

Behavioral Modeling and Simulation of Semiconductor Devices and Circuits Using VHDL-AMS

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Abstract: During the past few years, a lot of work has been done on behavioral models and simulation tools. But a need for modeling strategy still remains. The VHDL-AMS language supports the description of analog electronic circuits using Ordinary Differential Algebraic Equations (ODAEs), in addition to its support for describing discrete-event systems. For VHDL-AMS to be useful to the analog design community, efficient semiconductor device models must be available. In this paper, potential merits of the new IEEE VHDL-AMS standard in the field of modeling semiconductor devices are discussed. The device models for diodes and the principles, techniques, and methodology used to achieve the design of an analytical third generation Spice transistor MOS model named EKV are presented. This is done by taking into account the thermoelectrical effect in VHDL-AMS, and with relevant parameters set to match a deep submicron technology developed in VHDL-AMS. The models were validated using System Vision from Mentor Graphics.

Keywords: Behavioral Models, EKV Transistor, ODAE, Semiconductor Devices, Thermoelectrical Effect, VHDL-AMS.

1 Introduction

For the past three decades, hardware description languages (HDLs) have been widely used to model and simulate systems belonging to various engineering fields, from digital and analog electronics to mechanics and chemistry. For a long time, all these fields have been completely separated, each scientific community having its own design methodologies, tools, and idiosyncrasies. Dedicated HDLs supporting the description and the simulation of the logical structure of a system belonging to a particular engineering domain were, and are still available. They allow the description of a system as a possibly hierarchical connection of predefined submodels, or primitives. For example, in the electrical/electronic domain, the SPICE simulator and all its derivatives allow the description of the netlist of a circuit using electrical primitives such as resistors, capacitors, sources and transistors. In an attempt to support the modeling and simulation of nonelectrical

systems as well, several modeling methods using energy equivalences between the electrical domain and other domains, such as mechanical, thermal, or fluidic domains, have been proposed [1].

Neglecting the interaction effects or the cross coupling between parts may have disastrous consequences on the final design in terms of a loss in performance or an increase in design time. One way of addressing this issue is to use a consistent modeling and simulation framework that allows for the description of systems from different disciplines and for the description of interactions between these systems. This is where the VHDL-AMS HDL [2-5] comes in as an effective backbone of the aforementioned framework.

The increasing importance and the growing amount of mixed-signal hardware designs gave rise to the development of new mixed-signal hardware description languages (MS-HDLs). VHDL-AMS was standardized by IEEE recently and has found wide acceptance in industry since. In comparison to traditional analog description languages, such as SPICE, the VHDL-AMS allows mixed analog/digital hardware descriptions on different levels of abstraction ranging from transistor to system level. VHDL-AMS with its unique features such as general Ordinary Differential Algebraic Equations (ODAEs), discontinuity handling and processing, and the ability to communicate between discrete-event and

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continuous-time systems, allows a very rich model expressiveness for describing analog, digital and mixed signal behavior of an electronic circuit.

The analog behavior of an electronic circuit can be effectively described with the help of semiconductor devices, which necessitates the creation of efficient semiconductor device models in VHDL-AMS that are useful to the analog design community. The prime motivation behind this paper is to exploit the rich expressiveness of VHDL-AMS for describing semiconductor devices. Semiconductor device models can be derived from theoretical considerations or from an empirical approach. Based on the theoretical considerations of semiconductor devices, they can be classified into physical device models and equivalent-circuit models.

The organization of this paper is as follows. In the next section we first discuss the most significant features of VHDL-AMS, which are useful in describing the functional semiconductor device model. The advantages of VHDL-AMS in the aspects of multi-technological modeling are also exposed. In Section 3, we present VHDL-AMS modeling of a junction diode and VHDL-AMS model of third generation Spice transistor MOSFET named EKV 3.0 using System Vision. In Section 4, the verification of the model of devices with the test circuits for validation of these models using System Vision and also the experimental results obtained by exercising these test-circuits in SPICE and System Vision is discussed in order to compare the performance and accuracy of the models developed in VHDL-AMS with those already embedded in the SPICE simulator (HSpice). Thermal issues in the integrated circuits are becoming more and more important with the constant improvement of packing density, so without taking into account the thermal effects in modeling, the high accuracy results will not be achieved. For this reason, the electrothermal effect is detailed in Section 5 separately. Finally Section 6 discusses the results and draws some conclusions.

2 VHDL-AMS Modeling and Technological Domains

VHDL-AMS is integrated into several industrial design flows and, thereby, research on language specific issues is increasing. VHDL-AMS models have, like those of VHDL, two major parts: ENTITY and ARCHITECTURE. In the ENTITY part, the peripheral connections are defined via specific nodes related to the considered technological domain. Some variables called QUANTITY are declared, which are transferred to the ARCHITECTURE. In that part, the behavior of a device, a circuit or a system is described using some equations that follow the influence of the environment. Fig. 1 shows the structure of a model written in VHDL-AMS [6].

```
ENTITY entity_name IS
    declaration_of_the_connection
END [ENTITY] [entity_name];

ARCHITECTURE architecture_name OF entity_name
    declaration_of_the_architecture
BEGIN
    Behavioural_and_structural_description
END [ARCHITECTURE] [architecture name];
```

Fig. 1 Structure of a model written in VHDL-AMS.

In order to support conservative systems, VHDL-AMS is comprised of four new fundamental features which are presented below [7]:

2.1 Quantities

They represent the unknowns in the DAE's. Quantities can be scalar or composite (array and records), but must have scalar subelement of a floating point type. In addition to quantities declared *explicitly*, some quantities are declared *implicitly* to represent the dynamic (time-varying) behavior of a continuous-time system in VHDL-AMS, such as *'dot* and *'integ*. The *implicit quantity 'dot* is used to describe the differential of a quantity with respect to time and similarly *'integ* is used to describe the integral of the *quantity* with respect to time.

2.2 Terminals

They represent the nodes *across* or *through* where the *quantities* are defined. In a more general perspective, *terminals* in VHDL-AMS define connecting points where conservative laws will be applied.

2.3 Simultaneous Statements

These statements allow the user to describe Differential and Algebraic Equations (DAEs) which express a relationship among quantities. *Simultaneous statements* can appear anywhere a concurrent signal assignment is allowed. Simple *Simultaneous statements* are used to describe a continuous-time system without discontinuities, whereas *conditional simultaneous statements* are used to describe a continuous-time system.

2.4 Break Statement

It is used to manage discontinuities. In a continuous-time system, a *break statement* can be used to initialize conditions of the system which play an important role in solving the set of equations that represent the continuous-time system. In a mixed-signal system, a *break statement* is often used as a means of linking the discrete-event and continuous-time systems.

VHDL-AMS offers the possibility of choosing between three different modeling concepts: functional, behavioral/ structural and physical. It can also deal with

multiple physical domains. This makes VHDL-AMS suitable for development of models of semiconductor devices [6]. Table 1 presents a list of technological domains, called also *Natures* and their characteristics. Certain domains might appear unexpected, like financial and colorimetric domains.

3 VHDL-AMS Modeling of Devices

The main goal of this section is to present the application of VHDL-AMS through some examples.

3.1 Model of a Junction Diode

Firstly, we implement a VHDL-AMS model for a diode as described in Fig. 2. The below mathematical equations describe this diode:

$$i_d = I_s \left(e^{(v_d - R_s i_d) / N \cdot V_T} - 1 \right) \quad (1)$$

$$i_c = \frac{d}{dt} \left(TT \cdot i_d - 2 \cdot C_{j0} \cdot \sqrt{V_j^2 - V_j \cdot v_d} \right) \quad (2)$$

Table 1 Technological domains of VHDL-AMS [6].

NATURE	ACROSS	THROUGH
Electrical	Voltage	Current
Thermal	Temperature	Power (W)
Mechanical	Position (m)	Force (N)
Mechanical (rot.)	Ang.velocity (rad/sec)	Torque (N*m)
Magnetical	Magnetic Force	Flux (Wb)
Hydraulical	Pressure (Pa)	Fluid flow
Radiative	Dose (rad)	(Photo) Current

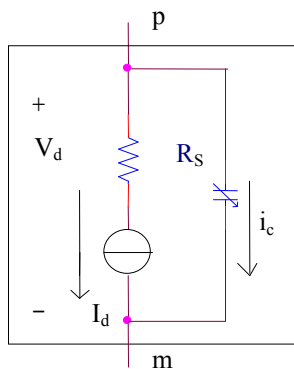


Fig. 2 Model of diode.

The description of these equations in VHDL-AMS is similar to the syntax of VHDL. Fig. 3 shows the VHDL-AMS model of diode. The name of the library *IEEE* means that the definitions contained in these packages can be used. The model interface is described in the *entity* declaration and is decomposed into the specification of generic parameters and interface ports. The diode's behavior is defined in a separate architecture body called *model*. The *quantities* in VHDL-AMS correspond to the unknowns of the above-mentioned equations and can be solved by an analog solver.

3.2 Electrical Model of the EKV 3.0 MOS Transistor

The EPFL-EKV MOSFET is a scalable and compact simulation model built on fundamental physical properties of the MOS structure. This model is dedicated to the design and simulation of low-voltage, low-current analog, and mixed analog-digital circuits using submicron CMOS technologies. This model has an important common feature: it is a charge-based model, meaning the terminal charges are associated with terminal voltages. This is one of the key points of the so-called third generation models. EKV 3.0 model is based on surface potential model combined with inversion charge linearization. The EKV model has gained in popularity owing to its simplicity. In addition, the EKV model has many other attractive features, which are listed below [8-11].

```

library IEEE;
use IEEE.MATH_REAL.all;
use IEEE.ELECTRICAL_SYSTEM.all;
library DICIPLINES;
use DICIPLINES_PHYSICAL.all;
use DICIPLINES_MAGNETIC_SYSTEM.all;
entity diode is
    generic (ISS, N, VT,
            TT, CJO, VJ, RS: Real);
    port (terminal p, m: Electrical);
end entity diode;
library IEEE;
use IEEE.Math_real.all;
architecture model of diode is
    quantity vd across id, ic through p to m;
    quantity qc: Real;
begin
    id == ISS *
        (exp((vd-RS*id)/(N*VT)) - 1.0);
    qc == TT*id - 2.O*CJO *
        sqrt(VJ**2 - VJ*vd);
    ic == qc'Dot
end architecture model;

```

Fig. 3 VHDL-AMS model of diode.

- Usage of substrate node as reference for all voltages. This is shown in Fig. 4.
- Symmetric forward/reverse operation of the MOSFET.
- Static, quasi-static, NQS aspects and thermal noise are consistent.
- Uses normalization of model quantities.
- An efficient approximation for depletion/accumulation charge.
- Single-expression model that preserves continuity for improved convergence in circuit simulation.
- High-field, short-channel, and narrow width effects including mobility degradation, velocity saturation, channel-length modulation (CLM), source-drain charge sharing (CS), and reverse short-channel effect (RSCE).
- Short-channel thermal noise modeling.
- Physics-based, thus minimum number of parameters.
- Quantum mechanical effects (QME).
- Specially suited for analog/RF application.
- Implementation in Circuit Simulators.
- Intrinsic Model: ~ 40 Parameters.

The expressions for model equations are given below.

$$I_{\text{spec}} = 2n\beta U_T^2 \quad (3)$$

$$\beta = KP \frac{W}{L} \quad (4)$$

$$U_T = KT/q \quad (5)$$

$$V_p = \frac{V_G - V_{TO}}{n_v} \quad (6)$$

$$n_v = 1 + \frac{\gamma}{2\sqrt{\phi + V_p}} \quad (7)$$

$$V_{TO} = V_{FB} + \phi + \gamma\sqrt{\phi} \quad (8)$$

$$v_p = \frac{V_p}{U_T} \quad \text{and} \quad v_{S(D)} = \frac{V_{S(D)}}{U_T} \quad (9)$$

$$v_p - v_{S(D)} = \ln(q_{f(r)}) + 2q_{f(r)} \quad (10)$$

$$i_{f(r)} = q_{f(r)}^2 + q_{f(r)} \quad (11)$$

$$I_D = I_{\text{spec}} (i_f - i_r) \quad (12)$$

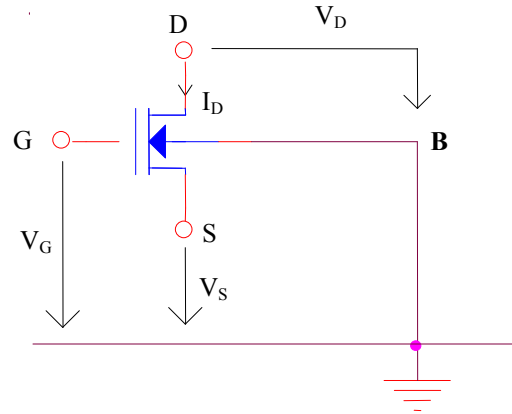


Fig. 4 Voltage definitions used in EKV model.

where I_{spec} is the specific current, V_p is the pinch-off voltage that relates the effect of the gate voltage, V_G , to the channel, V_{TO} is the threshold voltage, U_T is the thermal voltage, n_v is the slope factor and is a function of, V_p , n is charge linearization factor, ϕ is the bulk Fermi potential, and γ is the body effect factor. In order to ease the comparison among transconductances over different regions of inversion, and channel lengths, the current and voltages are normalized.

Fig. 5 shows the VHDL-AMS code for the EKV 3.0 model, named EKV.

```

library IEEE;
use IEEE.MATH_REAL.all;
Use IEEE.ELECTRICAL_SYSTEMS.all;
Use IEEE.ENERGY_SYSTEMS.all;
Use IEEE.THERMAL_SYSTEMS.all;

entity EKV is
  generic(
    micron: REAL :=1.0E-6;
    mili: real :=1.0e-3;
    n: real := 1.4;
    W: real := 1.0*1.0E-6;
    L: real := 0.15 *1.0E-6;
    VFB: real:= 0.45;
    PHI: real :=0.9;
    GMA: real :=0.71;
    KP: real:= 450.0*1.0E-6;
    THETA: REAL:= 50.0*1.0E-6;
    K: REAL :=1.4E-24;
    Q: REAL := 1.6E-19);
  port(
    terminal d,s,g,b: lectrical);
end entity EKV;
architecture model of EKV is
  constant KOQ :real:= K/Q;
  constant TEMPREF: real:= 300.0;
  -- quantities of electrical branch
  quantity vg across g to b;
  quantity vd across d to b;
  quantity vs across s to b;
  quantity id through d to s;

```

```

function F(constant v: real) return real is
  variable x: real;
begin
  return ((v**2)+v);
end function F;

quantity vt,qf,qr,iff,irr,beta,nv,n,vp,iss,
  vps,vpd :real;
begin
  ut== KOQ*TEMPREF;
  vt == VFB + PHI + GMA*sqrt(PHI);
  vp == (vg-vt)/nv;
  nv== 1.0+(GMA/(2.0*sqrt(PHI+vp)));
  vps==(vp-vs)/ut;
  vpd==(vp-vd)/ut;
  .
  .
  .
  qf== 0.5*(vp-vs-log(qf));
  qr== 0.5*(vp-vd-log(qr));
  iff == F(qf);
  irr==F(qr);
  beta==KP*(W/L);
  iss==2.0*n*beta*ut*ut;
  id== iss*(iff-irr);
end architecture model;

```

Fig. 5 VHDL-AMS model of EKV.

4 Verification of Device Models

To validate the characteristics of the junction diode we use a full wave rectifier circuit as shown in Fig. 6. The transformer shown in this figure is mainly used to exploit the expressive power of VHDL-AMS to

describe complex electrical circuits in addition to the device models.

The resulting waveforms by simulating this circuit in System Vision is shown in Fig. 7.

The second example shows the use of System Vision [12] for applying the methodology in a simple case: EKV 3.0 MOSFET behavioral modeling. Fig. 8 shows DC i_{ds} (v_{ds} , v_{gs}) characteristics of the EKV 3.0 MOSFET transistor. These examples have been simulated with Hspice simulator. The resulting waveforms are in close agreement with each other. We have developed VHDL-AMS models for half wave rectifier, inverter, VCO and PLL. The results are shown in Table 3. As can be seen in this section, we have developed VHDL-AMS models for several other devices such as Zener diode and BJT.

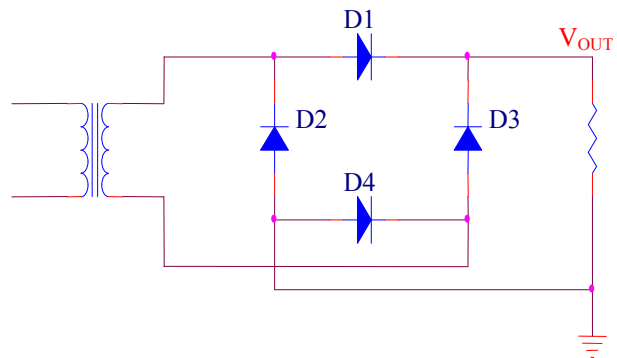


Fig. 6 Full wave rectifier circuit.

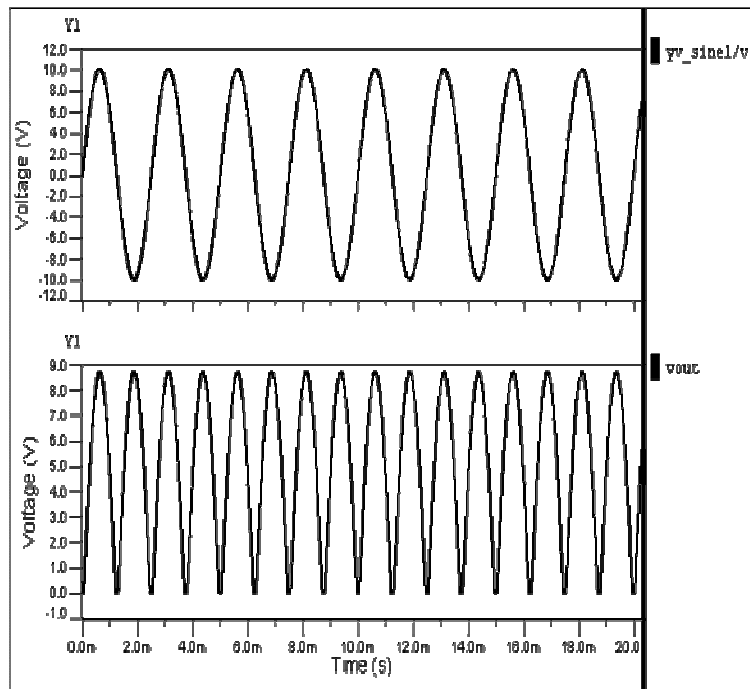


Fig. 7 VHDL-AMS simulation result.

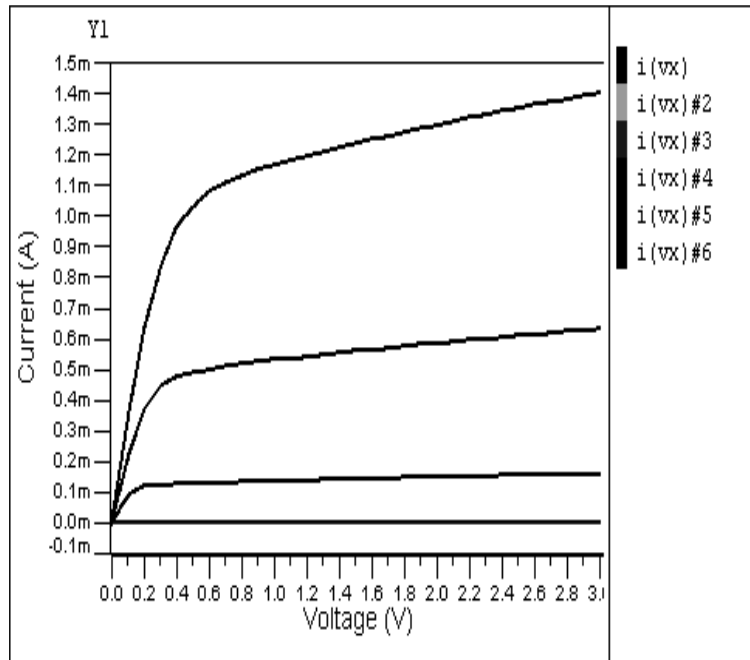


Fig. 8 ids (vds) characteristic.

To investigate the accuracy of the VHDL-AMS models by Hspice, we compare the result of execution time and error agreement percentage of VHDL-AMS with Hspice for above-mentioned circuits as shown in Table 3. Simulation results of these models with both simulators are comparable and show a good agreement with each other. According to the results, it can be seen that by increasing the complexity of the circuit, the behavioral modeling is the preferred method of simulation in a reasonable time and with a reasonable percentage of error.

The benefit of the behavioral model is specially felt in SOC (System On Chip) circuits design [13-15]. In these circuits which contain millions of transistors in analog and digital blocks on a common substrate, the analog and the digital blocks need to be simulated together. Transistor-level simulations are not feasible for this purpose. Behavioral modeling offers a possible way to abstract the features of interest in a circuit block in a reasonable time and at a reasonable cost.

5 Coupled Electrothermal Effect

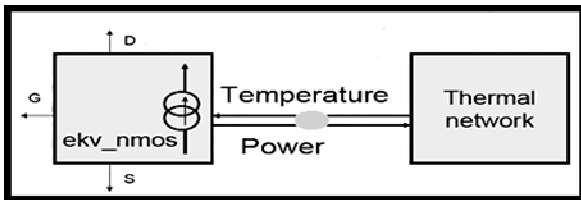
Thermal issues in the integrated circuits are becoming more and more important with the constant improvement of packing density and the resulting growth of power densities involved. When dealing with thermal effects, proper results cannot be obtained without taking into account the interactions between the electrical and the thermal domain. Since the size of the semiconductor devices is becoming smaller with advanced technology, and since the electrical characteristics of semiconductor devices are greatly

influenced by the temperature distribution inside the semiconductor devices (self-heating effects), it is important to simulate the coupled electrical and thermal systems simultaneously [16, 17]. Because most of the nonlinear semiconductor device models are implemented in the circuit simulators, it is advantageous to perform electrothermal simulations inside circuit simulators. The simulation temperature however, must be chosen by the user prior to the simulation and hence must remain constant at the predetermined value during the simulation, which can severely limit the scope for CAD. Semiconductor devices dissipate a considerable amount of heat and are often operated in high-temperature environments; this directly influences both their static and dynamic operational characteristics, and their associated failure rates. For these reasons, adding thermal effects to the circuit simulators requires the use of thermal circuit networks. A good approach to achieving high accuracy is to simulate the coupled electrical and thermal systems simultaneously. Fig. 9 shows the thermo-electrical interaction in semiconductor devices. The thermal system is governed by the Partial Differential Equation (PDE's) and the nonlinear electrical system is governed by the semiconductor equations (PDE's) and circuit equations (Ordinary Differential Equations-ODE's) [17, 18].

FDM(Finite Differential Method), FEM (Finite Element Method), FVM (Finite Volume Method), and BEM (Boundary Element Method) are popularly employed to solve these equations. But using these methods requires large amount of memory space and long run time of CPU.

Table 3 Comparison of accuracy and simulation time in VHDL-AMS and Hspice.

Circuit	Simulation time		Error percentage
	System Vision	Hspice	
Half wave Rectifier	290msec	310msec	1.5 %
Full wave Rectifier	570msec	720msec	3.5 %
Zener diode Voltage Reg.	330msec	510msec	2.7 %
Inverter BJT	620msec	15 sec	4.8 %
VCO	15 sec	150 sec	5.2 %
PLL	55 sec	800sec	9.7 %

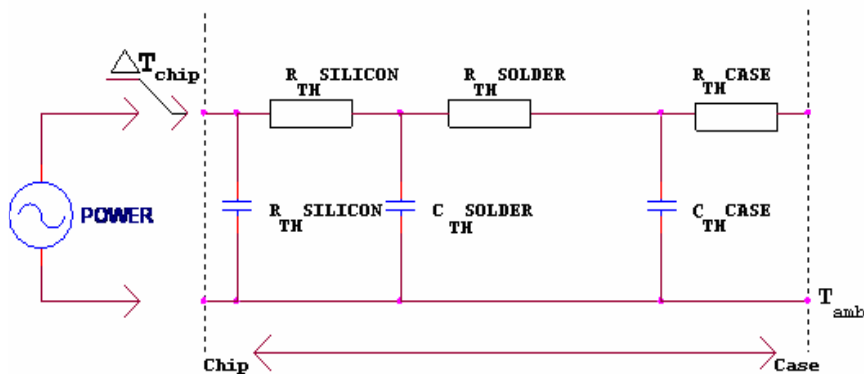
**Fig. 9** The thermo-electrical interaction [19].

VHDL-AMS offers the possibility of choosing between three different modeling concepts: functional, behavioral/structural and physical, dealing with multiple physical domains. This makes VHDL-AMS suitable for development of models of semiconductor devices [19].

5.1 Establishing the Thermal Network

The thermal system is governed by the partial differential equation:

$$\text{div}(K \text{ grad } T) = \rho c \frac{\partial T}{\partial t} \quad (13)$$

**Fig. 10** The thermal model [18].

where ρ is the material density, c is the specific heat capacity, and k is the thermal conductivity. Boundary conditions on conductive boundary and convective boundary (all other surfaces) are given by [18]:

$$k \frac{\partial T}{\partial n} = \begin{cases} \frac{P}{A} & \text{conductive} \\ h(T_a - T) & \text{convective} \end{cases} \quad (14)$$

where n is the vector normal to the boundary surface, P is input power dissipated in the top surface of the Si chip, A is the power cross section area, and T_a is the ambient temperature [18], [20].

In this context, for simplicity, thermal phenomena are described by one-dimensional (1-D) analytical model:

$$\frac{\partial^2 T(x, t)}{\partial x^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t} \quad (15)$$

The application of the Fourier transform shows that this equation may be represented by the well known RC network model (Fig. 10) [16], [18]. In this circuit current represents heat flow and potentials represent node temperatures. The current source value equals the dissipated power p and the voltage drop across the source is equal to the temperature of the silicon chip (ΔT_{chip}). There are different methods for determination of resistance and capacitance values in this model. The accuracy of the calculated values for R_{th} and C_{th} can be substantially improved considering that the heat flow follows a truncated cone with a cone angle varying according to the thicknesses and the thermal conductivities of the concerned layers [6], [18], [20].

The following values for the properties of the silicon substrate and its boundaries are used:

$$k = 1.41 \left[\frac{\text{W}}{\text{K} \cdot \text{cm}} \right] \quad (16)$$

$$\rho = 2.3 \left[\frac{\text{g}}{\text{cm}^3} \right] \quad (17)$$

$$c = 0.7 \left[\frac{\text{J}}{\text{g} \cdot \text{K}} \right] \quad (18)$$

$$h = 1000 \left[\frac{\text{W}}{\text{cm}^2 \cdot \text{K}} \right] \quad (19)$$

5.2 Electrothermal Modeling

VHDL-AMS provides an elegant solution to thermal-electronic interactions. Among the various packages provided with the simulation environment, the thermal system package simply adds thermal capabilities to electrical models. Fig. 11 shows how the electrothermal interactions between MOST and its direct environment and puts emphasis on the fact that the instantaneous power dissipated by the EKV model is directly propagated to the thermal node t_j , and also presents a complete design to validate the methodology. The transistor thus acts as a power source in the thermal network. Reciprocally, the instantaneous temperature computed by the RC network and back-propagated to the thermal node of the n-MOST model is the operating temperature of the n-MOST model. This allows the MOST model to adjust its characteristic equations as a function of its operating temperature. To take into account the thermal effect in this model, the thermal port, t_j , is introduced with relative *through* and *across* quantities bound to power and temperature respectively. The final EKV interface then becomes:

```
entity ekv1 is
port (terminal d,g,s,b : electrical ;
terminal tj : thermal);
end;
```

with the following quantity relations:

```
quantity temp across power through tj to thermal_ground ;
```

Showing that the temperature $temp$ is measured between the port and the thermal reference, while the heat power is flowing out of the device from the thermal

reference to the port. Thus, the thermal interaction is really bidirectional and the self-heating behavior of the device is properly taken into account. Thermal resistance and capacitance can respectively be described by these two statements:

```
temp == rth * power ;
power == cth * temp'dot ;
```

Using this approach, the VHDL-AMS code for thermal resistance and capacitance is shown below:

```
entity cthermal is
generic (
cth : thermal_capacitance; --
t_ic:temperature := real'low);
port (
terminal th1, th2 : thermal);
end entity cthermal;
architecture linear of cthermal is
quantity temp across power through th1 to th2;
begin
if domain = quiescent_domain and t_ic /= real'low use
temp == t_ic;
else
power == cth * temp'dot;
end use;
end architecture linear;
-- thermal resistance model -----
entity rthermal is
generic (
rth : thermal_resistance);
port (
terminal th1, th2 : thermal);
end entity rthermal;
architecture linear of rthermal is
begin
temp == power*rth;
end architecture linear;
```

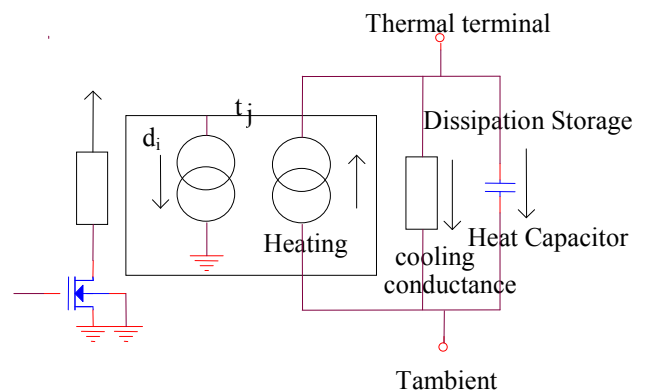


Fig. 11 Electrothermal interactions.

As is, the EKV model can be used to obtain numerous valuable simulation results. This section presents a few set of results examples. In the following simulations, the values of the thermal network are deliberately overstated in order to emphasize the downgrading of electrical characteristics. Fig. 12 presents the output characteristic of the MOST with the thermal effect which is comparable to Fig. 8 (without consideration of thermal effect).

Fig. 13 shows the simulation of the chip temperature variation and case temperature variation versus time during commutation of the transistor when the transistor is stimulated by a square wave stimulus and connected to the thermal RC network. The thermal network represents the thermal constants of the various material layers, and the values of the capacitances and resistances have been deliberately oversized to highlight the thermal effects.

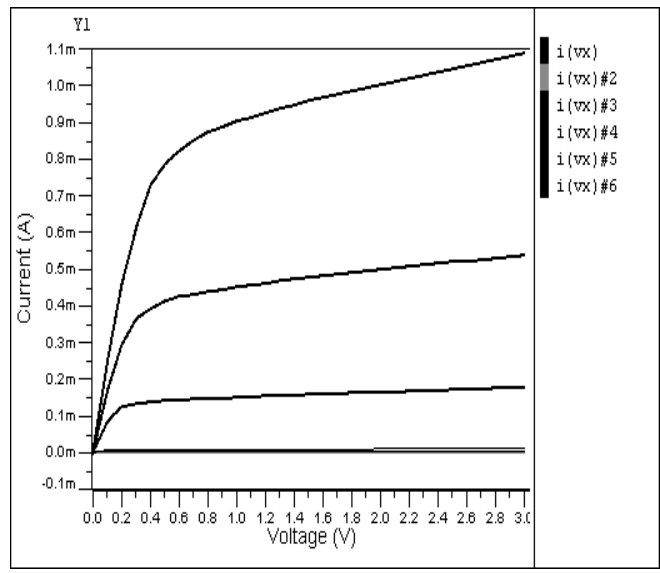


Fig. 12 Output characteristic with the thermal effect.

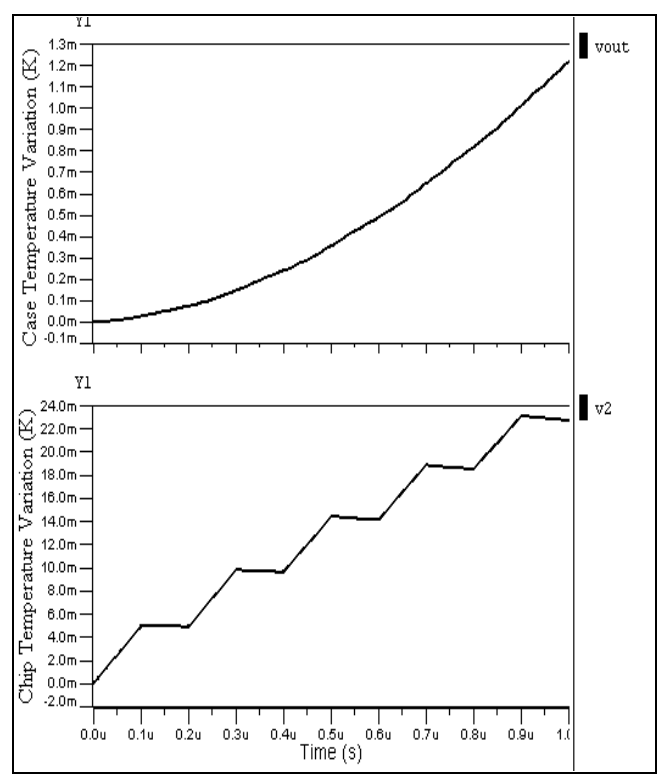


Fig. 13 The simulation of the chip temperature variation and case temperature variation versus time during commutation.

According to the result, it can be seen that behavioral modeling is the preferred way of simulation in a reasonable time and reasonable cost and simulation results are comparable with other similar works [8], [11].

6 Conclusion

In this paper potential merits of the new IEEE VHDL-AMS standard in the field of modeling semiconductor devices have been discussed. This work has described a strategy of modeling a diode and EKV 3.0 MOSFET by using VHDL-AMS. Simulation results of these models with both simulators were comparable and showed a good agreement with each other.

According to the results, it can be seen that by increasing the complexity of the circuit, the behavioral modeling is the preferred method of simulation in a reasonable time and at a reasonable cost. The electrothermal effect was also addressed. The EKV 3.0 model was presented taking into account the electrothermal effect. It was initially applied to simple devices before being applied to the complete system, using the potentiality of multi domain. The utilities of the methodology can be found in the development of electrothermal model which can create a library of models that allow a selection out of a range of temperatures. The models were validated by employing an appropriate test-bench and simulated using System Vision.

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