Coupled device, circuit and interconnect simulation

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Abstract:

In this paper, we discuss several aspects that are related to coupling device, circuit and interconnect simulation software. Straightforward co-simulation is too time-consuming, and hence reduced order modelling must be used in order to summarize the behaviour of individual simulations into compact models. From a theoretical point of view, the problem is complicated by the fact that equations of different type are being coupled. Mathematical techniques are indispensable for guaranteeing acceptable simulation times.
The European project CODESTAR aims at providing a framework in which the aforementioned coupled simulations can be performed. The examples given in this paper have been taken from that project.

1. Introduction

For the design of complex integrated systems, knowledge of the electromagnetic coupling in passive components like inductors, capacitors and critical parts of net lists are indispensable. Today's extraction software tools use the static approach to quantify this coupling, thereby ignoring the Maxwell or wave-dynamic aspect of electromagnetic radiation. Whereas such an approach is valid at moderate frequencies, high-frequency effects are a major design concern for the next generation of architectures. The International Technology Roadmap for Semiconductors recognizes the lack of appropriate future design tools. In particular design tools that include high frequency effects are a difficult challenge for a successful implementation of the 65 nm node corresponding to circuit frequencies exceeding 5 GHz. The effects are physically understood, but TCAD software programs that can deal with them are not available. Figure 1 (inspired by [6]) summarizes the effects that play a role in the analysis of passive structures: electric and magnetic coupling of segments through air and oxide, current crowding at edges due to the skin effect and eddy currents, proximity effects due to presence of nearby segments, radiation, substrate injection, and substrate current caused by ohmic, eddy and displacement currents.

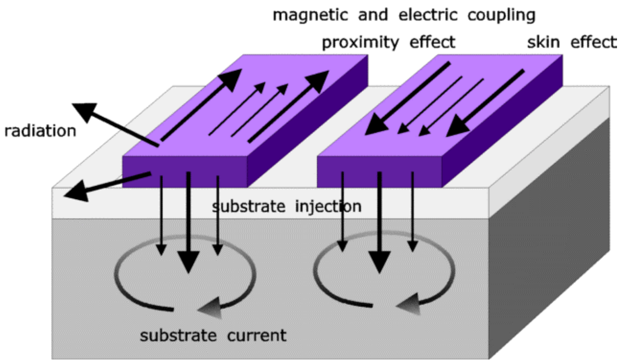

Figure 1. Summary of effects occurring in passive structures.

To accelerate the design of high-frequency passive on-chip structures and interconnects, the development of new modelling algorithms is needed. This task is addressed in the CODESTAR project. The resulting software will be used in a design cycle, starting from standardized geometrical data (GDS II format), and returning as output a manageable simulation net list that can be coupled to a network simulator such as SPICE or Pstar.
The situation becomes even more complicated when substrate noise analysis is required. As feature sizes decrease, substrate coupling noise may cause design failures and poor yields due to injected currents disturbing the operation of sensitive components. Any design targeted at sub-quarter micron process technologies may be vulnerable to substrate parasitics. Rule of thumb methodologies may turn out to be inadequate or lead to over-engineered designs. Reliable results can only be obtained by taking into account semiconductor physics. Tools like SubstrateStorm from Cadence perform such analyses by supplying RC net lists and reduced RC net lists, which can be coupled to network simulators. More accurate results are obtained when drift-diffusion models of semiconductor devices are used. In section 3 an example is given discussing precisely this topic, showing that it is indeed possible to couple device, circuit and interconnect simulations to obtain reliable models for substrate coupling noise.

2. Mathematical aspects of coupling

For all three types of simulation mentioned in the title of this paper, software modules are available to perform analyses. Especially for device and circuit simulation, sophisticated programmes exist which contain decades of experience and optimally tuned numerical methods. Unfortunately, straightforward coupling of these software packages is not feasible because of the computational burden. In addition, a detailed mathematical analysis reveals that there are hidden problems in constructing such couplings. This has been demonstrated in a number of papers by Ali and Günther [1],[2]. They derived appropriate coupling conditions for diodes and linear RLC networks, the latter being modelled by Modified Nodal Analysis. Due to the very different time scales related to the relaxation of diodes to equilibrium and to the electric current in the network, it is appropriate to model the devices by stationary drift-diffusion equations. This multi-physics approach yields a coupled system of elliptic partial differential equations (PDEs) and differential-algebraic equations (DAEs), leading to the new class of partial differential-algebraic equations (PDAEs). Günther et al show that, when using the appropriate coupling conditions, a solution exists. They have also analysed the case of coupling circuit equations to telegrapher's equations, the latter being of a hyperbolic nature. The message that is contained in their publications is that care should be taken in coupling different types of systems of differential equations, and that the existence of a solution is certainly not obvious.

Assuming that appropriate coupling conditions have been specified, we can return to the question how to approach the coupling of different aspects. As mentioned, straightforward coupling is out of the question, and other ways have to be found. An approach that is gaining popularity, also in other disciplines (such as computational fluid dynamics, or mechanical engineering) is to use reduced order modelling to capture the dominant behaviour into a compact model. In the electronics industry, this approach has been used in recent years to couple Maxwell-based simulations of passive interconnect structures with circuit simulations. The results of the electromagnetic simulations are projected onto a lower dimensional space by using well-known Krylov subspace methods such as the Arnoldi method and the Lanczos method. These methods are iterative in nature, and attempt to locate dominant eigenvalues.

Although many different approaches have been proposed for the reduced order modelling of interconnect structures, only a few have the property that the passivity of the original system is preserved. Clearly, this is essential when generating a realization of the reduced order model in terms of a net list: if the reduced model is not passive, it can generate energy and the simulation will explode. A well-known method suffering from this problem is PVL (Padé via Lanczos) [3]. This explains why, in recent years, methods have been designed with the constraint of passivity in mind. PRIMA [7] and the SVD-Laguerre method [4] are examples of methods preserving passivity.

There are several ways to extract reduced order models from electromagnetic simulation results. The first method is to semi-discretize the Maxwell equations, i.e. retain the time dependence of the equations. The resulting system can then be viewed as a (large) state-space system, and for such systems reduction techniques can be applied directly. An alternative method is to perform the simulations (or, alternatively, use measurements) and store the results in the time or frequency domain, and then attempt to find a small state-space model. Both techniques are being applied, the latter clearly delivering much smaller systems of equations.

Sometimes, it may not be necessary to use the full-wave Maxwell equations to describe the behaviour of passive structures. The Partial Element Equivalent Circuit (PEEC) method [8] automatically leads to much smaller descriptions of the electromagnetic behaviour. The price being paid is in the assumptions, but a nice side effect is that using reduced order modelling techniques can reduce the models generated even further. This is demonstrated in the example shown in Figure 2. Here, a spiral conductor is constructed of thin conducting plates. For this problem, the ports correspond to the two endpoints of the conductor, and in our tests we consider the H_{12} element of the transfer matrix. The original PEEC discretization led to a system with 522 unknowns. As can be seen from Figure 3, a reduction to a much smaller system of dimension 10 already yields rather accurate results. It should be mentioned, however, that the reduced order modelling technique employed here made use of a so-called shift-and-invert technique to locate the eigenvalues that really matter for the behaviour. If this is not done, the results are less impressive and reduced order models of larger dimension are necessary.

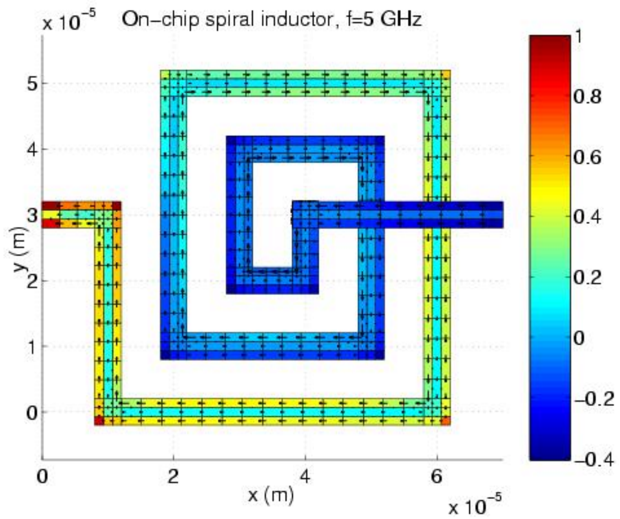

Figure 2. Scaled currents and charge densities for the first resonant mode of a spiral inductor.

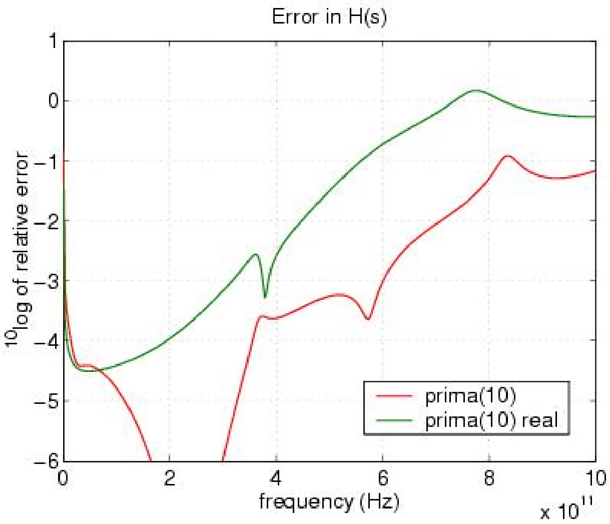

Figure 3. Error in (1,2) element of transfer matrix, using different versions of PRIMA combined with a shift-and-invert technique.

Although most publications focus on coupling electromagnetics with circuit simulation, the coupling of all three aspects as mentioned in the title of this paper also provides many challenges. When coupling the stationary drift-diffusion equations to the Maxwell and/or circuit equations, a rather large system of equations is found for which reduced order modelling techniques have not yet been applied to the best of our knowledge. Instead, the device simulation software is coupled to the reduced order circuit models, and a co-simulation is performed. When doing this (see the example in section 3), the electromagnetic/circuit equations and device equations are solved alternately, and slow convergence of the outer loop is observed especially at moderate and high frequencies. This problem can be solved by using vector extrapolation techniques, such as the minimum polynomial extraction (MPE) method or the reduced rank extrapolation (RRE) method. First tests indicate that this is a successful approach, leading to a drastic reduction in the number of outer iterations. In the next section, the results of a simulation are provided.

3. Example: self-consistent calculation of substrate currents at high frequencies

The aggressive RF consumer market requires early prediction of circuit behaviour, including layout and substrate effects, but for the moment, no tools are available for accurate modelling of large real-life interconnect structures on semiconductor substrates at RF frequencies.

Recently an approach was presented [5], [9], [10] to model the electromagnetic environment of on-chip structures and passives, taking carefully into account the behaviour of semi conducting materials and high-frequency effects. The Maxwell equations are solved together with Ohm's law for conductors and a drift-diffusion model for semiconductors as constitutive equations. In order to deal with a potential description (using the electric scalar potential and magnetic vector potential), we introduced the new concept of a 'ghost field' to stabilise the numerical solution schema. This ghost field is an extra-added scalar field that carries no energy, but facilitates the calculations.

As an example we show the first calculations of the current in a ring structure on top of a semi-conducting substrate.

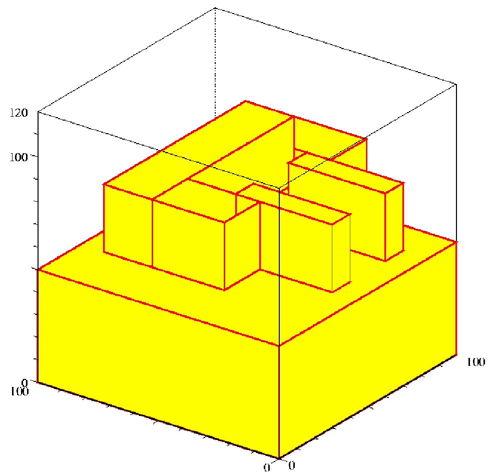

Figure 4. The ring structure under study.

The ring is metallic with $\sigma = 10^8$ S/m, on top of a moderately doped silicon substrate (Figure 4). The current density in the ring plane (Figure 5) and in the substrate (Figure 6) was calculated at a frequency of 0.15 Ghz.

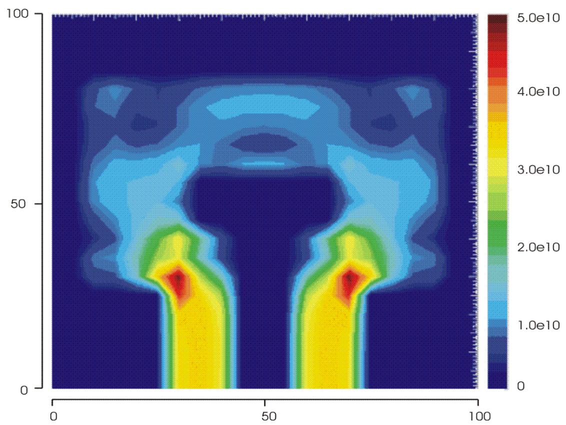

Figure 5. Magnitude of the current density in the metal ring.

The eddy currents in the substrate have the opposite direction of the currents in the metal ring, as requested by Lenz' law. The magnitude of the substrate currents density is at the given frequency five orders of magnitude smaller than the current density in the metal ring.

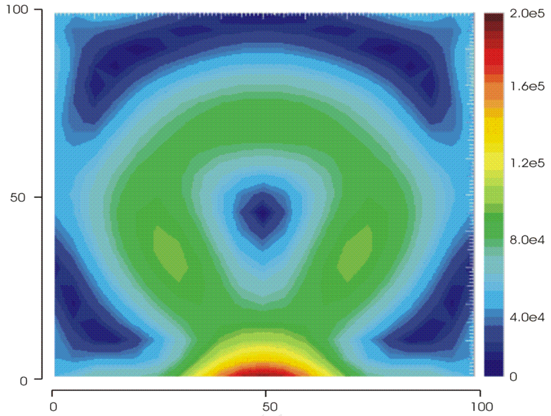

Figure 6. Magnitude of the current density in the substrate.

4. Conclusion

Coupled device, circuit and interconnect simulation is currently within reach, but one has to take care of underlying (seemingly hidden) problems and make use of sophisticated numerical techniques. Adequate coupling conditions have to be specified in order to overcome the problem related to the difference in type of equations (ODEs. PDEs, DAEs). Reduced order modelling has to be employed to capture the dominant behaviour into compact models that can be coupled. In the process of reducing, one should take care of the conservation of physical properties, such as passivity. State-of-the-art algorithms for determining dominant eigenvalues may lead to models of drastically reduced orders. When coupling full or reduced order models to obtain a coupled simulation result, employing accelaration methods (MPE, RRE) is essential to keep the simulation times within reasonable limits. Sometimes, models based on simplifying assumptions (PEEC) can aid in reducing computation times and yet obtain realistic results.

5. Acknowledgements

Wim Schoenmaker and Wim Magnus are gratefully acknowledged for valuable comments and inspiring discussions. Thanks are also due to Pieter Heres and Menno Verbeek for their assistance in preparing this paper. The work described here is partly financially supported by the European Commission in the framework of the CODESTAR IST project.

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Activities in the area of reduced order modelling are organised by WG02 and WG13 of the European MACSI-net initiative (Mathematics, Computing and Simulation for Industry). Information can be found on:

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