Bergische Universität Wuppertal

Fachbereich Mathematik und Naturwissenschaften

Institute of Mathematical Modelling, Analysis and Computational Mathematics (IMACM)

Preprint BUW-IMACM 15/02

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January 2015

http://www.math.uni-wuppertal.de

The European Project nanoCOPS for Nanoelectronic Coupled Problems Solutions

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Abstract The project nanoCOPS [1] is a collaborative research project within the FP7-ICT research program funded by the European Union. The consortium comprises experts in mathematics and electrical engineering from seven universities (BU Wuppertal, HU Berlin, Brno UT, TU Darmstadt, FH O Hagenberg, U Greifswald, KU Leuven), one research institute (MPI Magdeburg), two industrial partners (NXP Semiconductors Netherlands, ON Semiconductor Belgium) and two SMEs (MAGWEL - Belgium, ACCO Semiconductor - France).
We present an overview of the project subjects addressing the ”bottlenecks” in the currently-available infrastructure for nanoelectronic design and simulation. In particular, we discuss the issues of an electro-thermal-stress coupled simulation for Power-MOS device design and of simulation approaches for transceiver designs at high carrier frequencies and baseband waveforms such as OFDM (Orthogonal Frequency Division Multiplex).

1 Introduction

Designs in nanoelectronics often lead to large-size simulation problems and include strong feedback couplings. Industry demands the provisions of variability to guarantee quality and yield. It also requires the incorporation of higher abstraction levels to

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allow for system simulation in order to shorten the design cycles, while at the same time preserving accuracy. The nanoCOPS project addresses the simulation of two technically and commercially important problem classes identified by the industrial partners:

- Power-MOS devices, with applications in energy harvesting, that involve couplings between electromagnetics (EM), heat, and stress, and
- RF-circuitry in wireless communication, which involves EM-circuit-heat coupling and multirate behaviour, together with analogue-digital signals.

To meet market demands, the scientific challenges are to:

- create efficient and robust simulation techniques for strongly coupled systems, that exploit the different dynamics of sub-systems and that allow designers to predict reliability and ageing;
- include a variability capability such that robust design and optimization, worst case analysis, and yield estimation with tiny failures are possible (including large deviations like 6-sigma);
- reduce the complexity of the sub-systems while ensuring that the parameters can still be varied and that the reduced models offer higher abstraction models that are efficient to simulate.

Our solutions are

- to develop advanced co-simulation/multirate/monolithic techniques, combined with envelope/wavelet approaches;
- to produce new generalized techniques from Uncertainty Quantification (UQ) for coupled problems, tuned to the statistical demands from manufacturability;
- to develop enhanced, parameterized Model Order Reduction techniques for coupled problems and for UQ.

The best (efficient, robust) algorithms produced are currently being implemented and transferred to SME partner MAGWEL. Validation is conducted on industrial designs provided by the industrial partners. A thorough comparison to measurements on real devices will be made.

2 Coupled Problems, Co-simulation, Multirate

The coupling of various physical effects in nanoelectronics plays an important role in the operational reliability, at both circuits and systems level. This is the case for high-performance applications (CPUs, RF-circuits) as well as applications in hostile environments (e.g., such as high voltages and/or high currents in automotive applications, RF Power and Base Stations applications). Various types of coupled phenomena exist. For example, electro-thermal coupling is a key concern during operational cycles in industry where a substantial amount of heat is generated that (1) will affect the voltage and current distributions and (2) will indirectly impact the sources of the heat itself. The extent and impacts of electro-thermal-stress coupling is studied in the modelling of power-MOS devices in DC and in the transient regime (time domain), taking environmental aspects like metal stack and package into account. The determination of both reliability and ageing needs to be more effectively addressed by the combined simulation of these coupled effects. Another challenging coupling mechanism concerns Radio Frequency (RF) designs that have to involve with circuit-EM-heat couplings, where parasitic long-range electromagnetic (EM) effects induce substantial distortion at the circuit level, which can lead to the sudden malfunction of the circuit. In order to address both these types of problems, companies need to have a capability for the simulation of multi-physics with dynamics involving different time scales.

Co-simulation techniques are natural approaches in efficiently solving coupled problems. Field-circuit couplings have been considered in [2,3]. Using *source coupling*, the current **i** of an equivalent current source is calculated from the electromagnetic fields and becomes input for the circuit equations . Next, the circuit excites the electromagnetic fields by a time-dependent voltage source. Alternatively, using *inductive coupling*, the current source for the circuit is replaced by a resistor in series with a time-dependent inductor with an inductance that is fitted to the field quantities. This is a more preferred option. The complete probloem is now described as follows. The eddy-current field problem on Ω is

$$\sigma\partial_t\mathbf{a}^{(n)} + \nabla\times\left(\nu(|\nabla\times\mathbf{a}^{(n)}|)\,\nabla\times\mathbf{a}^{(n)}\right) = \chi\mathbf{j}^{(n)},$$

where $\mathbf{a}^{(n)}$ is the magnetic vector potential after the n-th iteration (with homogeneous Dirichlet conditions), σ and ν are conductivity and reluctivity, respectively and the winding functions $\chi = [\chi_1,\ldots,\chi_k,\ldots,\chi_K]^\top$ are functions of space that distribute the lumped currents $\mathbf{j}$ in the 3D domain. The circuit coupling is established via integration

$$\partial_t\int_\Omega \chi_k\mathbf{a}^{(n)}\,\mathrm{d}x + R_k j_k^{(n)} = v_k^{(n-1)} \qquad k=1,\ldots,K$$

to the circuit system of differential algebraic equations

$$\begin{aligned}
\mathbf{A}_\mathrm{C}\partial_t\mathbf{q}_\mathrm{C}(\mathbf{A}_\mathrm{C}^\mathrm{T}\mathbf{u}^{(n)},t) + \mathbf{A}_\mathrm{R}\mathbf{g}_\mathrm{R}(\mathbf{A}_\mathrm{R}^\mathrm{T}\mathbf{u},t) + \mathbf{A}_\mathrm{L}\mathbf{i}_\mathrm{L}^{(n)}&\\
+\mathbf{A}_\mathrm{M}\mathbf{j}^{(n)} + \mathbf{A}_\mathrm{V}\mathbf{i}_\mathrm{V}^{(n)} + \mathbf{A}_\mathrm{I}\mathbf{i}_\mathrm{s}(t) &= 0,\\
\partial_t\Phi_\mathrm{L}(\mathbf{i}_\mathrm{L}^{(n)},t) - \mathbf{A}_\mathrm{L}^\mathrm{T}\mathbf{u} &= 0,\\
\mathbf{A}_\mathrm{V}^\mathrm{T}\mathbf{u} - \mathbf{v}_\mathrm{s}(t) &= 0,
\end{aligned}$$

with incidence matrices $\mathbf{A}_*$ where $\mathbf{v}_* = \mathbf{A}_*^\mathrm{T}\mathbf{u}$ and constitutive laws for conductances, inductances and capacitances (functions with subscripts R, L and C), independent sources $\mathbf{i}_\mathrm{s}$ and $\mathbf{v}_\mathrm{s}$, unknowns are the potentials $\mathbf{u}$ and currents $\mathbf{i}_\mathrm{L}$ and $\mathbf{i}_\mathrm{V}$.

Apart from this we deal with a field-mechanical coupling in cavities, a field-thermal coupling and with a thermal-mechanical problem [4]. Dynamic iteration is per-

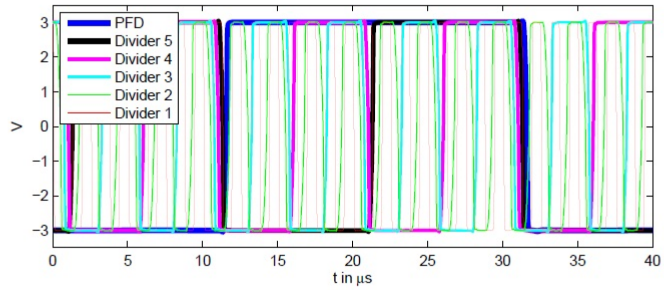

Fig. 1 Several signals in a frequency divider chain as part of a PLL.

formed at each time step. In [5], for the field-thermal coupling this is combined with a time-averaging for the heat source, thus exploiting *multirate* difference in the dynamics between the field and the heat quantities.
Multirate time integration for circuit simulation has been studied for circuit decomposition as well as for signals with a broad difference in the frequency domain. When different signal shapes are present in the circuit, these may be approximated more efficiently if individual grids are used for each of the signals. As an example we consider a chain of 5 frequency dividers (as part of a PLL). In each step the frequency is reduced by a factor 2 as one can see in Fig. 1. Obviously, for the low frequency signals towards the end of the divider chain a much sparser grid is sufficient for an accurate representation, in comparison to the high frequency input signal. In the approach, the problem is cast into a multi-time problem using a slowing varying time scale τ_1 and a second timescale τ_2 for a highly periodic problem. The Rothe method is used for time integration along τ_1. Spline wavelets are used to solve the periodic problems along τ_2. Very efficient discretizations in τ_2 are obtained, that vary with τ_1. From the solution in (τ_1, τ_2)-space, a 1-dimensional solution depending on $(t, \phi(t))$ (for a suitable phase-function ϕ) can be constructed, which provides an envelope solution. Recently, the method has been extended to deal with circuit partitions as well [6, 7]. Currently, one considers coupling with heat as well.

3 Model Order Reduction, Uncertainty Quantification

In [8] a robust algorithm for *parametrized Model Order Reduction* (pMOR)based on implicit moment matching has been derived, for linear systems based on state-space formulations, which directly applies to circuit equations. In [9] the method has been extended to second order systems coming from electromagnetic field discretizations. Additionally an a posteriori output error bound for reduced order models of micro- and nano-electrical(-mechanical) systems is derived. The error bound is independent of the discretization method (finite difference, finite element, finite volume) applied to the original PDEs. Secondly, the error bound can be directly used in the discretized vector space, without going back to the PDEs, and especially to the bilinear form (weak formulation) associated with the finite element discretization, which must be known a priori for deriving/using the error bound for the reduced basis method. The error bound enables automatic generation of the reduced models computed by parametric model reduction methods based on approximation (interpolation) of the transfer function, e.g., Krylov subspace based methods. Although established for parametrized systems, the error bound is also well-grounded for linear time invariant (LTI) systems without parameters, since it considers the non-parametric LTI systems as a special case [9].

For parameters coming from geometry, the expressions are not always easily obtainable (f.i., meshing for electromagnetic problems is done in the CAD environment) and thus the expansion may be even cumbersome [10]. Here a strategy is to use, for a given parameter, the expression handler in the CAD-environment before starting the simulation to evaluate the p-dependent sub-parts of all expressions (usually also circuit simulators have such an internal step in their expression handler) and then apply a MOR-projection for this parameter.

In [11] MOR for linear, coupled systems was derived based on low-rank approximations of the coupling matrices. When having obtained MOR models for subsystems an interesting application arizes for multirate simulation or in use with dynamic iteration and thus provides a link to Section 2. The lumped inductor coupling can be seen as a first MOR-model, used for coupling. Dynamic iteration with MOR can be much more robust than iteration with interpolation/extrapolation of values at simple interphases.

In [12,13] methods for *Uncertainty Quantification* (UQ) via generalized Polynomial Chaos (gPC) expansions have been proposed. These methods can greatly benefit when being combined with methods for pMOR [14]. Assuming that the discretization of the underlying structure of the electromatic problem is fixed, in [15, 16] UQ-results are obtained involving parameterized MOR. For three parameters a full model of ca 30k dofs was compared to ROM of 40 dofs, for different quadrature formules in Stochastic Collocation. Popular is the so-called Stroud-3 rule [17] to compute the collocation points. One can also use a Hermite Genz-Keister [15, 18] sparse grid that yields normally distributed sample points and weights in the quadrature rule. In [19] the sensitivity of the variance with respect to parameters is considered. This gives an indication of dominant parameters, see also [14]. Clearly, MOR should preserve the main statistical properties of the full model.

In [20] stochastically varying domains are considered, leading to topology optimization for a permanent magnet (PM) synchronous machine with material uncertainties. The variations of the non-linear material characteristics are modeled by the gPC method. During the iterative optimization process, the shapes of the rotor poles, represented by zero-level sets, are simultaneously optimized by redistributing the iron and magnet material over the design domain. The gradient directions of the multi-objective function with constraints, composed of the mean and the standard deviation, is evaluated by utilizing the continuous sensitivity equation approach and the Stochastic Collocation Method. Combined with the level set method this yields designs by using already existing deterministic solvers. Finally, a two-dimensional numerical result demonstrates that the proposed method is robust and effective. This example has already a non-trivial geometry. However, there still are a lot steps to be taken. For one of our industrial use cases, a Power-MOS, Fig. 2 shows a complex geometry, for which a lot of coupled effects have to be efficiently determined. Also UQ for large parameter variations is a point of attention [21].

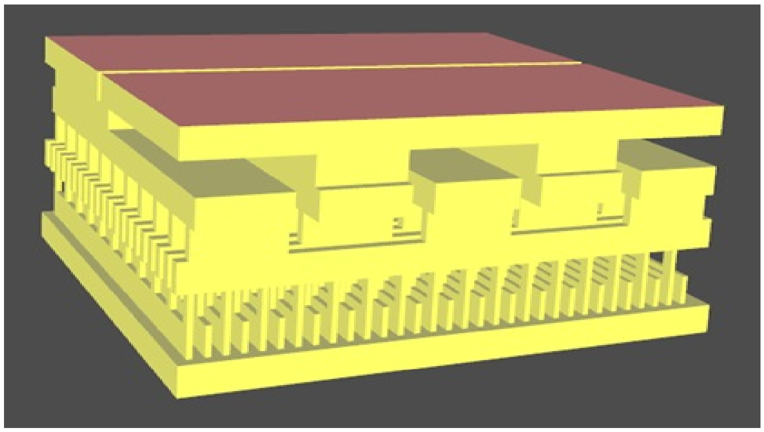

Fig. 2 Typical layout of the power transistor (stretched vertical direction) showing its complex geometry.

Acknowledgements We acknowledge the support from the project nanoCOPS, Nanoelectronic COupled Problems Solutions (FP7-ICT-2013-11/619166), `http://www.fp7-nanoCOPS.eu/`.

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