the finite differences method (FDM) to transform partial differential equations to sets of ordinary differential equations which can be directly formulated in Dolphin's analog hardware description language ABCD. The spatial variables of the partial differential equations are discretized and an algebraic equation is inserted for each node. This equation describes the behavior of the respective slot by regarding itself and some of its neighbors in both directions. The transformation of spatial derivatives up to the forth order can be done. For example, the equations containing the term $\frac{\partial^4 u}{\partial x^4}$ have to be duplicated n times, if n is the number of steps of the discretization. Each of these duplicated equations represents another node of the discretized domain, see Figure 2. For the spatial derivative of the above form, two neighboring nodes to the left and right have to be taken into account. This implies two additional nodes on the left and right side of the discretized domain. These nodes contain the boundary constraints.

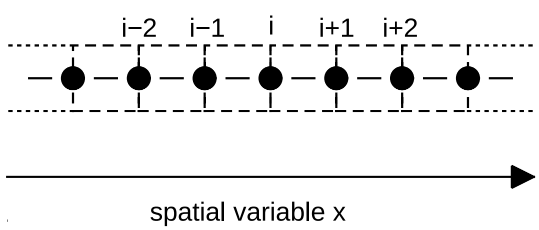

Figure 2: Discretization of spatial variable x.

Currently, arbitrary partial differential equations in one dimension and up to the forth order spatial derivative can be translated to ABCD by the transformation tool MEXEL. Coefficients, e.g. the modulus of elasticity or thermal conductivity, may be dependent of time and space. The equations for the following phenomena can be formulated: bending of elastic plates and beams, heat- and material-transport, diffusion and lossless wave propagation.

Furthermore, integrations over spatial variables are available which are for instance necessary to calculate the capacitance of the deflected pressure sensor element. The solution is based on Simpson's rule and is carried out by adding a specific equation to the equation set.

3 Simulation

The goal of our work is to dynamically simulate the electronical and mechanical parts of the system simultaneously with one simulator, i.e. Dolphin's SMASH, and one simulation approach. The following aspects of the system can be studied:

- shape of the bending line
- eigenfrequency of the sensor
- transduction of mechanical pressure to electronical capacitance
- sensivity of the sensor
- linearity of the sensor
- calibration of the sensor
- damping effects

Figures 3 and 4 show a transient SMASH simulation of the pressure sensor system. Figure 3 depicts the shape of the external pressure (top), the respective capacitance change of the pressure element (middle) and the output voltage prepared by the readout circuit. This capacitance change is due to the deflection of the pressure element which is shown in Figure 4 (top) together with the respective velocities (middle) and accelerations (bottom). The deflection as well as velocities and accelerations are shown for various Points which are spread equally on the radius of the upper plate.

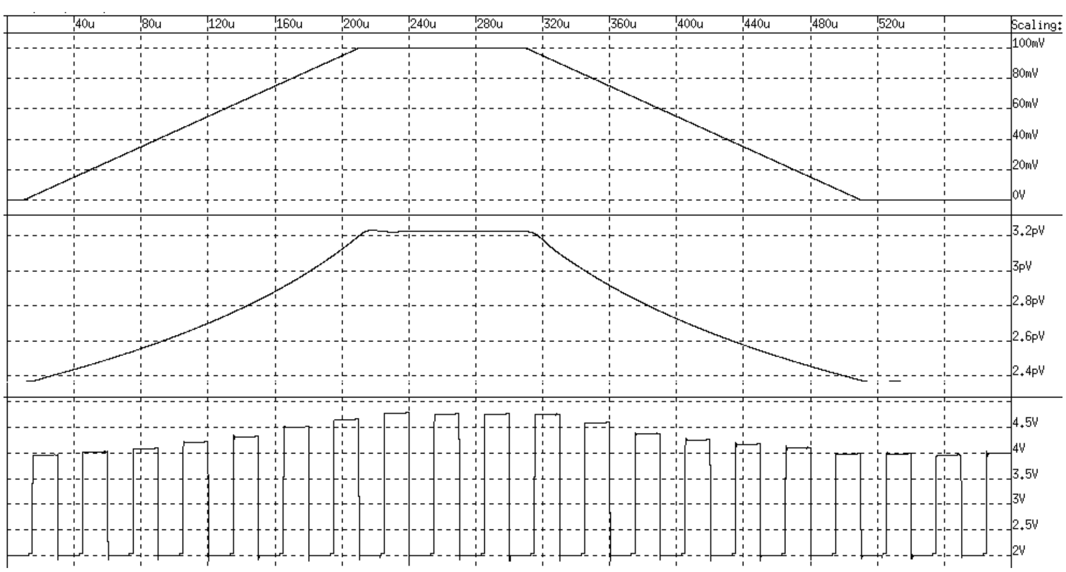

Figure 3: External pressure (top, $100mV = 1bar$), total capacitance of an array of 25 pressure elements (middle, $1pV = 1fF$) and output voltage of the readout circuit (bottom).

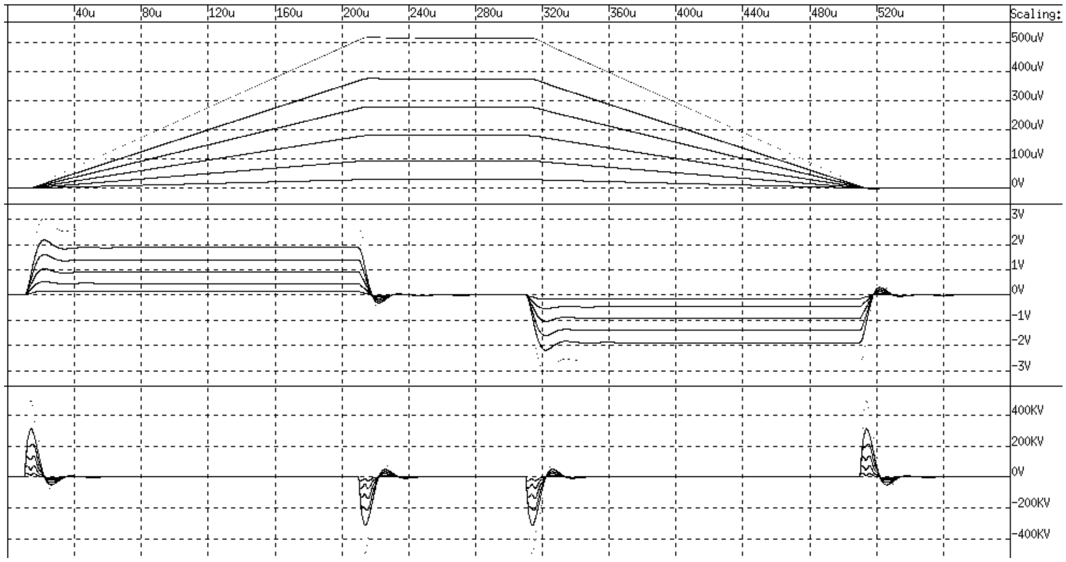

Figure 4: Deflection (top, $1uV = 1nm$), velocity (middle, $1V = 1mm/sec$) and acceleration (bottom, $1V = 1mm/sec^2$) of several points spread over the radius of the upper plate of the pressure sensor element.

4 Extensions

Several effects are currently not included in the model of the pressure element. The two most important ones are the electrostatic influence of the readout voltage between the capacitor plates and the touchdown of the upper plate on the isolator. Both effects can be neglected for our simulation testcase, since the upper plate stays some hundreds of nanometers away from the isolator.

5 References

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