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Design and numerical analysis of an electro-mechanical microsystem for material parameter extraction

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Abstract

The increasing complexity of microsystem designs requires the simulation at system level. We demonstrate that a pragmatic and efficient approach consists in the appropriate extension of standard electric circuit simulation, using compact models written in HDL-A for the nonelectrical parts of the microsystem. To this end we developed a microsystem that exhibits a strong electro-mechanical coupling. Based on the results of numerical simulations we propose it as a test-structure for the easy to perform electrical measurement of mechanical material properties.

1 Motivation

With growing complexity of microstructures and microsystems, computer-assisted design and computer simulations of the operation of the constituent components as well as the numerical analysis of the full system behavior prove to be increasingly helpful for achieving a systematically optimized and yet cost-effective and time-saving prototype development. Typical features of such microsystems are strong couplings between different physical energy or signal domains as they originate from the constituent sensor and actuator elements, and the hybrid linking or monolithic integration of the transducer elements with the electronic circuitry required for power supply, signal conditioning and system control. Hence, the optimization of the full system is a complicated problem where, in all phases of design and development, numerical modeling is perceived as superior alternative to the traditional experimental way [1].

A major problem in simulation is the calibration of the underlying physical device models. For predictive microsystem simulation, we have to adjust much more physical parameters than for the simulation of microelectronic devices and circuits alone, including in particular material properties such as the electro–thermo–mechanical coupling coefficients. Advanced parameter extraction methods employing special dedicated material characterization microstructures allow the determination of the required, typically process–dependent material data [2].

In this work we present the design and numerical analysis of an electromechanical microsystem comprising an electrostatically excited resonant micromembrane, which acts as electromechanical oscillator element in an appropriately designed electronic circuit. By design, this microdevice exhibits strong coupling between the mechanical and the electrical energy domain, which allows to extract the mechanical eigenfrequencies of the membrane by analyzing the electrical output signal of the circuit. We suggest this microsystem as teststructure for the easy and accurate determination of elastomechanical coefficients of thin freestanding layered structures.

In the following section, we briefly sketch the methodology which we pursue for microsystem modeling in the case of strong coupling between different physical domains. In the subsequent sections we describe the layout of the electromechanical microsystem proposed, introduce the simulation models and demonstrate the necessity of analog network simulation for the analysis and optimization of the full system operation.

2 Modeling concepts and approaches

Our simulation approach for microsystems satisfies three basic requirements: First, it enables the detailed analysis of each individual system component, in particular the involved transducer elements. Second, it allows the analysis of system blocks comprising an arbitrary subset of system components, up to the simulation of the entire microsystem. Third, it is consistent and compatible with the commonly used CAD–environments available from integrated circuit (IC) design.

Furthermore, we follow a hierarchical approach comprising three subsequent levels of abstraction, which are immediately reflected in the type of space and time discretization of the original problem which, in reality, is continuous.

First level of abstraction: The discretization is quasi–continuous in time, space and physical variables. This is the level of physical models based on partial differential equations, which allows an accurate and detailed analysis of small parts of a system. A typical example is Finite Element Modeling.

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Second level of abstraction: The discretization is quasi-continuous in time and physical variables, but discrete in space. In this approach, the system is partitioned into blocks (devices), which are modeled by a uniform "generic" mathematical description in terms of conjugate thermodynamic state variables [3], which are the driving forces ("affinities", "across quantities") and the pertinent currents ("fluxes", "through quantities") such as, e.g., pressure gradient and mass flow or voltage drop and electrical current. The internal behavior of each of the individual system components is described by a specific "tailored" version of the generic model. The full microsystem is assembled by linking the individual submodels of the constituent parts through flux-conserving interface conditions for the respective pairs of conjugate state variables in adjacent components. The resulting "Kirchhoffian network" model is described in terms of differential-algebraic equations derived from generalized mesh rules and node rules for each pair of conjugate state variables and, thus, constitutes a natural approach for analog system simulation, because the coupling between the different energy domains is governed by basic conservation laws for energy, particle numbers, mass, charge, etc. A well-known example is analog SPICE simulation in the electrical domain.

Third level of abstraction: The discretization is discrete in time, space and physical variables, leading to the concept of digital system simulation. The formal system description is managed by the use of a hardware description language (HDL) such as, e.g., VHDL-models.

On the level of physical modeling, numerous software tools are available which are dedicated to one specific physical domain (thermal, electrical, mechanical, etc.). Also several coupled effects between different domains have been implemented (e.g., thermomechanical or electrothermal analysis), but the usual situation is to simulate coupled physical effects by simulator-simulator coupling. The obvious disadvantages of this approach are the high numerical effort and lack of convergence, especially in the case of strong coupling between the subsystems. Generally this approach is limited to relatively small parts of a system, typically to a single device (e.g. a microvalve [4]).

On the level of analog network simulation and digital system simulation, compact models for each individual system element need to be developed, starting from a detailed analysis on the basis of physical modeling. Following the ideas of "tailored" modeling [5] yields a consistent description of the system by a Generalized Kirchhoffian Network. VHDL-AMS is a generic software representation for the implementation of this modeling concept. It provides the coupling between analog and digital system simulation, as well as the required integration into the CAD-environment used for IC-design.

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3 Description of the microstructure

The structure we present in this work is an electro-mechanical oscillator, realized as a flip-flop with the capacitors Cmemb1 and Cmemb2 in the feedback loops (Fig. 1). The resistances of the transistors Mr11 to Mr22 can be varied over a very wide range by adjusting the control voltages Vpctrl and Vnctrl, thus allowing for a flexible control of the charge/uncharge time constant of the capacitors. The resulting oscillation frequency of the flip-flop ranges from several kHz up to some 10MHz.

The above-mentioned capacitors are surface-micromachined polysilicon membranes with an area of $50\mu m$ x $150\mu m$, separated from the silicon substrate by a $0.5\mu m$ wide air gap. Together with the n^+-doped substrate as counterelectrode they form the two feedback capacitors of the flip-flop circuit. The membrane structure is capable of mechanical oscillations, excited by the electrical voltage applied across the capacitor. The capacitance varies due to the change in the distance between membrane and counterelectrode and, therefore, is responsible for the strong feedback between the mechanical and the electrical part of the system.

Typical applications of such micromembranes is the use in differential pressure sensors, microphones etc. They are fabricated in a standard CMOS process line which is equipped with additional facilities for surface micromachining [6].

4 Simulation models

The most appropriate simulation approach applicable to the given flip-flop microstructure is analog network simulation. To this end, a compact model of the membrane capacitor had to be developed. Performing a FEM analysis of the mechanical membrane properties, we obtained the oscillation modes and the associated eigenfrequencies (Fig. 2, 3). Since the higher modes showed a sufficiently large spacing from the ground mode, we could assume that, with properly chosen driving frequency of the electrostatic actuation, only the fundamental mode would be excited. Hence, we decided to neglect the higher modes in the compact model.

Consequently, the membrane could be represented as a simple damped oscillator. The electrostatic attraction between membrane and counterelectrode as caused by the applied voltage acts on the oscillator as an external force.

The coupling between the electrical and mechanical domains appears in two ways: First, the attracting force depends on the distance d between membrane and counterelectrode and on the applied voltage. Second, the electric capacitance of the membrane capacitor also depends on d, thus affecting the electric circuit behavior.

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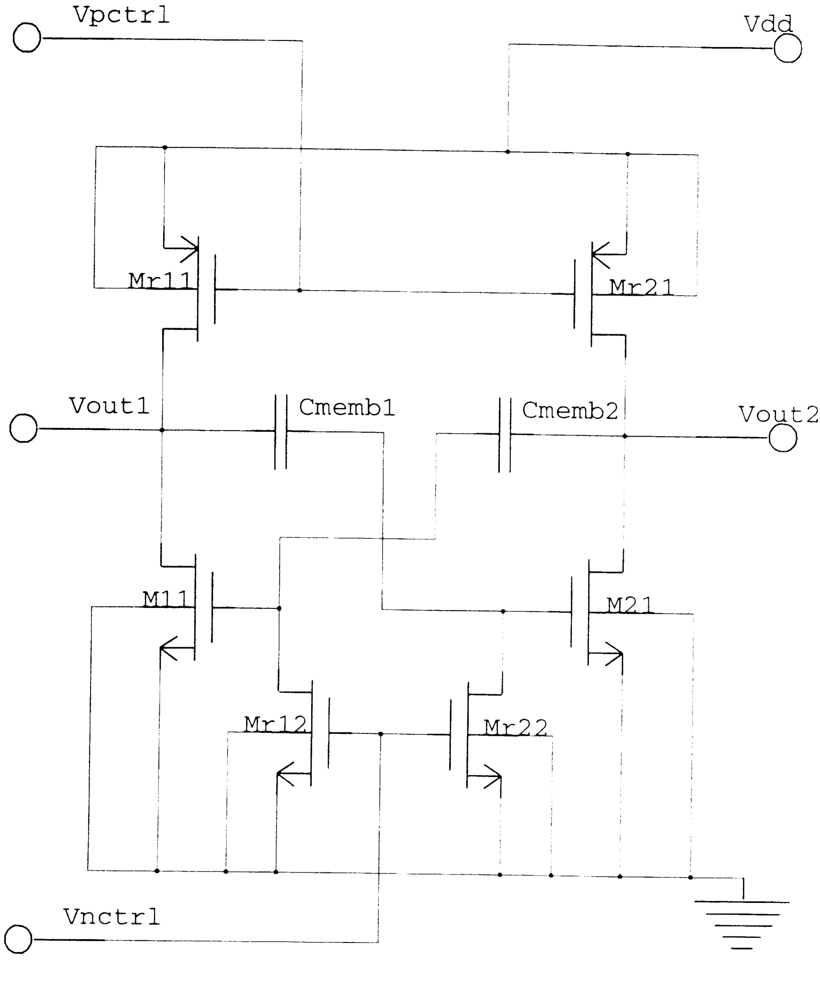

Figure 1: Schematic view of the flip–flop oscillator. Cmemb1 and Cmemb2 are membrane capacitors, allowing for mechanical oscillations.

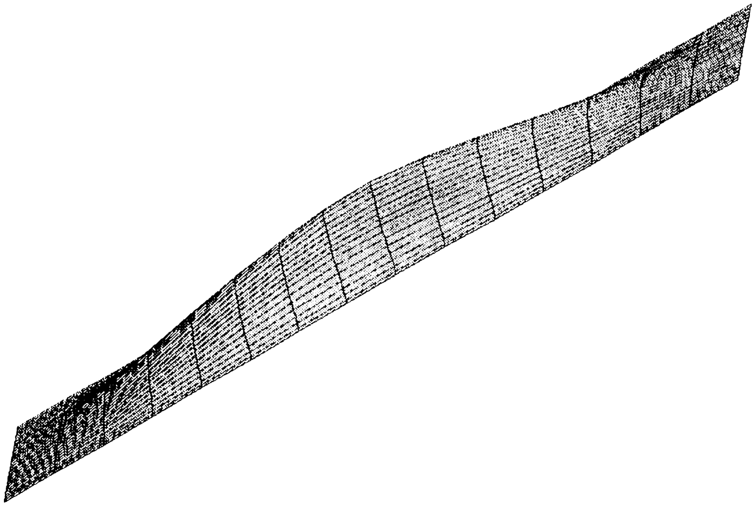

Figure 2: First eigenmode of the rectangular polysilicon membrane. The eigenfrequency is 2.1 MHz

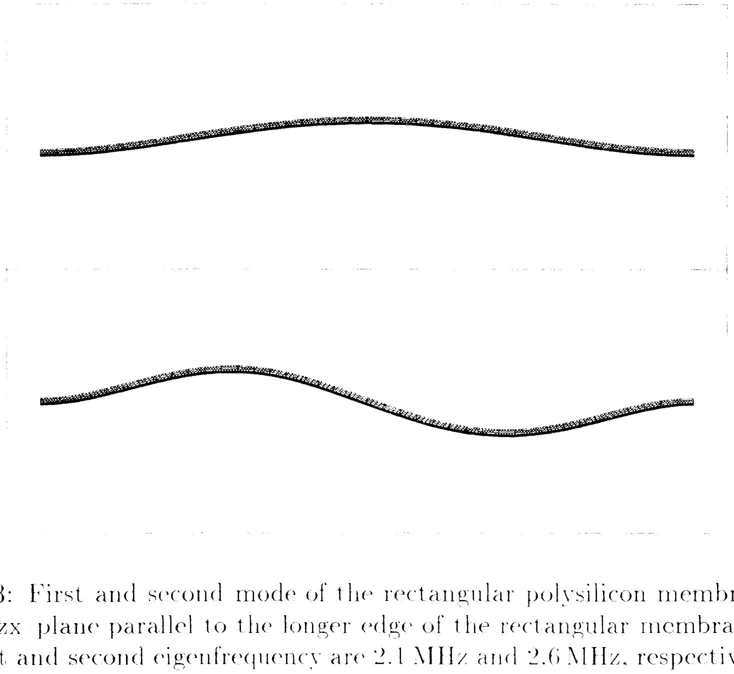

Figure 3: First and second mode of the rectangular polysilicon membrane (cut in zx plane parallel to the longer edge of the rectangular membrane). The first and second eigenfrequency are 2.1 MHz and 2.6 MHz, respectively.

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The resulting model was implemented in HDL–A [7] and SpectreHDL [8].

5 Simulation Results

The numerical analysis of the transient behavior of the flip–flop structure (Fig. 1) was performed using analog network simulators.

The control voltages Vnctrl and Vpctrl are adjusted such that the flip–flop oscillates near the mechanical resonance frequency of the membrane. During one cycle of operation, the membranes experience a voltage change ranging from near 0V to approximately Vdd. The attracting force due to the applied oscillating voltage bends them down, forcing the membrane to follow the voltage oscillation. If the flip–flop oscillation frequency matches the mechanical resonance frequency of the membrane, the amplitude of the membrane oscillation is significantly enhanced. The membrane capacitance also oscillates with time, causing a modulation of the flip–flop oscillation frequency which, in return, leads to a modulated membrane excitation (Fig. 4, 5). This effect becomes especially pronounced, if the flip–flop oscillates at the mechanical resonance frequency of the membrane. Thus, by analyzing the output signal of the flip–flop, it is possible to extract the resonance frequency of the membranes and, therefrom, their mechanical properties.

6 Conclusion

We designed and investigated a flip–flop circuit with two integrated micromembranes as a dedicated microstructure for mechanical parameter extraction, which exhibits strong coupling between the mechanical and electrical domains. We demonstrated that compact modeling is a powerful approach to the simulation of microsystems, in particular in the case of such a strong coupling. We do not see any other simulation approach, which would allow for a complete analysis of the transient system behavior.

Modeling the behavior of the above microsystem, we observed that the strong electromechanical coupling leads to the peculiar effect of modulated oscillations in the output signal, which allows us to determine the mechanical resonance behavior of the membrane by a purely electrical measurement. Therefore we propose this microsystem as a teststructure for a microelectromechanical testchip, allowing to extract mechanical properties of thin layers.

A test preparation to verify the simulation results is in progress.

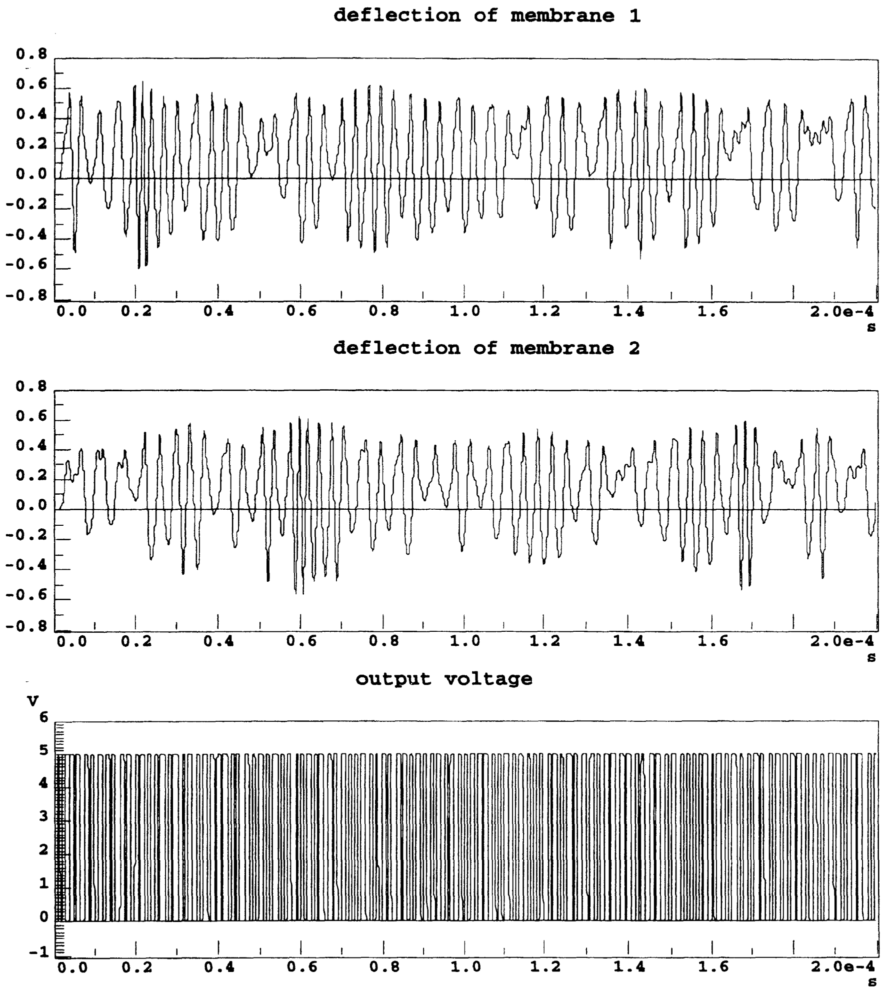

Figure 4: Transient behavior of the flip–flop oscillator. The input voltages Vnctrl and Vpctrl are tuned in such a way, that the flip–flop oscillation frequency is very close to the mechanical resonance frequency. The membrane deflection is given relative to the distance to the counterelectrode.

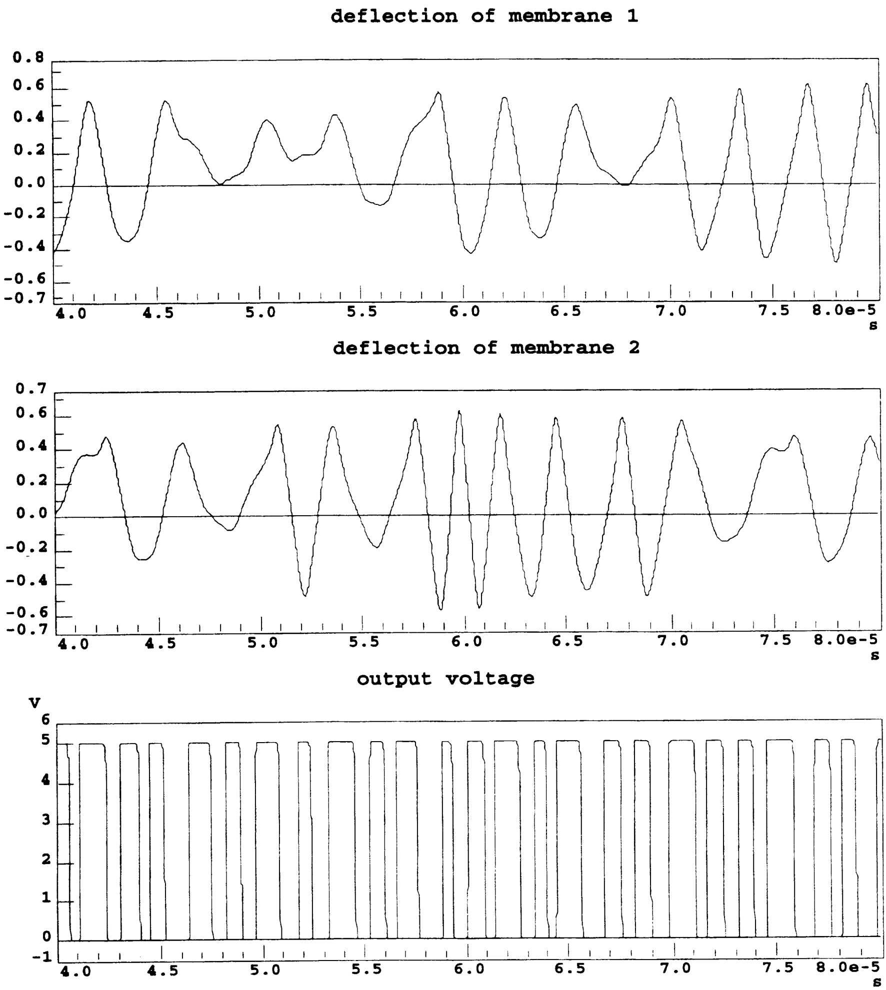

Figure 5: Transient behavior of the flip–flop oscillator, detailed view. Obvious is the modulation of the flip–flop oscillation frequency due to the mechanical membrane oscillations. The membrane deflection is given relative to the distance to the counterelectrode.

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