Eidgenössische Technische Hochschule Zürich
Ecole polytechnique fédérale de Zurich
Politecnico federale di Zurigo
Swiss Federal Institute of Technology Zurich

Computer Science Department
Advanced Power Semiconductor Laboratory

Prof. Dr. Peter Arbenz
Dr. Ivana Kovacevic-Badstuebner

Parallel electromagnetic solver for 3D modeling of power semiconductor modules

Proposal for a master thesis

Introduction

The ElectroMagnetic (EM) modeling of power semiconductor modules includes the calculation of both the EM field generated in the surrounding space and the electrical functionality of the device under test affected by the EM field distribution. As the electrical properties of power semiconductor modules and the power electronics system employing these modules are typically modeled in the circuit simulators, the EM modeling of power modules can be defined as field-circuit coupled problems. It has been shown that the Partial Element Equivalent Circuit (PEEC) method represents a very efficient numerical technique for solving the field-circuit problems as the way in which the PEEC method is derived provides a link between the field theory and circuit theory automatically. The derivation of the PEEC method starts from the integral formulation of Maxwell's equations either in the time domain or frequency domain. The frequency domain formulation is derived from:

$$KVL: \qquad \frac{\vec{J}(\vec{r},\omega)}{\sigma} + j\omega \cdot \int_V \frac{\mu_0 \vec{J}(\vec{r},\omega)}{4\pi|\vec{r}-\vec{r'}|}\,\mathrm{d}V + \nabla \frac{1}{\epsilon_0}\int_V \frac{\rho(\vec{r},\omega)}{4\pi|\vec{r}-\vec{r'}|}\,\mathrm{d}V - \vec{E}_\mathrm{S} = 0, \tag{1}$$

$$KCL: \qquad \nabla \cdot \vec{J}(\vec{r},\omega) + j\omega \cdot \rho(\vec{r},\omega) = 0. \tag{2}$$

KVL/KCL are short for Kirchhoff's Voltage/Current Law. Equation (1) represents the Electric Field Integral Equation (EFIE) and (2) represents the continuity equation for electric charges. This system of integral Maxwell equations is solved for the unknown volume current distribution $\vec{J}(\vec{r},\omega)$ and the electric charge distribution $\rho(\vec{r},\omega)$, observing a set of conductors occupying the volume V characterized by the permittivity ϵ_0 and permeability μ_0 of free space. The result of the PEEC discretization procedure is a set of PEEC mesh cells, which can be further defined as PEEC volume cells (υ_k, $k = 1,\ldots,N_\mathrm{V}$) and PEEC surface cells (S_i, $i = 1,\ldots,N_\mathrm{S}$). The current density distribution $\vec{J}(\vec{r},\omega)$ and the electric charge density distribution $\rho(\vec{r},\omega)$ of the conductors, are approximated by piecewise constant basis functions, $\vec{f}_{0k}$ and p_i,

$$\vec{J}(\vec{r},\omega) = \sum_{k=1}^{N_\mathrm{V}} j_k(\vec{r},\omega)\cdot\vec{f}_{0k}(\vec{r}) \quad \rho(\vec{r},\omega) = \sum_{i=1}^{N_\mathrm{S}} \rho_i(\vec{r},\omega)\cdot p_i(\vec{r}). \tag{3}$$

The three dimensional representation of the current flow is defined by the PEEC volume cells, which carry the unknown currents, $\vec{I_k} = \int_{\upsilon_k} J_k \vec{f}_{0k}\,\mathrm{d}\upsilon_\mathrm{k}$, $k = 1,\ldots,N_\mathrm{V}$. The charge density $\rho(\vec{r},\omega)$ of the observed system of conductors gives a 2D representation of the charge over the corresponding volume cells, as the charge resides on the conductor surfaces. Namely, the k-th PEEC volume cells carries a total current I_k in the defined direction $\vec{f}_{0k}$ between two PEEC nodes, e.g. P_l and P_{l+1}. The voltage drop across the k-th PEEC volume cell ΔV_k represents the difference between the potentials of the l-th and $(l+1)$-th PEEC nodes, $\Delta V_k = V_l - V_{l+1}$, and the charges of the PEEC surface cells represent the sources of the PEEC node potentials. Using the Galerkin approach, the PEEC system matrix $\mathbf{M}_\mathrm{sys}$ and PEEC system of equations in a matrix form are given by:

$$\mathbf{M}_\mathrm{sys} = \begin{bmatrix} \mathcal{A} & -(\mathbf{R}+j\omega\mathbf{L}) \\ (j\omega\mathbf{P}^{-1}+\mathbf{Y}) & \mathcal{A}^T \end{bmatrix}, \qquad \mathbf{M}_\mathrm{sys}\begin{bmatrix}\mathbf{V}\\ \mathbf{I}\end{bmatrix} = \begin{bmatrix}\mathbf{V}_\mathrm{S}\\ \mathbf{I}_\mathrm{S}\end{bmatrix}. \tag{4}$$

The $\mathbf{I}_S$ and $\mathbf{V}_S$ are current and voltage sources for the modeled external excitations. The matrix $\mathcal{A}$ is the connectivity matrix, which describes the connection of the PEEC volume cells via the common PEEC nodes. The so-called partial elements filling in the matrices $\mathbf{R}$, $\mathbf{L}$, and $\mathbf{P}$, are calculated from the first three terms in (1). The PEEC system is a linear system of equations, where $\mathbf{L}$ and $\mathbf{P}$ are full and dense symmetric matrices, and it is typically solved using direct solvers.
The main goal of this project is to investigate the parallel implementation of the PEEC method [1] that can allow speeding up both the calculation of the partial element matrices and solving a large PEEC system of linear equations ($> 10^5$ unknowns) starting from an existing PEEC solver implemented in a 3D tool for electromagnetic modeling of power modules.

Scope of work

The student will work on several 3D test geometries and use the 3D PEEC-based tool for electromagnetic modeling of power modules developed at ETH Zurich. The student will first start from the existing PEEC meshing procedure, in order to develop a meshing strategy to allow capturing the high frequency effects inside of conductors. In the second step, the student will implement the parallel computation of the partial element matrices and parallel solving of large PEEC systems of equations, which result from the developed PEEC mesh (geometry discretization) of the given 3D test structures.

Description of the task

The goal of this master thesis is to

1. Develop a meshing strategy to allow capturing the high frequency effects inside of conductors of the given 3D test structures.
2. Parallel computation of the partial element matrices and parallel solving of large PEEC systems of equations using ScaLAPACK.
3. Fast construction and solution of PEEC matrices with varying (geometry) parameters.
4. Investigate performance and speedup of the PEEC solver.

Procedure and deliverables

- After one month: short 15 minute talk on the project, including a schedule with tasks & milestones.
- There will be frequent meetings to check the progress of the work.
- The work is to be documented in a short and concise thesis (LaTeX, PDF). It must be written such that it is intelligible to a fellow-student.
- The thesis is to be presented in a 30 minutes talk.
- The code should be written as clean as possible.

Contact

- Prof. Dr. Peter Arbenz, Computer Science, ETH Zurich, arbenz@inf.ethz.ch
- Dr. Ivana Kovacevic-Badstuebner, APS Lab (D-ITET), ETH Zurich, kovacevic@aps.ee.ethz.ch

References

[1] D. Daroui and J. Ekman. Performance analysis of parallel non-orthogonal PEEC based solver for EMC applications, *Progress in Electromagnetics Research B*, vol. 41, pp. 77–100, 2012, DOI: 10.2528/PIERB12041008.

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