The new approach to the power semiconductor devices modeling

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ABSTRACT

Due to their specific structures the power devices need special models different from those developed for low power electronics. The development of such special models is far from being simple as distributed nature of phenomena often determinates the dynamic response of the device.

In this paper several modeling techniques will be discussed. These include the usage of the hardware description languages as well as of software developed at the Department of Microelectronics and Computer Science, which includes the 2D device simulator MOPS and the distributed model in VHDL-AMS language.

Keywords: Power semiconductor devices, device modeling, circuit simulation, hardware description languages.

1 2D SIMULATION WITH APPLICATION OF MOPS SOFTWARE

The electronic circuit simulation with the application of 2D distributed physical models of power semiconductor devices is very time-consuming and requires very strong computation tools. The physical models of bipolar devices are very complex because of big structure dimensions and high non-linear doping profile. Moreover, it is important to simulate power semiconductor devices with a realistic external circuit.

The development of a software that would enable to develop 2D device models and then to use them in circuit simulation was started by Napieralski and Turowski [1] and continued by Grecki and Jablonski [2]. In the developed MOPS software the computation process can be performed in parallel in order to reduce the computation time. The acceleration of computation in the case of circuits containing 2D distributed physical models of power semiconductor devices is based on the execution of computation tasks in many computers simultaneously.

The MOPS software contains many independent programs working on the different computers which communicate by the PVM (Parallel Virtual Machine) system (see Figure 1). The main program is the control unit, which controls the computation process and performs the circuit analysis. The other modules (D1…Dn) solve the separate power semiconductor equations. A visualization program permits the control of the simulation by the user and the circuit simulation is performed by means of a SPICE interface.

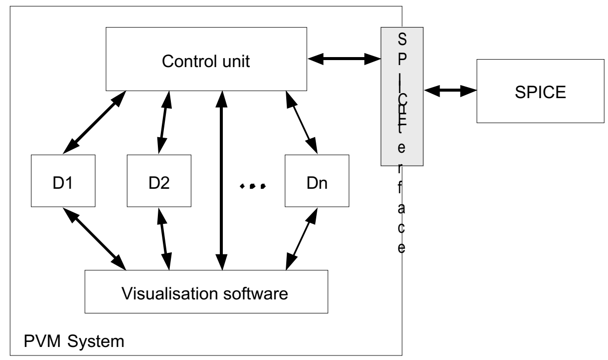

Figure 1: Links between the different modules in the MOPS software in the PVM (Parallel Virtual Machine) system.

Two-dimensional models allow not only to obtain very accurate current and voltage waveforms. They also make it possible to simulate power dissipation and the temperature distribution may then be easily calculated. This is particularly important for high power devices where simulation of thermal behavior is crucial to avoid structure damage during operation. MOPS has been successfully used with power diodes, GTO, SIT and other power bipolar devices.

2 1D PIN DIODE MODEL FOR THE SABER SIMULATOR

The 2D simulators cannot entirely satisfy the needs. Although they provide accurate results, the simulation times – up to 1 day for a complex structure – still are too important to take into account a big number of physical and geometrical parameters when optimising a semiconductor structure. The 2D model may be simplified to a 1D one using the modular approach [3] that consists in discerning in the considered device structure several regions of different physical and/or electrical nature. Then we assign to each of them a simplified sub-model where only the most relevant phenomena are taken into account. This allows for decreasing the simulation time considerably.

This approach will be discussed using the PIN diode example [6]. Like most power semiconductor devices, it contains the wide and lightly doped base layer, which provides high voltage blocking capability and where excess carriers are stored during the on-state. The big width of this central layer makes it necessary to take the distributed nature of phenomena into account. The one-dimensional

Benda-Spenke model [5] has been used for this purpose. The behaviour of stored charge carriers is there described by means of the ambipolar diffusion equation,

$$\frac{\partial^2 p(x,t)}{\partial x^2} - \frac{1}{D}\left(\frac{p(x,t)}{\tau} + \frac{\partial p(x,t)}{\partial t}\right) = 0\,, \tag{1}$$

where: p is the carrier concentration, D is the ambipolar diffusion constant and τ is the common electrons and holes lifetime. As no analytical solution to the equation (1) has been found, many different approaches to numerical solution have been presented. The developed model is based on algorithmic approach, i.e. the solution is obtained with a numerical algorithm [4]. The initial condition is obtained from static analysis, and the carrier concentration distribution at further analysis time steps is calculated using an iterative formula,

$$p_{r,s} = C_1\left(p_{r-1,s-1} + p_{r+1,s-1}\right) - C_2\, p_{r,s-1}\,, \tag{2}$$

where coefficients C_1 and C_2 depend on physical constants and discretization along the x and time axes.

After a solution of (1) is obtained, the negative voltage drop in the space charge region (situated in the lightly doped N^- base between the P^+ emitter and the carrier storage region) can be calculated after applying the Poisson's equation,

$$\frac{dE(x)}{dx} = \frac{\rho(x)}{\varepsilon}\,, \tag{3}$$

where: E is the electric field, _ is the charge density and _ is the permittivity.

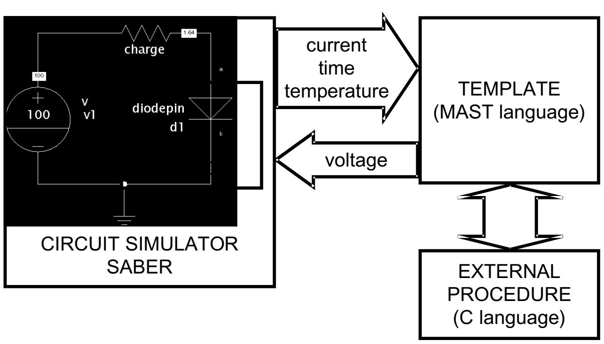

Figure 2: Structure of the PIN diode model for SABER circuit simulator.

The model has been implemented in the hardware description language MAST proper to the circuit simulator SABER [7]. However, some portions of the model couldn't have been handled by MAST and had to be coded in an external C module, which is accessed by the simulation kernel (see Figure 2). This solution causes convergence problems to occur and makes the model hybrid rather than uniform. Therefore, work is now performed to implement power devices models in VHDL-AMS language in order to avoid external procedures.

Some simulation results for the PIN diode during reverse and forward recovery using the MOPS software and the SABER model are presented in Figures 3 and 4.

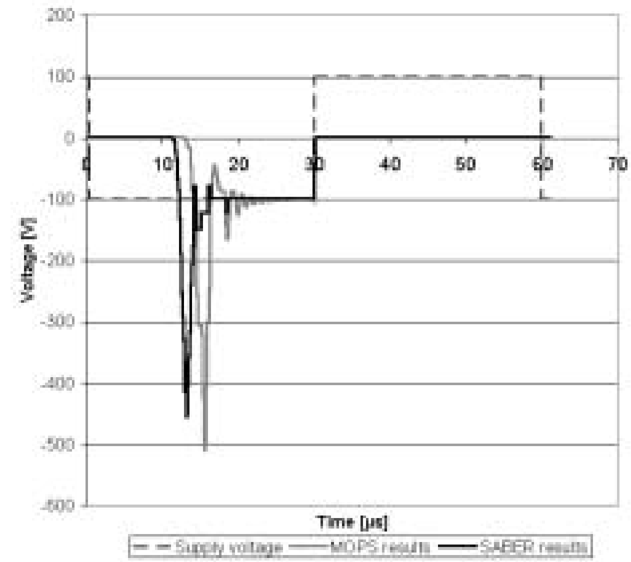

Figure 3: Simulation results of the PIN diode—voltage waveforms.

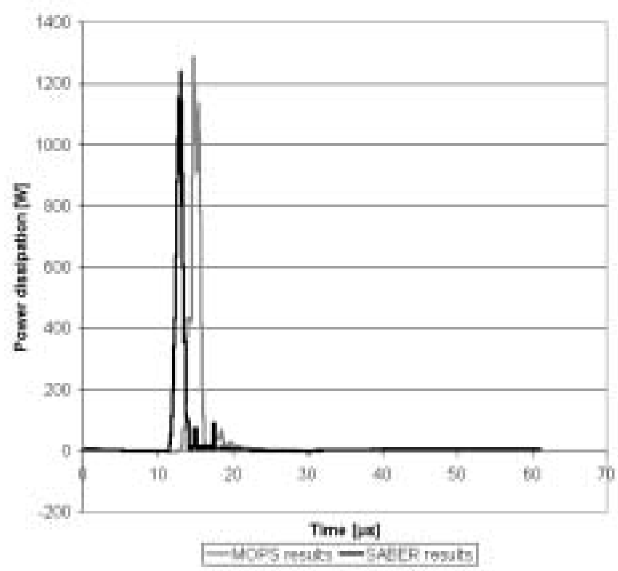

Figure 4: Simulation results of the PIN diode—anode power dissipation waveforms.

3 VHDL-AMS ELECTRO-THERMAL DIODE MODEL

Thermal issues in the integrated circuits are becoming more and more important with the constant improvement of packing density and the resulting growth of power densities involved. When dealing with thermal effects, proper results cannot be obtained without taking into account the interactions between the electrical and the thermal domain.

The VHDL-AMS [8] hardware description language has been approved as the IEEE 1076.1 standard in March 1999. It allows for implementing both behavioral and physical models of devices and systems. It provides also support for multi-domain modeling and simulation, which makes it well suited for electro-thermal coupling modeling.

Let us consider a simple diode model that is described with the following system of equations:

$$I_D = A\left[I_s\left(\exp\frac{V_D}{nV_T} - 1 \right) + \right.$$
$$\left. + k_{gen} I_{sr}\left(\exp\frac{V_D}{n_r V_T} - 1 \right) - I_{bv}\exp\left(-\frac{V_D + V_B}{V_T} \right) \right] \tag{4}$$

$$V_D = V_{AK} - I_D R_s \tag{5}$$

where: I_D is the diode current, V_D is the voltage across the intrinsic diode, V_{AK} is the anode-cathode voltage, A is the junction cross-section area, I_s is the saturation current, I_{sr} is the recombination current parameter, I_{BV} is the reverse breakdown knee current, n and n_r are the emission coefficients, V_T is the thermal voltage, R_s is the serial resistance, k_{gen} is the generation factor, V_B is the reverse breakdown knee voltage and V_J is the junction potential. V_T, I_s, E_g and V_J are temperature-dependent. During device operation, power is dissipated at the junction; the resulting energy emission causes the temperature to raise and the temperature-dependent parameters to vary.

With traditional SPICE-like modeling technique, the only way to implement the model is to create a subcircuit including standard elements. The resulting netlist contains 28 controlled sources; its form is very unclear as it is practically impossible to recognize the model equations.

VHDL-AMS has permitted to decompose the model into smaller blocks, which allows for better understanding of the model and facilitates its further modifications. Thanks to definition of two different natures – electrical and thermal – we can easily discern the thermal and the electrical part of the model. Both mathematical formulas and netlist description may be used whatever needed. The simulation results obtained with the VHDL-AMS model are shown in Figure 5. One can see junction temperature raise waveforms for two different ambient temperature values.

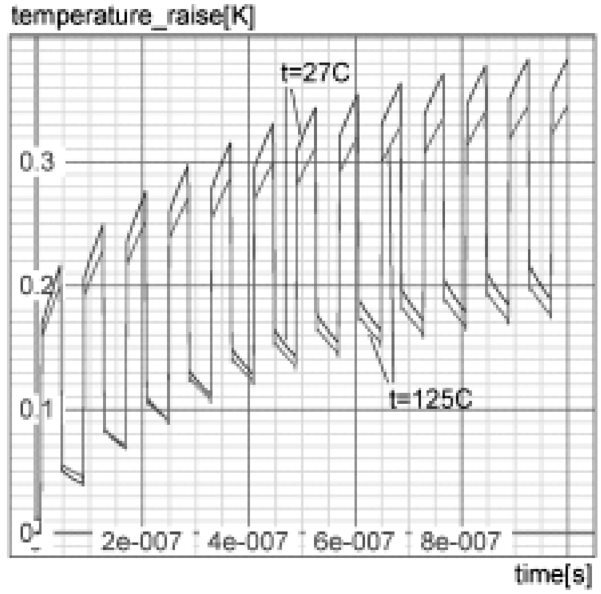

Figure 5: Simulation results of the electro-thermal diode model—junction temperature raise waveforms at t=27 C and t=125 C.

4 VHDL-AMS DISTRIBUTED DIODE MODEL

Most of simulation environments, such as SABER or ELDO ANACAD, are implemented using single precision floating point arithmetics and do not allow direct access to the signal history. Therefore, the one-dimensional distributed model of PIN diode presented in the section two has been implemented partly as an external function in C language (numerical algorithm) and the interface in the simulation language. Proposed model can be useful in the more precise and correct simulation of the whole complex power systems but its new implementation requires additional effort. Hence, the application of the VHDL-AMS language can be attractive from this point of view. The Finite Differences numerical approximation of the Drift-Diffusion (DD) diode model using Scharfetter and Gummel approach [9, 10] are presented in Figure 6. Unfortunately the correct simulation process of this devices should be controlled using break statements and quantity tolerance - not implemented in the chosen hAMSter simulator (VHDL-AMS simulation environment developed by Anasoft Corporation). Therefore, the complete simulations should be performed under efficient simulators compatible with VHDL-AMS standard.

```
LIBRARY DISCIPLINES;
LIBRARY IEEE;
USE DISCIPLINES.ELECTROMAGNETIC_SYSTEM.ALL;
USE IEEE.MATH_REAL.ALL;
ENTITY diode IS
    PORT(TERMINAL a,c: ELECTRICAL);
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```
END diode;
ARCHITECTURE V1_00 OF diode IS
    QUANTITY Vak ACROSS id  THROUGH a TO c;
--normalization factor [cm^-3]
    CONSTANT sfC0:REAL := 2.0E+20;
-- discretization [cm]
    CONSTANT H   : REAL := 1.0E-4;-- ...
    CONSTANT epsilon_Si: REAL := 1.035939974589E-10;
    CONSTANT mi_n: REAL := 1430.0;
    CONSTANT mi_p: REAL := 495.0;
    CONSTANT tau_n: REAL := 1.0E-5;
    CONSTANT tau_p: REAL := 3.3E-6;
    CONSTANT ni   : REAL := 9.45E9;
    CONSTANT nie  : REAL := 9462681909.35065;
    CONSTANT ni_sfC0: REAL := ni/sfC0;
    CONSTANT nie_sfC0  : REAL := nie/sfC0;
    CONSTANT lambda : REAL := epsilon_Si/(q*sfC0);
    CONSTANT Nda1: REAL:=-0.03; -- normalized
    CONSTANT Nda2: REAL:=-0.02990881480357218;--...
    CONSTANT Nda59: REAL:=-1.0708810805215245e-6;
    CONSTANT Nda60: REAL:=7.499999999999999e-7;--...
    CONSTANT Nda194: REAL:=7.499999999999999e-7;
    CONSTANT Nda195: REAL:=1.6240881765309771e-6;--...
    CONSTANT Nda229: REAL:=0.9891769027027469;
    CONSTANT Nda230: REAL:=1.0; -- normalized
    QUANTITY N2 : REAL;--...
    QUANTITY N229 : REAL; QUANTITY P2 : REAL;--...
    QUANTITY P229 : REAL; QUANTITY V2 : REAL;--...
    QUANTITY V229 : REAL;
function R(N0,P0,V0, NP,PP,VP:REAL) return REAL IS
VARIABLE gr,E,Jn,Jp : REAL;
BEGIN
gr:=sfC0*(N0*P0-ni_sfC0*ni_sfC0)/
(tau_n*(N0+nie_sfC0)+tau_p*
(P0+nie_sfC0)); E:=-(VP-V0)/H; Jn:=(N0*E/Ut+(NP-N0)/H)*Dn;
Jp:=(P0*E/Ut-(PP-N0)/H)*Dp;E:=abs(E);
if E>=1.0E-28 then
gr:=gr-(7.03E5*exp(-1.231E6/E)*abs(Jn)+1.582E6*exp(-
2.036E6/E)*abs(Jp));
end if; return gr; END function R;
BEGIN
(lambda*(Vak - V2 + V3))/H == H*(N2 - Nda2 - P2);
(lambda*(V2 - V3 + V4))/H == H*(N3 - Nda3 - P3); --...
 (lambda*(V228 - V229 + 0.0))/H == H*(N229 - Nda229 - P229);
((sqrt(Nda1*Nda1/4.0+ni_sfC0*ni_sfC0)+Nda1/2.0))*B((Vak -
V2)/Ut) - N2*(B((-Vak + V2)/Ut) + B((V2 - V3)/Ut)) + N3*B((-
V2 + V3)/Ut) == R(N2,P2,V2,N3,P3,V3)*H*H/Dn;
N2*B((V2 - V3)/Ut) - N3*(B((-V2 + V3)/Ut) + B((V3 - V4)/Ut))
+ N4*B((-V3 + V4)/Ut) == R(N3,P3,V3,N4,P4,V4) *H*H/Dn; --
...
N228*B((V228 - V229)/Ut) - N229*(B((-V228 + V229)/Ut) +
B((V229 - 0.0)/Ut)) + ((sqrt(Nda230*Nda230/4.0+ni_sfC0*
ni_sfC0)+Nda230/2.0))*B((-V229 + 0.0)/Ut) == R(N229,
P229,V229,N229,P229,0.0)*H*H/Dn;
((sqrt(Nda1*Nda1/4.0+ni_sfC0*ni_sfC0)-Nda1/2.0))*B((-Vak +
V2)/Ut) + P3*B((V2 - V3)/Ut) - P2*(B((Vak - V2)/Ut) + B((-V2
+ V3)/Ut)) == R(N2,P2,V2,N3,P3,V3)*H*H/Dp;
P2*B((-V2 + V3)/Ut) + P4*B((V3 - V4)/Ut) - P3*(B((V2 -
V3)/Ut) + B((-V3 + V4)/Ut)) == R(N3,P3,V3,N4,P4,V4)
*H*H/Dp; --...
P228*B((-V228 + V229)/Ut) +
((sqrt(Nda230*Nda230/4.0+ni_sfC0*
ni_sfC0)-Nda230/2.0))*B((V229 - 0.0)/Ut) - P229*(B((V228 -
V229)/
Ut)+B((-V229+0.0)/Ut))==R(N229,P229,V229,N229,P229,
0.0)*H*H/Dp;
END V1_00;
```

Figure 6: The DD model of diode in the VHDL-AMS.

5 SUMMARY

The simulation and modeling of power semiconductor devices is most imported for the power devices development and complex system verification. In principle, the required model accurate and portability are still crucial for its implementation. The most accurate electro-thermal model should be simulated using specialized simulation environments such MOPS simulator. As it was showed the simulation ability of selected distributed or coupled device phenomena can be enabled under commonly accessible simulation environment. The direct modeling of more complicated phenomena (eg. DD model) is still conditioned on the simulation system solver quality.

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