Modeling Concept for Susceptibility Behavior in Sensor Microsystems

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Abstract: In this article a concept for modeling of electromagnetic susceptibility resp. immunity of analogue bipolar system parts at sensory micro systems is introduced considering as example a miniaturized pressure sensor. Due to the small dimensions of systems only conducted disturbances are accounted. The concept based on RF models for bipolar technology (e.g. HICUM, MODELLA). The workflow of the concept that based on the use of numerical and symbolical tools is presented. First results are shown.
Key words: electromagnetic compatibility (EMC), electromagnetic interference (EMI), conducted disturbance, demodulation, operational amplifier, bipolar transistor

1. Introduction

A special problem during the development of sensory micro systems is the reliable prediction of the immunity resp. susceptibility of the sensitive analogue blocks against incoming electromagnetic (EM) disturbances.
This difficulty becomes more important due to the increase of occurring electromagnetic fields in the environment and the increase of component integration. At present, the EMC characteristics of a micro system can only be determined by measurements of prototypes of ready products. But a viability analysis regarding the immunity of a system based on the simulation is imperative to avoid a redesign.

2. Electromagnetic Interference of Sensor Micro Systems

Electromagnetic (EM) fields can practically not cause a direct influence on sensitive analogue modules of micro systems (e.g. signal processing IC) due to their small dimensions[1]. At frequencies less than 3 GHz EM fields only cause a indirect influence of the micro system by unintentional radiation at the leads of the micro system or at long conductors on the system itself converted into conducted disturbances. Thus an influence of the sensitive analogue modules is only possible by conducted EM disturbances via their connecting pins. For the modeling of susceptibility of micro systems by a limit of frequencies less than 3 GHz it should sufficient only to regard the effect of conducted EM disturbances.

2.1 Effect of Electromagnetic Disturbances

The effect of conducted disturbances is highly frequency dependent. Low-frequency disturbances that lie within the transferable frequency domain of the micro system will be transferred according to the transfer function and will be overlaid to the wanted signal.
High frequency disturbances which are located outside the frequency domain of which the micro system has been designed for can be converted into the In-Band-Frequency domain by dint of demodulation at the semi conductor device [2]. The demodulation of RF disturbance signals is done as a result of the rectifying effect on pn-depletion layers of diodes and transistors as well as on a number of parasitic pn-junctions of the used semi conductor device. Mostly a DC offset arises at the output of the amplifier circuit by this RF/LF conversion [2].
An additional effect can occur at components of the bipolar technology: The RF disturbance signals may cause a RF induced current crowding at bipolar transistors [3], [4].

3. Model System

In the literature [2] published tests on electromagnetic immunity of operation amplifiers show that different pins of operational amplifiers react different to EM noises. The input stages of the operation amplifiers proved to be extra susceptible. Measurements done on pressure cells [5] allocate that also on piezo resistive measuring cells strong rectification effect of the EM noises can appear. Starting from the mentioned tests for modeling the EM immunity a simplified sensory system was chosen which is shown in figure 1. It consists of a piezo resistive measuring cell as well as the following instrument amplifier

[1] Following [1] electromagnetic fields of integrated circuits can only lead to a direct disturbance when the dimensions of the conductive structures of the circuit are greater $\lambda/20$ than of the maximum irradiated wavelength. At frequencies of 1 GHz this demand comes up to a structure dimension of 1.5 cm. Therewith a direct disturbance is achieved.

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with idealized current and voltage supply. For the experimental investigation of the susceptibility of the model system the so-called Direct Power Injection (DPI) method [6] shall be used. For this method a RF signal is capacitive coupled on the tested pins and lines. The coupling positions are plotted in figure 1.

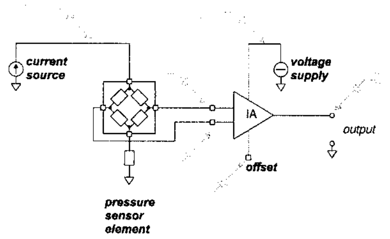

Figure 1: Model System

4. Modeling

The main approach of modeling is the use of technology dependent high frequency (RF) compact models for the occurring semi conductor elements in the micro system. In each case models for the description of vertical npn-transistors (resp. pn-diodes), lateral pnp-transistors, depletion layer and MIS-capacitors as well as p-diffusion resistors in integrated circuits were chosen. Latter is also used for the description of the piezo resistive pressure cell.
After a metrological RF characterization of the single elements (set for the LF area) and a following parameter extraction an exact description of the RF/LF conversion should be possible with these RF models. By dint of a simple combination of the above-mentioned models any micro system can be modeled bottom up.
Then a creation of behavior models of single system blocks based on these RF models will be possible before realization of the system. This can be supported by symbolic analysis [7], [8], [9].

4.1 Model Choice

For modeling the EMI (electromagnetic interference) of bipolar circuits on transistor level currently one-dimensional models are used [10], [11], [12], which are based on the Ebers-Moll or Gummel-Poon model. However, these models describe the real physical behavior only insufficient. For example, a (exact) modeling of the high current behavior, the quasi saturation including the Kirk effect, the conductivity modulation of the basis, the emitter current crowding as well as the avalanche breakdown is not possible. But the consideration of these effects and their out coming nonlinear distortions and interferences like cross- and intermodulation is decisive. Thus for the modeling a precise consideration of the physical processes of the single elements is needed. Therefore models are used which use at least a two-dimensional description of the charge carrier flow.

The RF model MODELLA [13] has been chosen for modeling the lateral pnp-transistor. The advantages of a two-dimensional modeling compared to a one dimensional modeling like in the Gummel-Poon model are as follows: More accurate modeling of high injection by taking the Webster effect into account i.e. a reduction by a factor of two in the base transit time at high injection; current crowding under the emitter is modeled; forward Early voltage is dependent on collector base and emitter base voltage; more accurate modeling of the depletion capacitances around the diffusion voltage; physical modeling of the diffusion capacitances; fall off of transient time and small signal forward gain is not only due to high injection but also to ohmic voltage drop across the emitter; more accurate modeling of the collator base voltage dependence of transit time; charge storage when the substrate-base junction is forward biased; separate saturation current for the substrate-base diode.

For the vertical npn-transistor there are the models VBIC, MEXTRAM as well as HICUM [14], [15], [16] to choose from. MEXTRAM and HICUM have been especially designed for RF applications and include the Kirk-effect to the descriptions of the quasi saturation and the Basis-Collector-Avalance cutout. HICUM was chosen due to the following reasons. HICUM is modularly built, scalable and the model formulation is physically oriented. Therewith a symbolic analysis and possibly simplifying with regard to special EMI effects are supported. Aside with only four internal nodes the HICUM model promises a simulation time advantage compared to the two other models. For modeling the depletion layer capacity the diode model Philips Level 500 [17] was chosen. Unlike SPICE level 1 and level 3 diode models it contains an additional description of the nonlinear forward current and DC-reverse current. The model JUNCAP [17] is used for modeling the MIS-capacities which has been developed especially for MOS-structures.
According to the circumstances in these structures JUNCAP describes the current flow and the capacity spreading of a MIS-structure for the bottom-, side-, wall- and gate-edge-fraction of the pn-junction independent from each other. Thus an improved weighting of possible AC effects in this domain is gained. For the p-diffusion resistor a resistor model is used which is extended by a well-substrate-junction. The well-substrate-transition is substituted with two diodes which are modeled by dint of the diode model Level 500. Therewith a better description of the parasitic pn-junction should be possible.

5. Modeling Concept

The modeling concept is shown in figure 2. The light gray areas describe a possible numeric and symbolic modeling and optimization process for a micro system using the circuit simulator PSpice™ and the symbolic tool Analog Insydes™ [9]. The planned expansions are illustrated with the dark gray areas.

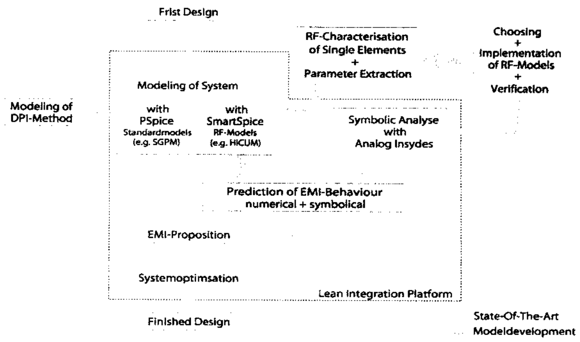

Figure 2: Modeling concept

Starting from the first system concept it is currently possible to perform the modeling on transistor level by using the in PSpice™ available models. PSpice™ models are also implemented in Analog Insydes™ and can be used for symbolic analysis of linear systems and also on a limited scale of non-linear systems.

Thus an EMI modeling would be possible by using an emulation of DPI method. But the significance of such an EMI analysis would be minor (only insufficient modeling e. g. for parasitic transistors).

An elaboration of EMI-behavior under consideration of RF/LF conversion on semiconductor devices will be possible with the planned expansions. These contain the following items: Implementation of the selected RF-models in Analog Insydes™, RF-characterization by measurement of the chosen single elements for the extraction of model parameters and an accurate modeling of the measuring setup of the DPI method.

Because the RF models are already implemented in the circuit simulator SmartSpice™, they can be used for numeric simulations. The implementation in Analog Insydes™ takes place in time with so called Analog Behavior Models (ABM). For validation of implemented models the results of numerical simulations are used. The extraction of the model parameters is accomplished by characterization of suitable test structures. After that any circuit of a micro system can modeled with SmartSpice™ by combining single elements. Thus it then can be numerical evaluated concerning its immunity. The exact modeling of an existing DPI test environment allows then the validation of the simulation results. With the symbolic analysis based on the RF models additionally semiconductor effects can be determined which are important for the description of the RF/LF conversion. Furthermore behavior models for single system blocks can be provided. They simplify the design process by reducing the simulation time without having an existing system implementation. Thus the developer can gain a deeper insight of system behavior during synthesis phase. In addition design rules which consider EMI effects can be generated for simple system blocks e.g. differential amplifier, current mirror etc.

5.1 Pre-investigation of EMI Behavioral Modeling

To comprehend the possibilities and limits of the behavior modeling with Analog Insydes™ preliminary inspections were made with help of a developer version of Analog Insydes™. This evaluation version allows for the first time to simplify non-linear systems of differential algebraic equations (DAE) on the basis of transient signal characteristics. For this purpose the available models (SGP, Diode Level 1) in Analog Insydes™ were used. A test circuit (simple emulation of the DPI method) was simulated with PSpice™. The basic circuit was an opamp which is connected as a voltage follower. A noise voltage was placed with a frequency of 5 MHz and an amplitude of 2 V on a non inverted input of simple opamp circuit.

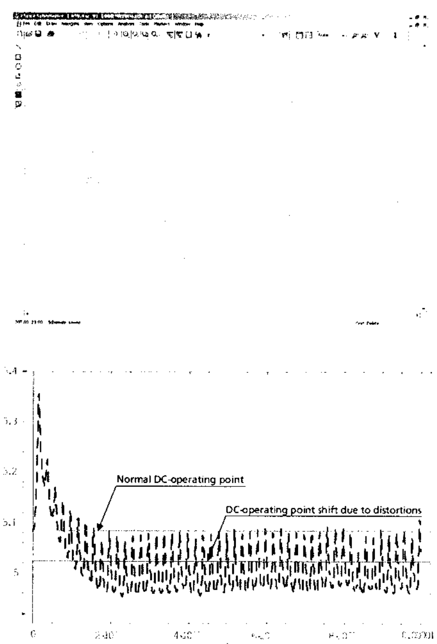

Figure 3: left – opamp, right – comparison simplified DAE-system (--), original system ( )

The opamp consisted of 12 transistors. The light-colored curve in figure 3 shows the noise signal driven behavior of the output of the opamp in the PSpice™ simulation. A displacement of the operating point can be recognized as a result of the disturbance (due to the used models the simulation has only a limited expressiveness). Based on the non-linear original differential algebraic equations system of the opamp a simplification of the time depended differential equations systems was made. This was done by use of the transient ranking method *One-Step-Solver* [7] and a maximum error tolerance of 10 % orientated on the original output signal. During the simplification 644 terms of overall 1614 terms were eliminated. The succeeding simulation shows a good matching between the nonlinear original differential equations system and the simplified nonlinear DAE system. The simulation time was reduced by approximately 30 %. Future comparisons should show which area of validity this simplified DAE system has e.g. by different frequencies and distinctive resonances. An affirmation of the validity for a special frequency range would mean to have a computing time advantage for further simulations.

5.2 Implementation of RF models

Based on the above-mentioned, the chosen RF models have to be implemented into Analog Insydes™ for having the possibility to perform the planned symbolic analysis and behavior modeling. To validate the up to now implemented RF models in Analog Insydes™ comparative numerical simulation were accomplished.

As an example for other already implemented models figure 4 shows the behavior of a diode level 500 model for the given circuit. It shows the behavior at a falling edge ($t_r = 10^{-12}$ s) of a symmetrical rectangle signal (-5 V, +5 V, f = 25 MHz). In the graph the transient characteristics of current through the series resistance R = 50 Ω is plotted. A good matching between SmartSpice™- and appropriate Analog Insydes™- simulation results is apparitional.

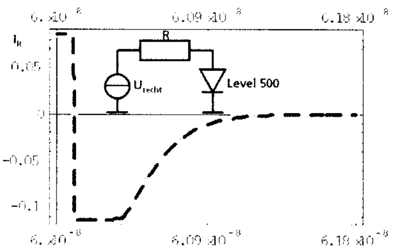

Figure 4: Simulation with model Level 500 under SmartSpice ( ) and Analog Insydes (- -)

This example demonstrates the successful implementation of the diode level 500 model. It is representative for validation of the already implemented models JUNCAP, Diode Level 500 and MODELLA [4].

6. Conclusion

The implementation of above-named RF models in Analog Insydes™ and behavior modeling and symbolic analysis with these RF models are still in work. For the RF characterization and following parameter extraction a test chip was produced. It includes the to be analyzed single elements and the referring de-embedding structures. Additionally the above-mentioned opamp in voltage following circuit was integrated on the chip. This allows on the one hand an analysis of electromagnetic interference directly on the wafer and on the other hand an exemplary verification of generated behavior models and symbolic design rules.

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