Chapter 1
The COMSON Project

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Abstract This chapter serves as an introduction into the outcome of the COMSON project, and links the subsequent chapters to the overall idea of COMSON and its objectives. We start with a discussion of the state-of-the-art and open problems in nanoelectronics simulation at the timepoint when the COMSON Project was started. Therefrom the main scientific objectives of the COMSON project are derived. Special attention is devoted to a uniform methodology for both testing the new achievements and simultaneously educating young researchers: All mathematical codes are linked into a new Demonstrator Platform (Chap. 8), which itself is embedded into an E-Learning environment (Chap. 9). Subsequently the scientific objectives are shortly reviewed. They comprise: (i) Development of new coupled mathematical models, capturing the mutual interactions between the physical domains of interest in nanoelectronis. These are based on the PDAE approach (Chap. 2). (ii) Investigation of numerical methods to simulate these models. Our focus is on dynamic iteration schemes (Chap. 3) and for efficiency on MOR techniques (Chaps. 4–6). (iii) Usage of models and simulation tools for optimal design of nanoelectronic circuits by means of multi-objective optimisation in a compound design space (Chap. 7).

1.1 Trends in Microelectronics

The design of complex integrated circuits ICs requires adequate simulation and optimisation tools. The current design approach involves simulations and optimisations in different physical domains (device, circuit, thermal, electromagnetic) as well as in electrical engineering disciplines (logic, timing, power, crosstalk, signal

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M. Günther (ed.), *Coupled Multiscale Simulation and Optimization in Nanoelectronics*, Mathematics in Industry 21,
DOI 10.1007/978-3-662-46672-8_1

integrity, system functionality). Our interests focus on the physical aspects, which are fundamental for characterising circuit behavior on an electrical engineering and system oriented level. To limit the complexity of the design task, these domains are currently treated in isolation ("divide and conquer" approach), and dedicated simulation and optimisation tools have been developed for the individual domains. However, this methodology approaches its limits of validity. As semiconductor technology is progressing down to the nanometer regime, it turns out that the complexity in simulating and optimising designs goes beyond the capabilities of the software and design environments used so far. Several shortcomings are clearly visible:

- With ever smaller characteristic dimensions, higher operating frequency, and increasing power density many simplifying assumptions are losing their validity. Particularly, coupling effects between the different physical domains as well as 2D/3D and higher order nonlinear effects have to be taken into account.
- Due to very high levels of integration, simulation times are becoming prohibitively long because of growing problem size and coupling effects.
- More complex design specifications have to be satisfied in a widely extended design and parameter space, while simulations for assessing a design with a given parameter configuration get more costly.

Clearly, substantial progress in this situation is not possible by just improving the single components of the design system being used, and this observation led to the setup of the COMSON project.

1.2 Scope of the COMSON Project

The COMSON project was initiated by three major European semiconductor companies in cooperation with five academic partners from Europe being experienced in simulation and optimisation of integrated circuits. The primary objective was to combine the expertise distributed over the partner nodes in their particular fields in a joint effort, to get a more global progress for the coupled systems as a whole.

Mathematical modelling and the development of numerical methods were seen as key enablers in this project. To cope with the coupled nature of problems, it was planned to pursue cosimulation strategies, where the different domains are described by Partial Differential-Algebraic Equations PDAEs or ordinary Differential-Algebraic Equations DAEs, which are – as far as possible – simply coupled by source terms or boundary conditions. For their numerical solution dynamic iteration schemes were appealing, since they naturally exploit the widely separated spectrum of time scales inherent in the various domains.

As a promising side effect of this approach it was seen that it offers to replace parts of the huge coupled system by reduced order models at least for some of the domains. So, linear and nonlinear Model Order Reduction MOR became another essential part of research in COMSON.

Finally, multi-objective optimisation in the very complex design space formed the third mathematical item of research.

The global view introduced in COMSON by coupling domains in simulation and optimisation did not only stimulate mathematical research, but also imposed two methodological problems:

- How can the new developments be assessed at hand of real life industrial designs, without implementing them into all of the commercial design tools used by the industrial partners?
- How can the transfer of knowledge be organised to assure that a researcher working at a – possibly multi-domain – coupled problem has the background information about all of the domains being involved?

For the COMSON project, these questions were answered by the decision to include the development of a software *Demonstrator Platform* into the project, as well as an E-Learning environment into which both the *Demonstrator Platform* and the real life applications foreseen as a reference problem are embedded.

In total the scope of the COMSON project comprises

- Mathematical research on modelling and discretisation of coupled PDAE systems, model order reduction, and optimisation
- And a methodological part by linking a new *Demonstrator Platform* for coupled simulation and benchmark problems of industrial relevance into an E-Learning environment.

The project name COMSON is derived from this scope: "**CO**upled **M**ultiscale **S**imulation and **O**ptimisation in **N**anoelectronics". The following sections will give a more detailed introduction into the single parts.

1.3 Methodology

In the following we explain the methodology (linkage of a *Demonstrator Platform* and E-Learning environment) used for both testing mathematical methods and educating young researchers.

Since the general scope of COMSON was too comprehensive for the restricted project time, research and development were focused on solving a few benchmark problems. The latter were specified by the industries, close to actual real life designs of medium complexity. Academic abstractions and simplifications should be avoided. Hence actual technological data and design specifications were to be used, and physical models as well as compact transistor models being state-of-the-art have been taken as a reference.

Even though there were only a few benchmark problems specified, their simulation and optimisation requires to couple all of the domains which had been considered to be relevant: Semiconductor devices, circuits, interconnects, electromagnetic EM fields, and heat flow. To this end the *Demonstrator Platform* concept was introduced, to provide an experimental framework in software for coupled simulation of the various domains. This gives excellent opportunities to test new numerical methods even in an early stage, and to make sure that they contribute to handle the coupled problems of interest. At the end, the *Demonstrator Platform* offers all coupled simulation capabilities being necessary for multi-domain optimisation of the benchmark problems. To realise this concept, and to demonstrate its functionality, became a key objective of the project.

Another methodological aspect was to provide means for rapid dissemination of knowledge over the geographically widespread partner nodes of the project. Somehow, every project member had been active in this field before, however with different focus and target applications. Now, since all of the partners were starting towards the same objectives – namely to develop and implement methods for coupled simulation and optimisation of the benchmark problems specified by industry – quick and reliable exchange of knowledge became very essential for the project. Having the complexity of multi-coupled simulation and of advanced design specifications as well as the different status of knowledge of researchers in mind, the COMSON members were convinced about the needs to include E-Learning facilities into the project. A natural step at this stage was the decision to embed the *Demonstrator Platform* into the E-Learning environment. This opened very flexible and valuable means for researchers, at any level of experience, to learn about models, methods and backgrounds of coupled nanolectronics simulation and design.

1.3.1 The Demonstrator Platform

1.3.1.1 Objectives and Benefits

The main objective of the *Demonstrator Platform* was to provide an experimental software platform for coupled simulation, which serves as a testbench for new models and methods, and finally offers an adequate simulation tool for optimisation of the benchmark design problems in a compound design space.

By the rule to integrate their new developments – be it model codes or mathematical methods – into the platform, the researchers get a natural test bench with state-of-the-art models and parameters from the different domains, rather than academic simplifications. And they get immediate feedback on the capability to address problems of industrial relevance. Furthermore, it is assured that the individual contributions seamlessly integrate into the whole system from the early beginning.

Another benefit of such a platform is to collect all knowledge about models, methods, and coupling principles. This way a homogeneous embedding into an E-Learning environment becomes possible, thus offering excellent opportunities for transfer of knowledge and mutual stimulation of new research.

1.3.1.2 State of the Art

Since the development of the coupled device/circuit simulators MEDUSA [5] and CODECS [10], there is a long tradition in coupling *two* domains in one code. At present there are powerful commercial tools like the platforms MEDICI (Synopsys Inc.) and ATLAS (Silvaco International) for coupled device/circuit simulation in use. However, they aim at device engineering and device characterisation with a very limited number of transistors. Hence they cannot be used for designing integrated circuits of a medium size complexity, nor do they allow for experiments with new mathematical algorithms from outside the software companies.

Coupling of device and circuit problems under a rigorous PDAE framework was introduced in [15, 17]; this served as a basis for the work to be done here.

Signal propagation effects have a large impact on integrated circuits performance, in general, and therefore coupled interconnect/circuit simulation is widely practised since a long time. Roughly, there are two mainstreams: One is to solve the telegraphers equations for coupled interconnect lines analytically under some simplifying assumptions, ending up in a transmission line (T-Line) model being built from controlled sources for circuit simulation [12]. The other one is to split the interconnect lines into small pieces, which are modelled by lumped R-, L-, and C-elements for circuit simulation. Due to mutual coupling, the corresponding resistance/conductance, inductance, and capacitance matrices are very large in general, and almost dense. Therefore some kind of network reduction or MOR is applied before including them into circuit simulation [2, 16].

Fully bidirectional coupling of interconnect and circuit simulation is reported in several papers, see e.g. [8, 11, 13], and the PDAE setting of this coupled problem was introduced in [9].

Coupling from EM field simulation to circuit simulation is well established in the literature and in industrial practice, however often under restrictive assumptions. Most approaches pursue the concept of partially equivalent electrical circuits (PEEC) developed by A.E. Ruehli [14], and apply linear MOR techniques for getting circuit models of a reasonable size. Alternatively, field simulators often generate scattering parameters (S-parameters) for an electro-magnetic component, which are used in circuit simulation.

Closer coupling between EM field and circuit simulation is necessary for handling the substrate noise problem in mixed-signal ICs [4], and for analysing mutual interaction of on-chip integrated passives (inductors) with semiconductor devices on radio frequency RF chips. To this end some powerful commercial tools have been developed by the companies Magwel and Sonnet Software, for example.

The coupling of the circuit domain with the thermal domain is straightforward, in principle, since due to the electrothermal analogy any circuit simulator can be "misused" for analysing thermal problems, once the latter are modelled by lumped elements [7]. This kind of coupled simulation is often done in practice. For small sized problems the more general approach of directly coupling a 2D or 3D thermal solver and a circuit simulator was pursued, see e.g. [19]. Finally, a general PDAE oriented framework for coupling thermal and circuit problems was developed in [3].

The coupling of the device and the thermal domain was mainly driven by power electronics applications, and started in the late 1970s [1]. While in the beginning the coupling terms were pretty simple, more consistent models evolved since 1990 [18]. Overall, this kind of coupling has found much attention, and is very well developed.

As an extension of the electro-thermal analogy to other physical domains, the simulator fREEDA [6] was developed for simulation of coupled multiphysics problems in an open source project. It is based on a flexible modeling concept, such that a network built from elements from different physical domains can be brought into equilibrium under an energy norm. Clearly, the scope of this approach is on the physical modeling side, while ours is more focused on mathematical analysis and numerics of coupling existing physical models.

In summary it can be stated that bilateral coupled simulation has been extensively investigated, and is implemented in a variety of tools and models which are used in academic and industrial practice. However, simultaneous coupling of all the domains which are addressed here under a common mathematical framework of DAEs/PDAEs, and with inclusion of Model Order Reduction is new, to our knowledge. Furthermore, we are not aware of any other attempt to tightly embed a software package for coupled simulation in multiple domains into an E-Learning environment, for the ease and flexibility of transfer of knowledge.

1.3.1.3 Basic Concepts

To achieve an optimal design in the very complex design space, a multi-objective optimiser will interact with a simulation platform which provides consistent data about all parts of the design specifications, inclusive their mutual dependencies. To this end the platform operates on a hierarchy of parameterised subdomains, which are connected in a common network as a carrier. In the simplest case, the subdomains on top level are electric (sub)circuits. The subdomains on the lower levels can either be other subcircuits, or semiconductor devices, or interconnects, or EM domains, or thermal domains, or Reduced Order Models ROMs for one of these domains (see Fig. 1.1).

The network approach implies coupling of domains by source terms or boundary conditions. This will not be flexible enough in certain cases, hence the subdomains may constitute internally coupled problems by themselves. However, with the network approach it requires less efforts in general to include existing model codes. Furthermore, it is well suited for mathematical analysis and development of numerical methods.

Mathematically, the coupling of domains in a network means to couple partial differential equations PDEs or differential algebraic equations DAEs by algebraic or differential algebraic equations, thus getting PDAE systems. The concept is to solve them by co-simulation in dynamic iteration schemes. To cope with the complexity, comprehensive physical subdomain models must be substituted by ROMs. Noteably, the ROMs should be parameterised, in order to be efficient along several steps of the optimisation process. For the same objective it is an important aspect of the models

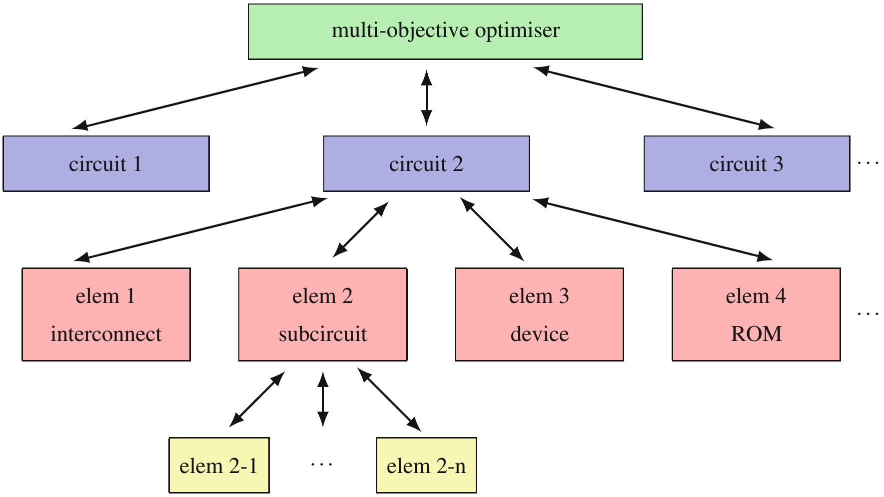

Fig. 1.1 The *Demonstrator Platform* is working on a hierarchy of parameterised subdomains

and codes to provide efficient calculation of sensitivities. Finally, for estimation of yield, an efficient handling of technological spread is a prerequisite.

1.3.2 E-Learning

One of the main aims of the CoMSON project was to define and to develop a system of E-Learning in Industrial Mathematics with applications to Microelectronics, in order to facilitate the exchange of information; to share resources, scientific and educational materials; to create common standards; to facilitate the use of advanced tools. The common idea of this project was to create a bridge being able to fill the gap that exists in the knowledge flow from University to Industry and vice-versa, and to overcome problems due to Intellectual Property claims raised by the Industries working together in the project.

1.4 Modelling, Simulation and Optimisation

The modelling is based on the PDAE approach. For numerical simulation efficient methods have to be used, applying dynamic iteration schemes and MOR techniques. Based on these models and simulation tools, multi-objective optimisation is addressed.

1.4.1 Partial Differential Algebraic Equations

Up to now, mathematical research has been mainly focused on models of one single domain, e.g. semiconductor equations. Including effects of other domains like thermal and electromagnetic coupling and high frequency aspects to improve the accuracy of the models results in so-called *Partial Differential-Algebraic Equations* (PDAEs), which couple differential-algebraic network models for lumped descriptions and partial differential equations for the spatially distributed elements and effects via source terms or boundary conditions. This approach requires new analysis with respect to consistency and validity of the overall PDAE model that links different domains and levels of physical description, existence of solutions, and robustness and efficiency of the numerical methods being applied for solving the extended sets of equations.

New, robust and efficient methods are needed to solve the resulting equations. Depending on the type of coupling and accuracy to be achieved within simulation, two approaches are feasible to cope with these coupling effects:

- Simulator coupling for systems of PDAEs based ony dynamic iteration and
- Model order reduction.

1.4.2 Dynamic Iteration

In the first approach, all *dynamic* effects (for circuits, devices, thermal effects etc.) are modeled and simulated separately using their own simulation package which is based on their own time stepping algorithm in the numerical kernel. In this approach, modular, i.e., distributed time integration methods are quite natural which exploit different time constants of the single models by using different time step sizes (multirate approach).

Assuming the packages are equipped with appropriate interfaces, the coupling of the PDAE model via right-hand sides, source terms or boundary conditions can be done by coupling the simulators at communication time points. As the PDAE systems are coupled dynamically, an outer iteration process (dynamic iteration) has to be performed until getting convergence within a macro time step from one communication time point to the next one. Equipped with adequate relaxation and overlapping techniques, dynamic iteration schemes have to be derived which can guarantee a stable error propagation from one macro time step to the next one, thus ensuring rapid convergence as well as robustness and stability of the overall scheme used for coupling the models and simulators, respectively. This *distributed time integration* approach can quite naturally exploit the multirate, i.e., multiscale behavior in the time domain, as the different time stepping algorithms can use different time step sizes in accordance with the different time constants of the single models.

1.4.3 Model Order Reduction

If all the domains are coupled together for optimisation, then the resulting systems will become very large. Moreover, they have to be solved very often, in particular if multi-objective optimisation methods are employed and/or yield improvement is one of the optimisation targets. In this setting the usage of reduced order models is appealing, since it helps to save simulation time and memory needs, and supports to focus on those features of the various domains which are the most relevant ones for achieving the design objectives. Another benefit of using reduced order models might be in some cases to enable global optimisation of a design, while hiding technological or circuit design details which are related to intellectual property issues.

One way to obtain reduced order models is to develop structural macromodels or behavioral descriptions, or to employ network reduction techiques. Alternatively, for a given set of equations – which are possibly obtained by (semi)discretisation of the original problem – numerical MOR techniques may be used to get a system of the same structure but reduced dimension. The latter approach, quite well established in the electronics design community, was to be pursued in the COMSON project. Clearly, to be useful in the framework of design optimisation, the MOR has to generate *parameterised reduced order models*, and should be insensitive against small changes of the technological parameters. Other needed features are *maintaining the DAE/PDAE structure of the models*, and tuning for usage of reduced order models in simulation of *large nonlinear systems*.

1.4.4 Optimisation

Aiming at a realistic, medium size coupled problem of industrial relevance, one faces a multiple domain space with a large number of design objectives and restrictions (about 10–100), and works in a very complex parameter space (several hundreds to thousands of parameters). As far as manufacturability requirements are concerned, optimisation deals with discrete as well as continuous variables. In addition, any evaluation of a model (functions, constraints) is very costly (each requiring a coupled simulation), and possibly noisy. So usage of sensitivity analysis techniques is advisable, but how they can be based on noisy simulation results will require special attention.

Last, the reliability and robustness of a simulator depends on the accuracy of the implemented models and, in particular, the model parameters. In fact each separate model already has several hundreds of parameters. Therefore, in order to calibrate the models, new advanced and efficient parameter extraction techniques are needed.

The hot spot benchmark example, a Power-MOS circuit introduced by STMicroelectronics as an example for electro-thermal coupling, will show how all these different levels are linked: in Sect. 2.2.2, the PDAE model describing the hot spot benchmark example is carefully discussed. Simulation results for the coupled system based on the *Demonstrator Platform* methodology can be found in Sect. 8.3. Finally, Chap. 7 discusses how to embedd an optimization flow in an industrial environment to optimize the benchmark circuit with respect to the peak current.

References

1. Adler, M.S.: Accurate calculations of the forward drop and power dissipation in thyristors. IEEE Trans. Electron Devices **25**(1), 16–22 (1978)
2. Bai, Z., Dewilde, P., Freund, R.: Reduced order modeling. In: Schilders, W., ter Maten, E.J.W. (eds.) Handbook of Numerical Analysis, vol. XIII, pp. 825–895. NorthHolland/Elsevier, Amsterdam (2005)
3. Bartel, A.: Partial Differential-Algebraic Models in Chip Design-Thermal and Semiconductor Problems. Fortschritt-Berichte VDI, vol. 391, Reihe 20. VDI-Verlag, Düsseldorf (2004)
4. Brandtner, Th.: Chip-package codesign flow for mixed-signal SiP designs. IEEE Design Test Comput. **23**(3), 196–202 (2006)
5. Engl, W.L., Laur, R., Dirks, H.K.: Medusa – a simulator for modular circuits. IEEE Trans. Comput. Aided Design Integr. Circuits Syst. **1**(2), 85–93 (2006)
6. Freeda: An Open-Source Multiphysics Simulator [Online]. Available: http://www.freeda.org/
7. Fukahori, K.: Computer simulation of monolithic circuit performance in the presence of electro-thermal interactions. Ph.D. thesis, University of California, Berkeley (1977)
8. Grotelüschen, E., Grabinksi, H., Rochel, S., Winkel, T.-M.: LOSSYWIRE – a model implementation for transient and AC analysis of lossy coupled transmission lines in the circuit simulator ELCO. AEÜ **49**, 37–43 (1995)
9. Günther, M.: Partielle Differential-Algebraische Systeme in der Numerischen Zeitbereichsanalyse Elektrischer Schaltungen. VDI-Verlag, Düsseldorf (2001)
10. Mayaram, K.: CODECS: a Mixed-level Circuit and Device Simulator. University of California, Berkeley (1988)
11. Orhanovic, N., Tripathi, V.K.: Nonlinear transient analysis of coupled RLGC lines by the method of characteristics. Int. J. Microw. Millim. Wave Comput. Aided Eng. **2**(2), 108–115 (2007)
12. Schutt-Aine, J.E.: Static analysis of V transmission lines. IEEE Trans. Microw. Theory Tech. **40**(4), 2151–2156 (1992)
13. Roychowdhury, J.S., Newton, A.R., Pederson, D.O.: Algorithms for the transient simulation of lossy interconnect. IEEE Trans. Comput. Aided Design Integr. Circuits Syst. **12**, 96–104 (1994)
14. Ruehli, A.E.: Equivalent circuit models for three-dimensional multiconductor systems. IEEE Trans. Microw. Theory Tech. **22**(3), 216–224 (1974)
15. Selva Soto, M., Tischendorf, C.: Numerical analysis of DAEs from coupled circuit and semiconductor simulation. Appl. Numer. Math. **53**(2–4), 471–488 (2005)
16. Sheehan, B.N.: Realizable reduction of RC networks. IEEE Trans. Comput. Aided Design Integr. Circuits Syst. **26**(8), 1393–1407 (2007)
17. Tischendorf, C.: Coupled Systems of Differential Algebraic and Partial Differential Equations in Circuit and Device Simulation. Humboldt Universität zu Berlin, Habilitation (2004)
18. Wachutka, G.K.: Rigorous thermodynamic treatment of heat generation and conduction in semiconductor device modeling. IEEE Trans. Comput. Aided Design Integr. Circuits Syst. **9**(11), 1141–1149 (1990)
19. Wünusche, S., Clauß, C., Schwarz, P., Winkler, F.: Electro-thermal circuit simulation using simulator coupling. IEEE Trans. Very Large Scale Integr. (VLSI) Syst. **5**(3), 277–282 (1997)