Design Automation for Microsystems[1]

Lars Voßkämper [a b], André Lüdecke [a], Michael Leineweber [a,] and Georg Pelz [a],
[a] Gerhard Mercator-University -GH- Duisburg, Finkenstr. 61, D-47057 Duisburg, Germany
[b] Dolphin Integration GmbH, Bismarckstr. 142a, D-47057 Duisburg, Germany

Abstract

The paper features a methodology for the cooperative generation of micro-mechanical layouts and derivation of the respective circuit simulator models which is especially suited for systems requiring continuous mechanics even on system level. For these applications the final development level is lifted from layout to circuit abstraction which supports designers and boosts mechatronics intellectual property applications, since it allows to separate component from system development.

1. Introduction

Computer-aided design for microelectromecanical systems (MEMS) today is in a state comparable with that of microelectronics 20 years ago. While the primary focus was on component design, the system view quickly is catching up. On both sides things are much easier this time, since many of the CAD-algorithms and -tools can be recycled from microelectronics. Research should be focussed on the remaining gaps.

Two of these gaps being very important for system design are layout generation and device modeling for circuit simulation. Both have to be completely reformulated for micromechanical components. Moreover, they are now tightly linked. While in electronics layout generation the respective subcircuit is a simulatable model by itself, things are different in micromechanics. Here two cases can be identified:

- suspended-systems
  Suspended systems contain masses which are supported by several kinds of suspensions. Examples include acceleration sensors, resonators or micromirrors. The common denominator of all these systems is that they can be decomposed into a collection of rigid bodies, springs and dampers, i.e. a multi-body abstraction, for which a “mechanical” circuit can be derived. This circuit again is a simulatable model by itself, see [1].
- non-suspended-systems
  In all other cases, the continuous nature of mechanics has to be taken into account even in circuit simulation. This requires suitable mechanics models which have to be created or at least parametrized in parallel to the layout generation.

The described work is focussed on the second case which encloses the cooperative generation of layouts and derivation of device models for circuit simulation.

As in microelectronics, manual layout design for micromechanical devices is involved and error-prone. With the applications growing more and more mature, the manual layout design will be replaced by bottom-up layout generation or top-down layout synthesis which mainly depends on the nature of the respective mechanical component. Nonetheless, whatever method will be used, it has to be tailored to the specific application. In this, layout generation/synthesis for micromechanics is quite similar to that of analog circuits.

Layout generation is just one side of the coin. For system design it is indispensable to include micromechanical components into circuit simulation. This in turn calls for the respective models. It is obvious, that they should be generated or at least personalized by the generator in charge of the layout. In this way, design and simulation are tightly bound together.

The merit of our work is to consequently apply this methodology to a volume production industrial application and to illustrate and solve the problems coming along in doing so. Especially, the question of including continuous mechanics into a circuit simulation is investigated. All this is applied to a demonstrator, i.e. a surface-micro-machined capacitive pressure sensor, see [7].

2. Demonstrator: Pressure Sensor

In our approach, we explore the design methodology for MEMS which cannot be described through the mass-spring-damper paradigm, i.e. non-suspended systems. A good example for this is the surface micromachined capacitive pressure sensor with integrated readout electronics [7], see Fig. 1 and 2.

[1] Work was carried out in close cooperation with Dolphin Integration GmbH, Duisburg.

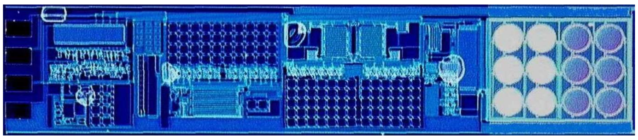

Fig. 1: Chipfoto of a system-on-chip pressure sensor.

Its basic principle is, that some external pressure deflects the upper plate of the sensor element, which in turn leads to a change in its capacitance detected by the readout circuitry. The system behavior basically depends on the shape of the deflected upper plate, since it determines the pressure element's capacitance. Thus, the deflection has to be taken into account in a continuous way.

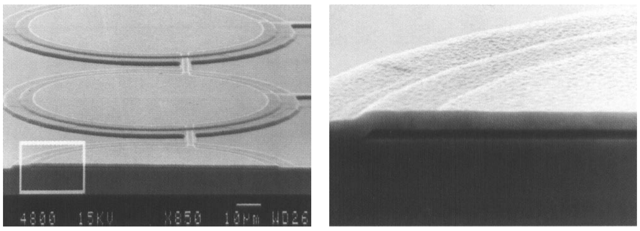

Fig. 2: SEM-pictures of the pressure elements.

The readout is accomplished through two consecutive stages adopting the switched capacitor technique. The first stage compares the capacitance of sensor elements with that of passivated reference elements. The second stage performs the amplification of the output signal. The output signal's shape is conditioned through some sample & hold stage. The chip comprises about 300 analog devices. The 6 pressure and 6 reference elements are connected in parallel, which allows us to use just one mechanics model instance for sensor and reference whose capacitance is multiplied by respectively.

3. Layout Generation and Model Derivation

The layout generator in our case is restricted to the mechanical part of the system, i.e. the pressure elements. It is based on GDS-Compiler[2], which provides the environment to develop all kinds of layout generators, e.g. RAM- or ROM-generators, in the ADA programming language. The generator's inputs and outputs are:

- inputs:
  layout design rules, technology parameters, e.g. modulus of elasticity, design parameters, e.g. diameter of pressure elements or array size and shape.
- outputs:
  layout of the requested array of pressure elements in GDS II format, electrical instance of the pressure element array used to personalize the analytical circuit simulator model described later.

[2] Dolphin Integration S.A., Grenoble, France.

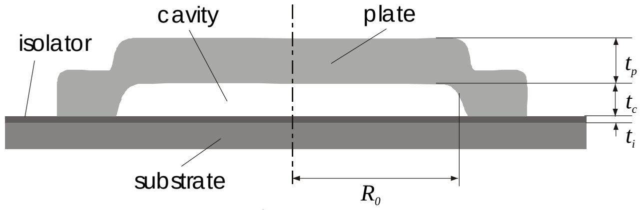

Fig. 4: Basic structure of pressure element.

Fig. 3 shows some real-life arrays of pressure elements produced by the generator. The generation process just takes some seconds. As in other cases, it is necessary to check the results in order to guarantee the quality of *any* generated micromechanical component. Currently, this is accomplished by design rule check and will be extendend through layout extraction and comparison with some generated reference circuit in future.

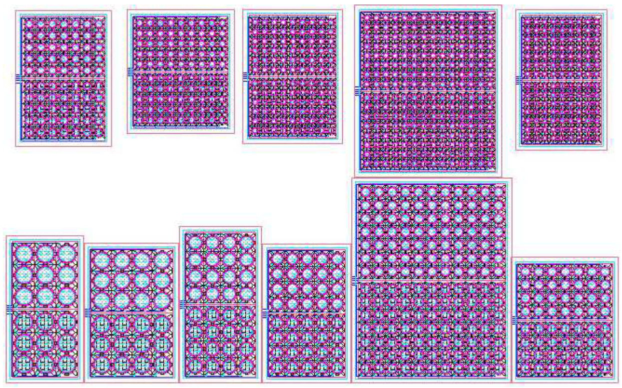

Fig. 3: Several real-life arrays of pressure elements.

The analytical modeling of the pressure element, see Fig. 4, is to be performed on the basis of the following bending equation, see [8]:

(1) $$\Delta\Delta w = \frac{1}{D}(p + p_{el})$$

with the Laplace operator Δ, the deflection w, the external pressure p, some additional 'pressure' p_{el}, which is due to the electrostatic force of the readout voltage and D, the flexural rigidity of the plate:

(2) $$D = \frac{E}{1-\nu^2}\frac{t_p^3}{12}$$

with modulus of elasticity E, Poisson's number ν and the thickness of the plate t_p. The electrical pressure is derived through the following equation:

(3) $$p_{el}(r) = \frac{1}{2}\varepsilon_0\varepsilon_{r,eff}(r)\left(\frac{V}{t_c + t_i - w(r)}\right)^2$$

with the dielectric constants ε_0 and $\varepsilon_{r,eff}$, the radius r, and the readout voltage V. Since this equation itself contains w, it leads to serious problems, if we apply the four integrations to receive some expression for the deflection w. Thus we approximate p_{el} in a polynomial way. This is accomplished through an intermediate Chebyshev approximation to achieve a first smoothening.

$$p_{el}(r) \approx \sum_{i=0}^{n} A_i r^i \tag{4}$$

The general solution of equation (1) then calculates to:

$$\begin{aligned} w = \; & \frac{1}{64}\frac{p}{D}r^4 + \frac{1}{4}C_1 r^2\left(\ln\frac{r}{R_0} - 1\right) + \\ & \frac{1}{4}C_2 r^2 + C_3 \ln\frac{r}{R_0} + C_4 + \\ & \sum_{i=0}^{n}\frac{A_i}{(i+2)^2(i+4)^2} r^{i+4} \end{aligned} \tag{5}$$

with the pressure element radius R_0 and the four constants C_1 to C_4 induced by the four integrations. Finally, we have to solve for C_1 to C_4 which is accomplished by means of the boundary conditions. Two cases have to be taken into account for this: the plate before touching the isolator and the plate after touching the isolator. Another effect to be taken into account by some correction term is due to the elasticity of the plate's suspension.
The model described above was formulated in the analog hardware description language ABCD[3] which serves the circuit simulator SMASH[2]. The model is by no means restricted to ABCD and could be written in almost any analog hardware description language.

4. Results

In the following, several simulations will be carried out to demonstrate the benefit of the analytic model described above. First of all, we want to find out whether the derived model is mechanically valid. To do so, we obtained several bending lines for three different types of pressure elements (50, 70 and 120µm in diameter). For these, the respective pressure range was covered by applying three pressure values. Figures 5-7 compare the results to values obtained by the finite element simulator ANSYS[4]. The maximum difference is below 1% indicating that the analytical results are at least as good as those accomplished by a fully-fledged finite element simulator.

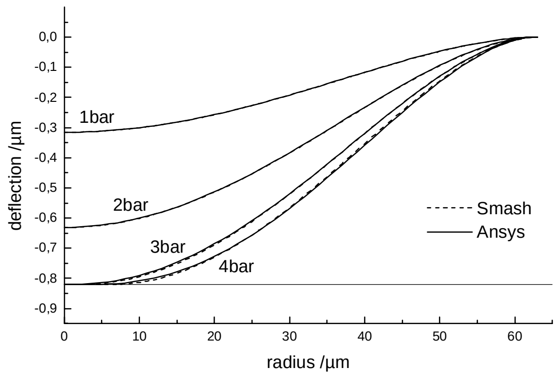

Fig. 5: Bending lines for 120 µm diameter pressure elements under several pressure conditions.

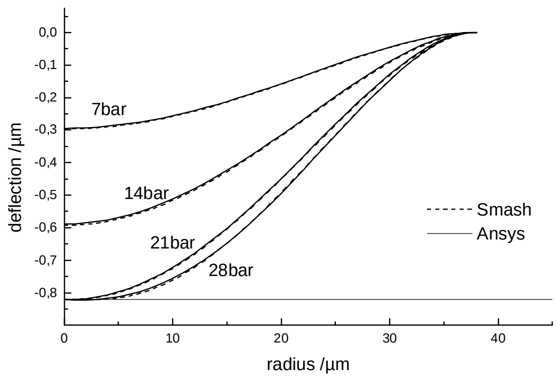

Fig. 6: Bending lines for 70 µm diameter pressure elements under several pressure conditions.

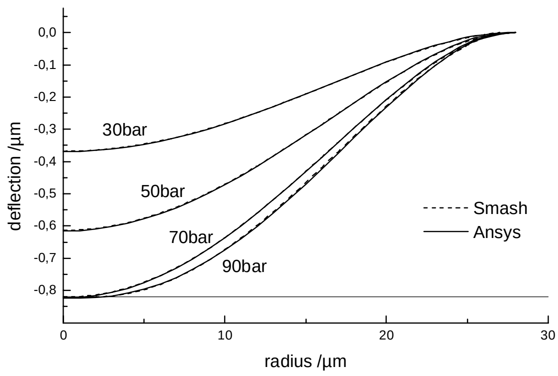

Fig. 7: Bending lines for 50 µm diameter pressure elements under several pressure conditions.

Finally, we want to show that the described analytical model is even suitable for the simulation of a complete system on a chip, see Fig. 1. For this, a transient simulation was carried out which featured a linear rise of the pressure. The resulting output voltage could thus easily be drawn versus pressure. It can be compared to measurements which were available at certain pressure conditions. Fig. 8 shows a good correspondence between simulation and measurement. Note that the rough shape

[3] Dolphin Integration S.A., Grenoble, France.
[4] Ansys Inc., Houston, PA, USA.

of the simulation results is due to the switched capacitor readout circuit. Besides overall function, sensitivity, linearity etc., the simulation also allows to predict that the limited output swing will apply at about 1.7 bar. For our application, the measurement of blood pressure, this does not seriously impair the function, since the expected values range up to 1.5 bar. The complete simulation takes about 98 CPU minutes on a SUN Ultra 2. Note that a simulation with fixed capacitors in place of the pressure element models is just about 5% faster, so the runtime is mostly due to the electronics.

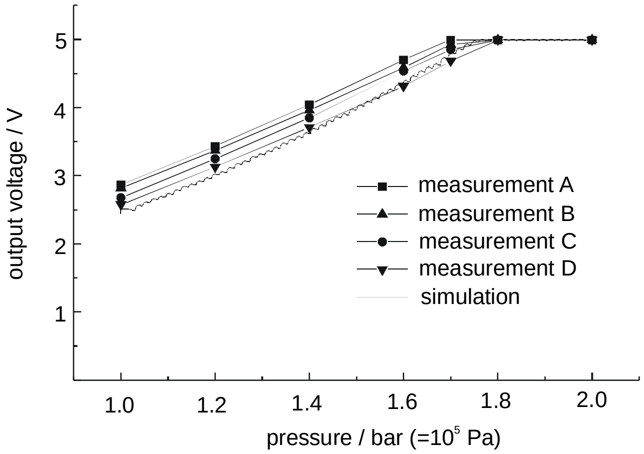

Fig. 8: Simulation versus measurement for a pressure sensor system on a chip.

5. Conclusion

One of the major concerns in CAE for microelectronics as well as for MEMS is to increase the abstraction of system design as much as possible. For the step from layout to analog circuit level, two things are indispensable for micromechanics: automatic layout generation and an opportunity to feed the resulting mechanical behavior into a circuit simulation. This work offers both which forms the basis of a design kit for micromechanical pressure sensors.

6. Literature

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