

# Defect-Oriented Experiments in Fault Modelling and Fault Simulation of Microsystem Components\*

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## Abstract

*Based on fault simulation experiments with two microsystems, a resonant silicon beam force sensor and a miniature opto-electric transformer, this paper demonstrates the necessity to consider the interrelations between nominal system models, fault models, the construction of simulation models being capable of injecting faults, and the representation of faults in a fault list of a fault simulator from the very beginning. Some suggestions will be discussed how to tackle these problems occurring in fault modelling and fault simulation of microsystems.*

## 1. Introduction

Due to the expanding applications of microsystems the necessity of their testing will be increased. It is widely accepted that a functional testing approach is only suitable for small-sized microsystems. Since general purpose constructive techniques for generating real-valued test signals are not available fault simulation is the important means to support the testing task. Fault simulation, which can be regarded as modelling and simulation of a testing process, has always to be referred to faults. Faults are already an abstraction of physical defects occurring randomly during manufacturing a microsystem. The defects are mapped via a fault model from the layout level to the level which the microsystem model is described at. Therefore, only such defects can be taken into consideration which can be described or modelled by components or expressions that are admitted at the microsystem representation level and, moreover, injectable into the description of the microsystem to be fault simulated.

Two tasks have to be solved before starting a microsystem fault simulation:

- Fault modelling for the microsystem, i. e. the mapping of defects to faults which can be described in terms of the microsystem description.
- Assuring the injectability of faults into the microsystem simulation model.

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The fault simulation of a microsystem is impeded by the interaction of non-electric and electric components, complicated and complex characteristics, mixed-mode type of signals, missing standard models and, moreover, missing standard fault models. Compared to other fields the electric circuit simulators have always been the most developed real-valued simulators. Therefore it has been common practice for years to model microsystems by equivalent electric circuits if the underlying behaviour can be described by ordinary differential equations. Consequently such simulators are also appropriate for the fault simulation of real-valued microsystem components.

The purpose of this paper is to put together and to generalise some problems arisen in fault modelling and fault injecting for microsystem components. In order to achieve dependable results of a microsystem fault simulation it is necessary to pay attention to the interrelations between nominal system models, fault models, the construction of simulation models being capable of injecting faults, and the representation of the faults in the fault list of a fault simulator, from the very beginning of the model building process. In fault simulating two different kinds of microsystems these problems have arisen. Suggestions how to tackle some of them will be discussed.

Section 2 surveys the related work in the field of fault modelling and fault simulation of analogue circuits as well as of microsystem components. In section 3 and 4 it will be demonstrated with two examples for microsystems that realistic defects cannot always be captured by the given fault-free nominal simulation model at a higher abstraction level and that fault assumptions made at a higher abstraction level can have no or only a weak correspondence to realistic defects. Based on experimentally obtained results aspects and requirements of microsystem fault modelling and fault simulation are summarised and generalised in section 5.

## 2. Related work

In modelling faults in real-valued components of microsystems for fault simulation purposes the on-going research in fault modelling for fault simulation of analogue circuits has to be taken into consideration since similar problems and

difficulties occur there. Apart from some controversial discussions on fault modelling and the lack of a generally accepted analogue fault model, the classification in hard faults (catastrophic, structural) and soft faults (deviation, non-structural) is used. The problems concerning the related fault modelling for analogue circuits have been dealt with in great detail e. g. in [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. There and in [21, 22, 23, 24, 25] several fault simulation approaches have already been reported for analogue circuits and the encountered problems have been discussed.

Similar and even more difficult problems are expected for defect and fault modelling of microsystem components to be fault simulated because of their large variety of physical, chemical and other effects which they are based on. However, this subject has been treated by only a few papers so far. In [26] theoretical and experimental methods have been presented to solve thermo-mechanical reliability problems in microsystem technology. By coupling measurements with numerical simulation tools failure hypotheses have been established. Investigations into the interrelation between low and high level fault models for different tasks have been reported in [27].

In [28] it was pointed out that microsystem fault simulations ought to be performed in order to get insights and experiences into the behaviour of a microsystem in presence of non-ideal or defective devices, to investigate into testability, or to determine the most fault-suspected parameters that should be analysed during the test run. They also set out the well-known fact that fault simulation could be used to generating fault dictionaries for microsystems. But no fault simulation experiments were done. In [27] first experiences have been reported on fault simulation experiments which have been carried out with a miniature opto-electric transformer (MOET) [29]. On the one hand faults were injected in the MOET layout parameters and transformed by analytical formulae into the parameters of the equivalent electric circuit of the MOET and on the other hand in the electric parameters themselves. In [23] the above-mentioned fault simulation investigations have been extended to experiments with a resonant silicon beam force sensor. The difficulties of fault modelling per se and of injecting these developed fault models in the simulation model of the resonant silicon beam force sensor which is a spatially distributed parameter system originally has been reported.

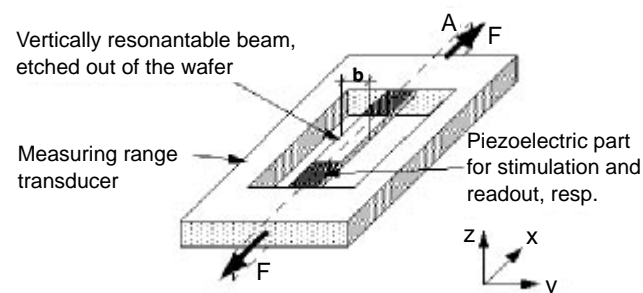
BIST and diagnosis strategies for safety-critical microsystems are described in [30]. Different approaches are compared. The importance of utilising reliability indicators for on-chip monitoring and diagnosis are shown. But there is no discussion which faults should be diagnosed and how to evaluate the presented strategies.

In solving BIST and diagnosis problems for microsystems the question arises how the corresponding approaches for

analogue and mixed-signal circuits, e. g. [31, 32, 33, 34, 35], can be applied to.

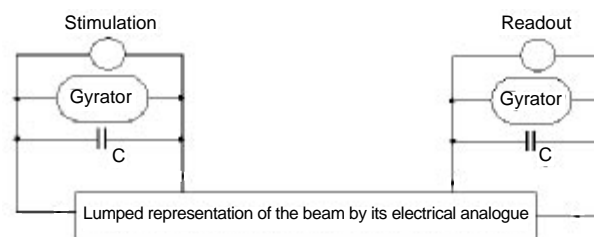
### 3. The influence of physical defect phenomena on constructing a system model

The necessity of taking the effects of defects into consideration already from the very beginning of the development of the simulation models is demonstrated with a resonant silicon beam force sensor (Figure 1).



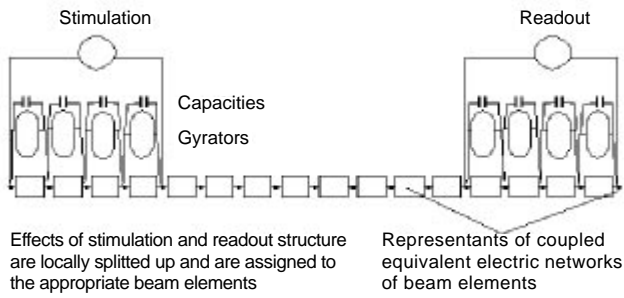
**Figure 1: Resonant silicon beam force sensor with frame**

The nominal behaviour of the sensor has been modelled as macromodel whose equivalent electric circuit is depicted schematically in Figure 2.



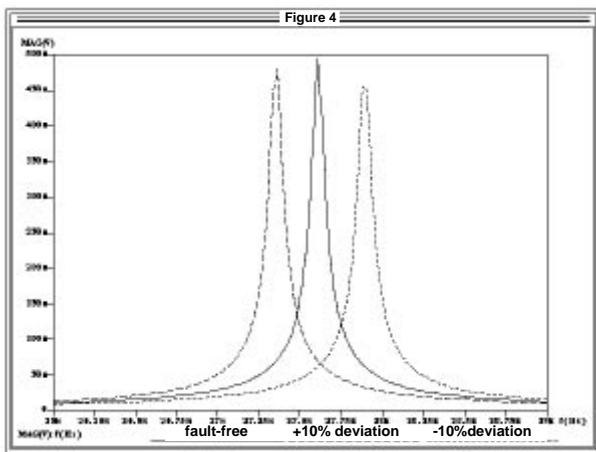
**Figure 2: Schematic diagram of the equivalent electric circuit of the beam force sensor modelled for the simulation of nominal behaviour**

However, not all relations to the spatial distribution of the physical phenomena can be found in that model due to their combination and compression in the lumped parameter components of the macromodel. Therefore locally physical defects (e. g. missing or irregular material as local defects in film thicknesses) are not describable. Such problems are avoided by involving the effects of the defects in the simulation model building process already at an early stage. Then, such an approach results in modified equivalent electric circuits with parameters which relate to physical defect phenomena [36] (Figure 3).



**Figure 3: Schematic diagram of the equivalent electric circuit of the beam force sensor able to injecting faults caused by locally appearing defects**

Only in this way a fault, as a model of a locally physical defect, can be injected in the simulation model by changing the corresponding parameters. Figure 4 shows as result of a fault simulation the effect of  $\pm 10\%$  missing material (deviation of beam thickness) in a part of the stimulation region (2nd quarter of this region) in comparison to the nominal behaviour of the resonant silicon beam force sensor.



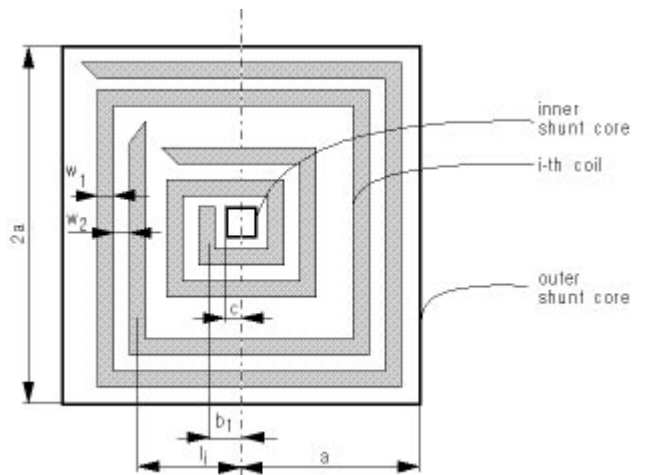
**Figure 4: Comparison between fault-free simulation and a fault simulation with a defect of  $\pm 10\%$  of missing beam thickness in a part of the stimulation region of the beam force sensor (amplitude frequency analysis)**

Such a defect could not be described with the original beam model because of the strong concentration of the spatial distribution. The fault modelling of this system has been carried out by appropriate computer-aided transformation (manipulation

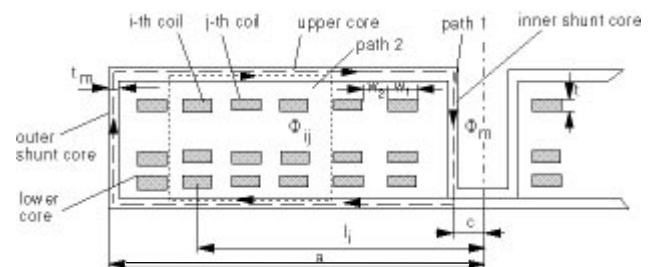
of given analytic formulae) from deviations of geometrical layout parameters (the defects) to deviations of parameters of the components of the refined equivalent electric network.

#### 4. Fault assumptions at higher abstraction levels and the detectability of realistic defects

To point to problems which arise if defects are to be represented as faults at higher abstraction levels another example is used. It is a miniature opto-electric transformer (MOET) (Figure 5)



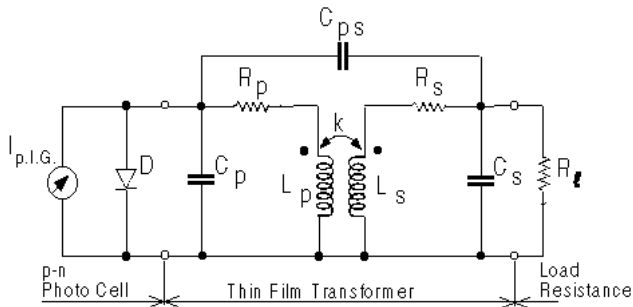
**Figure 5a**



**Figure 5b**

**Figure 5: Schematic diagram of a multilayer transformer with outer closed core for the model of the inductance; (a) top view, (b) cross sectional view (acc. to [29])**

whose non-electric components are modelled by their electric analogies [29]. The dependencies of the parameters of the equivalent electric circuit (Figure 6) on the physical and layout ones are given by analytic formulae.



**Figure 6: Equivalent electric circuit of the MOET (acc. to [29])**

Fault simulations have been carried out with faults which have been assumed to be out-of-range values of the MOET layout parameters as well as of the electric parameters themselves [27].

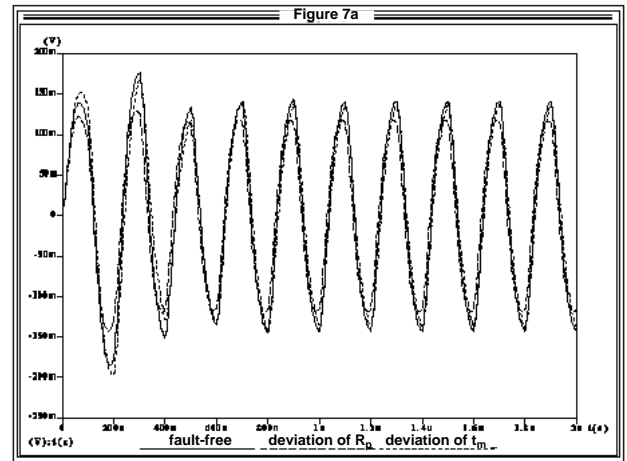
Compared to the MOET layout level the simulation of faults which are assumed as deviations of the electric parameters values can be regarded as fault simulations at a higher abstraction level. Due to the lower complexity a fast overview of the behavioural differences in presence of faults might be achieved. However, a single fault assumption at a higher level causes fault detection problems since a stimulus which can detect such a higher level fault can be incapable of detecting realistic defects in some cases (cf. Figure 7).

Since a single layout parameter relates to many electric model parameters, a single electric parameter fault usually cannot represent a defect as out-of-tolerance deviations of even one single layout parameter. Therefore, the correct transformation of faults from lower to higher level descriptions is of a very high importance. A multiple fault model comprising several single electric parameters is inevitable. However, in injecting faults into layout parameters directly and carrying out fault simulations, the effects to intermediate variables remain hidden.

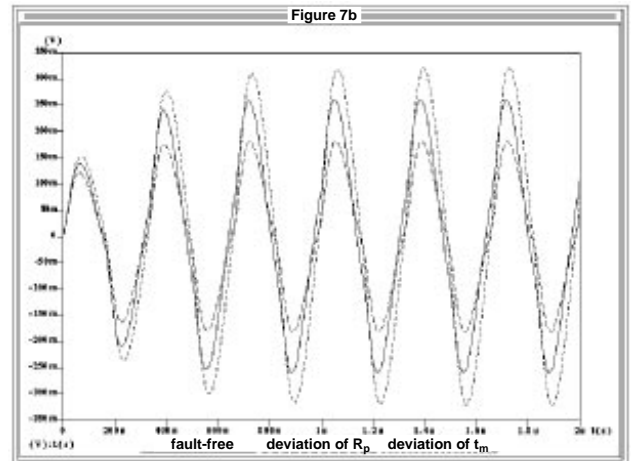
## 5. Summary and Conclusions

In order to achieve dependable results for the fault simulation or, in future, the test signal generation for micro-systems the following aspects should be taken into consideration.

- Simultaneously with the development of the functional and behavioural models of a microsystem at higher levels of abstraction, their corresponding simulation models for the faulty behaviours have also to be developed.
- The simulation models for the system as well as for the faults and the data of the fault list have to meet the requirements of the underlying physical laws even if the microsystem under test operates due to a fault out of its normal range of operation.



**Figure 7a**



**Figure 7b**

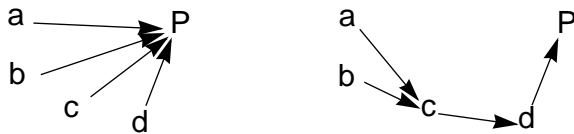
**Figure 7: Comparison between fault-free simulation (—) and fault simulations with a fault and a defect injected in the parameters  $R_p$  (deviation +66%) (---) and  $t_m$  (deviation +10%) (---), resp., (transient analyses)**

(a) signal capable of detecting the fault in  $R_p$  (high level fault) is incapable of detecting the defect in  $t_m$  (geometrical parameter)

(b) changed signal (other frequency) is capable of detecting the fault in  $R_p$  and the defect in  $t_m$

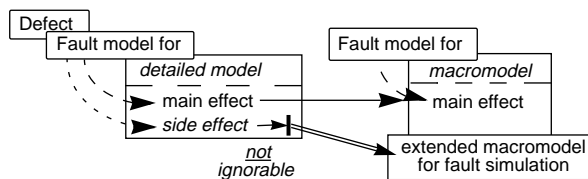
For example, if a fault is described by changing geometrical layout parameters (widths, ...) then they must not be set independently of each other.

Generally speaking, a formula which transforms layout parameters to those of an equivalent electric circuit should try to be structured in direct dependencies. Figure 8 depicts an example where the electric parameter P depends on the layout parameters a, b, c, and d. However, a thorough analysis might show that c depends on a and b, d on c, and eventually P on d only.



**Figure 8: Example of directed parameter dependencies**

- Side effects must not be neglected in setting-up the (fault-free) simulation model because some effects of a defect could need such a side effect for its representation (cf. Figure 9). That means the effects of a defect have to be kept describable at the higher abstraction level. This is often hindered by weak description possibilities for high level microsystem models provided by the simulation-tools even for the fault-free models.



**Figure 9: Necessity of model extension for fault simulation purposes by considering side effects**

- By means of a variety of analyses, such as small and large ac signals, dc conditions, transient analyses, temperature, noise, sensitivity, cross-sensitivities, tolerance analyses (cf. [1, 28]) useful information can be made available to achieve a more realistic fault simulation.
- The generation of test signals will be simplified if the signals are derived only from a microsystem modelled with equivalent electric circuits or descriptions at higher abstraction levels. However, by fault simulation it has to be approved that these signals are capable of detecting realistic (layout) faults.
- A single fault model of electric parameters of an equivalent electric circuit is preferred to others. However, its adequacy has to be checked carefully.
- Systematic methods of fault list reduction, like those being currently under development for analogue fault simulation, are to apply when they are available for microsystems eventually.

- An approach like Inductive Fault Analysis (IFA) [37] should be made available for components of microsystems.

The experiments described in this paper have been carried out with our analogue fault simulator "aFSIM" [38] which is based on the commercially available analogue simulation-tool Saber (Analog) as the kernel and uses additionally developed pre-processor, post-processor, and control modules to automate the fault simulation process.

Our future work deals with the development of simplified fault models to achieve an acceleration of fault simulations.

## 6. Acknowledgement

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