Coupled Electro-Mechanical Simulation of Integrated Micro-Electro-Mechanical Systems

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ABSTRACT

Micro-electro-mechanical systems equipped with active devices (iMEMS) are commonly employed in sensor applications. In this paper, simulation of the mechanical and electrical properties of a deformable structure containing an integrated MOS sensor is described.

Keywords: Accelerometer, iMEMS, TCAD, Self-consistent electromechanical device simulation

INTRODUCTION

The interaction between electrical and mechanical systems can be of great impact on the operation of integrated micro-electro-mechanical systems. When developing the design of an iMEMS sensor, methods for realistic simulation of such couplings are of prime importance. Here, such a coupled simulation of a novel accelerometer device is presented.

The coupling of the mechanical and the electronic systems is two-fold: The mechanical deformation caused by acceleration changes electrical properties of the sensor device and thus the detected signal. Furthermore, the electrical properties of the device give rise to induced electrical forces acting on the interface between the two systems.

Due to the wide range of physical effects involved, the complete simulation of such a structure is well beyond the capabilities of a single simulation tool. Therefore, a mixed approach involving several specialized simulators was chosen. A thermo-electro-mechanical simulator (SOLIDIS-$_{ISE}$) was used for simulation of the electro-mechanical effects, i. e., the deformation of the device caused by acceleration and electrostatic force. A semiconductor device simulator (DESSIS-$_{ISE}$) simulates the electrical part, i. e., the transport of charge carriers in the non-uniformly doped semiconductor. An iterative solution process leads to a self-consistent solution of the interdependent mechanical and electrical systems. As the coupling between the two simulators is bi-directional, various effects can be taken into account, such as the impact of mechanical stress on the electrical conductivity of the semiconductor, or the influence of current-generated heat and electrical fields on mechanical stress and displacements.

A challenge is the consistent creation of the structure and the mesh generation for the different simulators, taking the changing geometry into account. The structure generation is performed from the mask layout and the process description using 3D solid modeling. This allows the generation of both the initial macro-element mesh used for the subsequent electro-mechanical simulation (on a more general, adaptively refined oct-tree-type finite element mesh) and the mixed element finite element mesh needed for the semiconductor device simulation. Doping profiles in the electrically active transistor region can be given analytically or, as an alternative, from accurate physical process simulation in one or two dimensions.

The simulation takes place in a TCAD (Technology Computer Aided Design) simulation environment, which provides integration of the various tools that are involved in the simulation, i. e. process simulators and emulators, device simulators and back-end tools for extraction and visualization, as well as the possibility of optimization of all aspects of the device by DOE (Design of Experiment) techniques with response surface fitting.

STRUCTURE GENERATION

A key issue in coupled iMEMS simulation is the generation of a realistic device structure. Here, the process emulator PROSIT-$_{ISE}$ was used to generate a boundary representation of the iMEMS device. Using information about the manufacturing process, a symbolic sequence of processing steps such as deposition, etching and polishing methods acting on a multi-layer mask layout can be emulated. An important aspect of efficient process emulation is the application of adaptive resolution algorithms to accurately describe regions crucial to device operation while simultaneously ensuring high emulation speed in non-critical regions.

DEVICE SIMULATION

The electrophysical properties characterizing the actual state of the sensor device can be summarized in a relation between the controlling signal (gate voltage V_g) and the resulting response (drain current I_d) at otherwise fixed conditions. Extraction of such sets of characteristic curves in function of a multitude of parameters is a fundamental task in performance-driven engineering. Thus, coupling of various simulation tools is required to span the complete range of effects to be considered.

The aim of the integrated TCAD simulation presented here is to extract the electrical characteristics of an accelerometer with an integral sensor under different operating conditions of the device. Among the quantities determining the electrical response of the sensor itself are however also the actual geometrical properties of the device, the processing parameters of the semiconductive regions (doping profile, channel region geometry) as well as the acceleration imposed upon the device. A device simulation must therefore be linked to all these parameters, i. e. a well integrated TCAD environment is required.

A crucial issue in the simulation of device physics is the access to accurate doping profiles, as these largely determine the quality of the solution of the charge carrier transport equations. Clearly, the meshing of the channel region is another important task in this context. In many cases though, simulation of the device operation can be carried out in two dimensions, thereby saving substantial amounts of time which can be better spent on optimizing the device design itself.

ELECTROMECHANICAL SIMULATION

Primary coupling

The primary coupling between the mechanical and the electrical systems is by means of the mechanical displacement of the gate material as induced by gravitational forces. Moving the gate relative to the substrate through acceleration while maintaining a constant drain potential will induce changes in the flux of charge carriers through the channel region, thus generating an electrical signal in response to the acceleration of the device. SOLIDIS-$_{ISE}$ uses adaptive mesh refinement algorithms for achieving high accuracy in the mechanical simulation with a minimal number of finite elements, thereby saving on memory and simulation time requirements [1].

The system of equations describing the deformation of the structure in response to external forces is

$$\frac{\partial \sigma_{ij}}{\partial x_j} + F_i = 0 \tag{1}$$

where σ is the stress tensor. F symbolizes the external forces applied to the system.

A further unidirectional electromechanical coupling may be introduced by including the effects of mechanical and thermomechanically induced stresses in the crystal lattice into the device simulation. In this way, bandgap size and charge carrier mobility correction factors can be applied according to the local stress distribution value. Also, the effect of stresses arising from operating conditions and/or influences from the sensor environment on the sensor signal may be taken into account already at the device design stage. In such cases, the thermo-electro-mechanical simulator SOLIDIS-$_{ISE}$ can be used to compute the effective stress distribution, whose components are included in the DESSIS-$_{ISE}$ device simulation. Such couplings are routineously carried out in state-of-the-art device simulation [2].

Electrostatic correction terms

From the initial device simulation, the electrical field strength distribution is known. It's normal component is related to the charge induced on the equipotential surface of the gate material. In this way, electrostatic forces acting on the movable parts of the accelerometer can be taken into consideration during the mechanical simulation by coupling the additional electrostatic interactions back into the set of mechanical equations. Technically, the electromechanical simulation is coupled to the device simulation through the electric charges induced on the surface of the gate region.

Here, the additional forces coupled to the system (1) of mechanical equations are of the form

$$F_i = \int \left(E_i D_k - \frac{1}{2}\delta_{ik} E_i D_i \right) \bar{n}_k \, ds \tag{2}$$

Starting from an initial simulation of the mechanical displacements, a device simulation of the accelerated structure is carried out. From the electrical field distribution, additional electrostatic boundary conditions of the deformed region are extracted and coupled back into the mechanical simulation. This sequence of device and electromechanical simulations is iterated until the norm of the mechanical displacements converges. In this way, a self-consistent solution of the different physical models describing the iMEMS device is obtained.

DESIGN OPTIMIZATION OF iMEMS DEVICES

By self-consistent coupling of the semiconductor- and the electromechanical models, a novel tool for device design is created. Such a tool can be used to tailor the response signal of the iMEMS device with respect to chosen parameters. In the application discussed below, one could imagine introducing parameters for values crucial to the operation of device, such as gate material thickness, operating voltages and processing parameters. Using mathematical methods, a variation in parameter space can give information on the shape of the response function of the device, thus allowing for automatic optimization of device design [3]. Such capabilities of a TCAD environment may allow for further reduction of the design cycle time.

APPLICATION EXAMPLE

As an example of the type of coupled simulation described previsously, an accelerometer iMEMS device was investigated. Here, the various simulation steps are reviewed before describing the simulation results.

In figure 1, the mask layout and the corresponding structure resulting from three-dimensional process emulation is shown.

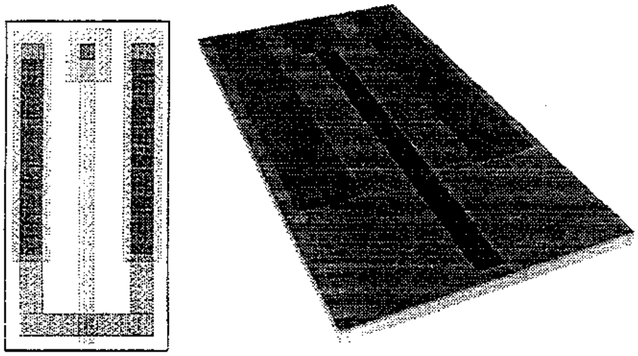

Figure 1: Mask layout (left) and boundary representation of an integrated micro-electro-mechanical system consisting of a deformable structure with directly changing MOS transistor properties created by process emulation (right)

The resulting boundary representation is meshed and the finite element mesh for the electromechanical simulation (SOLIDIS-$_{ISE}$) is further reduced to the smallest number of elements by a line elimination algorithm. A cut through the active region of the device is differently meshed for solution of the equations of charge carrier transport (DESSIS-$_{ISE}$). In figure 2, the result of such a two-dimensional simulation of the active region of the iMEMS device is shown.

The mechanical displacement of the flexible gate material induced by acceleration of the device is presented in figures 3 and 4. Figure 5 shows a comparison of the extracted characteristic curves describing the electrical properties of the accelerometer with and without the correction terms of the electromechanical simulation. In figure 6, the simulated electrostatic forces acting on the gate material in the vicinity of the active region are shown.

As indicated by the magnitude of the electrostatic forces, the influence of the additional coupling was negligible in this example, and thus iteration over both simulation models quickly converges. A separate analysis showed the mechanical deformation resulting from induced electrostatic forces alone to be below levels of significance to the resulting characteristics of the sensor device. For a different device design, where the electrostatic coupling might be of higher importance, a full threedimensional device simulation could be carried out using the same simulation tools and model couplings.

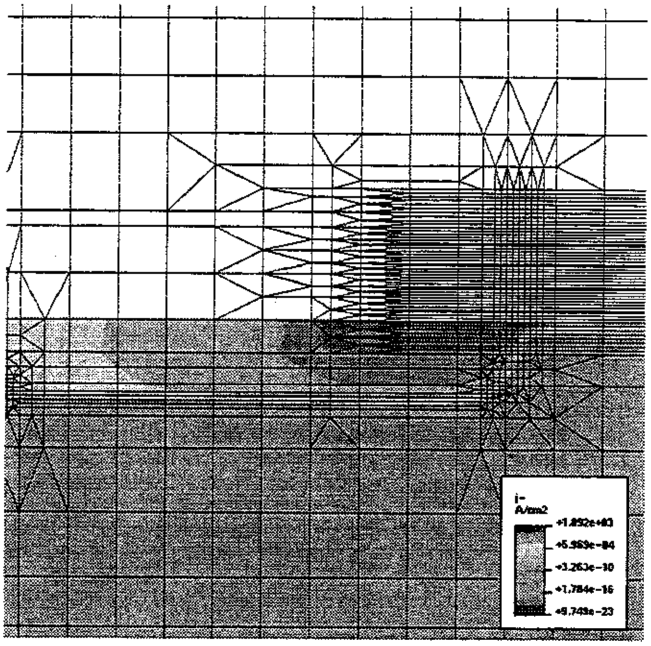

Figure 2: Electron current density as a result of a 2D device simulation with DESSIS-$_{ISE}$ on a cut across the active region of the 3D structure (one half of the transistor shown)

CONCLUSIONS

Coupling of physical models describing different aspects of device behaviour to create new design tools allows for taking coupling effects into consideration already at the device design stage. Such coupling of tools ensures that the particular strengths of each simulation type are preserved while gaining the advantage of combined use. A thorough integration of tools in a TCAD environment thus allows for fast and efficient design cycles using specialiced tools to describe complicated interactions of several physical models.

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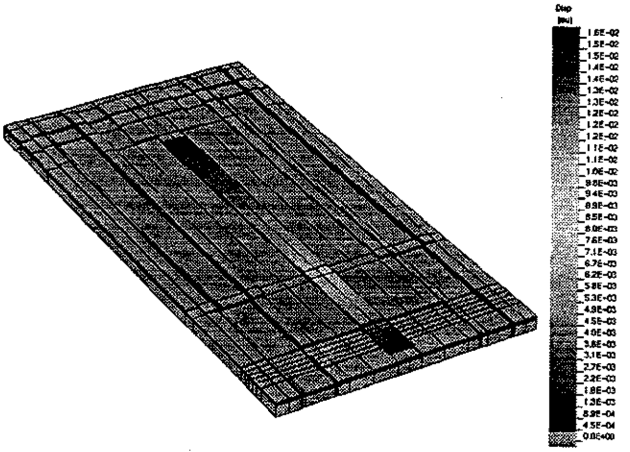

Figure 3: Effect of fixed acceleration on the movable gate of the iMEMS structure. The colour scale indicates the level of mechanical deformation arising from an acceleration of 50 g

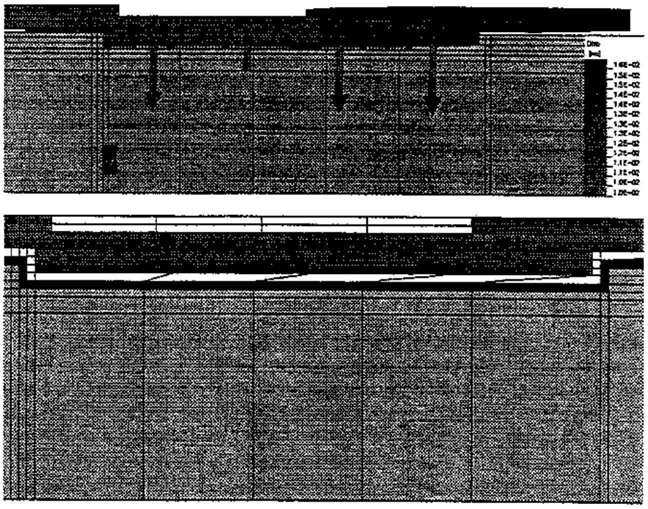

Figure 4: Cut showing the displacement of the gate material due to acceleration (top). Layer structure of the iMEMS device (bottom)

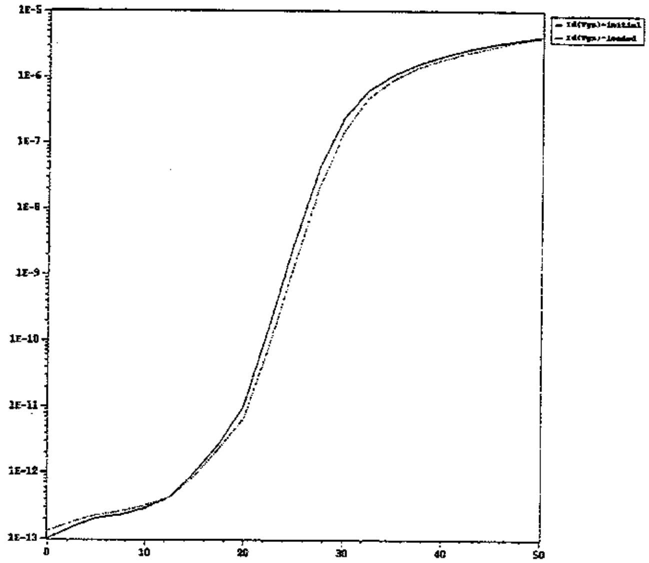

Figure 5: Extracted characteristic $I_d V_g$ curves showing the response of the initially undeformed structure (solid line) and the influence of acceleration and electrostatic correction terms (dashed line)

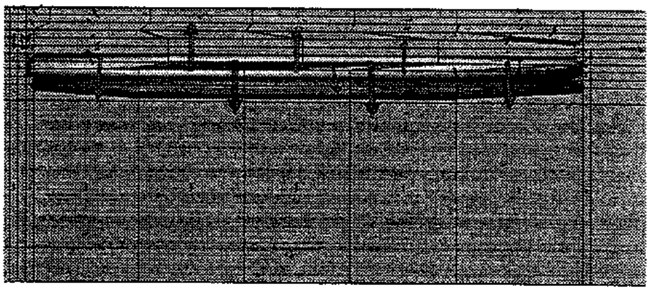

Figure 6: Close-up of the electromechanical coupling of the iMEMS simulation. The electrostatic forces shown are extracted from a device simulation taking the doping profile of the semiconductor material into consideration. These induced forces are coupled back into the mechanical simulation