Fully-Coupled Electro-Thermal Power Device Fields

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Abstract—**This paper presents a new solution method to deal with thermal effects in power designs. The new ingredients are: 1) the treatment of the electric and thermal fields are done fully self-consistent 2) the dealing with (fragments of) the transistor fingers by using table models.**

Keywords- electro-thermal, simulation, table models, field solvers

I. INTRODUCTION

Power devices are very challenging from a designer's perspective. Whereas their basic operation principles are rather straightforward, numerous complications can arise due to less than optimal balancing of the current distributions, local heating effects and ultimately failure due to positive feed back loops. Until now thermal issues have been usually addressed by adding a 'thermal verification cycle' to the electrical design flow. This way of working has been 'justified' by the conviction that the thermal response takes place on a much larger time scale than the electrical one. As a consequence, the thermal variation is only noticeable at a much larger length scale and as a consequence, if we want an impression of the thermal field, a coarse-grain thermal mesh suffices to characterize the thermal response. However, we have found (using in-depth and detailed electro-thermal field solving) that this picture can not be sustained. In particular, there are fine-grained variations observed in the thermal plots, thereby falsifying above view point that thermal variations need to be incorporated only on a coarse-grain level. Moreover, the local variations not only impact the local current densities because the electrical conductance depends on the local temperature, but the thermal fields must be determined in a self-consistent way with the electric field intensities, since the latter directly provide the local heat generation. To summarize: power device characterization is only complete if the thermal response is incorporated in a fully consistent way with the electrical response. Popular means to address different problem areas (here: electrical and thermal) is by performing co-simulation. The basic idea is that through an iterative process one visits a series a simulation tools and feeding the latest finding of the prior sub-system simulation into the next one. This process is repeated until convergence (no noticeable updates) is found. Unfortunately, this approach is only applicable if the feedback of one tool on (one of) the other tool(s) is limited. In other words: if the physical coupling is weak. The latter is the case for long range correlations, but as we have argued, the electrical and thermal interfere on quite a local scale. The correlations are short-range and as a consequence co-simulation requires many cycles in order to reach convergence provided it is reached at all and not hooked up a limit cycle or divergence. Therefore, we propose (and present) an alternative to co-simulation, which we may view as a "holistic" or integrated simulation approach. The key idea is to deal with all the degrees of freedom at an integrated level. The cross coupling between sub groups of the degrees of freedom (electrical and thermal) are fully included. These couplings induce flow patterns is the state space which are not reachable in the co-simulation approach and thereby the number of iterations towards the solution is much smaller than in the co-simulation approach. Of course the holistic approach is less generic than the co-simulation approach because the data structures inside 3rd party software tools are usually not accessible. Therefore the couplings can not be determined and prohibiting a holistic solution strategy. As a consequence, the holistic solver must be constructed from scratch. This will be done in the next section.

II. THE INTEGRATED ET SOLVER

A. Electric Field Solver

The electrical part of the holistic field solver addresses the current-continuity equation

$$\nabla\cdot J+\frac{\partial \rho}{\partial t}=0\ ,\ J=\sigma E\ ,\ E=-\nabla V \qquad \rho=-\nabla\left(\varepsilon\nabla V\right) \tag{1}$$

In the present modeling, we will not consider local charging effects. Therefore, the current-continuity equation reduces to a Poisson problem for conductive domains, being interconnects and active devices, i.e. the fingers of the power transistors. On the scale of the die, these fingers are truly microscopic and solving the current continuity equation in a detailed manner inside the device channel (TCAD) would require meshes with a prohibitively large number of nodes.

Therefore, one must refrain from addressing sub-micron device details in the modeling and replace the transistor fingers (or fragments there off) by *compact models* as far as there current-voltage response in concerned. This approach is common in power transistor modeling, where the active channels are replaced by an on-resistance R_{on}. Provided that local heating is not a major concern, this approach suffices. However, it should be remembered that the conductance, $\sigma = \sigma(T)$, is a temperature-dependent material parameter and if the temperature varies over position and time, $T=T(\mathbf{x},t)$, this will effect the solution of (1). So it becomes mandatory to determine $T(\mathbf{x},t)$.

B. Thermal Field Solver

The thermal part of the holistic field solver addressed the heat equation

$$\nabla \cdot Q + \frac{\partial w(T)}{\partial t} = \Sigma_H \ , \ Q = -\kappa \nabla T$$
$$w(T) = C_T \left(T - T^{ref} \right) \qquad (2)$$

In here, **Q** is the heat flux, κ is the thermal conductance and w the local energy storage characterized by the thermal capacitance C_T and T^{ref} is a typical reference (operational, environment) temperature.

The solution of this equation provides the desired temperature information to be fed into (1). However, the solution is only computable, provided that the heat source is known. The source may consist of several contributions. Energy may be converted to heat by radiative absorption. The boundaries of the simulation domain may contain heat-injecting or extracting properties. Besides these sources the Joule self heating is of particular interest.

$$\Sigma_{SH} = E \cdot J \qquad (3)$$

Note that this term is determined by (1) and therefore, is it mandatory to solve (1) and (2) simultaneously. Just as for the active devices in the electrical part of the system, we also apply a compact model for the self heating of the devices. For transistor structures, the self heating is determined as a function of the source-drain voltage, the gate-source voltage and the local temperature. Here we assume that to each gate finger fragment we may assign a unique temperature value, which may vary in going from one fragment or finger to another.

$$\Sigma_{SH}^{device} = V_{DS} I_{DS} \left(V_{DS}, V_{GS}, T \right) \qquad (4)$$

This (almost) completes the definition of our holistic electro-thermal approach. In the present stage we have implemented two kinds of boundary conditions: at metallic contacts we can select electrical voltage boundary conditions or current boundary conditions or a (primitive) circuit may be selected from a build-in library of circuits. The metallic contacts also serve as heat sinks/ sources meaning that fixed temperature boundary conditions can be selected. Alternatively, one may option for thermal-current boundary conditions. The side walls of the simulation domain are dealt with using Neumann boundary conditions. This corresponds to ideal thermally and electrically insulating walls.

Finally we note that the boundary conditions can be time-dependent. Even when the voltages adapt instantaneously to the time-dependent contact voltage: no charge effects are considered in equation (1), we still deal with a transient problem because of the thermal capacitive term in equation (2). Thus our solver will be able to explore in a fully self-consistent way the occurrence of thermal runaway. Of course, predictive simulation requires the availability of accurate compact models over a sufficiently wide temperature range.

C. Compact Device Representation

Despite the fact that we address the electrical and thermal variables from a field perspective we do not sustain this practice all the way down into the active devices. Doing so, would mean imply that the field solving approach not only must be applied at a much smaller length scale (sub micron) but moreover, new degrees of freedom (the electron and hole Fermi levels) must be considered. The purpose of underlying scheme is not to contribute to progress in process and device technology but to provide an EDA tool suitable optimize designs. Just because the active devices are very limited size, we may replace them by entities with negligible volume. The active devices are then only 'visible' through their contacts to which we may assign compact models.

III. SIMULATION OF SELF HEATING IN POWER SWITCHES

In the section we will apply our self-consistent ET solver to a multi-finger power transistor. The simulation confirms our statement made in the introduction that temperature variations appear at a true micro-scale (i.e. at a scale between different transistor fingers).

On this power device, a step function with rise time of 1 microsecond is applied. The voltages and temperatures are calculated self-consistently over a period of 1 ms. Simulation time is 1000 seconds using a state-of-the art single-core simulation server.

In the middle of the active area, the maximum temperature as a function of time is given in Fig 1. The overall temperature rise can hide local differences, as shown in Fig 2. In particular, this figure shows that the finger sections give rise to local temperature differences.

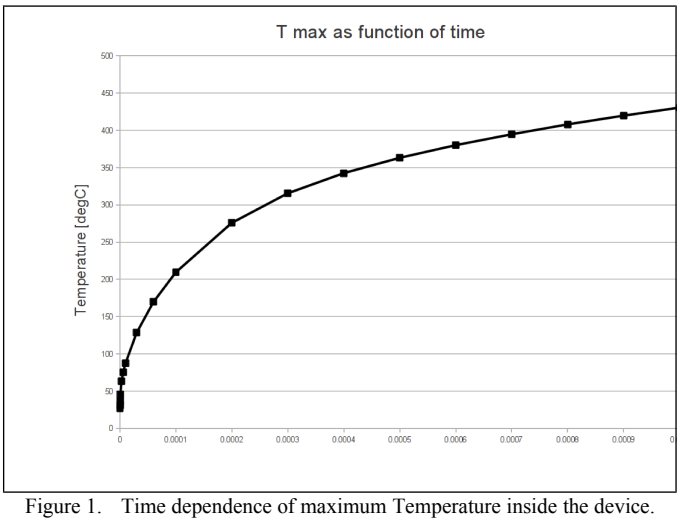

Figure 1. Time dependence of maximum Temperature inside the device.

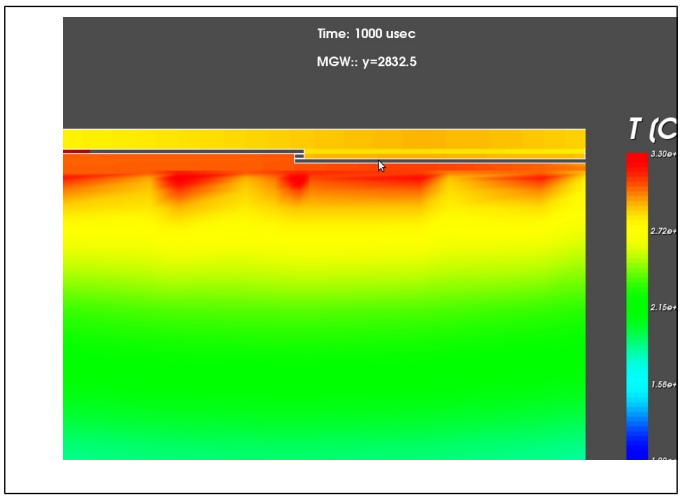

Figure 2. Local temperature variations, cross section

The dependence of electric and thermal conductivity on the local temperature is taken into account, by using a power law model, valid over the full temperature range.

$$\kappa = \kappa_0 T^{-a}$$
$$\sigma = \sigma_0 T^{-b} \qquad (5)$$

The power is dissipated in the different transistor fingers. However we can and have included the dissipation as well as in metalization. The transistor fingers are modeled by using a table model that describes the nonlinear I-V characteristics of the device. The table is created from the dedicated compact model net list model for the device. A successful use of the table is possible provided that it can be used over a sufficient wide range for the input parameters. The reason for this is that the self-consistent solver is using an iterative method for finding the solution and therefore may wander in the search space temporarily into the wrong direction. finding the solution and therefore may wander in the search space temporarily into the wrong direction.

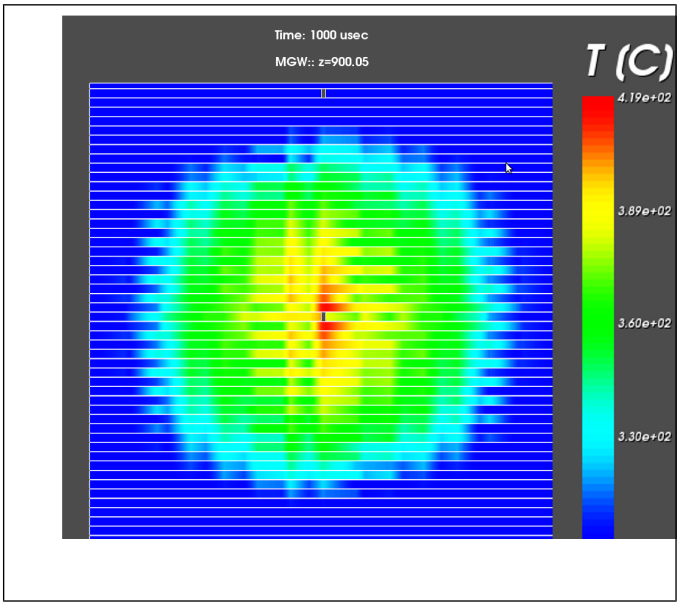

Figure 3. Cross section of local temperatures in the active area.

IV. CONCLUSIONS

We presented a new method for dealing with electro-thermal simulation. Contrary to the long-known technology computer-aided design approach (TCAD) where also the electrical and thermal equations are solved self-consistently, we have avoided the need for computing the detailed carrier distributions by incorporating all junction and depletion-region related details in compact models. In this way the self consistency is restricted to merely two degrees of freedom per mesh node. We also demonstrated that self consistency is a necessary aspect for dealing with self heating since local temperature is variable at a very local scale.

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