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THE NANOCOPS PROJECT ON ALGORITHMS FOR NANOELECTRONIC COUPLED PROBLEMS SOLUTIONS

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Abstract. The nanoCOPS project [1, 2] is a collaborative research project within the FP7-ICT research program funded by the European Union. The consortium comprises experts in mathematics, physics and electrical engineering from seven universities (BU Wuppertal, HU Berlin, Brno UT, TU Darmstadt, FH OÖ Hagenberg, U Greifswald, KU Leuven), one research institute (MPG Magdeburg), two industrial partners (NXP Semiconductors Netherland and ON Semiconductor Belgium) and two SMEs (MAGWEL and ACCO Semiconductor). 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 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. A public online progress report can be found in [3].

2 SIMULATION OF COUPLED PROBLEMS: CO-SIMULATION, MULTIRATE, AND MONOLITHIC

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 [4, 5]. Dynamic iteration can be performed within each time window [6]. In [7], 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. When strong couplings arise one will reside to efficient monolithic algorithms to solve the coupled problem (see also Fig. 1).

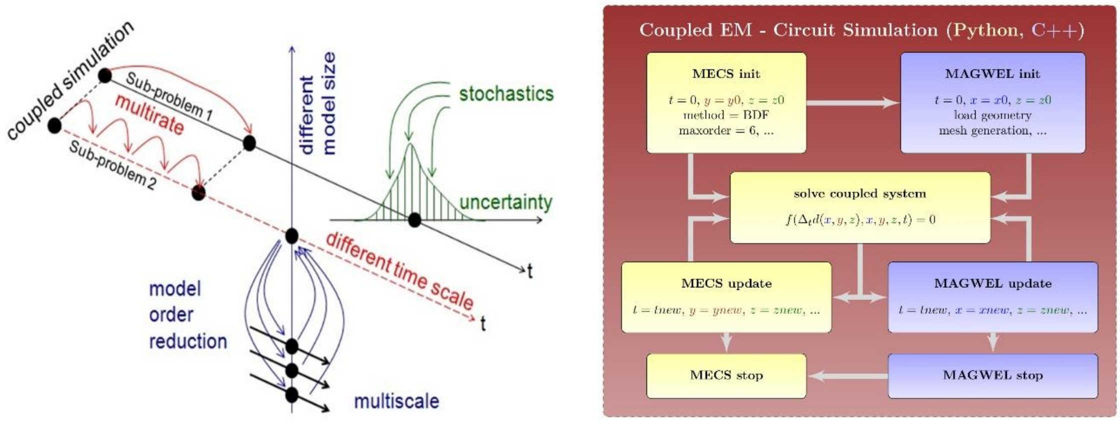

Fig. 1. **Left:** Schematic of a coupled problem (consisting of two sub-problems), including uncertainties. In nanoCOPS, those problems are efficiently solved in time domain and probability space with exploitation of their multirate (different time steps) and multiscale behaviour (different discretizations). The discretized models will lead to different reduced models by techniques from MOR. Parameterized MOR will guarantee the ability to properly deal with the uncertainties in parameters, geometries, and coupling quantities. **Right:** Overview flow for strongly coupled problems, yielding a monolithic coupled simulation.

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. The problem is cast in a hyperbolic time-domain formulation involving two time directions, one mimicking a low-frequency behavior, the other one a high-frequency one with periodic boundary conditions: an MPDAE system (Multirate Partial Differential-Algebraic Equations). This splitting can be adaptively optimized during the process. The grid points along the fast-varying direction may vary when progressing in the low-frequency time direction (see Fig. 2 (left)). Spline/wavelet methods are exploited for reasons of compactness of the support of the basis functions.

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. 2 (right). From the solution in $(\tau_{1,}\tau_2)$-time-domain 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 [8, 9]. Currently, one considers coupling with heat as well.

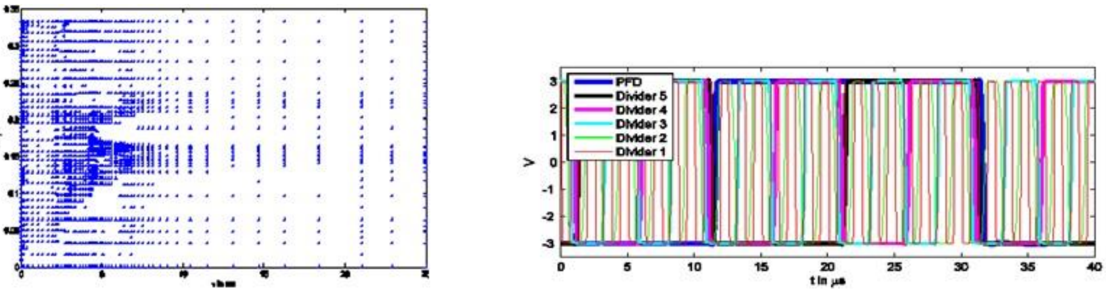

Fig. 2. **Left:** Adaptive grid for a Colpitss oscillator. **Right:** Several signals in a frequency divider chain as part of a PLL.

A highlighting monolithic simulation for a coupled electromagnetic-heat problem is shown in Fig. 3. It couples large-scale (millimeter) structures to small-scale (sub-micron) finger details of a power MOS.

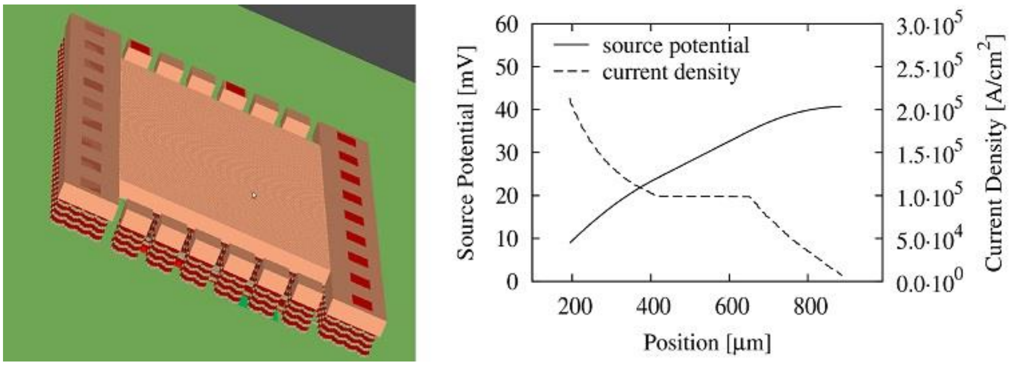

Fig. 3: Analysis of a power MOS (left) resulting into an asymmetric current density due to thermally induced conductance variations in the metallic interconnect (right).

3 MODEL ORDER REDUCTION, UNCERTAINTY QUANTIFICATION

The involvement of varying parameters, needed in the design process, affects the performance of time-domain simulation techniques: the dynamics can change (resulting in different time steps in a monolithic simulation, or in more iterations for Dynamic Iteration in co-simulation, or in different multirate behavior of MPDAEs. Also projection matrices in Model Order Reduction techniques depend on chosen parameters. In [10] a robust algorithm for parametrized Model Order Reduction (pMOR), based on implicit moment matching involving Krylov-space techniques, has been derived, for linear systems based on state-space formulations, which directly applies to circuit equations. In [11] the method has been extended to second order systems coming from electromagnetic field discretizations. In a monolithic coupling the electromagnetic vector potential generates a heat coupling to heat by a power term giving a quadratic term. For such couplings special MOR methods have been developed recently [12]: bilinear and quadratic-linear models were considered that allow treatments in the frequency domain (involving multiple frequencies). Additionally in [11] 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. This can be combined with adaptive selection of expansion points. These techniques enable 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.

Fig. 4: Relative error of the expectation of the electrical field in a coplanar waveguide after using a pMOR Krylov-space technique within Uncertainty Quantification based on generalized Polynomial Chaos expansions.

In [13, 14] 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 [15] (see also Fig. 4). Assuming that the discretization of the underlying structure of the electromagnetic problem is fixed, in [16] UQ-results are obtained involving parameterized MOR. In [17] the sensitivity of the variance with respect to parameters is considered. This gives an indication of dominant parameters, see also [15]. With Stroud-quadrature [18] one can deal with a number of parameters that are of interest for industrial purposes.

In [19] stochastically varying domains are considered, leading to topology optimization for a permanent magnet (PM) synchronous machine with material uncertainties. These techniques are now applied to problems in nanoscale. In [20] for variation of the solution due to varying the thickness of a layer in a power MOS transistor model, or due to varying the conductivity in the layer, gPC was used to efficiently estimate mean and standard variation.

In [21] the effect of the number of parameter variations on the impact of noise from digital parts on the isolation sensitive RF domains was investigated, i.e., the number of downbonds, the number of ground pins, the domain spacing and shape, the application of deep-Nwell and exposed diepad, and the number of exposed diepad vias.

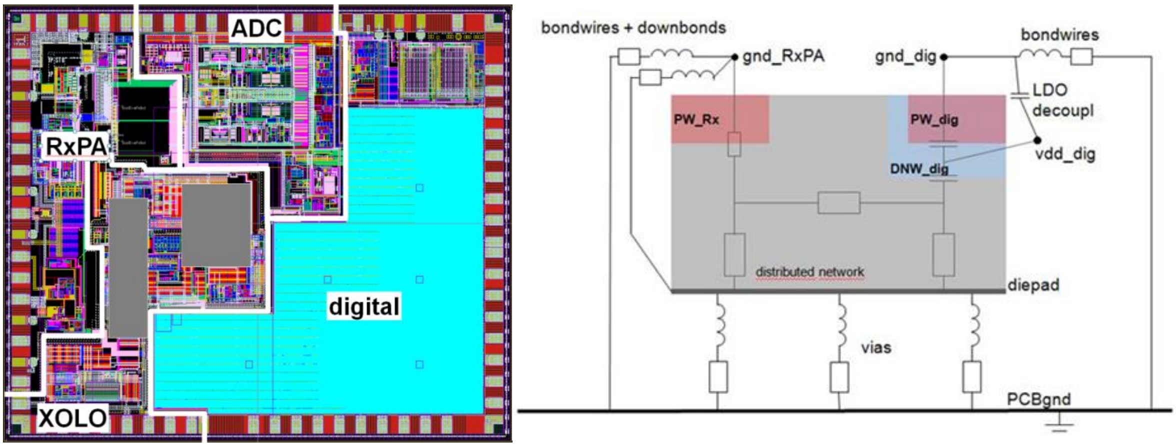

Fig. 5: **Left:** Integrated RF-CMOS automotive transceiver design. **Right:** Floorplan model for isolation and grounding strategies.

In order to minimize interference issues and coupling effects in RF products, it is essential to apply proper floorplanning and grounding strategies. The interaction of the IC with its physical environment needs to be accounted for, so as to certify that the final packaged and mounted product meets the specifications.
The first focus is on the key requirements to address physical design issues in the early design phases of complex RF designs. Typical physical design issues encountered, such as on-chip coupling effects, chip-package interaction, substrate coupling and co-habitation, have been investigated.
The main challenges are the first order prediction of cross-domain coupling. Therefore we apply a floorplan methodology to quantify the impact of floorplanning choices and isolation grounding strategies. This methodology is based on a very high level floorplan EM/circuit simulation model, including the most important interference contributors and including on-chip, package and PCB elements, to be applied in the very early design phases (initial floorplanning).
The overall model of a complete RF product contains the following parts (see Fig. 5):

- On-chip: domain-regions, padring, sealring, splittercells, substrate effects.
- Package: ground and power pins, bondwires/downbonds, exposed diepad.
- PCB: ground plane and exposed diepad connections.

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