FELLINI–A CAD-Tool for the Design of Microsystems

M. Lang and M. Glesner

Darmstadt University of Technology, Institute of Microelectronic Systems
Karlstrasse 15, 64283 Darmstadt, Germany, lang@mes.tu-darmstadt.de

ABSTRACT

This paper reports of the CAD-tool FELLINI, which supports the design of microsystems on the lower levels of abstraction. FELLINI provides a bidirectional interface between the structural and the layout level. A Layout-to-FEM converter as well as a FEM-to-Layout converter are integrated into FELLINI. These modules enable a fast and easy realization of user specific designs. FELLINI uses existing CAD tools for microelectronics and mechanics providing interfaces adapted to the needs of MEMS design.

The use of FELLINI is demonstrated with the design of an acceleration sensor, which has been fabricated in a commercial CMOS process. This sensor can be used as parametric standard cell and adapted with FELLINI in order to meet user specific constraints.

Keywords: FEM, Layout, Interface, bidirectional

INTRODUCTION

Today's design of microsystems still suffer from the lack of powerful CAD tools which could lead the designer to a fast and easy development of new devices or systems. This in return prevents MEMS from having the big impact on the technology market as predicted some years ago. One of the reasons for that is, that there exists a strong interaction between several physical effects (e.g. mechanical, thermal, electrical). Therefore, different tools for all relevant domains are necessary, which then need specific interfaces or coupling methods to interact correctly.

In the recent years, special attention has been drawn to design support in the MEMS area on higher levels of abstraction in order to enable and facilitate the design and system simulations [1]–[3]. Other tools which deal with the problem of interfacing the structural and the layout level try to cover various different micromachining processes with a general approach [4], [5]. This imposes the problem of covering all technologies (of which lots more exist than in the microelectronics) with one tool. Additionally, there are several parts integrated in these tools, which already exist as stand-alone solutions for a long time and which promise more powerful design support. A coupling or interfacing of these existing tools therefore seems to be more flexible.

Like in the microelectronic world, CAD support for the design of microsystem components only promises a good solution, if fixed design rules are available and if the process itself is not subject to a permanent change (i.e. that the process is changed after each design). A promising solution therefore is the use of extended CMOS processes as sensor technology [6], [7]. The CMOS technology is the standard technology of today and the microelectronics design flow is widely used. Therefore it seems to be logical to extend existing microelectronic CAD tools and combine them with tools from other domains towards MEMS designer needs. The goal then is to create a design flow comparable to the microelectronic world. This solution may not satisfy all design aspects but makes it easier to adapt it to process changes and it works faster than the global approach.

In the following we present FELLINI (Finite **EL**ement – Layout **IN**terface for Integrated Microsystems), which provides a bidirectional model-generator as interface between structural and layout level and which makes use of existing CAD-tools from both the microelectronic and mechanical worlds.

EXTENDED CMOS-PROCESS

The CAD-tool presented in the following has been conceived for the use in an extended CMOS-process but is not limited to this type of processes. As the benefit is the highest with this processes, the principles are explained in that framework.

Within a CMOS process micromechanical structures can be realized by a front- or back-side anisotropic etch step. The extended CMOS process provided by CMP (Grenoble) uses a time-controlled front-side etch step (EDP) to form suspended structures [8]. These suspended structures consist at least of four layers (silicondioxide and siliconnitride), which are also used in microelectronics itself. The inclusion of functional layers as metal or polysilicon is also possible. Therefore no additional masks for processing micromechanical structures are necessary. As all these layers are very thin in comparison with the lateral dimensions of micromechanical structures, one can speak of a $2\frac{1}{2}$-dimensional structure, as no real third dimension exists. With such a kind of process several sensor types such as thermal sensors, infrared sensors or others can be realized [6].

FEM2CIF/EDIF

The most important way to model micromechanical components on structural level is the use of the Finite-Element method (in our case ANSYS[1]). It can be used for the determination of mechanical as well as thermal or magnetic properties.

For the representation on layout level the CIF-format has been chosen as it is readable and sufficient for the representation of geometries. An EDIF output is also possible for the automatic generation of the layout from a FE-model, but this option will not further be developed, as newer versions of EDIF don't support the layout level anymore.

Automatic layout generation

As mentioned before, there is no real third dimension in extended CMOS-processes with front side etching. Therefore a two-dimensional modeling with an inherent third dimension and a three-dimensional simulation on structural level is sufficient. A layered shell element representing all forming layers can be used for the Finite-Element mesh and the underlying solid model can be formed by areas. The simulation on the other hand is kept three-dimensional.

For the generation of the layout out of a FE-model, the keypoint-, line- and area-lists of the solid model extracted in ANSYS are used. As on structural level a model represents a body and on the layout level the etch masks represent the etch holes around the body where the passivation is opened and the etchant can attack the silicon, an inversion is necessary to receive the corresponding layout. This inversion is realized by deleting all lines shared by two or more solid-model areas and connecting the remaining lines, which all then form the border line, to closed polygons.

Moreover, as mentioned before, the suspended structures consist of four layers, which are not identical but have a certain overlap relative to each other. The principal mask determining the overall dimensions is therefore derived through the inversion process whereas the others are generated by zooming out the first one. The amount of overlap of these new masks depends on the process and can be specified interactively or through a kind of technology-file together with other relevant parameters. Besides the always necessary and executed inversion and zooming action, a rotation during the mask generation can also be forced. This is helpful as the orientation of a model on structural level (horizontal–vertical) often varies from the orientation of the layout (diagonal) because of the preferred etching angles ({100}) on commonly used wafers with {110}-orientation.

As FE-simulations mostly are time consuming and require a large amount of disk space, FE-models are often built as halfs or quarters of the original structure, if this is permitted by symmetry. FELLINI also allows to use this partial models as input and generates the completed layout by single or double mirroring.

The layout obtained in such a way can be stored in CIF or EDIF for further use in a layout editor, e.g. Cadence DFW II[2], in order to add microelectronic components (amplification, signal processing) which directly can be integrated on-chip. Figure 1 shows the general concept of the automatic layout generation out of a mask description [9].

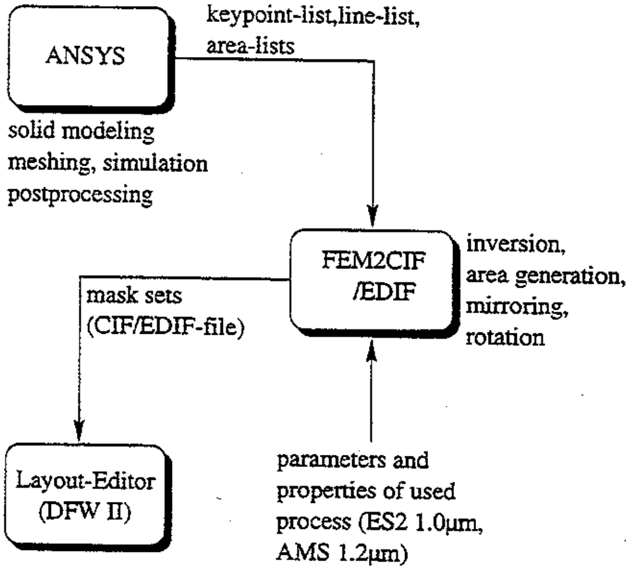

Figure 1: Concept of FEM2CIF/EDIF

Mask adaptation

As devices, which can be fabricated with the described process, also can be complex systems with integrated electronics, an adaptation of an existing micromechanical device within a system could be necessary in order to meet user specific requirements or to enable a reuse for new designs. This adaptation must not change the electronic circuit. Therefore, FELLINI enables a designer to extract a micromechanical part of an existing design, adapt certain geometries and reintegrate the component into the system.

The micromechanical parts in a system design are enclosed by a fictitious layer. Therefore these parts can be

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[1] ANSYS is a registered trademark of Swanson Analysis Systems Inc.

[2] Design Framework II is a trademark of Cadence Design Systems Inc.

identified in a CIF representation for the subsequent extraction and separated from the electronics. There are two ways to adapt the extracted parts: firstly, the layout can be depicted in an integrated viewer, where relevant parts can be marked and new absolute or relative dimensions are possible inputs. These new dimensions are then transferred back into the polygon notation, which replace the old ones the original CIF-file. The second possibility is to do separate optimization loops in ANSYS starting with the original model and to re-enter the new structural model into FELLINI. After an automatic translation into the layout following the same steps as the original design, the corresponding parts in the system layout are replaced in the polygon notation [10]. The second possibility for mask adaptation presume, that the basic solid model has not changed in numbering of the keypoints, lines and areas. Therefore the model must not be re-built (or only if numbering is consistent), but changed by shifting lines or keypoints.

CIF2FEM

The module CIF2FEM within FELLINI realizes the opposite interface direction meaning the automatic generation of a FE-model out of a mask description. For that, the polygons determining the outer border of the etch holes are extracted from the CIF-file and internally stored for further operations. Out of this CIF-representation a batch file in APDL (ANSYS **P**arametric **D**esign **L**anguage) is generated which in return forces the solid modeling and meshing action when read into ANSYS. Again process dependent parameters like layer-declarations or necessary rotations (see above) as well as adjustable element sizes can be specified in order to affect the modeling results. Figure 2 shows the concept of the structural model generator CIF2FEM.

As in the case of the FEM2CIF/EDIF converter, It has to be stressed that the solid modeling and meshing is not done separately in FELLINI but controlled by the generated ANSYS input file.

Two ways of creating the needed mesh in ANSYS are implemented in CIF2FEM, which are described in the following.

Free mesh

For a free mesh there are no limitations regarding the underlying geometry. Therefore, to achieve the again necessary inversion of the model (from layout to FE-model), Boolean Operations supplied by APDL can be used. In a first step, the etch hole polygons obtained from the CIF representation are transferred into the keypoint-line-area-declaration used in ANSYS. Afterwards, these areas are "subtracted" from an additionally created area covering all etch holes. For the resulting area a automatic free mesh is started within ANSYS. The basic element dimension for this mesh can be specified in CIF2FEM. Problems arising from a free mesh are, that the element shapes and aspect ratios are often quite poor and that the mostly occurring three-sided elements show an increased stiffness, which influences the accuracy of the simulation results and the simulation time. Therefore a manual refinement or adaptation of the obtained mesh might be necessary.

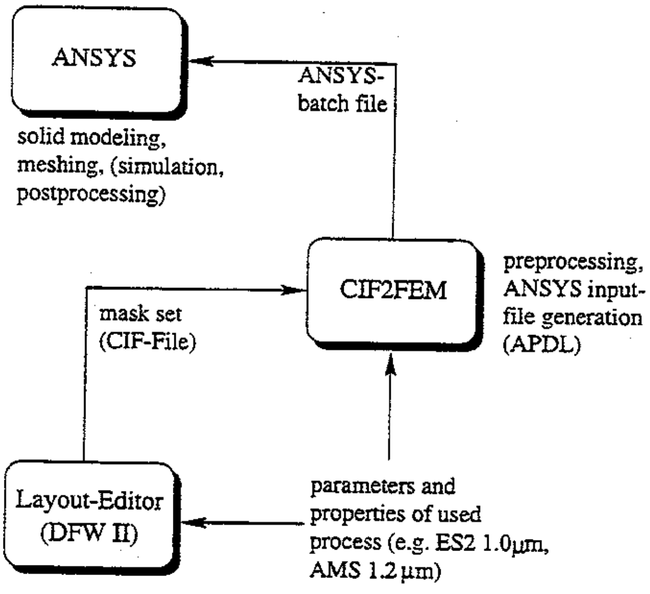

Figure 2: Concept of CIF2FEM

Mapped mesh

For that reason a better solution is to create a mapped mesh with only four-sided elements (same number of elements on opposite sides) which are, in the best case, also rectangular. ANSYS itself is only capable to create such a mesh if the underlying area is four-sided, whereas the boundary of holes inside an area count as additional sides. By adding additional keypoints and lines into the original layout, CIF2FEM creates small subareas which are four-sided (mostly rectangular) and concatenated with each other. These subareas are then practical for a mapped mesh, which then again is forced by the corresponding APDL commands in ANSYS. The element dimensions also can be determined in CIF2FEM. Fig. 3 shows different possibilities for subdividing an area with an etch hole.

For a mapped mesh no Boolean Operation in ANSYS is necessary (which can be very time consuming and sometimes even fails) as the subareas are directly created, while the etch holes are omitted [11]. Up to now only areas which have (convex or concave) right angles can be transferred into a FE-model with a mapped mesh. As these are practically the only angles used in this process, this is no serious limitation (a design, which

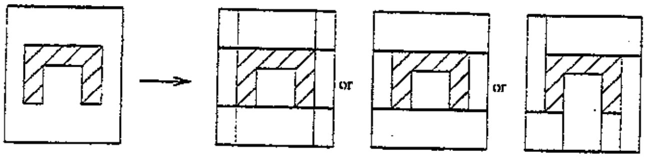

Figure 3: Different possibilities for substructuring

is completely rotated by 45° because of etch angles, but except that only consist of right angles can be transferred into a mapped mesh). However, an extension towards other angles is planned for the next generation. A batch-file for model generation in ANSYS which produces a mapped mesh is noticeably larger than one for a free mesh. But the simulation time and matrices are much smaller and the accuracy of the result much higher, so that this method should be preferred if applicable.
The advantage of the previously presented procedure is, that in contrast to [4], [5] no process simulator is necessary to build the solid model. The knowledge of the process is directly used to derive the information about the third dimension.

FELLINI

The CAD-tool FELLINI has been realized with a GUI in order to provide an easy access in all phases of the design. There is also a previewer integrated to show the layout/FE-model before and after transformation. Independent from the starting point of a design, a switch to the other level of abstraction is always possible. Designers, who normally work as component engineer and who are familiar with FE-modeling and simulation, as well as process engineers, who are more familiar with layout tools are able to work on the design of microsystem components. Moreover, multiple design cycles are possible in order to find an optimal design which meets the requirements best. Apart from saving time due to the automated model transfer, FELLINI decreases error rates and increases the reliability of the design. Figure 4 shows the integration of the two previously presented modules into FELLINI.
Connecting FELLINI with an interface to the behavioral level a CAD-environment is realized which has a structure comparable to the microelectronic design flow [12]. The implementation bases on standard tools of the microelectronic and mechanical world, which are interfaced for a joint use.

The necessary process dependent properties can be obtained from a kind of technology file, e.g. the layer declaration and the masks overlap are stored there. Up to now, a digital 1.0μm (ES2) and an analog 1.2 μm (AMS) CMOS process are included. Other emerging technologies which are also 2½-dimensional like GaAs or different CMOS-processes can directly be included in the design flow. The inclusion of processes, where the third dimension can not be neglected (e.g. LIGA, real bulk-micromachining) is subject to current investigation.

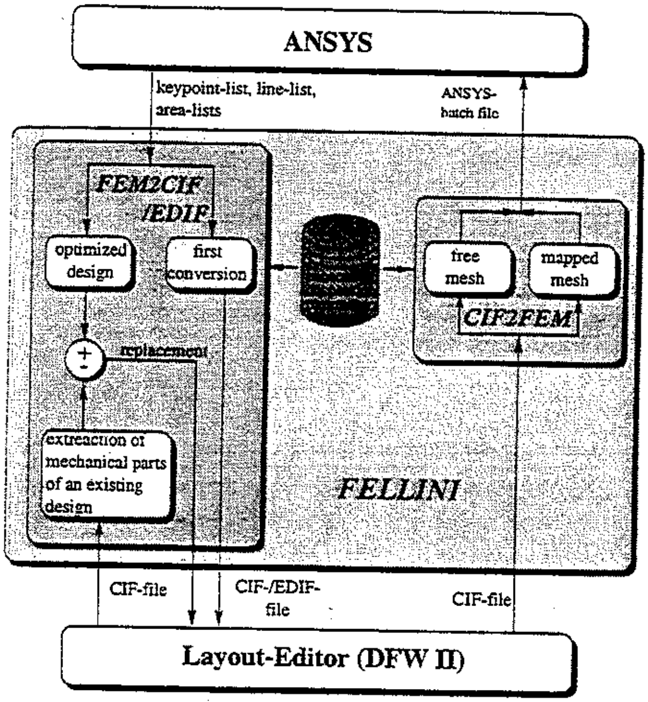

Figure 4: Concept of FELLINI

EXAMPLE

Figure 5 shows the FE-model of a suspended membrane with additional etch holes, which is fixed by two arms. The border of the cavity formed by {111} planes underneath the membrane has been omitted for clarity reasons. This membrane has been designed as acceleration sensor with a resistive signal detection. It has been fabricated with an on-chip operational amplifier in a commercial 1.0μm digital CMOS process with a subsequent anisotropic etch step. In Fig. 6 the layout of the membrane can be seen which has been automatically generated with FELLINI (FEM2CIF/EDIF). The hatched areas show the etch holes where the passivation is opened and the etch process starts. Is has to be stressed, that these regions not only consist of one mask (passivation opening) but of four, which are all necessary to form suspended structures and which have a certain overlap relative to each other.

The FE-model as shown in Fig. 5 has not directly been created by hand. In a first step, a fast and straight forward modeling strategy has been used to form the underlying solid model. As this solid model was far away from being as regular as needed for a mapped mesh, the resulting elements were quite poor. For

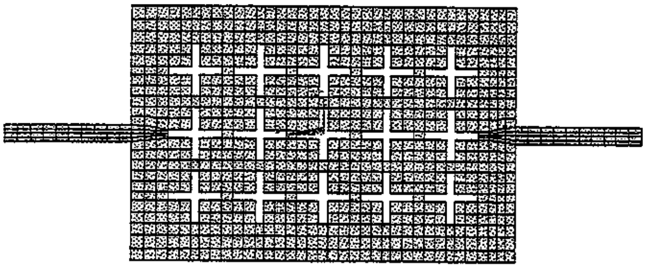

Figure 5: FE-model of a suspended membrane with etch holes

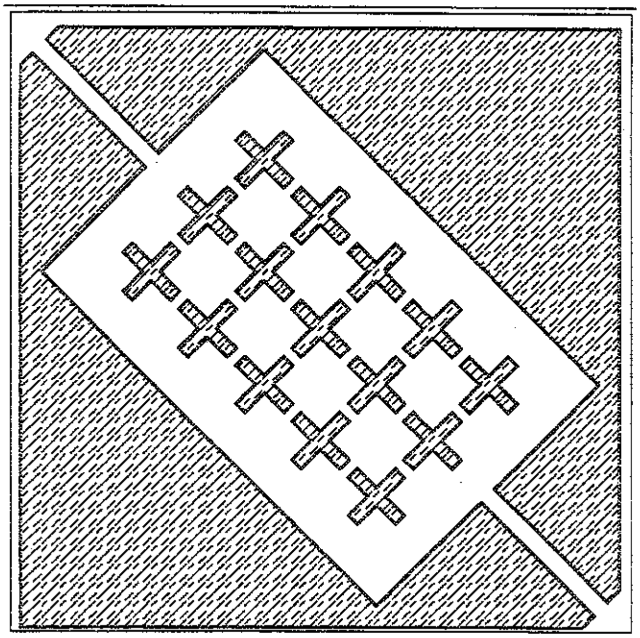

Figure 6: Layout of suspended structure with etch holes

that reason, FELLINI was used for the generation of a sub-structured area with a subsequent mapped mesh (CIF2FEM) directly after the generation of the layout with FEM2CIF/EDIF. It can be seen, that only four-sided elements are used, of which nearly all are rectangular.

The measurements of sensitivity and resonance frequency of the acceleration sensor showed a good agreement with the simulation results. Fig. 7 shows the differential voltage change across a bridge formed by four polysilicon resistors located on the arms of the sensor. The chosen approach to model the sensor with $2\frac{1}{2}$ dimensions seems to be sufficient. The slight difference results from a uncertainty about the piezoresistive coefficient and is below the discretization error of the FE-model.

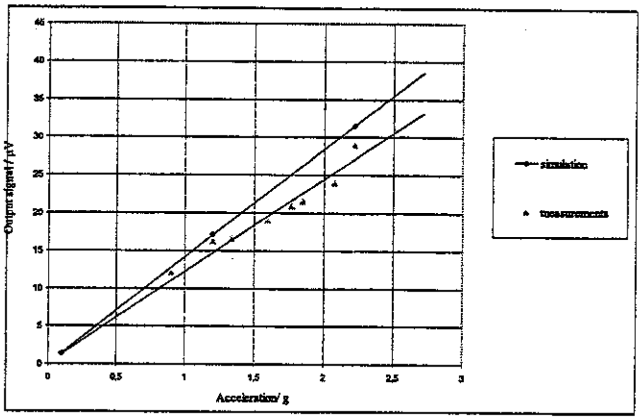

Figure 7: Output signal of the acceleration sensor

This micromachined acceleration sensor can be used as a standard cell in complex designs. To meet constraints regarding sensitivity, resonance frequency or maximal acceleration certain geometric properties as length and width of the suspended arms can be adjusted. It is also possible to adjust the width and length of the membrane, but this makes necessary a re-arrangement of the etch holes. Figure 8 shows the dependency of the sensitivity of the acceleration sensor with respect to the length and width of the arms. This diagram can serve as a guideline for a first decision about the dimensions. If a layout or FE-model of the original design exists, FELLINI can be used for adaptation and model transfer in order to accurately determine the behavior on structural level.

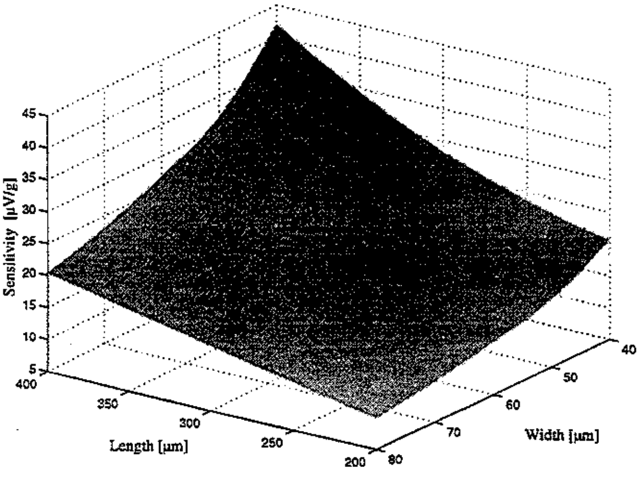

Figure 8: Parametric dependency of the sensitivity of a suspended membrane

CONCLUSION AND OUTLOOK

In this paper we presented FELLINI, a CAD-tool for the design of microsystems. FELLINI provides a bidirectional interface between the structural and the layout level. Design cycles can be realized with FELLINI, as well as designs can be started from either level. This enables the access to microsystem design for engineers mainly dealing with structural questions as well as for process oriented engineers.

Despite the fact that FELLINI has been conceived for extended CMOS-processes, it is not limited to these processes. By dividing a real three dimensional structural model in ANSYS into the relevant forming layers, FEM2CIF/EDIF is already able to transfer models of other processes with a real third dimension into the corresponding layout. The inclusion of a 3D-model generator into CIF2FEM is part of future investigations. As mentioned before, additional work has to be done to make CIF2FEM accessible to arbitrary geometries for mapped mesh.

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