Modeling and Simulating Semiconductor Devices using VHDL-AMS

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Abstract

The VHDL-AMS[1] 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 model must be available. This paper attempts to exploit the rich expressiveness of VHDL-AMS to describe semiconductor device models. The device models for diodes and transistors have been developed in VHDL-AMS and were validated using SEAMS[2], a mixed-signal simulator under development at the Distributed Processing Laboratory, University of Cincinnati.

Keywords

Analog, Mixed-Signal, Semiconductor, Transistor, Large-signal, Models, Simulated.

1 Introduction

VHDL-AMS with it's uniques features such as general ordinary differential algebraic equations(ODAEs), discontinuity handling and processing and the ability to communicate between discrete-event and continuous-time systems, allow 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.* Physical device models are based on the carrier transport equations of device physics while the equivalent-circuit models are based on the electrical characteristics of the device in association with the device structure. The equivalent-circuit models relate the dimensions of the device to the electrical properties of the device and transform the carrier transport equations of the device into closed loop analytical equations, which are easier and faster to solve, hence are preferred over physical device models for computer-aided circuit analysis. SPICE[3] is one of the widely used analog circuit simulator, which exclusively uses equivalent-circuit models to represent semiconductor devices. Hence, we chose SPICE[4] equivalent-circuit models for semiconductor devices to be represented in VHDL-AMS. This also serves the purpose of comparing our results, for accuracy, with that of the SPICE[5] simulator.

Over recent years, several semiconductor device models have been designed for representation in SPICE [10]. The device models presented in this paper, which were described in VHDL-AMS[6] [7] are based on the LEVEL 1 models of the SPICE simulator [2][3]. This paper presents a set of diode and transistor models useful for describing active electronic circuits in VHDL-AMS. Prior to this paper, no other device models described in VHDL-AMS were presented, which are know to simulate correctly.

In this paper, we first discuss the most significant features of VHDL-AMS, which were useful in describing the functional semiconductor device models. Then we present a junction diode model along with the test-

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[1] **A**nalog and **M**ixed **S**ignal extensions to VHDL(**V**ery high speed integrated circuit **H**ardware **D**esription **L**anguage)

[2] **S**imulation **E**nvironment for vhdl-**AMS**

[3] **S**imulation **P**rogram with **I**ntegrated **C**ircuit **E**mphasis

[4] here SPICE is referred to with a general meaning

[5] here after, the SPICE simulator refers to the SPICE3 simulator, the SPICE language refers to the language used for the SPICE3 simulator

[6] syntax and semantics according to Language Refernce Manual(LRM) April 1998

circuits, which were used for validating these models using SEAMS[7] [1]. Later we present the experimental results obtained by excercising these test-circuits in SPICE and SEAMS to compare the performance and accuracy of the models developed in VHDL-AMS with those already embedded in the SPICE simulator. Lastly we conclude this paper with a few remarks and also provide with some information on the related research.

2 VHDL-AMS

IEEE Std. 1076-1993 [5] together with *IEEE Std. 1076.1-1999* [4] is informally known as VHDL-AMS [6]. The VHDL-AMS language targets the behavior of both discrete-event systems and continuous-time systems. The most significant features of VHDL-AMS which were used for describing semiconductor device models are presented here:

- **Quantities**, by themselves, represent the static behavior of a continuous-time system. The representation of the dynamic behavior(time-varying) behavior of a continuous-time system is facilitated, in VHDL-AMS, with the help of *implicit quantities* 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.

- **Terminals** represent the nodes *across* or *through* which the *quantities* are defined. In a more general perspective, *terminals* in VHDL-AMS represent the nodes in an electrical circuit, through which the electrical components remain connected to each other.

- **Simultaneous statements** are used to describe the behavior of a continuous-time system by means of ODAEs. *Simple Simulatneous statements* are used to describe a continuous-time system without discontinuities, where as *conditional simultaneous statements* are used to describe a continuous-time system with first-order discontinuities or non-linear piece-wise characteristics of a system.

- **Break Statement** is used to describe a range of properties of a mixed-signal system. In a continuous-time system a *break statement* can be used to describe the discontinuities in the system or to describe the initial conditions of the system, which play a significant 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 communication between the discrete-event and continuous-time systems.

- **Nature** in VHDL-AMS represents the physical domain for a conservative system. The semiconductor device models (equivalent-circuit models) fall into the category of electrical *nature*, which obeys the *Kirchoff's Voltage and current laws* (conservative laws for a system of electrical nature).

- **Across and Through** quantities preseve the laws of conservation in any physical system. The *across quantites* in an electrical system represent the voltages across two *terminals* and the *through quantities* represent the current through the *terminals*.

VHDL-AMS has many other unique features which allow rich model expressiveness. Here we have discussed only a few of those features pertinent to this paper. To learm more about the features of VHDL-AMS please refer to the language reference manual(LRM) [7]. The application of the features discussed above, to describe semiconductor device models, will be presented in the following section.

3 Semiconductor Device Models

Before we introduce the device models we present a few rules to be followed for correct execution of the models described in VHDL-AMS.

3.1 VHDL-AMS Rules

Here we present a few rules to be obeyed for proper execution of models, especially device models, described in VHDL-AMS.

- A neccessary, but not sufficient, condition for the solvability of the models is to ensure that *the total number of unknowns in the model should be equal to the total number of characteristics equations in the model.* The total number of unknowns in the model is determined by the total number of *free quantities*, *through quantities* and *interface quantities* with mode *out*. the total number of characteristic equations in a model is determined by the total number of scalar simultaneous statements in the model.

- The discontinuities in quantities and their derivatives should be dealt with utter caution. The discontinities in first derivative are usually used

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[7] version 1.1b

to express the non-linear piece-wise behavior of a system. It should be made sure that the two consecutive piece-wise regions should converge to a same value at the point of dicontinuity.

- Intial conditions play a signficant role in solving a set of equations representing a continuous-time system.
- Device models mostly use some form of dependent(controlled) sources to represent its behavior. Dependent sources may lead to “divide by zero” situations in the model. These situations should be avoided.
- Model parameters are very important in characterizing a model. Unrealistic model parameters may lead to unsovability of the model.

These were a few observations made while creating device models in VHDL-AMS. For other modeling guidelines and techniques please refer to the tutorial [11] made available by Analogy Inc. [9].

3.2 VHDL-AMS models

Here we present the equivalent-circuit models of the semiconductor devices described in VHDL-AMS. The equivalent-circuit models are strongly dependent on frequency, DC bais and signal level. Based on these criteria the equivalent-circuit models can be broadly divided into static, large-signal and small-signal models. By static models we refer to those models which operate for low frequecies(Say below 1kHz) or at DC and are independent of signal-level. By large-signal models we refer to those models which operate at high-frequencies, take into account the charge-storage effects of devices and can tolerate large-signal variations. By small-signal models we refer to those models, which are same as large-signal models but can tolerate only small-signal variations around the DC operating point. The small-signal models are implicitly represented in the SPICE simulator by linearing the large-signal models around the DC operating point, hence are not discussed here. Here we present only the large-signal models, which can operate for all frequencies and all signal levels. The static models are treated as a subset of large-signal models and are presented in conjunction with them. Only the large-signal model for a junction diode is presented here to accommodate the imposed page limitations. For a complete list of models please refer to [12].

3.2.1 Large-Signal Model of a Junction Diode

The most fundamental linear element of lumped parameter electronic circuits is the semiconductor junction diode. At low frequencies or at DC, the realistic approximation of a junction diode can be represented by a non-linear current source(I_D) in series with a ohmic resistance as shown in Figure 1(a)(without the capacitor), whose value is determined by the following relations:

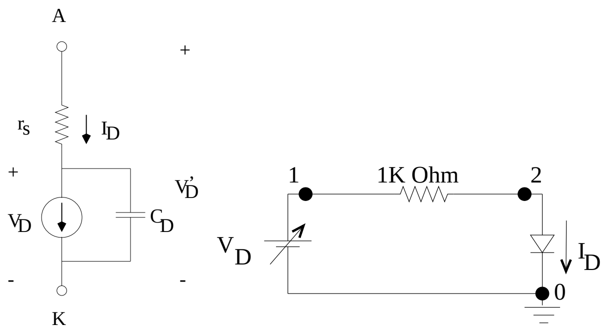

Figure 1: (a) Large signal model of a Diode (b) Curve Tracer Circuit

$$I_D = \begin{cases} I_S(e^{qV_D/nkT} - 1) & \text{for} \quad V_D \geq -5\frac{nkT}{q} \\ I_S & \text{for} \quad -\text{BV} \leq V_D \leq -5\frac{nkT}{q} \\ -\text{IBV} & \text{for} \quad V_D = -\text{BV} \\ I_S(e^{-q(BV+V_D)/kT} & \\ \quad -1 + \frac{qBV}{kT}) & \text{for} \quad V_D \leq -\text{BV} \end{cases} \tag{1}$$

where V_D is the voltage applied across the diode junction, I_S is the saturation current, n is the emission coefficient, BV is the breakdown voltage and IBV is the breakdown current.

To represent these characteristics of a junction diode in VHDL-AMS we use *simultaneous if statement*, which belongs to the class of a *conditional simultaneous statements*. The following VHDL-AMS code represents the description of the non-linear current source I_D, as a function of junction voltage V_D.

```
diodecondition : if(vd >= -5.0*(vt*n)) use
  dfow : id == ((isat*(exp(vd/(vt*n))
                        - 1.0)) + (gmin*vd));
elsif(vd < -5.0*(vt*n)  and (vd > -1.0*bv))
                                            use
  drev: id == ((-1.0*isat) + (gmin*vd));
elsif vd = -1.0*bv use
  dbv : id == -1.0*ibv;
elsif vd < -1.0*bv use
  blbv : id == -1.0*Isat*(exp(-1.0*((bv
             + vd)/vt)) - 1.0 + (bv/vt));
end use;
```

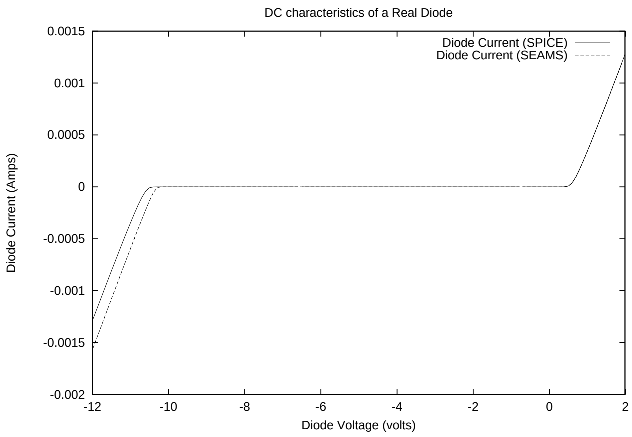

Figure 2: DC Characteristics of a real Diode under static conditions

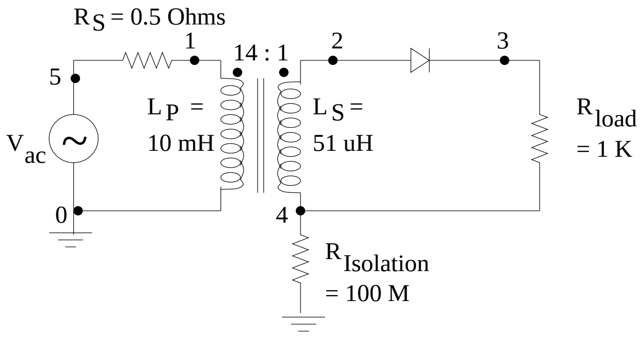

Figure 3: Half-wave rectifier circuit

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brk : break vd => -1.0;
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where GMIN, a transconductance factor, is included to aid convergence of the model. In addition to the *simultaneous if statement*, we also used the *simple break statement* to describe the initial condition of the model, which ensures the first solution point to lie in the reverse region of a junction diode operation.

The charge-storage effects, which are very significant at high frequencies, are represented by the capacitor C_D as shown Figure 1(a). The capacitance C_D, which is a sum of junction(depletion) capacitance(C_j) and diffusion capacitance(C_d), is given by the following relations:

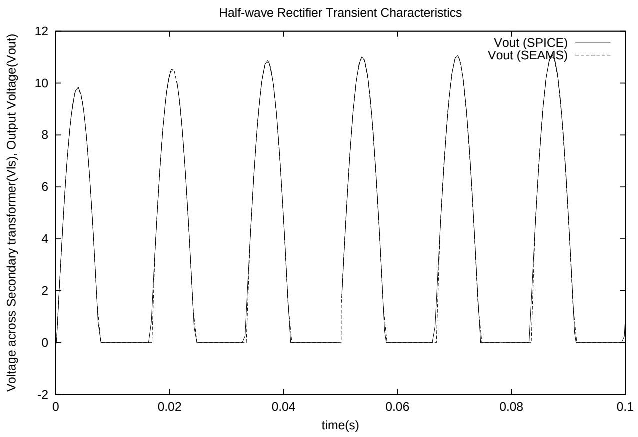

Figure 4: Half-wave rectifier circuit transient characteristics

$$C_D = \begin{cases} \tau_D \frac{dI_D}{dV_D} + C_j(0)\left(1-\frac{V_D}{\phi_0}\right)^{-m} & \text{for} \quad V_D \le FC \times \phi_0 \\ \tau_D \frac{dI_D}{dV_D} + \frac{C_j(0)}{F_2}\left(F_3+\frac{mV_D}{\phi_0}\right) & \text{for} \quad V_D \ge FC \times \phi_0 \end{cases} \tag{2}$$

where τ_d is the transit time, $C_j(0)$ is the zero-bais junction capacitance, m is the grading coefficient, ϕ_0 is the junction potential, FC is the coefficient of forward-bias depletion capacitance formula and F_2 and F_3 are the model constants, whose values are given by the following relations.

$$\begin{aligned} F_2 &= (1-FC)^{1+m} \\ F_3 &= 1-FC(1+m) \end{aligned} \tag{3}$$

These capacitance relations are described in VHDL-AMS with the help of *simultaneous if statments* and a *simple break statement*, similar to those presented above for a non-linear current source I_D.

To validate the static characteristics of a junction diode model, we set up a curve tracer arrangement as shown in Figure 1(b). This arrangement is used to obtain the terminal characters of a junction diode under static(DC) conditions. The resulting waverforms obtained by excercising this circuit in SPICE and SEAMS are shown in Figure 2. It can be seen that both the waveforms are in close affrement with each other. The parameter values[8] of the diode used in this curve tracer circuit are shown in Table 1. To validatge the large-signal characteriscties of a junction

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[8] the NA values in the table represent Not Applicable for this circuit

Parameter	Description	Value	
		Curve Tracer	Half-wave Rectifier
IS	saturation current (I_S)	100pA	0.1 pA
RS	ohmic resistance (r_S)	16	16
N	emission coefficient (n)	1.679	1
BV	breakdown voltage (BV)	10V	100V
IBV	breakdown current (IBV)	1nA	0.1pA
TT	Transit time (τ_D)	NA	12n
CJO	Zero-bias junction capacitance [$C_j(0)$]	NA	2p

Table 1: Junction Diode Parameter Values

diode we set up a half-wave rectifier circuit arrangement as shown in Figure 3. The transofrmer 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 transformer converts the main power supply to a 12v peak voltage, which is then rectified by the diode. The resulting waveforms obtained by excercising this circiuit in SPICE and SEAMS are shown in Figure 4. As can be seen in the figure both the waveforms are in close agreement with each other. The parameter values of the diode used in this half-wave rectifer circuit are shown in Table 1.

4 Experimental Results

In the previous section we presented the large-signal model of a junction diode. As a part of the research carried at our laboratory we have developed VHDL-AMS models for several other semiconductor devices such as BJT[9], JFET[10] and MOSFET[11]. All the models were validated by incorporating them in several test circuits and exercising these test-circuits both in SPICE and SEAMS. The results(waveforms) obtained from the SPICE simulator are assumed to be accurate and is used as a reference for comparing the VHDL-AMS models executed in SEAMS.

Machine hardware	:	sun4u
Operating System	:	SunOS 5.7
Processor type	:	sparc
Number of Processors	:	4

Table 2: Platform used for Simulations

The criteria used for comparing the accuracy of the VHDL-AMS models with those in SPICE is *precentage maximum peak-peak error*(ϵ_{p-p}), which can be defined as the ratio of maximum peak-peak error between the waveforms(ϵ_{max}) and maximum peak-peak signal variation in the reference waveform(Δ_{p-p}).

$$\% \text{ maximum peak-peak error}(\epsilon_{p-p}) = \frac{|\epsilon_{max}|}{|\Delta_{p-p}|} \times 100 \qquad (4)$$

In addition to comparing the accuracy of the VHDL-AMS models with those in SPICE, we also compared the performance of the simulators, SPICE3 and SEAMS so as to aid research being carried at our laboratory to improve the performance of SEAMS. For this purpose we compare the execution times of the test-circuits in SPICE and SEAMS and the specifications of the platform used for these simulations is given in Table 2. It was observed that the execution time was varying with the total number of points solved. Hence, we developed another criteria, *average execution time per point*, to compare the performance of SEAMS with SPICE.

The percentage maximum peak-peak error calculated for the test-circuits[12] incorporating diode, BJT and MOSFET models are given in Table 3. The average exection time per point ratio, which is defined as the ratio of average execution per point in SEAMS and the average execution time per point in SPICE, for the test-circuits is also tabulated. As shown in the table the error between the waveforms obtained from SPICE and SEAMS is well within acceptable range. It can also be noticed that the error increases with the complexity of the model or test-circuit increases. As can be seen in the table the execution time for simulating a model in SEAMS is large as compared to that in SPICE. This large ratio of execution times can be attributed to many factors of SEAMS. The first and very significant reason is that SEAMS is a mixed-signal simulator and SPICE is a special purpose analog circuit simulator. The second reason is that the discontinuity identification and processing techniques

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[9] Bipolar Junction Transistor

[10] Junction Field-Effect Transistor

[11] Metal-Oxide Seminconductor Field-Effect Transistor

[12] all the test-circuits listed here employ large-signal device models

Model Circuit	Sim Time	Avg Exec Time per point(ms)		Exec Time Ratio	% max p-p error
		SPICE	SEAMS		
Diode Half-wave Rectifier	100 ms	0.648	22.095	34.09	1.04 %
Diode Voltage Doubler	10 ms	0.572	27.072	47.32	1.99 %
Diode DC Restorer	10 ms	0.386	35.043	90.78	3.20 %
npn BJT Switch	25 ms	0.655	48.129	73.47	5.65 %
pnp BJT Switch	20 ms	0.564	41.324	73.26	4.38 %
p-MOS Inverter	200 ns	0.494	151.38	306.43	5.75 %
n-MOS Inverter	200 ns	0.554	74.987	135.27	5.75 %

Table 3: Accuracy and Performace of VHDL-AMS models as compared to those in SPICE

employed in SEAMS differ from those employed in SPICE and almost all the test-circuits presented here have a finite number of discontinuities. Here also it is observed that the execution time ratio increases with the complexity of the model or the test-circuit.

5 Conclusions and Future Work

The primary goal of the research presented in this paper was to exploit the rich expressiveness of VHDL-AMS to describe semiconductor devices. We have developed models for a junction diode, BJT, JFET and MOSFET using VHDL-AMS as a part of research at our laboratory; here we presented only the large-signal model of a junction diode. All these models were validated by employing appropriate test-circuits and were simulated using SEAMS and SPICE. The models developed in VHDL-AMS were observed to be well within the acceptable range of accuracy as compared to those in SPICE. The performance of SEAMS is observed to be very poor as compared to the SPICE simulator and the reasons for the poor performance are also discussed. At this early stage of research, VHDL-AMS soure-level transistor models are inefficient compared to SPICE or other analog circuit simulators, with a well-defined analog modeling capability. This leads to the need for further research for semiconductor models that are tuned to VHDL-AMS description capabilities; models that may look quite different than those we are used to today. *This paper presents the first known functional device models developed in VHDL-AMS that are known to simulate correctly.*

This research is being continued at our laboratory to improve the performance of SEAMS and also to investigate into the possibility of designing novel approaches for representing device models, taking into consideration the features of VHDL-AMS.

Complete thesis [12] describing this effort is available at our laboratory (Distributed Processing Laboratory) home page [1]. The VHDL-AMS code for all the models and test-circuits is also available at the same site. The mixed-signal simulator, SEAMS, can also be downloaded from the same site.

Acknowledgements

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