The Role of TCAD in Compact Modeling

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ABSTRACT

This paper is an introduction to semiconductor process and device simulation and its role in compact modeling for circuit simulation. A brief history of TCAD is given. One use of TCAD is in the generation of compact models for circuit simulation. TCAD also has an emerging role in the development of the compact models themselves. Examples of TCAD being used for both these applications are presented.

Keywords: TCAD, compact modeling, semiconductor, simulation.

1 TCAD

1.1 Definitions

TCAD, or Technology CAD, is the numeric simulation of semiconductor processes and devices. A semiconductor process recipe, including times, temperatures, doses, and energies, is used as the input to a process simulator, which then produces a final cross-sectional structure. This structure is passed to a device simulator, which predicts the electrical behavior of the device. The device characteristics can be collapsed into a set of coefficients of a compact model, which are then used in a circuit simulator.

1.2 History

The history of commercial TCAD began with the formation of Technology Modeling Associates (TMA) in 1979. The software was an outgrowth of research done at Stanford under the direction of Professors Dutton and Plummer. The most famous of the Stanford TCAD software programs are SUPREM and PISCES. SUPREM3 is a one-dimensional process simulator, while SUPREM4 is two-dimensional. PISCES is the corresponding two-dimensional device simulator. These are general purpose simulators, designed to work with arbitrary semiconductor structures. TMA's versions of these programs were TSUPREM4 and MEDICI. Silvaco later licensed these programs from Stanford and offered a commercial alternative (ATHENA and ATLAS). The third major TCAD vendor is Integrated Systems Engineering (ISE). Their equivalent product offerings are DIOS and DESSIS. TMA was later acquired by Avant!, which is now in the process of being acquired by Synopsis.

MOSFET specific device simulators include MINIMOS from the Technical University of Vienna and SEQUOIA Device Designer. FLOOPS/FLOODS are process/device simulators available from the University of Florida. Other well known simulators include IBM's FEDSS/FIELDAY, and Agere's PROPHET/PADRE.

There are certainly earlier examples of numeric simulation of semiconductors [1-3]. A good early history of process simulation can be found in [4].

1.3 Applications and Limitations

Major semiconductor manufacturers routinely use TCAD for process and device development. Key advantages of a simulation based approach are rapid prototyping and the ability to analyze the internal aspects of devices. TCAD is typically used to simulate a single device. An extended region that includes several devices can also be simulated, as in a latch-up analysis. Despite strong adherence by its proponents, pockets of TCAD skepticism remain within the industry. The underlying cause of this skepticism is due to the fact that cases can always be found where TCAD does not correctly predict the experimental results. Two of the primary reasons for these discrepancies are the lack of adequate metrology in determining two-dimensional dopant profiles, and the constant evolution of technology. This evolution results in new material introductions, as well as the need to account for more effects as the technology is scaled (e.g., quantum mechanical modeling of gate oxide capacitance; mechanical stress effects). More on TCAD applications and challenges can be found in [5-6].

2 COMPACT MODELING

There is a natural connection between TCAD and ECAD, with compact modeling as the bridge between them. Unfortunately, few engineers work in both worlds. Nonetheless, there have been some successful uses of TCAD in compact modeling.

2.1 Compact Model Development

One potential use of TCAD is in the development of the compact models themselves (as opposed to the parameters for those models). Most standard compact models have not taken this route. There are some recent examples of this application, although often for special devices. A frequency dependent compact model for MOS capacitors was developed, using TCAD to verify the model [8]. A new equivalent circuit model for the basic p-n junction was created using TCAD as an "arbiter" to access various approximations during its development [9]. Power MOSFETs are often simulated using conventional low-voltage elements. A modified version of SPICE was created for lateral DMOS transistors that began with a physically based TCAD model [10]. A SPICE sub-circuit was developed for an ESD protection device with extensive use of TCAD tools [11].

More recently, a revolutionary new approach for compact model development was presented [12]. Equivalent circuits are automatically generated from device simulation.

2.2 Compact Model Coefficients

TCAD is frequently used for the generation of compact model coefficients; more often than the literature would indicate. For expediency, technology development and circuit design proceed in parallel. That is, circuits are designed before the process technology is developed. This results in "Rev_0" compact models. A key advantage to using TCAD for Rev_0 models is that the parameters will be physically self-consistent.

Nearly thirty years ago, this approach was outlined in an IEDM abstract [13]:

> Transistor simulators, computer programs which calculate device characteristics as determined by materials properties and impurity profiles, can be employed directly in the performance evaluation of circuit designs. To be practical, two-dimensional effects must be included while simulation costs must not be prohibitive. The program TRANSIM described in this paper, employs a highly efficient algorithm specialized for bipolar transistor simulation, which reduces simulation costs for one-dimensional analysis by an order of magnitude over previously published approaches. Two-dimensional effects are approximated without the complexity of a full two-dimensional analysis.

Simulation based compact models are advantageous for high frequency effects, where analytic formulas may not be adequate [14]. They are also useful when a technology contains a variety of device types (e.g., digital, analog, low and high power, and non-volatile) [15] or whenever the there is a break in the technology (e.g., migration from bulk to SOI). A commonly cited weakness of simulation based compact models is the lack of widely available three-dimensional process simulators. But in a manner analogous to the abstract above, narrow width effects can be approximated by two or more two-dimensional devices in parallel.

An alternative to TCAD based compact models are simpler geometry and process based models. A handful of process and geometric factors control much of the device behavior, especially in a MOSFET [16]. Similarly, a small number of electrical parameters are important to the circuit performance. An approach has been outlined for efficiently generating compact models using these facts, although TCAD remains a component in the process [17].

2.3 Statistical Compact Models

A robust circuit design requires knowledge about the variation in key device parameters. TCAD has been used extensively to estimate these effects [18-19]. Starting with a baseline process simulation, known process variations can be simulated in a Monte Carlo fashion to generate statistical distributions of device or even circuit parameters. This approach can be used to discern correlations between compact model parameters and to generate realistic worst-case corner models.

3 SUMMARY

The role of TCAD in compact model development and coefficient estimation was presented. TCAD is widely used to generate compact models before a process technology is developed, although this is not meant to imply that it is universally used for this purpose. Historically, TCAD was not used to develop the compact models themselves, but that may be changing. TCAD has also found application in the generation of statistical compact models, which are useful for yield and performance improvement. There are certainly opportunities for further interactions as devices continue to scale and new devices emerge.

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